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*J.C. Pernetta and P.J. Hughes (Eds.):*

# *Implications of expected climate changes in the South Pacific region: an overview*

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# PREFACE

In spite of uncertainties surrounding the predicted climate changes, greenhouse gases seem to have accumulated in the atmosphere to such a level that the changes may have started already and their continuation may now be inevitable.

The environmental problems associated with the potential impact of expected climate changes may prove to be among the major environmental problems facing the marine environment and adjacent coastal areas in the near future. Therefore, in line with the Decision of the Fourteenth Session of the UNEP Governing Council on "Global climate change"[1], the Oceans and Coastal Areas Programme Activity Centre (OCA/PAC) of UNEP launched and supported a number of activities designed to assess the potential impact of climate changes and to assist the Governments in identification and implementation of suitable response measures which may mitigate the negative consequences of the impact.

In 1987, Task Teams on Implications of Climate Change were established for six regions covered by the UNEP Regional Seas Programme (Mediterranean, Wider Caribbean, South Pacific, East Asian Seas, South Asian Seas and South-East Pacific). The Task Team for the South Pacific region was jointly sponsored by UNEP, the Association of South Pacific Environmental Institutions (ASPEI) and by the South Pacific Regional Environment Programme (SPREP), with ASPEI co-ordinating the work of the Task Team.

The initial objective of the Task Teams was to prepare regional overviews and site specific case studies on the possible impact of predicted climate changes on the ecological systems, as well as on the socio-economic structures and activities of their respective regions. The overviews and case studies were expected:

- to examine the possible effects of the sea level changes on the coastal ecosystems (deltas, estuaries, wetlands, coastal plains, coral reefs, mangroves, lagoons, etc.);

- to examine the possible effects of temperature elevations on the terrestrial and aquatic ecosystems, including the possible effects on economically important species;

- to examine the possible effects of climatic, physiographic and ecological changes on the socio-economic structures and activities; and

- to determine areas or systems which appear to be most vulnerable to the above changes.

The regional studies were intended to cover the marine environment and adjacent coastal areas influenced by or influencing the marine environment.

The regional studies prepared by the Task Teams were planned to be presented to the intergovernmental meetings convened in the framework of the relevant Regional Seas Action Plans in order to draw the countries' attention to the problems associated with expected climate change and to prompt their involvement in development of policy options and response measures suitable for their region.

The site specific case studies developed by the Task Teams were planned to be presented to national seminars.

Once the initial objective of the Task Teams (impact studies) is achieved, they concentrate on providing assistance to national authorities in defining specific policy options and suitable response measures.

A preliminary version of this publication was the basic working document of a special intergovernmental meeting convened by SPREP, ASPEI and UNEP in mid-1989 in Marshall islands for the 19 island States of the South Pacific to consider their policy options, suitable response mechanisms and additional site specific case studies to be developed[2].

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[1] UNEP/GC/DEC/14/20.

[2] Report of the SPC/UNEP/ASPEI Intergovernmental meeting on climatic change and sea level rise in the South Pacific (Majuro, 17-20 July 1989), SPC, 1989.

This publication was prepared by Messrs. J.C. Pernetta and P.J. Hughes on the basis of the work carried out by the UNEP/ASPEI/SPREP Task Team on Implications of Climate Change in the South Pacific region. The Task Team comprised J.C. Pernetta (Team Coordinator), G. McGregor, P. Hughes, M. Sullivan, P. Nunn, L. Bualia, and M. O'Collins. The report was edited and prepared for publication by Philip Tortell of Environmental Management Limited, New Zealand.

## EDITORIAL FOREWORD

In late 1986 the Oceans and Coastal Areas Programme Activity Centre (OCA/PCA) of the United Nations Environment Programme (UNEP) proposed to the Association of South Pacific Environmental Institutions (ASPEI) the formation of a regional task team to investigate the potential impacts of global warming on the island countries of the South Pacific. A task team was formed, and over the last two years 19 individuals from nine Institutions and five different countries have contributed the reviews of available data, and individual site-specific case studies relevant to the region, which are contained in this volume.

In mid-1988 at the Intergovernmental Meeting held in Noumea, New Caledonia to consider the work programme of the South Pacific Regional Environmental Programme (SPREP) a preliminary report of the team's work was presented. At this meeting the suggestion was made that following completion of the work a special Intergovernmental Meeting should be held of representatives of the SPREP member countries to review the likely impacts of global warming and to plan future courses of action.

The preliminary report was expanded, revised and presented to the Joint Meeting of the Task Team on Implications of Climatic Changes in the Mediterranean and the Co-ordinators of Task Teams for the Caribbean, South-East Pacific, South Pacific, East Asian Seas and South Asian Seas Regions held in Split, Yugoslavia, in October 1988. Subsequently additional studies were completed and a popular booklet, entitled 'A Climate of Crisis', on the potential impacts was produced. These documents were then presented to an Intergovernmental Meeting of SPREP member countries held in Majuro, Republic of the Marshall Islands, in July 1989. This meeting recommended various courses of action including the preparation of eight country studies. The meeting also passed a strong resolution calling on the industrialised nations to provide technical and financial assistance to countries such as the smaller island nations of the Pacific, which have contributed little to the greenhouse problem but which are likely to be severely impacted.

To date no other region has held such a meeting of high level government officials and scientific advisors and the SPREP region therefore provides a model which may be followed in other Regional Seas Programme Areas. Several of the larger developed countries in the region already have in place national programmes of awareness raising, impact prediction, planning and policy-making. For the smaller developing countries of the Pacific basin, such national programmes may place too great a strain on their limited manpower and financial resources. The task team therefore has a role to play in assisting the implementation of the recommendations of the Majuro meeting, since through its work the team makes available to smaller countries lacking scientific manpower the skills and expertise necessary to conduct an appraisal of individual country policy and planning needs.

In line with UNEP's desire to foster inter-regional co-operation and linkages, representatives of the South Asian and Caribbean task teams participated as observers in the Majuro meeting, sharing their similar concerns and experiences with the Pacific islands representatives. In December 1988 the co-ordinator of the task team for the Pacific region was asked, together with a member of the Mediterranean task team, to visit the Republic of the Maldives and prepare a report on proposed assistance from UNEP to the Government of the Maldives in planning for climatic change. The Maldivian islands and the atoll states of the Pacific are physically very similar, and face similar impacts resulting from global warming. The need for inter-linkage and sharing of experiences is therefore obvious.

The present volume contains the results of the South Pacific task team's work between March 1987 and March 1989; it represents a first attempt at identifying the potential impacts of global warming and sea level rise which might be expected to affect the countries of the Pacific Basin. Not all impacts will be evenly felt throughout the region, with those impacts of importance to small atolls being quite different from those which can be expected on the higher islands of Melanesia. Nevertheless, no country within the region can expect to emerge unscathed from the changes which face the region over the coming decades. It is timely therefore that national appraisals should be undertaken to more specifically identify those impacts which are applicable to particular areas and countries and determine the likely economic and social costs of those impacts. Equally important will be the development of policy and planning alternatives to assist the governments of the region in mitigating the expected impacts. The next phase of the task team's work aims to address these issues at a national level.

The first two papers in this report provide an overview of the potential impacts of climatic change in the region as a whole, and the first paper concludes with recommendations for future investigations, many of which are already being implemented. The next seven papers examine at a regional or sub-regional level likely impacts on specific, often inter-related, aspects of the physical, biological, social and economic environment: these are climate, the physical environments of atolls and tropical riverine lowlands, island groundwater resources, agricultural crops and Pacific islands social, cultural and economic systems. The remaining papers are site-specific case studies which concentrate on the likely impacts of sea level rise on a diverse range of coastal locations throughout the region. The concluding paper addresses the likely effects that climatic change will have on agricultural production in the highlands of Papua New Guinea.

John Pernetta and Philip Hughes

August 1989

## ACKNOWLEDGEMENTS

The task team members wish to place on record their appreciation of the financial support accorded this work by OCA/PAC and the contributions of many individuals to the provision of information and personal experiences which have been utilised in the preparation of many of the papers contained in this report.

Typing of the many drafts was undertaken without complaint by Mary George and Kwani Kego; their patience and accuracy is gratefully acknowledged by the editors, as is the sub-editorial assistance of Pam Flannery and the cartographic services of Vagoli Bouauka.

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# GLOSSARY

| | |
|---|---|
| % | per cent |
| $CO_2$ | carbon dioxide |
| °C | degrees Celcius (or centigrade) |
| | |
| mm | millimetres |
| cm | centimetres |
| m | metres |
| km | kilometres |
| $m^2$ | square metres |
| ha | hectares |
| $km^2$ | square kilometres |
| $m^3$ | cubic metres |
| | |
| °& ' N & S | degrees and minutes of latitude North and South |
| °& ' E & W | degrees and minutes of longitude East and West |

# OVERVIEW OF POTENTIAL IMPACTS OF CLIMATIC CHANGE IN THE SPREP REGION

**ASPEI Task Team Members**

## BACKGROUND

An International Conference was convened by UNEP/WMO/ICSO in October 1985 to assess the role of carbon dioxide and other atmospheric constituents with similar properties, on climatic change, and the consequential, associated environmental and socio-economic impacts. Scientific consensus has been reached that increased concentrations of greenhouse gases in the atmosphere will cause significant changes to the earth's biosphere within the next few decades.

If present trends continue, the change in level of greenhouse gases in the atmosphere would be equivalent to a doubling of carbon dioxide from pre-industrial levels by around the year 2030. This is predicted to cause a warming of global average temperatures of between 1.5 and 4.5°C. This in turn will lead to sea level rise through a combination of factors involving, thermal expansion of the sea, ice melt and changes in albedo. The extent of this consequent sea level rise is subject to some disagreements; estimates vary from the ultra conservative of a mere 20 cm to estimates of several metres. Estimates vary according to the input parameters of the models used.

Local variations may be expected as evidenced by the global, spatial differences of the time by which maximum sea level was achieved following the climatic amelioration post the most recent glacial maximum. Local variations will be enhanced by existing and future changes in tectonic patterns which result in some Pacific islands currently sinking, others rising.

Recognising the potentially enormous environmental, social and economic impacts which could arise from quite small changes in existing sea levels many countries have established national programmes to examine and evaluate potential impacts on coastal systems and plan accordingly. Cognizant of the importance of sea level changes to the small island states of the Pacific Basin, and cognizant further of the inability of most Pacific island states to independently evaluate potential impacts, ASPEI proposed in September 1986 to initiate and undertake a regional review of potential impacts. This proposal was financially supported by the Coastal and Oceans Programme Activity Centre (OCA/PAC) of UNEP, through the South Pacific Regional Environment Programme (SPREP).

## OBJECTIVES

To examine on a regional basis the potential effects of projected sea level changes on the coastal ecosystems, including reefs, lagoons, mangroves, coastal river flood plains.

To examine the possible effects of climatic change (particularly temperature elevations) on the terrestrial and aquatic ecosystems, with special reference to the effects on economically important species.

To examine the potential effects of climatic, physiographic and ecological changes on the socio-economic structures and activities of the South Pacific States and Territories.

To identify primary areas of need in terms of further research and contingency planning.

## WORKPLAN AND TIMETABLE

A working group of principal investigators was established in 1987 to co-ordinate inputs from specialists in the region. Each sub-group has used the projections of sea level rise as adopted by the regional seas programme of UNEP.

To date researchers have prepared case studies covering individual aspects of the projected changes as they might be expected to affect particular locations. Case study reports are contained in this document. A four day meeting was held in April 1988 at which the regional overview was prepared for submission to the 4th consultative meeting and SPREP Inter-Governmental meeting in June 1988.

The report identifies areas of immediate regional concern for research and monitoring. It presents recommendations for immediate and medium term actions on the part of SPREP.

## RESULTS: IDENTIFICATION OF POTENTIAL IMPACTS

### Climatic impacts

#### Model

The model adopted during these studies assumes a 2°C rise in temperature by the year 2100 AD for the tropical Pacific Region. This gives an approximate rate of warming of 0.3°C/decade.

Table 1. Relationship between global warming and warming of low latitudes assumed during the present studies.

| Year AD | Mean global warming | Range for low latitudes |
|---|---|---|
| 2000 | 0.5 | 0.45-0.35 |
| 2020 | 0.8 | 0.72-0.56 |
| 2040 | 1.4 | 1.26-0.98 |
| 2060 | 2.0 | 1.80-1.40 |
| 2080 | 2.5 | 2.25-1.75 |

This model is conservative and changes greater than this are predicted under different assumptions. While the magnitude of the change may be subject to debate, scientists are generally agreed that such changes will occur within the foreseeable future.

#### Climatic change impacts

Figure 1 provides a flow chart indicating the interactions and linkages between the various climatic components and vegetation. Of major importance to the Pacific island states are changes in regional circulation patterns which can be expected to change local climates quite dramatically.

In general it seems likely that areas currently receiving the bulk of their rainfall during the southeast season will continue to do so. Some of these areas may in fact experience slight increases in rainfall amounts. Areas in which a southeast dry season predominates may experience a prolongation of the dry period. Northwest season rainfall amounts will decrease slightly with implications for those areas which are heavily dependent upon northwesterly rains for the bulk of their annual rainfall.

Small island states or regions of larger countries which presently experience pronounced dry seasons are likely to be affected by desertification by the year 2100. These include the Port Moresby area, Trans-Fly, Markham-Ramu, and Sepik areas of Papua New Guinea; western Viti Levu in Fiji and parts of Vanuatu, the Solomon Islands and New Caledonia.

Storm erosion is likely to increase in desertified areas due to increased exposure of the soil surface.

Seasonal duration will change with most of Papua New Guinea having a shorter wet season for example and surface wind patterns may result in prolongation of dry seasons (McGregor, this volume). A northwards shift of the tropical convergence zone may result in changes to the surface wind patterns, oceanic currents and zones of upwelling.

Changes to wind patterns will impact via waves on coastal beach plan forms, resulting in increased shore-line retreat and erosion in some areas.

Changes in the distribution of zones of upwelling may affect both subsistence and commercial fisheries production within the exclusive economic zones of island states.

Frequency of cyclonic storms in the Milne Bay Province of Papua New Guinea, in Vanuatu and the Solomon Islands may be expected to increase.

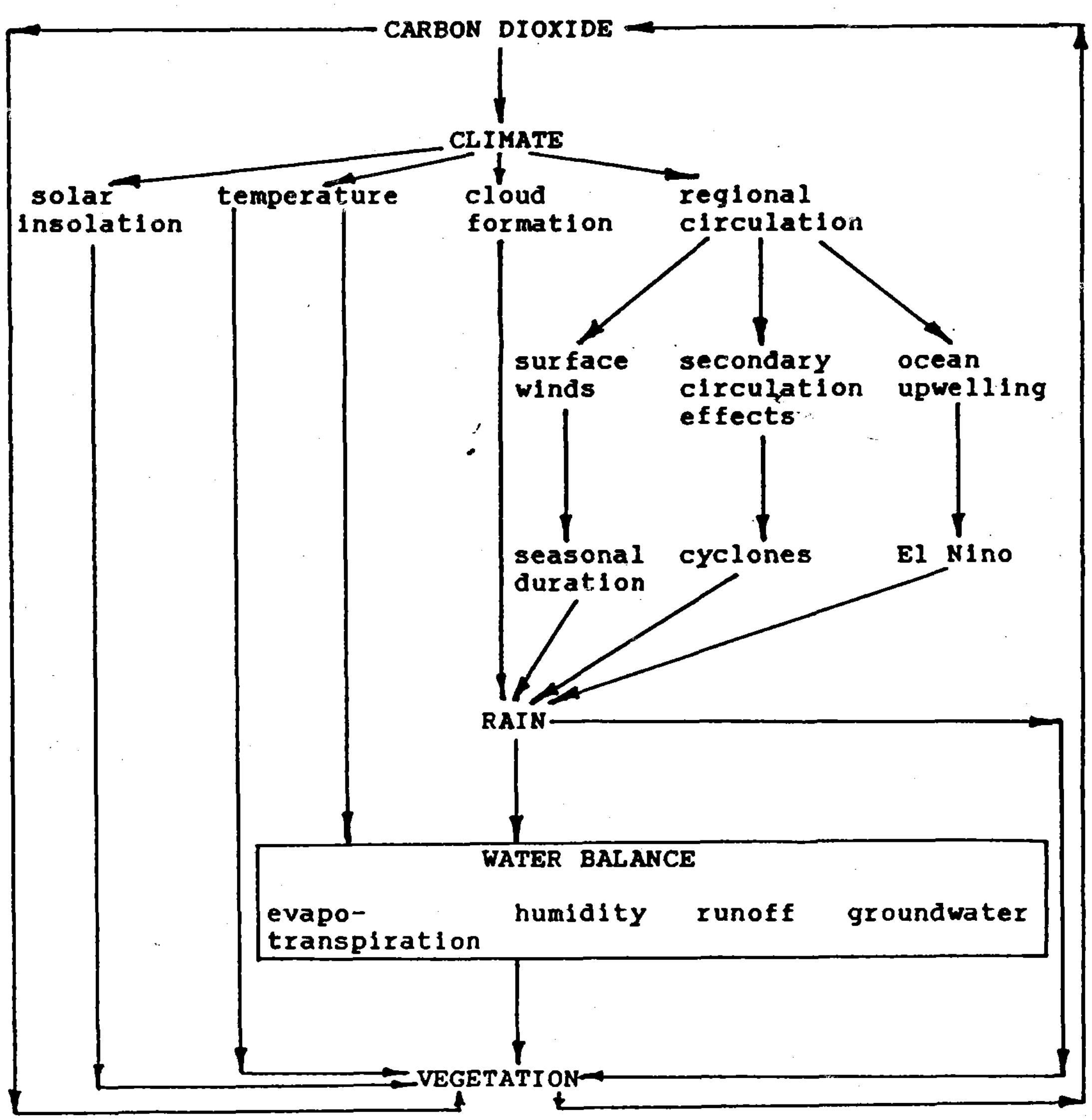


Figure 1. Influence of global increase in carbon dioxide on climate and vegetation

Water balance: changes to both rainfall patterns and temperature may be expected to have an impact on terrestrial biological and human communities through changes in evapo-transpiration rates, humidity, run-off and groundwater supplies. Impacts will vary according to the secondary circulation patterns in the atmosphere and the extent to which these are changed.

Increased temperature will increase evapo-transpiration rates thus increasing drought stress in areas of current water limitation. In areas where wilting of agricultural crops is currently a serious problem an increase in the number of wilting days per annum may be expected.

Vegetational impacts: direct impacts of climatic change on vegetation include vegetational responses to carbon dioxide directly; to temperature and to water balance. The latter two sources of impact can be expected to vary greatly on a geographic basis dependent upon local changes in circulation patterns and rainfall. Temperature and water balance changes will however have the greatest impact on vegetation, both natural and anthropogenic.

Vegetation responses to carbon dioxide: potentially enhanced growth of some species due to increased carbon-dioxide levels, and reduced transpiration losses due to changes in patterns of stomatal opening, may occur. The relative importance of these effects is difficult to quantify at the present time and is better assessed via a global rather than a regional approach.

Vegetation responses to temperature rise: altitudinally delimited vegetation zones will rise by around 330 m but the time lag for the vegetation response following temperature rise is unknown.

Alpine grassland habitats will be decreased in Papua New Guinea by more than 50% and will be confined to no more than 10 isolated areas. Such habitats are not found elsewhere in the region but corresponding decreases in the vegetation formations at higher altitudes on smaller islands will occur.

Lower and mid-montane rainforest from 1,400-2,300 m altitude (communities which are already under threat from land use pressures) will experience increased human impacts due to improved productivity in this altitudinal zone.

The savannah/lowland rainforest boundary will change towards savannah, and in general marginal ecotones and relict habitats will be decreased or disappear, the extent of this problem on a regional basis is unknown.

Vegetation responses to changed rainfall patterns: on a regional basis a decrease in the extent of coastal freshwater wetlands may be expected since most areas will be subject to sea level rise coupled with changes in freshwater inputs. Exceptions in Papua New Guinea are the Fly, Sepik-Ramu, Vanapa and Musa basins which can be expected to become wetter hence increasing the area of inland wetlands. This vegetational change will be a dynamic interaction between changed climate and sea level rise causing inundation of low altitude coastal wetlands.

All of the above effects can be expected to have major tertiary implications in terms of species loss; conservation; and changes in species composition with r-adapted species being at least initially favoured, in comparison with K-adapted species.

Soil impacts

Under warmer and drier conditions which will occur in some areas increased capillarity in limestone island soils may change the sodium, calcium balance in the soil hence reducing soil fertility.

Under conditions of increased rainfall, higher rates of erosion from agricultural and urban land use might be expected in areas where land use practices are not designed to reduce soil loss.

Impacts on agriculture and forestry

Vertical shifts of the position of mean annual isotherms will extend the altitudinal limit of important subsistence crops. This will occur through an increase in the length of the growing season at higher altitudes; reduction in the number of days of frost; increased yield and reduced time to harvest (Hughes & Sullivan, this volume). Since the present limits to agriculture correspond to climatic limits reflecting land pressure in the highlands of Papua New Guinea, subsistence farmers can be expected to extend their agricultural activity to higher altitudes.

Such changes in land use may have profound impacts on human demographic patterns in the highlands of New Guinea but will have lesser impacts in other Pacific island states where the areas of land outside the current altitudinal limits of agriculture are absent or greatly restricted in extent. Increased subsistence activity will result in reduction of the extent of upper montane forests which cannot be expected to respond with a corresponding upwards altitudinal shift as rapidly as human activity patterns.

Forest plantings of *Pinus carabaea* in rain shadow areas may be adversely affected by decreased rainfall, as will many commercial and subsistence crops which may require irrigation. Irrigation may be successfully increased as a response to crop wilting only in those areas where surface run-off and/or underground aquifers provide a large enough water resource. It is likely that in most areas affected by increased drought these two sources will prove inadequate for such purposes.

Changed temperature regimes apart from their direct effects on crop plants may be expected to influence agricultural production through changes in other components of the natural/agricultural system. Agricultural crops which are stressed by increased temperature and/or changed rainfall may become more susceptible to diseases particularly pathogenic diseases such as bacterial wilt. The generation time of pests may be changed such that more than one generation may affect a single crop generation hence the impacts may be changed. Pollination and seed set may be adversely affected in species which are pollinated by animals through changes to the natural pollinator populations.

The nature of the resource may itself be changed, winged beans for example set tubers only under certain conditions of temperature and water availability. Stock fertility (particularly males) may be adversely affected by increased temperature.

The balance between plantation and small-holder production of important cash crops may be affected, thus causing changes to national economies. Coffee in the highlands of Papua New Guinea for example is currently grown by both small and large scale producers. An upward altitudinal shift will favour increased small-holder production on somewhat steeper slopes than the larger plantation production which at present is located on the lower, flatter, valley floors. Small holder coffee is of a generally more variable quality than that produced through plantation systems.

Impacts on health and comfort

Diseases: in general epidemiological patterns can be expected to change as a consequence of changed climatic patterns. Warmer, drier conditions as predicted to occur in some areas may result in increased wind borne dust, hence an increase in respiratory inflammation/infections. The patterns of incidence of TB, other respiratory diseases and skin infections can be expected to change with increases occurring in areas of higher rainfall and humidity.

Perhaps the most dramatic change to health patterns is likely to occur through changes in the distribution patterns of disease vectors, in particular mosquitoes.

Altitudinal shifts in the distribution of the mosquito vector of malaria can be expected to result in increased incidence of malaria in the highly populated highlands of Papua New Guinea. These populations are currently at and beyond the altitudinal limit of the mosquito vector which may well become endemic in these areas in the future. This impact is unlikely to be important elsewhere in the Pacific since malaria is confined to Melanesia and in the Solomons and Vanuatu no major centres of population are found outside the altitudinal limit of the vector.

Other regionally important vector borne diseases include filariasis and dengue fever. Areas which experience increased rainfall and extended wet seasons are likely to experience extended breeding seasons for the mosquito vectors and hence increased frequency of outbreaks and cases of these diseases. Areas where such diseases are currently of low frequency are generally rather dry with distinctly seasonal rainfall, they are unlikely to experience increased incidences of these diseases.

Human comfort: at higher altitudes where fuel wood is used extensively for heating dwellings increased temperatures may result in reduced fuel-wood use with consequent flow on effects in terms of reduced forest clearance and reduction in respiratory infections. The reduction in forest clearance, if any, is likely to be counter-balanced by increased clearing for subsistence agricultural production.

Low-lying areas, which are currently inhabited, may become untenable due to more frequent and longer-lasting flooding patterns.

Cyclone destruction of human habitation and infra-structure can be expected to increase regionally as areas not currently in the cyclone belt become subject to such episodic events due to a northwards shift of the tropical convergence zone.

The Relative Strain Index is a measure of the suitability of local climates for human comfort. It takes into account both temperature and relative humidity and is related therefore to sweat production in humans as a temperature regulatory mechanism. In general terms there will be a ubiquitous deterioration of climate from the point of view of human comfort throughout the region. This will be particularly so in areas of current high humidity (see McGregor, this volume, for a more detailed discussion of this index and its application).

Changes in temperature and humidity affect work efficiency and whilst this may be uncontrollable in an external environment, buildings are frequently environmentally controlled. More buildings will require air-conditioning, hence increased power consumption. Changes to architectural design and economic costs will be necessary consequences of this change. We can expect therefore that workers in the primary sector will have reduced productivity whilst workers in the service, industrial and commercial sectors will require increased environmental control if current productivity is to be maintained. Some areas within the region are currently close to the limit of comfortable conditions for habitation, many of these will exceed this limit under the climatic regimes predicted (McGregor, this volume).

## SEA LEVEL RISE

### Background

Assuming a global rise in temperature of between 2 and 4°C by the year 2100 we can expect a rise in sea level as a consequence of thermal expansion of the oceans, and ice melt. The present case studies are based on an assumption of a 1 m rise in sea level by around the year 2050. It is further assumed that the rise will continue beyond this date. Again this figure is conservative and other estimates suggest an increase in sea level of up to 4.5 m by the end of the next century.

As with climatic change it seems realistic to assume that sea level rise will occur, what is at issue is the magnitude and rate of the rise. Again models used for predictions of sea level rise can only be developed on a global scale and hence are considered outside the scope of this report.

### Impacts

#### Coastal inundation

Permanent coastal inundation may be expected to occur to a significant extent in areas where the coastal profile is flat or gently sloping. The extent and nature of land loss is estimated in a number of case studies (Bualia & Sullivan; Hughes & Bualia; Nunn, this volume).

Inundation may be expected to be economically important in the region, given the distribution of fertile agricultural areas at or close to present sea level; the number of roads on smaller islands which lie in close proximity to the sea and the number of low-lying urban centres in the region.

There will be an overall decrease in the extent of low-lying wetlands, with a corresponding decrease in freshwater species diversity and abundance for most catchments except possibly the Fly and Sepik-Ramu systems of Papua New Guinea (see above).

Inundation of coastal agricultural areas will result in increased agricultural activities inland, frequently in areas of increased slope with consequent increases in erosion and soil fertility problems.

By and large the biggest estuarine/deltaic systems in the region are backed by relatively flat coastal plains, coastal regression may be extensive in such areas resulting in reduced habitats for some species of conservation concern such as crocodiles and turtles.

Inundation of outlying islands and loss of land above the high tide mark may result in loss of exclusive economic rights over extensive areas of the marine environment.

Coastal flooding

Episodic flooding of the coastal zone may be expected to increase both in frequency and geographically as a consequence of increased cyclonic activity. Flooding can be expected to have impacts on storm water drainage and sewage disposal systems in urban areas.

Flooding may be expected to have detrimental effects on recruitment to populations of saltwater crocodiles and other species where reproductive success is largely determined by egg mortality due to flooding of nests.

Extension of the periods of inundation may render coastal areas, particularly in areas of beach ridges backed by swamp uninhabitable in the long-term (see Bualia; Hughes & Bualia, this volume).

Changes to coastal morphology

The case studies presented in this report are all predicated on the assumption that coral growth rates will keep pace with rising sea level and hence that existing barrier reefs will continue to provide the same level of protection to the coastline as they do at present. Should this assumption not be correct then increased wave action may result in an exaggeration of both the rate and extent of the impacts discussed below.

The impact of global changes to carbon dioxide availability on the growth of symbiotic algae and hence the hermatypic, reef-building corals is not known. A rise in temperature will decrease the solubility of carbon dioxide, but increase the solubility of calcium carbonate, the consequences of these two processes for symbiotic algal growth and reproduction and hence skeleton formation are not known. Similarly the changes in species composition which might result from changed temperature regimes and deeper water have not been evaluated to date. Changes in species composition may affect the degree of protection afforded a coast; may affect the rate of storm damage and hence the rate of sand production.

It is clear that depositional coastal processes will be affected by any rise in sea level and the following figure illustrates the components of this sub-system. Whilst sediment deposition will continue in estuarine and deltaic areas, beaches will tend to lose sediments to off-shore sinks resulting in increased rates of shore-line regression.

As illustrated above an increase in sea level will result in increased volumes of the sediment sinks in the system causing reduced fluxes between sinks. Overall, beaches with a stable beach plan form which currently receive sediment inputs via longshore drift will, under increased sea level receive lower inputs of sediment resulting in consequent beach erosion and shoreline retreat. The extent of this retreat will depend upon the profile of the terrestrial/marine inter-face and the current importance of sediments derived from longshore drift.

Depending upon the rate of sediment input into the coastal system from riverine sources the system can be expected to stabilise only if sea level itself stabilises, and only following filling of the transitory sinks in the system (estuarine, and beach sinks). In areas of reduced rainfall riverine sediment inputs may be reduced further exacerbating coastal erosion. In areas of higher rainfall sediment inputs may not be significantly increased depending on the nature of the vegetation cover.

Beach plan forms will be changed by changing wave patterns resulting from modification of regional and sub-regional wind patterns. Such changes will have important to patterns for coastal marine communities of sea grasses, coral flats and algal beds. These processes can be expected to be of importance along the coasts of all Pacific high islands.

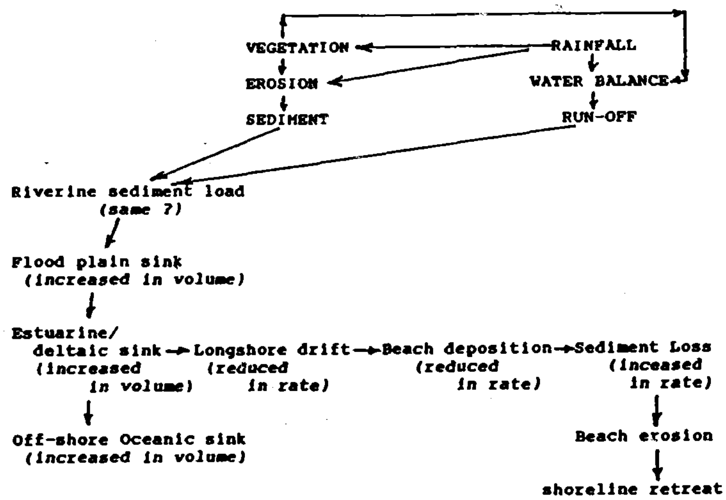


Figure 2. Consequences of sea level rise on coastal sediment flux

Coral atolls and cays may be expected to decrease in size and/or be eroded entirely as a result of accelerated loss of sand to off-shore sinks. Even if coral growth rates were to keep pace with sea level rise it seems unlikely that sand production would be sufficient to keep pace both with accelerated loss from the system as a whole and the increased volume of the lagoonal sink (see Figure 3).

Saline intrusion

In estuarine areas an inland extension of the tidal prism may be expected. In coastal plains saltwater contamination of the groundwater may have profound effects on both the suitability of areas for human occupation and upon the nature of the vegetation.

Water table elevation

A rise in sea level will cause a rise in water table which may have important consequences for freshwater lenses which currently float on saline water bodies. In the case of sand and limestone aquifers this will result in a significant decrease in the volume of the fresh water aquifer both for human consumption and agricultural use.

Loss or reduction in the volume of freshwater resources may render small atoll and limestone islands uninhabitable long before the loss of material results in land loss.

At least one urban centre (Kavieng) close to sea level in the Pacific derives its drinking water from a limestone aquifer. This centre and others like it may be significantly affected by reduction in the volume of water supplies for human use.

Compression of the marine terrestrial/transition

Changes in coastal vegetation following sea level rise and inundation may be dramatic, in areas currently having a flat coastal plain (Pernetta & Osborne, this volume). The distribution and zonation of vegetation, in particular mangroves, will be altered. Zonation is likely to be compressed, resulting not only in an overall reduction in the extent of such transitional habitats but extensive reduction in the seaward seres.

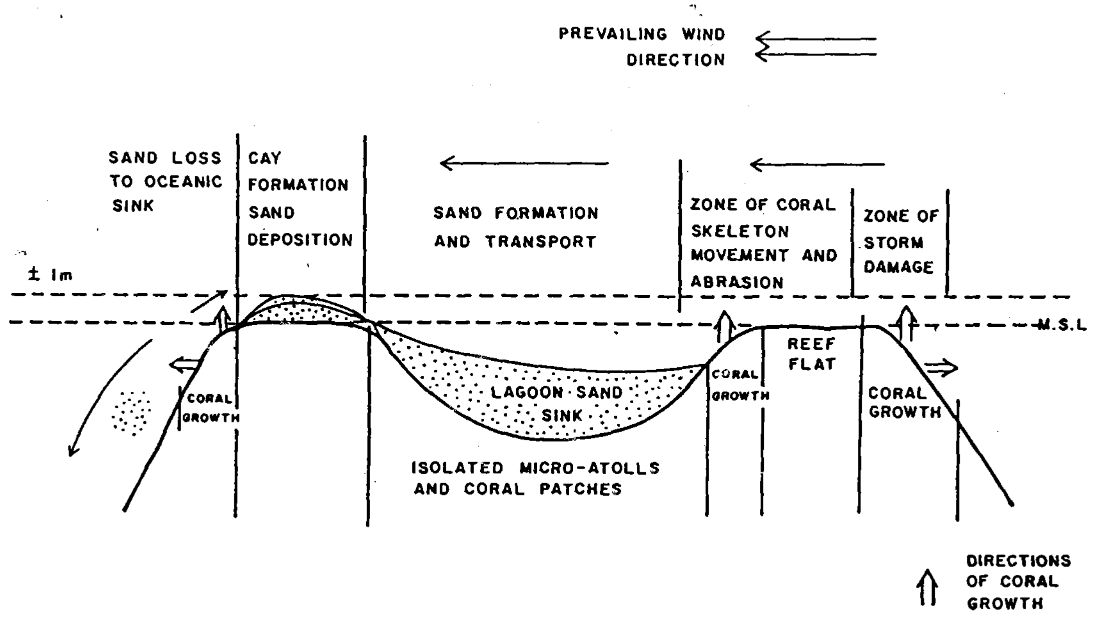


Figure 3. Simplified diagram of sand genesis, transport and loss from atoll systems

Such coastal habitat reduction will result in important changes to the distribution of wild species of flora and fauna of subsistence and commercial importance, and a general loss of estuarine/mangrove species. In general both individual species abundance and species richness will decline.

Turbidity

Turbidity in the coastal zone is linked with rainfall and soil erosion, increased turbidity may affect primary producers, including corals, sea grasses and macro-algae. Increased turbidity in the coastal zone is likely to become a pronounced problem in smaller island ecosystems with high density human populations. Following inundation of coastal plains hillslopes will have to be brought into production and re-location of settlements on slopes will take place, both processes will result in increased mobility of soils and sediments and their transport into the coastal marine system.

## SOCIO-ECONOMIC EFFECTS

### Background

Both climatic change and rise in sea level will have profound economic and social impacts. The extent of these impacts will be great for Pacific island states where land areas are generally small, insularity is high, and the length of the coast is consequently great. For most Pacific islands coastal locations are favoured for human habitation, for road construction, for large scale plantation agriculture, and for the development of secondary industry. Coastal erosion and inundation will therefore not only affect marine based human activities but will also impinge upon all aspects of human survival in such situations.

Whilst some impacts may be countered by changes to patterns of human activity other impacts may be impossible for the economies of small island states to absorb. Where modified development strategies can be adopted to mediate or obviate the described impacts, these should be adopted immediately and island governments and administrations should incorporate consideration of future coastal changes into the planning process.

Climatically related impacts

Urban centres in areas of predicted higher rainfall will need to invest large sums in storm run-off drainage systems; flood control works and sewage disposal systems.

Given the predicted increase in cyclone frequency, episodic damage to engineered structures can be expected to become a significant economic burden for some states. Changes in architectural design should be considered to minimise potential impacts from such events.

Loss of agriculturally productive land will have economic costs not merely in terms of lost production but in terms of the costs of bringing other areas perhaps less suited to agriculture into production. Such changes will have important consequences for land use practices which must be modified to suit the environmental characteristics of different land types.

Whilst irrigation schemes might be seen as a potential answer to problems of agricultural water supply in areas identified as becoming drier, such schemes should be approached with caution as they may provide little more than a short-term solution which would become impossible to maintain in the medium and longer term future, and in areas of increased capillarity may contribute to soil salination.

The pattern of marine productivity in the region can be expected to change, hence zones of upwelling which currently support important pelagic fisheries may move, resulting in both positive and negative economic consequences for small island states. This impact may be fundamental to a number of the smaller states whose sole or major source of export income is marine-pelagic fisheries.

Important changes may be anticipated in the hydro-electric power generating potential of different areas as rainfall patterns change. Power demands will be affected particularly in areas where air-conditioning is already necessary. Such areas will require more air-conditioning in the future, hence increasing power demand. These changes may result in some major urban centres becoming economically insupportable by the end of the next century.

Areas which currently experience a prolonged dry season will become drier and such areas may experience both domestic and industrial water supply problems. These problems may be particularly critical for centres where hydro-power generation is dependent on the same source as the domestic water supply.

Climatic changes will generally adversely affect the tourist potential of many Pacific island states, although changed wind regimes may improve the quality of some areas such as Port Moresby through a longer sailing season. Adverse affects will have substantial impacts on the economies of the smaller nations, dependent upon tourist income.

Sea level rise

Saline contamination of drinking water supplies can be expected to become a major economic problem for atoll and raised limestone islands, for populations on coastal plains and for urban centres dependent upon aquifer water supply on high islands. Such impacts will be felt economically through higher costs of alternate supplies of drinking water.

Rising saline water tables may adversely affect agricultural production particularly on atoll islands which may become uninhabitable resulting in out-migration and economic and social costs of resettlement.

Economic costs for maintaining existing engineered structures such as roads, sea walls, piers, harbours, wharves, houses, hotels, sewage systems, storm and waste water disposal, and bridges will rise. Future structures should be planned taking into account rising sea levels.

Resettlement and out-migration can be expected to have major social and economic costs both within island states and regionally. For some of the smaller atoll based nations out-migration may mean resettlement in another country with consequent costs both to the original and the recipient state. Global and regional solutions will be required to this problem.

Associated with resettlement, both social and psychological trauma will be experienced, resettlement programmes therefore should be designed to minimise such trauma. Resettlement will often also involve major changes to life style and economic practices and schemes should be planned accordingly (O'Collins, this volume).

In some circumstances, resettlement will be a gradual process, involving increased out-migration of disproportionate numbers of younger members of the community. Those left behind will be likely to be older, less economically active and consequently more dependent for their survival on external support. (See Morauta 1988, for a discussion of the impact of out-migration on home communities)*.

Local populations will need to adjust their management practices in relation to changes in land and marine resources. Traditional methods and local knowledge may not be appropriate and new crops may need to be introduced. External assistance will be needed to train local farmers and extension officers to respond to the changes in their environment.

Changes to the local distribution and abundance of marine and coastal resources can be expected to have major economic impacts at the local and subsistence levels. In some instances major commercial resources such as prawns and deep water snapper may be affected resulting in changes to the local and national economies.

Loss of small outlying islands through accelerated erosion will mean loss and/or reduction in the size of exclusive economic zones. Japan has demonstrated that this must be taken seriously by constructing an artificial island on an outlying reef system where erosion had removed the land above high water mark. This impact is potentially of major importance to the smaller atoll island states of Micronesia and Polynesia, but may be expected to impact even larger high island states.

All economic changes regardless of whether these are due to climate or sea level rise will result in a need for major budgetary re-allocation on a national and regional scale. The involvement of the metropolitan countries in planning for such changes is imperative since resettlement will impact upon those countries on the Pacific Rim, particularly New Zealand and Australia.

Loss of cultural heritage will occur, not only as a consequence of movement and resettlement isolating people from their traditional islands and land but through the inundation of important archaeological and anthropological sites.

Land values will change as people become aware of the impacts of rising sea level, within nations this will result in substantial economic and social change. In more developed urban centres substantial insurance claims may prove an economic burden.

## FUTURE RESEARCH

### Introduction

As indicated in the title this is a preliminary report which aims to identify potential impacts resulting from global climatic change and sea level rise in the countries of the Pacific Basin. It is therefore neither a definitive statement of what will happen, nor a statement of precisely when it will occur. It was recognised by members of the task team that a considerable amount of additional work could be undertaken to further define the impacts and to estimate in more detail the scale of such impacts. The details provided below indicate two levels of further work.

1. The first involves a continuation of present activities to expand the geographic coverage of the existing approaches and to investigate in a similar manner certain aspects which have not been considered to date.

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*[Morauta, L., 1984. Left Behind in the Village, Boroko: Institute of Applied Social and Economic Research].

2. The second involves the implementation of data oriented programmes of field research designed to answer specific questions raised during the present work.

Extension of present activities: regional reviews

1. The climatic case study is limited in geographic coverage, it can be extended in two ways: firstly to cover other parts of the region; secondly through a comparison of selected sets of warm and cold years for the mid-Pacific basin, regional circulation patterns and local climatic conditions can then be predicted with greater accuracy.

2. The use of the relative strain index can be extended to cover all major urban centres in Pacific island states, hence providing a regional picture of expected changes to human comfort.

3. Crop physiological tolerances need to be investigated and the working group meeting agreed that the physiological tolerance, and present geographic distribution/importance of the following crops would be investigated and compared with predicted future climatic patterns.

| | |
|---|---|
| Commercial crops: | sugar, tobacco, cocoa, robusta coffee. |
| Subsistence staples: | taro, sweet potato, cassava. |
| Subsistence & small-scale commercial crops: | tomatoes, ginger, pawpaw, citrus, cowpeas. |

4. Review of coral reef growth rates, and potential changes to species composition resulting from differential growth; temperature tolerance and its influence on growth rates.

5. Atoll sand budgets and aquifers; existing data needs to be regionally reviewed and refinements to predictions of impacts made as a matter of urgency. It was felt by the working group that this island type was one of the most susceptible to massive impacts within the region.

6. Some attempt needs to be made to assess the impacts of climatic change on the environment of shallow water lagoons using existing data sources where possible.

7. An attempt should be made to assemble a geographic data-base for Pacific island nations relevant to sea level change. This needs to include number of islands, land areas, coastline length, population density and areas of exclusive economic zones at the very least.

8. Urban case studies of the kind undertaken by the University of the South Pacific team should be extended to other centres within the region where possible.

9. Continued monitoring of the Atolls Resettlement Scheme should be undertaken.

Specific data-oriented case studies

Identified as major systems requiring further detailed study in the field were the following (in order of priority):

coral atolls;
raised limestone islands;
mangroves/ estuarine systems;
floodplains;
small high islands.

It was suggested by the working group meeting that triplicates of each system should be studied in Melanesia, Micronesia and Polynesia and that each study should be undertaken in an agreed, identical format by each team of around eight individuals.

Each research team should include geomorphologists, social geographers/anthropologists, and biologists and should be asked to answer specific objectives with regard to each major system. Thus priority questions for examination in atolls for example relate to sand movements and sand budgets, aquifer size and location and the extent of agricultural use of the aquifer. Plan and profile mapping is required together with geomorphic mapping, preparation of a vegetation/land use map and interviews with local people to ascertain the traditional knowledge base concerned with currents sand movement erosion and storm problems.

RECOMMENDATIONS TO THE FOURTH CONSULTATIVE MEETING

The task team recommends that the 4th consultative meeting adopt the following resolutions.

**This meeting endorses the continuation of the studies initiated through ASPEI on potential impacts of climatic change and sea level rise on the countries of the Pacific Basin and recommends to the Inter-Governmental Meeting (IGM) that that meeting continue to support the work of the Task Team to extend the geographic coverage and nature of the present work.**

**The meeting further recommends that the IGM and sponsoring agencies should support financially the implementation of programmes of field data collection as the second phase of the work of the task team during the next biennium.**

**The meeting further recommends that the island governments and Administrations take note of the potential problems which may arise as a consequence of global climatic changes and incorporate appropriate considerations into their environmental and development planning processes.**

# PROJECTED CLIMATE CHANGE AND SEA LEVEL RISE: A RELATIVE IMPACT RATING FOR THE COUNTRIES OF THE PACIFIC BASIN

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## INTRODUCTION AND GEOGRAPHY OF THE REGION

Excluding the countries of the Pacific Rim and those of the South East Asian Seas Region such as the Philippines, the Pacific Basin includes a number of independent micro-states, dependencies and territories of major powers such as the United States, France, United Kingdom, Australia and New Zealand.

Table 1 provides some basic data for these 'political entities' (hereafter referred to as 'countries') including land area; area of the exclusive economic zones (sea area), population size and ratios between these parameters. It can be seen that for most of the 25 'countries' the land area is insignificant in global terms (just over 500,000 $km^2$); 85% of this area is contained within the boundaries of Papua New Guinea.

In contrast the areas of the exclusive economic zones are considerable (Figure 1). An isolated atoll as small as 1 $km^2$ and having no neighbouring islands represents an area of marine resources covering some 125,000 $km^2$. For most Pacific countries land forms less than 0.001% of the area within the exclusive economic zones. It is hardly surprising therefore that most countries of the region depend upon marine resource exploitation both for subsistence and commercial use. Many countries in Micronesia depend heavily on pelagic fish resources such as tuna as a major source of income for development.

Coastal lengths have not been calculated for most countries as these are unreliable, the variation being dependent on the scale of the maps used to measure the coast. This source of error is compounded where the insularity is high, as in Micronesia. Islands vary from low lying atolls at or below 4 m above sea level to high volcanic islands with steep profile, island relief is important in terms of both coastal inundation and rainfall/run-off patterns hence the impacts of climatic change will differ in islands of differing relief.

Population levels, in terms of density are high for most of the smaller states (up to 386 people/$km^2$). Again the absolute numbers of people are small in global terms. Some of the smallest micro-states in the world both in terms of land area and in population are found in the Pacific Basin.

Any change in sea level is likely to have profound effects upon the economic viability of these micro-states, both through land loss, and loss of exclusive economic rights at the periphery of their existing national boundaries. Both impacts will be highly significant economically.

## ISLAND TYPES

The islands of the Pacific are divided into several major categories having different susceptibilities to changes in sea level resulting from global warming. Table 2 presents a country by country analysis of island type and size based on data contained in the Review of the Protected Areas System in Oceania and the Commonwealth Science Councils' Science for Technology for Development. Since different islands generally have quite different susceptibility to changes in sea level the island types are briefly described below.

Table 1. Political status, population, land area, altitude, island numbers and area of exclusive economic zones for SPREP member countries.

| | Political status | Land area sq km | Sea area sq km | Est. pop'n | Coast km | Land area/ sea area | Pop'n/sq km land | Pop'n/sq km sea | No. islands | No. islets | Maximum altitude m |
|---|---|---|---|---|---|---|---|---|---|---|---|
| American Samoa | US unincorporated Territory | 197 | 390000 | 33200 | | .00000051 | 169 | .000085 | 7 | 7 | 931 |
| Cook Islands | Self Governing, free association with NZ | 241 | 1830000 | 18200 | 120 | .00000013 | 76 | .000010 | 8 | 15 | 652 |
| Federated States of Micronesia | Free association with USA | 727 | 2978000 | 79500 | | .00000024 | 109 | .000027 | 17 | 62 | 791 |
| Fiji | Independent | 18272 | 1290000 | 671712 | 1129 | .00001416 | 37 | .000521 | 22 | 200 | 1323 |
| French Polynesia | Overseas Territory of France | 3265 | 5030000 | 166700 | | .00000065 | 51 | .000033 | 38 | 125 | 2237 |
| Guam | US Unincorporated Territory | 549 | 218000 | 107000 | | .00000252 | 195 | .000491 | 1 | 1 | 393 |
| Kiribati | Independent | 690 | 3550000 | 59900 | 1143 | .00000019 | 87 | .000017 | 14 | 32 | 81 |
| Marshall Islands | American Trust Territory | 171 | 2131000 | 31800 | | .00000008 | 186 | .000015 | 10 | 10 | 4 |
| Nauru | Independent | 21 | 320000 | 8100 | 24 | .00000007 | 386 | .000025 | 1 | 1 | 71 |
| New Caledonia | Overseas Territory of France | 19103 | 1740000 | 139400 | | .00001098 | 7 | .000080 | 11 | 11 | 1628 |
| Niue | Self Governing, free association with NZ | 259 | 390000 | 3600 | | .00000066 | 14 | .000009 | 1 | 1 | 67 |
| Northern Marianas | US Commonwealth | 475 | 1823000 | 17600 | | .00000026 | 37 | .000010 | 14 | 14 | 965 |
| Palau (Belau) | Republic, free association with USA | 512 | 629000 | 14800 | | .00000081 | 29 | .000024 | 16 | 32 | 207 |
| Papua New Guinea | Independent | 466973 | 3120000 | 3010727 | 5152 | .00014967 | 6 | .000965 | 22 | 160 | 4694 |
| Pitcairn | British Dependency | 45 | 800000 | 44 | | .00000006 | 1 | .000000 | 3 | 3 | 304 |
| Solomon Islands | Independent | 27556 | 1340000 | 235000 | 5313 | .00002056 | 9 | .000175 | 19 | 69 | 2446 |
| Tokelau | New Zealand Dependency | 10 | 290000 | 1600 | | .00000003 | 160 | .000006 | 3 | 3 | 4 |
| Tonga | Independent | 699 | 700000 | 97400 | 419 | .00000100 | 139 | .000139 | 29 | 70 | 1125 |
| Tuvalu | Independent | 26 | 900000 | 7600 | 24 | .00000003 | 292 | .000008 | 2 | 10 | 4 |
| Vanuatu | Independent | 11880 | 680000 | 117500 | | .00001747 | 10 | .000173 | 9 | 9 | 1979 |
| Wallis & Fortuna | Overseas Territory of France | 255 | 300000 | 12408 | | .00000085 | 49 | .000041 | 3 | 3 | 762 |
| Western Samoa | Independent | 2935 | 120000 | 156400 | 403 | .00002446 | 53 | .001303 | 8 | 8 | 1857 |
| Line Islands | US Territory | 10 | 130000 | 40 | | .00000008 | 4 | .000000 | 5 | 54 | 8 |
| Philip, Norfolk, Lord Howe | Australian Territory | 53 | 130000 | 1849 | | .00000041 | 35 | .000014 | 13 | 13 | 875 |
| Sunday Island | NZ Territory | 29 | 411870 | not known | | .00000007 | | | 1 | 1 | 516 |
| Easter Island | Chilean | 166 | 105200 | 1200 | | .00000158 | 7 | .000011 | 2 | 2 | 600 |
| Totals | | 555119 | 31346070 | 4993280 | | | | | 279 | 916 | |

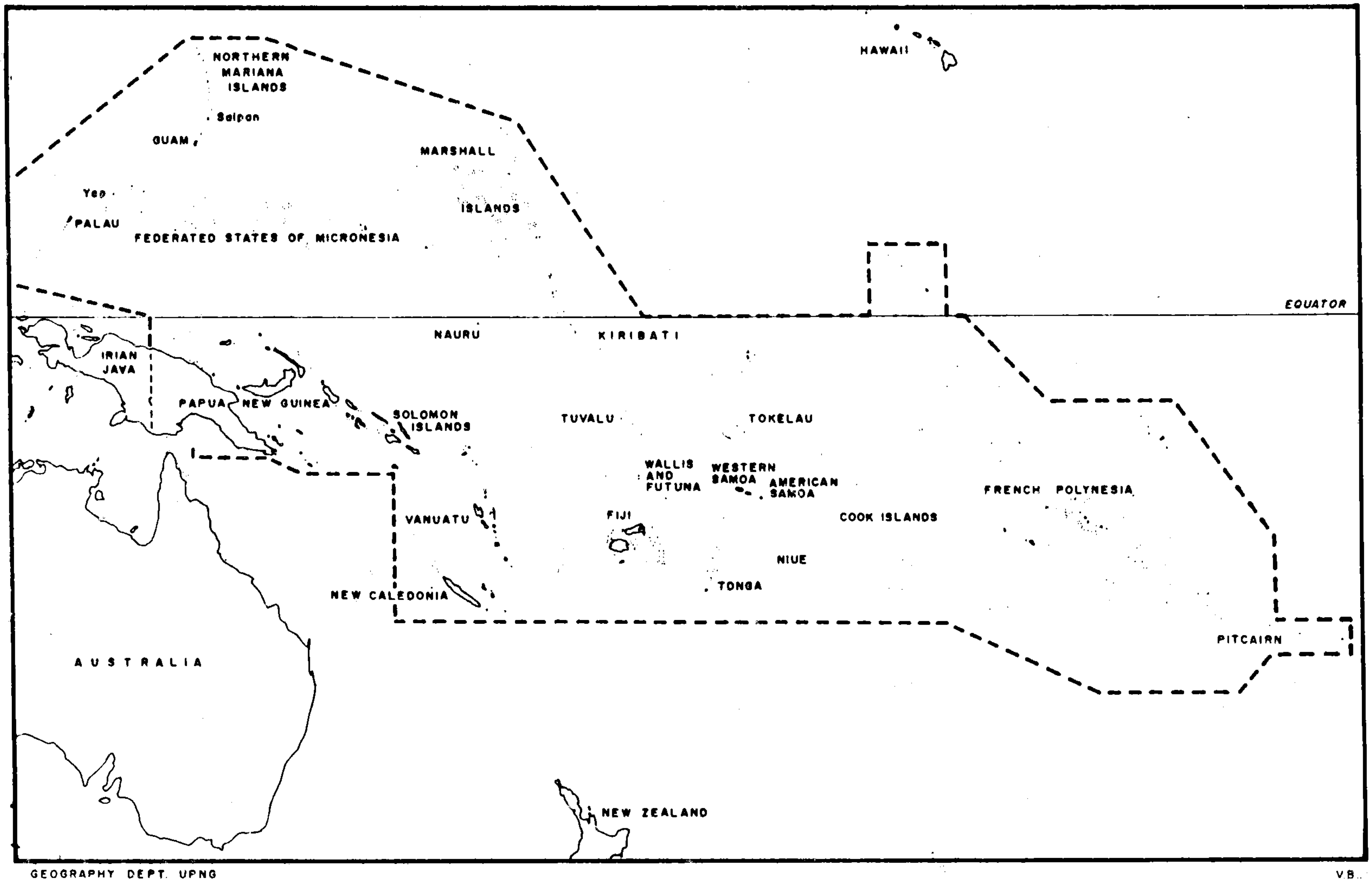


Figure 1. The countries of the Pacific basin. The dashed line represents the boundary of the SPREP region

Volcanic

Generally high islands of predominantly volcanic origin, these islands are some of the highest in the Pacific with a generally steep profile and rapid oceanic drop-off into deeper waters.

Mixed

This category covers those islands of essentially a volcanic core with raised sedimentary facies, usually reef limestone, and larger islands of complex geology such as New Caledonia and New Guinea.

Metamorphic

This category is relatively unimportant and covers islands composed of variable geological origin generally of small size.

Coral

Such islands are composed of raised limestone of coral reef origin, soils are generally much poorer than those of the preceding three types and surface freshwater is generally absent. Freshwater for drinking and agriculture is obtained from the subterranean freshwater lens.

Atolls

Atolls are coral reefs growing on submerged volcanic cones (Guyots). When present, atoll islands are piles of coral sand heaped onto the surface of the reef flat; called cays or motu such islands are generally no more than 4 m above present sea level and are formed in long narrow strips either entirely enclosing a central lagoon or forming a series of small islets around its periphery. Such islands are highly susceptible to total destruction through hurricanes, are biotically impoverished and freshwater is confined to a small underground lens. Many such islands are currently uninhabited and they presently represent a marginal habitat for human existence.

## SUSCEPTIBILITY OF DIFFERENT ISLAND TYPES TO IMPACTS

Volcanic and metamorphic

Climate change is likely to be more important than sea level changes, although local impacts resulting from flooding of low lying agricultural land and urban centres may be severe.

Mixed

Generally smaller islands of this type consist of a steep sided volcanic cone or cones with surrounding raised limestone flatlands on which most urban, transport and agricultural land tends to be concentrated. Sea level rise impacts are likely to be severe depending on the total land area and the height of the coral platforms. In some instances urban water supplies are derived from aquifer sources in the limestone, these are likely to be contaminated by sea water.

This category also contains the largest islands which are the least likely to suffer in terms of the proportion of land lost due to sea level rise although such effects may be locally severe and important to certain specific coastal habitats including swamps and wetlands. For larger islands changes in temperature and rainfall may profoundly affect both agricultural activity and the distribution of natural biomes.

Table 2. Island type by country, SPREP region. Areas are in $km^2$, altitudes are in m.

| | Island type | | | | | | |
|---|---|---|---|---|---|---|---|
| Country | Volcanic | Metamorphic | Mixed | Raised coral | Atoll | Unknown | Total |
| **Northern Marianas** | | | | | | | |
| Number | 13 | | | | | 1 | 14 |
| Mean area | 36 | | | | | 7 | |
| Range | 0.9-122.9 | | | | | | |
| Mean altitude | 505 | | | | | | |
| Range | 81-965 | | | | | | |
| **Guam** | | | | | | | |
| Number | | | 1 | | | | 1 |
| Mean area | | | 541 | | | | |
| Range | | | | | | | |
| Mean altitude | | | 393 | | | | |
| Range | | | | | | | |
| **Belau** | | | | | | | |
| Number | 1 | | 2 | (97} 27 | (6+} 3 | 6 | (112) 39 |
| Mean area | 5 | | | 11.60 | (0.25) 1.5 | | |
| Range | | | 9.3-397 | 0.65-47 | 0.9-1.94 | | |
| Mean altitude | | | [122] | 82 | [2] | | |
| Range | | | | <5-207 | | | |
| **Federated States of Micronesia** | | | | | | | |
| Number | 8 | 4 | | 7 | (266) 30 | 10 | (295) 59 |
| Mean area | 53.60 | | | 1.20 | (0.18) 1.6 | 0.57 | |
| Range | 4.7-334 | | | 0.1-2.8 | 0.06-16 | 0.049-1.6 | |
| Mean altitude | 408.90 | | | 17.70 | 3.35 | 61 | |
| Range | 152-791 | | | <5-30 | 2.4-4 | 61 | |
| **Marshall Islands** | | | | | | | |
| Number | | | | 5 | (1085) 28 | | (1118) 33 |
| Mean area | | | | 0.85 | (0.15) 6.1 | | |
| Range | | | | 0.16-1.8 | 0.5-16 | | |
| Mean altitude | | | | <10m ? | 3.35 | | |
| Range | | | | | 2.4-4 | | |
| **Papua New Guinea** | | | | | | | |
| Number | (25)21 | | 1 | 7 | (15)8 | 112 | (160) 149 |
| Mean area | 3258 | | [400000] | | (0.42)3 | | |
| Range | 7.9-36,520 | | | 0.4-1110 | | | |
| Mean altitude | 1386 | | [4694] | | [3] | | |
| Range | 50-3123 | | | 10-370 | | | |
| **Solomon Islands** | | | | | | | |
| Number | 26 | | 6 | (15)6 | 4 | 83 | (139)125 |
| Mean area | 1403.20 | | 1886.80 | 352.10 | | 130.25 | |
| Range | 4-5336 | | 200-4243 | 29-675 | | 3-386 | |
| Mean altitude | 1031.50 | | 1325.50 | 78.30 | | 222.50 | |
| Range | 374-2331 | | [1219-1432] | 60-91.5 | | [65-380] | |
| **Vanuatu** | | | | | | | |
| Number | 18 | | 9 | (15)9 | | 11 | (61)47 |
| Mean area | 168 | | 905 | | | | |
| Range | [8.9-414] | | 360-3937 | | | | |
| Mean altitud | 870 | | 917 | 162.40 | | 237 | |
| Range | [125-1496] | | 326-1879 | 6-366 | | 64-494 | |

| Country | Volcanic | Metamorphic | Mixed | Raised coral | Atoll | Unknown | Total |
|---|---|---|---|---|---|---|---|
| **New Caledonia** | | | | | | | |
| Number | 2 | | (6)5 | (9)6 | 2 | 13 | (32)28 |
| Mean area | 0.26 | | 4437.78 | 332.30 | | | |
| Range | [0.12-0.4] | | 67-16890 | 0.12-1196 | | | |
| Mean altitude | 220 | | 493.60 | 65.80 | | | |
| Range | [140-300] | | 138-1628 | 4-104 | | | |
| **Australian Territories** | | | | | | | |
| Number | 3 | | 1 | 1 | 8 | | 13 |
| Mean area | 6 | | [34.5] | | | | |
| Range | 2.6-14.6 | | | | | | |
| Mean altitude | 577.50 | | [319] | [32] | | | |
| Range | 280-875 | | | | | | |
| **N.Z. Territories** | | | | | | | |
| Number | 5 | | | | | 7 | 12 |
| Mean area | 16.50 | | | | | [0.3] | |
| Range | 3-33 | | | | | | |
| Mean altitude | 377 | | | | | | |
| Range | 238-516 | | | | | | |
| **Fiji** | | | | | | | |
| Number | (59)57 | | 8 | (45+)44 | (23)16 | 57 | (196)186 |
| Mean area | (31)57.7 | | 2699.80 | 22.80 | | 3.59 | |
| Range | 0.7-435 | | 7.7-10544 | 7.7-53 | | 0.16-10 | |
| Mean altitude | 244 | | 384.10 | 89.70 | | 123 | |
| Range | 3-1224 | | 34-1323 | 1.2-283 | 2-9 | 22-270 | |
| **Tonga** | | | | | | | |
| Number | 16 | | | 25 | 2 | 25 | 68 |
| Mean area | 17.82 | | | 17.70 | 0.41 | 0.23 | |
| Range | 0.12-35 | | | 0.34-257 | 0.33-0.49 | 0.2-0.4 | |
| Mean altitude | 292.40 | | | 54 | | 26.33 | |
| Range | 37-1030 | | | 15-204 | | 17-42 | |
| **Niue** | | | | | | | |
| Number | | | | 1 | | | 1 |
| Mean area | | | | [259] | | | |
| Range | | | | | | | |
| Mean altitude | | | | [67] | | | |
| Range | | | | | | | |
| **Wallis & Futuna** | | | | | | | |
| Number | 2 | | 1 | | | | 3 |
| Mean area | 88 | | [32] | | | | |
| Range | 80-96 | | | | | | |
| Mean altitude | 455.50 | | [366] | | | | |
| Range | 149-762 | | | | | | |
| **Western Samoa** | | | | | | | |
| Number | 7 | | | | | | 7 |
| Mean area | 735.40 | | | | | | |
| Range | 1.75-1821 | | | | | | |
| Mean altitude | 795.75 | | | | | | |
| Range | 0-1857 | | | | | | |
| **American Samoa** | | | | | | | |
| Number | 5 | | | | 2 | | 7 |
| Mean area | 38.92 | | | | 1.45 | | |
| Range | 2.6-135 | | | | 0.8-2.1 | | |
| Mean altitude | 554 | | | | 4.50 | | |
| Range | 61-931 | | | | 3-6 | | |

| Country | Volcanic | Metamorphic | Mixed | Raised coral | Atoll | Unknown | Total |
|---|---|---|---|---|---|---|---|
| Tokelau | | | | | | | |
| Number | | | | | (127)3 | | (127)3 |
| Mean area | | | | | (0.08)3.4 | | |
| Range | | | | | 2.2-5.4 | | |
| Mean altitude | | | | | 4 | | |
| Range | | | | | 4 | | |
| Tuvalu | | | | | | | |
| Number | | | | 4 | (63)5 | | (67)9 |
| Mean area | | | | 2.85 | 3.05 | | |
| Range | | | | 0.4-5.6 | 1.8-3.9 | | |
| Mean altitude | | | | <10 m ? | | | |
| Range | | | | | | | |
| Kiribati | | | | | | | |
| Number | | | | (19)17 | (109)16 | | (136)33 |
| Mean area | | | | 11.70 | (5.1)34 | | |
| Range | | | | 0.2-49 | 9.1-321 | | |
| Mean altitude | | | | 12.60 | 5.60 | | |
| Range | | | | 4-81 | 4-9 | | |
| Line Islands | | | | | | | |
| Number | | | | 4 | (50+)1 | | (54)5 |
| Mean area | | | | 1.90 | (0.06)3 | | |
| Range | | | | 0.3-4.5 | | | |
| Mean altitude | | | | 7.70 | [2] | | |
| Range | | | | 7-8 | | | |
| Cook Islands | | | | | | | |
| Number | 13 | 1 | 5 | 1 | (49)7 | | (69+)15 |
| Mean area | [18.1] | 1.30 | 36.54 | [1.2] | (0.6) 4 | | |
| Range | | | 18.4-64 | | 0.4-9.8 | | |
| Mean altitude | [137] | | 235 | | | | |
| Range 30-652 | | | | | | | |
| French Polynesia | | | | | | | |
| Number | (46)32 | | 4 | 6 | (635)77 | 3 | [691]122 |
| Mean area | 84.40 | | 17 | [28] | 11.90 | [1.3] | |
| Range | 0.26-1042 | | 2-18 | | 1.3-43 | | |
| Mean altitude | 544 | | 308 | 57 | 3.9 | [360] | |
| Range | 105-1259 | | 95-433 | 3-111 | 1.8-6.5 | | |
| Pitcairn | | | | | | | |
| Number | 1 | | | 1 | 2 | | 4 |
| Mean area | [4.5] | | | [32] | 0.68 | | |
| Range | | | | | 0.65-0.7 | | |
| Mean altitude | [304] | | | [33] | 4 | | |
| Range | | | | | | | |
| Easter Island | | | | | | | |
| Number | 2 | | | | | | (2)1 |
| Mean area | [166] | | | | | | |
| Range | | | | | | | |
| Mean altitude | [29&600] | | | | | | |
| Range | | | | | | | |

Coral

Raised limestone islands will be affected to varying degrees according to their present height above sea level; for lower lying islands, changes to the aquifer combined with accelerated erosion will result in many such islands becoming uninhabitable.

Atolls

Such islands will be most profoundly affected both in terms of loss of freshwater lenses; land loss and increased frequency of episodic destruction through hurricanes. Most such islands will become uninhabitable by the middle of the next century if predicted sea level rises occur. Since maximum altitude is usually no more than 4 m above sea level, small rises will result in rapid restriction of the volume of the freshwater lens.

IMPACTS ON COUNTRIES

From an examination of Table 2 it is clear that the countries of the South Pacific vary in their insularity and the composition of their islands. Assessing impacts in specific case study areas has provided insights into the nature of likely impacts and allows assessment of the relative susceptibility of island types. Impacts will be greatest for atolls and least for large continental or volcanic islands. Impacts will be greater on smaller islands than on larger ones, it is possible therefore to measure the relative overall impacts, country by country in terms of both insularity, island type and land area.

Insularity was measured in terms of total land area and number of islands, where atolls were scored as single islands even though they might be composed of many smaller islets. The log of this was then taken and values adjusted to a range of five units.

Relative size of the country was measured in terms of the log of total area again adjusted to a range of five units.

Relative relief was scaled by dividing the maximum altitude by the land area, taking a logrithmic value and adjusting to a scale of five units.

The relative susceptibility of atolls and raised coral islands merits their inclusion as a separate phrase within the algorithm. Clearly the proportion of these islands types will affect the extent to which countries are likely to be impacted hence the number of atolls and half the number of raised coral islands was divided by the total number of islands, scaled to five.

The components are given in Table 3 by country. The index may be written as follows:

Impact level = 15-{[log(area/no islands) + log(total land area) + log(maximum altitude/land area)] + [{(total atoll nos + 1/2 nos coral islands)/total number of islands} x 5]

This provides approximately equal weighting for altitude, island numbers, total land area and island type and results in the following ranking for Pacific Island countries.

Table 3. Calculation of relative index of susceptibility

| | Land area (km2) | No. of islands | Insularity | | Size | | Max. alt. (m) | Relief/km2 | | Atoll index | Partial index | Index |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | raw | adj | raw | adj | | raw | adj | | | |
| American Samoa | 197 | 7 | 1.45 | 2.27 | 2.29 | 2.44 | 931 | 0.67 | 1.03 | 1.43 | 9.26 | 10.69 |
| Cook Islands | 241 | 15 | 1.21 | 1.89 | 2.38 | 2.53 | 652 | 0.43 | 0.66 | 2.50 | 9.92 | 12.42 |
| Federated States of Micronesia | 727 | 59 | 1.09 | 1.70 | 2.86 | 3.04 | 791 | 0.04 | 0.06 | 3.42 | 10.20 | 13.62 |
| Fiji | 18272 | 186 | 1.99 | 3.11 | 4.26 | 4.53 | 1323 | -1.14 | -1.75 | 0.85 | 9.11 | 9.96 |
| French Polynesia | 3265 | 122 | 1.43 | 2.23 | 3.51 | 3.73 | 2237 | -0.16 | -0.25 | 3.36 | 9.29 | 12.65 |
| Guam | 549 | 1 | 2.74 | 4.28 | 2.74 | 2.91 | 393 | -0.15 | -0.23 | 0 | 8.04 | 8.04 |
| Kiribati | 690 | 33 | 1.32 | 2.06 | 2.84 | 3.02 | 81 | -0.93 | -1.43 | 3.71 | 11.35 | 15.06 |
| Marshall Islands | 171 | 33 | 0.71 | 1.11 | 2.23 | 2.37 | 4 | -1.63 | -2.51 | 4.62 | 14.03 | 18.65 |
| Nauru | 21 | 1 | 1.32 | 2.06 | 1.32 | 1.40 | 71 | 0.53 | 0.82 | 2.50 | 10.72 | 13.22 |
| New Caledonia | 19103 | 28 | 2.83 | 4.42 | 4.28 | 4.55 | 1628 | -1.07 | -1.65 | 2 | 7.68 | 9.68 |
| Niue | 259 | 1 | 2.41 | 3.77 | 2.41 | 2.56 | 67 | -0.59 | -0.91 | 2.50 | 9.58 | 12.08 |
| Northern Marianas | 475 | 14 | 1.53 | 2.39 | 2.68 | 2.85 | 965 | 0.31 | 0.48 | 0 | 9.28 | 9.28 |
| Palau (Belau) | 512 | 39 | 1.12 | 1.75 | 2.71 | 2.88 | 207 | -0.39 | -0.60 | 2.50 | 10.97 | 13.47 |
| Papua New Guinea | 466973 | 149 | 3.50 | 5.47 | 5.67 | 6.03 | 4694 | -2 | -3.08 | 1.55 | 6.58 | 8.13 |
| Pitcairn | 45 | 4 | 1.05 | 1.64 | 1.65 | 1.76 | 304 | 0.83 | 1.28 | 3.13 | 10.32 | 13.45 |
| Solomon Islands | 27556 | 125 | 2.34 | 3.66 | 4.44 | 4.72 | 2446 | -1.05 | -1.62 | 0.95 | 8.24 | 9.19 |
| Tokelau | 10 | 3 | 0.52 | 0.81 | 1 | 1.06 | 4 | -0.40 | -0.62 | 5 | 13.75 | 18.74 |
| Tonga | 699 | 68 | 1.01 | 1.58 | 2.84 | 3.02 | 1125 | 0.21 | 0.32 | 1.69 | 10.08 | 11.77 |
| Tuvalu | 26 | 9 | 0.46 | 0.72 | 1.41 | 1.50 | 4 | -0.81 | -1.25 | 3.89 | 14.03 | 17.92 |
| Vanuatu | 11880 | 47 | 2.40 | 3.75 | 4.07 | 4.33 | 1979 | -0.78 | -1.20 | 0.63 | 8.12 | 8.75 |
| Wallis & Futuna | 255 | 3 | 1.93 | 3.02 | 2.41 | 2.56 | 762 | 0.48 | 0.74 | 0 | 8.68 | 8.68 |
| Western Samoa | 2935 | 8 | 2.56 | 4 | 3.47 | 3.69 | 1857 | -0.20 | -.31 | 0 | 7.62 | 7.62 |
| US Territories (Line Islands) | 10 | 5 | 0.30 | 0.47 | 1 | 1.06 | 8 | -0.10 | -0.15 | 3 | 13.62 | 16.62 |
| Australian Territories | 53 | 13 | 0.61 | 0.95 | 1.72 | 1.83 | 875 | 1.22 | 1.88 | 3.27 | 10.34 | 13.61 |
| NZ Territories | 29 | 12 | 0.38 | 0.59 | 1.46 | 1.55 | 516 | 1.25 | 1.92 | 0 | 10.94 | 10.93 |
| Chilean Territories (Easter) | 166 | 1 | 2.22 | 3.47 | 2.22 | 2.36 | 600 | 0.56 | 0.86 | 0 | 8.31 | 8.31 |
| | | | | | | | | | | | | |
| Maximum | 466973 | 186 | 3.50 | 5.47 | 5.67 | 6.03 | 4694 | 1.25 | 1.92 | 5 | 14.03 | 18.74 |
| Minimum | 10 | 1 | 0.30 | 0.47 | 1 | 1.06 | 4 | -2 | -3.08 | 0 | 6.58 | 7.62 |

| Country | Impact level | Comments |
|---|---|---|
| **Category A** | | |
| Tokelau | 18.7 | Profound impacts |
| Marshall Islands | 18.65 | may result in these |
| Tuvalu | 17.92 | states ceasing |
| Line Islands | 16.62 | to exist, if the worst |
| Kiribati | 15.06 | case scenarios apply |
| **Category B** | | |
| Federated States of Micronesia | 13.62 | Severe impacts will |
| Australian Territories | 13.61 | cause economic and |
| Palau (Belau) | 13.47 | social disruption with |
| Pitcairn | 13.45 | inter-island movement |
| Nauru | 13.22 | of populations, and |
| French Polynesia | 12.65 | out migration. |
| Cook Islands | 12.42 | |
| Niue | 12.08 | |
| Tonga | 11.77 | |
| **Category C** | | |
| NZ Territories | 10.93 | Moderate to severe impacts |
| American Samoa | 10.69 | will occur; locally |
| Fiji | 9.96 | devastating. Major changes |
| New Caledonia | 9.68 | to crop production systems, |
| Northern Marianas | 9.28 | demographic patterns and |
| Solomon Islands | 9.19 | social infrastructures. |
| **Category D** | | |
| Vanuatu | 8.75 | Impacts locally severe |
| Wallis & Futuna | 8.68 | to catastrophic |
| Easter | 8.31 | requiring considerable |
| Papua New Guinea | 8.13 | forward planning on a |
| Guam | 8.04 | local and sub-regional |
| Western Samoa | 7.62 | level. |

Category A countries are composed entirely of atolls and raised coral islands which will be devastated if projected rises occur and consequently such states may cease to contain habitable islands.

Category B countries are composed of atolls, and other island types. Loss of atolls will result in significant population movements to smaller high islands straining in many instances an already over-burdened agricultural production system. These countries will require substantial outside assistance and considerable out-migration may be expected to occur to the rim countries of Australia and New Zealand. It is unlikely that many of these small island countries will survive in their present social and economic form.

Category C countries are composed of a greater number of high islands and impacts will be locally severe affecting urban centres and transport systems. Agricultural land will be disproportionately lost through inundation of productive flood plain and coastal areas in these countries. Again extensive inter-island and out-migration can be expected.

Category D countries will be the least affected in terms of major disruptions resulting from inundation and loss of islands. Local climatic change may be expected to affect agricultural production resulting in changes to export cash crop productivity. Inundation of low lying coastal areas will reduce the extent of existing mangrove stands and coastal wetlands. Within island relocation of people will result in some significant local social tensions. The epidemiology of diseases such as malaria will be altered with some significant social and economic consequences.

## CONCLUSIONS

All Pacific States will be significantly affected through the loss of outlying islands. Such losses may be unimportant in terms of land area but will result in a substantial reduction in the size of the exclusive economic zones (EEZs). This problem has already been addressed by Japan which has taken steps to ensure continued rights to areas at the southern extremity of that country's EEZ by construction of artificial islands in place of eroding natural islands.

Whilst it might be concluded on the basis of population size that in a global context the potential loss of Pacific micro-states constitutes an insignificant component of changes resulting from climate and sea level change such a view takes no account of the loss of human cultural diversity. It is important to recognise that Melanesia contains one third of the worlds languages and that loss of human cultural groupings within the Pacific through amalgamation and incorporation into neighbouring states represents a significant loss of the human heritage.

Regionally severe problems of social and cultural disruption can be predicted as populations move from eroding, waterless atolls and coral islands, first to neighbouring high islands and then to neighbouring rim countries. It is imperative that the problem of 'ecological refugees' be addressed at a regional level, particularly as the neighbouring rim countries of Australia and New Zealand can be expected to be the target destinations for such refugees.

Economically all countries will be adversely affected by changing climatic patterns causing alterations to existing agricultural systems of production. Climatic changes will result in increased costs to the economy through generation and consumption of more electricity, whilst freshwater availability will change with consequences for human settlement.

# POSSIBLE CONSEQUENCES OF CLIMATIC WARMING IN PAPUA NEW GUINEA WITH IMPLICATIONS FOR THE TROPICAL SOUTHWEST PACIFIC AREA

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## INTRODUCTION

A number of climate change scenarios have been developed based on possible global rates of decadal temperate increase. These rates are related to continued emissions of atmospheric greenhouse gases. The three global temperature change scenarios are

1. low scenario - 0.06°C/decade;
2. middle scenario - 0.3°C/decade;
3. upper scenario - 0.8°C/decade.

In addition to the global scenarios a number of regional or latitudinal scenarios have also been proposed. These latitudinal scenarios are necessary since the magnitude of $CO_2$ forced temperature change will vary latitudinally due mainly to ice-albedo effects. Greatest temperature increases are expected for the polar latitudes while the smallest changes are expected for the tropical and sub tropical latitudes (0-30° North and South).

Taking the middle scenario of 0.3°C/decade and the 0 - 30° latitudinal temperature change of 0.9 to 0.7 times the global average a timetable of warming for the tropical latitudes may be estimated (Table 1).

Table 1. Low latitude temperature change scenario based on mean global warming rate of 0.3°C/Decade.

| Year AD | Global warming °C | Range for low latitudes |
|---|---|---|
| 2000 | 0.5 | 0.45 - 0.35 |
| 2020 | 0.8 | 0.72 - 0.56 |
| 2040 | 1.4 | 1.26 - 0.98 |
| 2060 | 2.0 | 1.80 - 1.40 |
| 2080 | 2.5 | 2.25 - 1.75 |
| 2100 | 3.4 | 3.06 - 2.38 |

The results presented in Table 1 are in general agreement with the range of temperature increases predicted by General Circulation Models (GCMs) for the low latitudes (Manabe & Weatherald, 1980; Wilson & Mitchell, 1987).

The effects such temperature changes will have on low latitude climates is not yet well established. However there appears to be a general consensus that the humid tropics and semi arid/sub humid tropics will both be impacted in similar ways (Table 2).

Of the three tropical climate zones the semi-arid and sub humid regions which are already highly susceptible to climatic variability are likely to be impacted the most given a change in climate. Some areas that are sensitive to current climatic variability with associated negative impacts are likely therefore to find that periods of prolonged drought with implications for desertification will become exacerbated. For the humid tropics, an area which in some cases already suffers from excess rainfall, high humidities and temperatures, climate changes could have important implications for flood management, human comfort and disease.

Table 2. Possible $CO_2$ forced climate changes for the humid and semi arid/sub humid tropics

| Climate parameter | Humid | Semi-arid/ Sub humid |
|---|---|---|
| Temperature | 1-3°C increase | 1-3°C increase |
| Precipitation totals | 5-20% increase | Increase, but geographically variable in magnitude, decreases in some areas |
| Precipitation intensity & frequency | Increased intensity but not frequency | Increased intensity but not frequency |
| Evaporation | Increase by same magnitude as precipitation, increased tendency to drought stress | Increase with increased drought stress in areas that will experience precipitation decreases. |
| Tropical cyclones | Expansion of zone of tropical disturbance genesis | Increase likelihood of tropical cyclone impact |

Although broad statements such as those above concerning likely climate change related impacts are useful, the central issue of climate change impact assessment is to determine the nature of likely impacts for areas at the sub regional or country level. It is these sub-regional impact assessments which will be of most use to regional governments in developing policies that will address the projected $CO_2$ forced climate change.

This paper is therefore concerned specifically with evaluating likely changes in the magnitude and distribution of rainfall in Papua New Guinea with implications for the rest of the southwest Pacific tropical zone. As Papua New Guinea possesses a range of tropical sub-climates generally representative of those found elsewhere in the tropical southwest Pacific results for the Papua New Guinea region may be applicable to other areas throughout the southwest Pacific. In addition to rainfall the impact of temperature increases on human comfort is also highlighted in this paper.

## PRESENT METEOROLOGICAL CONTROLS ON CLIMATE IN PAPUA NEW GUINEA

Three large scale circulation systems presently dominate the climate of the region surrounding Papua New Guinea. These are -

1. The Hadley cell circulation which is a thermally driven mean meridional circulation;
2. Polar or extended low pressure troughs of great meridional extent, and

3. The Walker circulation which is a large scale east-west circulation system.

Both the Hadley and extended meridional trough system are responsible for the transport of heat energy from the tropics to higher latitudes. The Walker circulation brings cool moist air from the eastern Pacific into the region of the western Pacific where it is heated and supplied with moisture. The general area of western Melanesia is therefore dominated by strong convection which is thermally driven by both meridional and zonal circulations (Figure 1).

Although there are short transitional periods between seasons, two distinct seasons exist in Papua New Guinea. The seasons are related to the positioning of the equatorial trough (which lies between the northern and southern meridional Hadley circulations) relative to the location of the Papua New Guinea land mass.

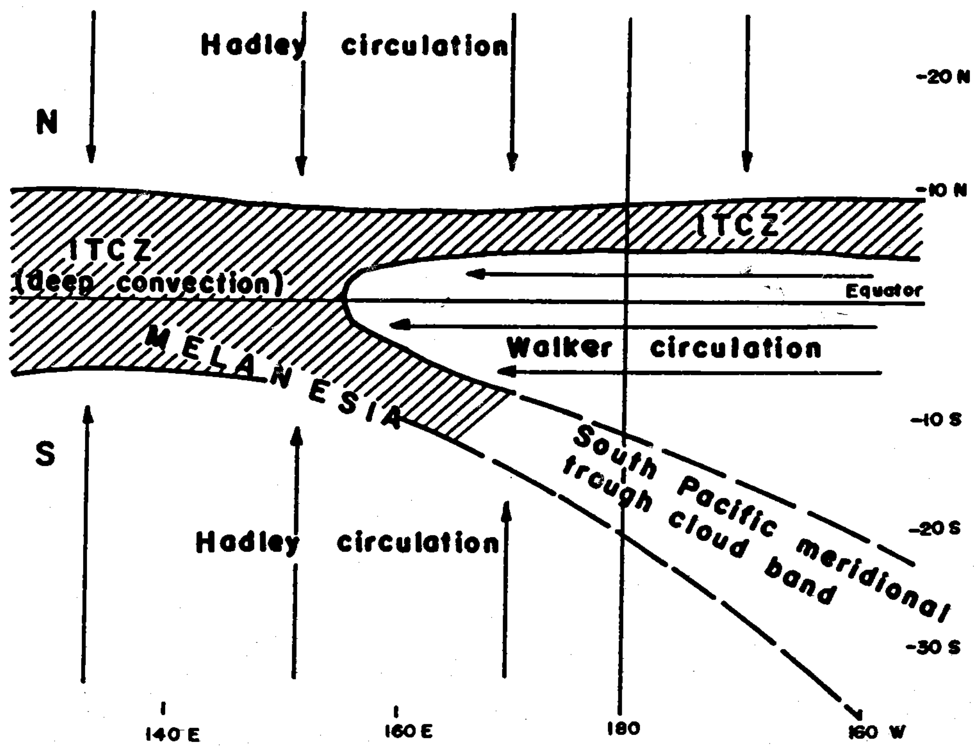


Figure 1. Model of general atmospheric circulation in the Melanesian area (taken from Falls 1983)

The 'southeast' season lasting from May to October is dominated by southeasterly flows (the trades) emanating from a sub-tropical ridge at 25° to 30°S. This southeasterly flow extends equator-ward in a divergent stream (Falls, 1983). At approximately the position of the equator this divergent southeasterly flow is turned northeastwards at the southern monsoon shear line to become the southwesterly flow of the southwest monsoon affecting the Philippines archipelago. Generally the mean monthly rainfall during the 'southeast' season in Papua New Guinea is low, however for areas backed by mountains and lying normal to the southeasterly flow rainfall is at a maximum during the southeast season.

With the onset of the southern summer the equatorial trough begins to develop in the southern hemisphere. At the same time the northern equatorial trough weakens and the band of westerlies contained between the northern and southern equatorial troughs extends southward and eastward of their southern 'winter' position to affect Melanesia (Falls, 1983). With these developments the southeasterly trades are weakened and pushed further south. This short transitional period is followed by the 'northwest' season.

By the beginning of December equatorial westerlies have penetrated the region overlying Papua New Guinea and remain dominant over Papua New Guinea until March. During this season mean monthly rainfall is between 250 and 300 mm in January (McAlpine *et al.*, 1983) in sharp contrast to mean monthly rainfall of 100-150 mm for July in the southeast season. Areas of maximum rainfall during the 'northwest' season are those lying across the northwesterly flow and exerting maximum orographic effect.

## CONSEQUENCES OF GLOBAL WARMING

### Rainfall

Several approaches for assessing likely rainfall distributions as a result of $CO_2$ forced global warming are available. These are:

1. application of results of general circulation models (Manabe & Wetherald, 1980; Mitchell, 1987);
2. comparing ensembles of warm and cold years in terms of their respective rainfall anomalies or departure from long term means (Wigley *et al.*, 1980; Williams, 1980; Namias, 1980; Pittock & Salinger, 1982);
3. using established linkages between atmospheric circulation and climate to ascertain how climates will change given a specified change in atmospheric dynamics, and
4. the use of historical analogues or regional climate reconstructions of globally warmer periods to model future warmer conditions.

As pointed out by Pittock & Salinger (1982) each of these approaches has limitations as none of them are based on a perfect analogy. However, despite the various limitations the combination of results from individual approaches may allow some first order estimates of possible regional climate changes to be made. This is of course contingent upon result agreement between results of different the approaches.

Presented below are the results of three of the above approaches in an attempt to shed some light on possible $CO_2$ forced changes in rainfall distribution specifically for Papua New Guinea and more generally for the tropical southwest Pacific.

General Circulation Models

The confidence that can be placed in the results of General Circulation Models (GCMs) depends on the degree to which the GCM is based on physical principles. Given the difficulty of modelling complex feedback relationships between the atmosphere and ocean systems, and the problem of representing clouds in GCMs, the results produced by GCMs to date, can not be interpreted literally. This is especially true with reference to precipitation changes. A further limitation of GCMs is that they present an equilibrium picture of $CO_2$ forced climate change without revealing details of the transient response of climate to $CO_2$ forcing. A full review of GCM limitation will not be given here but the reader is referred to Dickinson (1986) and Wigley (1988).

Despite the deficiencies in GCMs there are some broad-scale GCM results which can be used as indicators of likely climate change. These have been summarised by Wigley (1988) and include such global changes as warming of the lower troposphere, increased precipitation, cooling of the stratosphere, and warming of the tropical upper troposphere. Although some confidence exists in these global predictions the GCMs fall down at the regional scale, the scale that is of immediate interest to individual governments for assessing likely climate impacts arising from increased greenhouse gas concentrations. Problems in predicting climate changes at the regional scale arise due to the coarse resolution of the GCMs, thus they do not take into account small scale climatic processes which interact in a number of ways to influence regional cloudiness, precipitation and zones of cyclogenesis. Additionally complex interactions between orographic and climatic processes which are important at the regional scale are usually simplified in GCMs.

As regional scale assessments are one of the principal objectives of making impact statements concerning $CO_2$ forced climate change it seems that GCM results are of little use for this task. However in the absence of other methods for predicting likely changes in climate parameters, especially precipitation, GCMs can be used to develop scenarios of possible future climate.

Presented below is a comparison of results from two GCMs. The purpose of the comparison is to establish if the two GCMs exhibit compatible results with reference to precipitation changes for the Papua New Guinea - southwest Pacific area. The relative degree of convergence or divergence of the two GCM model results will influence the degree of confidence that can be placed in any climate change scenarios based on GCM results.

A number of GCMs exist. These include the GISS model (Hansen *et al.*, 1984), the GFDL model (Manabe & Stouffer, 1980) the CCM model (Washington & Meehl, 1984) and the UKMO model (Wilson & Mitchell, 1987). Of these the equilibrium results for a $2xCO_2$ situation for the latter two models will be reviewed here. As noted by Wigley (1988) the 'control run' of the CCM model has not been assessed as to its accuracy for simulating contemporary climate at the regional level. The UKMO model has undergone control runs and has reproduced most of the main features of observed temperature and precipitation. Wilson & Mitchell (1987:13325) in fact consider that the model simulation of present climate is as good as and often better than that of other models used to study the effects of enhanced $CO_2$. Various features of the two GCMS are compared in Table 3.

Results of the two GCMs were compared by dividing the area encompassed by the points 135°E 0°S, 135°E 15°S, 135°W 0°S and 135°W 15°S into eight areas of 23.5° latitude by 7.5° longitude. The changes in precipitation for each 23.5° x 7.5° area was compared for the two models. Results for December to January (wet season) and June to August (dry season) simulations are shown in Table 4. What is immediately apparent is the large variation in precipitation changes over very short distances in the CCM Model. This has also been noted by Wigley (1988) in a similar study for the Mediterranean Basin and is attributed to serious defects in the physics of the models. Despite this a comparison of changes in precipitation as depicted by the two models may serve as a guide to the likely direction of change in precipitation given a $CO_2$ forced global warming.

Table 3. Comparison of various features of two GCM models.

| | Washington and Meehl model (CCM) | Wilson and Mitchell model (UKMO) |
|---|---|---|
| Atmospheric model | 9 layer, 15 wave rhomboidal, spectral | 11 layer, 5° latitude 7.5° longitude, grid |
| Ocean model | 50 m simple mixed layer | 50 m mixed layer |
| Cloud prescription | Clouds with precipitation | Cloud prediction for both convective and layer cloud with precipitation |
| Sea ice model | One slab thermo-dynamic | Energy balance. |
| Snow albedo | 0.8 independent of depth or latitude. | Varies with depth. |
| Ice albedo | Snow albedo if snow covered, 0.70 for bare ice | 0.06 unfrozen sea, 0.7 over land ice. |

Table 4. Comparison of results from two GCMS of likely precipitation changes (mmd$^{-1}$) for 2 x $CO_2$ situation.

| | GCM model | |
|---|---|---|
| | Washington and Meehl | Wilson and Mitchell |
| Season Area | | |
| DJF | | |
| A | -2(NW) + 2 (SE) | -2(NW), + 2(SE) |
| B | 0(NW), + 4(SE) | 0 |
| C | +2 | +1 |
| D | +1(NW), + 2(SE) | NW +1 |
| E | -2(NW), + 3(SE) | +1(NW), + 3(SE) |
| F | +3(NW), + 1(SE) | +1(NW), + 2(SE) |
| G | +3(NW), -1(S), 0(SE) | -1 |
| H | +1(NW), 0(SE) | -1 |
| JJA | | |
| A | -1(NW), + 1(SE) | -1(NW), + 1(SE) |
| B | +1(NW), + 2(SE) | 0(NW), + 1(SE) |
| C | 0(NW), + 1(SE) | +1 |
| D | +2 | 0 |
| E | -2(NW), + 1(SE) | +1(NW), - 1(SE) |
| F | +2 | +1 |
| G | +1 | +2 |
| H | +1 | -1 |

Generally both models show the same direction of change in precipitation (i.e. increase or decrease) for the eight 23.5° x 7.5° areas for both season simulations. Both in both seasonal simulations, show large internal variation in the direction of change in precipitation with up to 4 mmd$^{-1}$ difference between the northwestern and southeastern parts of the area A, for example. Of the two GCMS the within area differences in precipitation change are smaller for the UKMO model.

From the results presented in Table 4 little can be said about actual magnitudes of precipitation change. However common features of the two GCM results do suggest that there maybe little change or a possible decrease in precipitation over Papua New Guinea for the period JJA with little change during the period DJF. The JJA scenario developed here has implications for Papua New Guinea. If there are decreases in rainfall for the JJA period this will force the drought stress presently experienced in these dry season months. For areas east of Papua New Guinea both JJA and DJF simulations reveal possible increases in precipitation on the whole but do indicate that some areas may experience decrease in the DFJ period.

Although the exact nature and magnitude of seasonal changes in precipitation can not be detailed using present GCM results the GCMs do indicate that some change in regional precipitation patterns may occur. If there are decreases in precipitation amounts in the dry season months of June to September this will force drought stress in these months and have implications for rain-fed agriculture. This problem will be further exacerbated if such areas also experience decreased wet season precipitation, as it is the wet season rains which restore soil moisture deficits built up during the preceding dry season. This scenario has implication not only for areas dependent on rain-fed agriculture but also settlements dependent on rain-fed water supply for domestic and industrial use and power generation. In contrast areas that may experience increased precipitation, are likely to be faced with problems of flood and erosion management. If increased rainfalls are brought by an increased frequency of tropical cyclones, tropical cyclone induced damage to small islands and coastal developments in general is likely to also increase.

Atmospheric dynamics climate relations

The major meteorological controls on climate for Papua New Guinea have been discussed above. It is considered here that what is important for determining future climates in Papua New Guinea is not warming on a regional scale but the global distribution of $CO_2$ forced warming. It is believed that the differential warming of polar and equatorial regions, with the former experiencing greater relative warming, will result in an exaggeration of the present asymmetry of the northern and southern hemisphere circulations with the southern hemisphere circulation increasing in strength relative to the northern hemisphere. Such asymmetry will develop as a product of the pronouncement of the present larger Antarctic-Equator temperature differential compared to the Arctic-Equator temperature differential.

Flohn (1980) has estimated for a drastically reduced ice coverage in Arctic latitudes and a year round temperature increase of 7°C in the Arctic that the northern subtropical high pressure belt would shift from the present mean position of 37°N to 43-45°N. It is believed that the position of the southern subtropical high pressure belt will remain at its present position of 31°S. If such a large shift of the northern subtropical high pressure zone occurs, the position of the meteorological equator and hence the zone in which the average meridonal wind component changes, will also be shifted north.

A greater displacement is expected in the southern summer months (the present Papua New Guinea 'northwest' season). The implications of such a displacement for the climate of the 'northwest' season in Papua New Guinea are considerable. With the displacement of the meteorological equator to 9-10°N the zone of moist westerly air contained between the monsoon shear lines and responsible for the increased rainfall amounts would be displaced north of the Papua New Guinea landmass. As a consequence the equatorial rains of the southern summer corresponding to the present northwest monsoon in Papua New Guinea would only rarely penetrate south of the equator. Under such a set of conditions decreases of summer 'northwest' season rainfall amounts may be experienced in Papua New Guinea. Moreover this situation would be exacerbated in the mid Pacific by a probable increase in equatorial upwelling due to the greater intensity of the southern Hadley circulation causing a reduction in oceanic evaporation and thus rainfall south of the equator. This situation would most likely reach its maximum at the height of the northern summer when the meteorological equator reaches its northern most latitude. Northward displacement of the meteorological equator in the northern summer would possibly bring the southern monsoon shear line to lie somewhere over Papua New Guinea resulting in weather conditions similar to that presently experienced in the transition period between the 'southeast' and 'northwest' seasons. The summer time months of December to February could possibly become dominated by periods of fine weather with light variable winds or 'doldrums'.

Rainfall in this period would be reduced in comparison to present amounts. The major implication of this set of conditions would be the disappearance of the 'northwest' monsoon over Papua New Guinea and the failure of the 'wet' season. With this set of circumstances Flohn (1980) believes that the moisture bearing westerly would also not reach Indonesia and northern Australia.

On a seasonal basis therefore maximum climate impacts would occur in the 'northwest' or 'wet' season. Most areas in Papua New Guinea presently experience rainfall maxima during the 'northwest' season months of December to March. This is especially so for areas that presently possess a distinct 'dry' season in the months of May to October when southeasterly flows predominate. For these areas the failure or disappearance of the 'wet' season will mean the extension of the 'dry' season. The imposition of these conditions may lead to severe reductions in present mean annual rainfall amounts.

In contrast to the possible disappearance of the 'northwest' season with a mean global warming of 4°C and the development of a pronounced asymmetry in the ocean-atmosphere circulation system, the 'southeast' season is likely to remain unchanged apart from a decrease in the intensity of the southeasterly trade flow due to a weakening of the intensity of the subtropical high pressure zone. Assuming the intensity of the southeasterly flow falls only slightly and the associated surface stress wind vector remains near its present level the vertical flow component within the oceanic Ekman layer will be sufficient to sustain ocean upwelling. This will maintain surface water temperatures below air temperatures. In such a case the sensible heat flux will be directed to the ocean surface, relative humidity will increase and evaporation decrease sharply. Air flowing over cooler waters (relative to the air) will remain stable with no increases in rainfall amounts even though surface water temperatures may have risen. Flohn (1984) has summarised the climatic effects of oceanic upwelling (Table 5). The extension of the period and possibly the zone of upwelling in the equatorial Pacific will have major implications for those islands in the mid Pacific such as Kiribati and Line Islands which already experience low rainfall amounts due to the onshore effects of oceanic upwelling. However these future climatic impacts may be insignificant for these countries if a sea level rise of 1 m is realised (Pernetta, this volume).

Areas in Papua New Guinea that presently experience 'southeast' season rainfall minima will continue to do so given the likely set of developments described above. Likewise the *status quo* will be preserved in areas currently with 'southeast' season rainfall maxima.

Table 5. Climatic effects of upwelling (Flohn, 1984)

| Climatic parameter | Climatic effect |
|---|---|
| Sensible heat (enthalpy) | Downward flux stabilisation of air |
| Convection | Suppressed |
| Cloudiness, rainfall | Suppressed |
| Vertical momentum exchange | Reduced |
| Surface windspeed | Low |
| Saturation deficit | High (80% +) |
| Precipitable water | Low (20 - 30l/$m^2$) |
| Evaporation | Strongly reduced |

Discussed so far have been the likely changes in the large scale meteorological controls on climate in Papua New Guinea due to a 4°C warming of the global climate. Climatic warming and an associated asymmetric ocean atmosphere circulation system are likely to have impacts on secondary circulations which affect short term weather patterns more so than the long term climate.

Associated with the southern monsoon shear line mentioned previously is the development of low pressure disturbances. These disturbances are most frequent in summer when they develop in the southern monsoon shear line which is coincident with the equatorial trough lying south and southeast of the southeastern tip of Papua New Guinea at about 13° to 16°S. Disturbances do not develop north of 5°S due to negligible vorticity as a result of the Coriolis force being reduced to zero at the equator. Presently Papua New Guinea is little affected by these low pressure tropical disturbances in contrast to the Solomon Islands where tropical cyclones are well known. However with an increased mean global temperature of 4°C and northward displacement of the equatorial trough in the southern summer the zone of low pressure disturbance genesis could be brought into the region of the Pacific ocean lying off the North Solomon Islands and also into the northern parts of the Solomon sea around 9°-10°S between the Papua New Guinea mainland and the Solomon Islands.

A northwards shift of the zone of low pressure disturbance genesis could well have implications for areas in the North Solomons Islands and along the northern coast of the southeastern tip of Papua New Guinea. Disturbances, if generated in the area west of the North Solomons, or in the northern parts of the Solomon sea will move southwards gaining intensity. Though the genesis of low pressure disturbances in these areas are uncommon presently, the northwards summertime displacement of the equatorial trough and related zone of cyclone genesis may result in a greater number of cyclones impacting the Milne Bay, D'entrecasteaux and Louisade archipelago areas. Possible future cyclone tracks may resemble that of cyclone Hannah which caused considerable damage in the Tufi-Milne Bay area in 1972.

If a northward displacement of the zone of cyclone genesis does not eventuate the increased sea surface temperatures associated with global warming could result in an increase in the intensity of tropical cyclones and an associated increase in their destructive power from wind, storm surge and flooding effects. Further sea surface temperature increases may result in a southern extension of the zone of tropical cyclone genesis, with tropical cyclones being able to push further south than at present.

The above discussion has been directed at assessing the possible changes of the meteorological controls on climate in Papua New Guinea given a mean global warming of 4°C. It should however be stressed that the possible developments outlined above are those to be expected following a continuum of change from present conditions and do not represent a set of conditions that will suddenly precipitate.

It should also be stressed that it has been assumed in this discussion that a pronounced asymmetry in the southern hemisphere circulation and the maintenance of the mean position of the southern sub tropical high will be the predominant responses to mean global warming to 4°C. However it should be mentioned that if the southern sub tropical high does move southwards, and this is favoured by Pittock & Salinger (1982) due to considerations of baroclinic instability but not Flohn (1980), then the southeasterly trade season would in fact decrease with associated increases in the length of the wet season. Obviously determination of the likely behaviour of the sub-tropical high pressure belt is crucial for assessing the response of tropical southwest Pacific climates to global warming. Another important determinant of climatic variability in the tropical southwest Pacific is the behaviour of the southern oscillation (a component of the zonal Walker circulation) which in its negative phase (i.e. a high pressure anomaly over the Indo-Melanesian area) is responsible for the onset of El Niño events. If in a globally warmer situation the area of maximum convergence and convective ascent is maintained over the Indo-Melanesian area then the western Pacific will remain an area of large scale convective activity and high rainfall. As the western ascending arm of the Walker circulation is driven by both dynamic and thermal forces an increase in surficial heating (thermal forces) in the Indonesian area due to higher temperatures may be enough to offset any decrease in dynamic forces that may be associated with global warming and zones of convergence.

If however the dynamic forces (i.e. convergence) are predominant in driving the western arm of Walker circulation and thus maintaining the positive phase of the southern oscillation then decreases in convergence will result in a greater frequency of southern oscillation negative phase occurrences. In such a situation El Niño like events with prolonged droughts in the western Pacific and anomalously high mid Pacific rainfall will be a predominant feature of future $CO_2$ forced tropical climates in the southwest Pacific region.

Predictions based on warm and cold year ensembles

This analysis is based on a comparison of the climatic variability between a set of cold and warm years. The basic assumption inherent in such an approach is that warm year circulation systems will give an indication of those circulation-climate systems that may be expected for a warmer global situation. Pittock & Salinger (1982) believe that the main drawback with such an analogy is that individual warm years are a product of a short term variability of the climate system not the result of a progressive change of the climate system due to a forcing factor. Wigley *et al.* (1980) however argue that internal consistency of the dynamics of warm years will produce similar climatic effects for an ensemble of warm years. Based on this argument ensembles of warm years may be used to indicate possible scenarios for a warmer earth (Wigley *et al.*, 1980).

The ensemble of warm and cold years used in this analysis for the southern hemisphere are those identified by Pittock & Salinger (1982). The warm years are 1957, 1961, 1968, 1970, 1973, 1975 and 1977. The cold years are 1958, 1959, 1963, 1964, 1965, 1969, 1976. 'Cold' and 'warm' here refers to departures below and above mean surface temperatures for the annual time series 1957 to 1978 for 11 island stations in the southern ocean and 11 stations located on the Antarctic continent.

The general method adopted in this warm cold year ensemble approach was that for six coastal stations throughout Papua New Guinea a rainfall anomaly index was calculated. This was done by calculating mean and standard deviation of annual rainfall (January to December) for each station. Departures of individual yearly rainfall from the long term mean value were divided by the standard deviation. Such a procedure produces a normalized departure and reduces the inherent spatial and temporal variability of tropical rainfall (Hackett & Hastenrath, 1986) which is a result of its highly localised nature. An overall Papua New Guinea rainfall anomaly index was produced by taking the six station mean. As Papua New Guinea rainfall is seasonal in nature the year was broken into three approximately 120 day periods in an attempt to highlight any pronounced contrast between anomaly patterns for the dry and wet seasons. For each station 120 day rainfall anomaly indices were also calculated. Unfortunately this analysis is only restricted to a consideration of lowland sites as frequent breaks in the annual rainfall time series for Highlands stations precluded the inclusion of those stations in the analysis. As there is little spatial coherence of rainfall between lowland and highland sites as has been shown by McAlpine *et al.* (1983) the results presented here may differ to those produced if highland stations were included in the analysis.

Once rainfall anomaly indices had been calculated for warm and cold year ensembles mean warm and cold 120 day and yearly indices for each station were tested for significant differences by means of the students 't' test. The results are presented in Table 6.

What is apparent from Table 6 is that the annual Papua New Guinea rainfall anomaly is significantly different between warm and cold year ensembles. This also applies to the individual stations of Kavieng and Madang. An interesting feature of this analysis is the results for Madang and Lae. For Lae significant differences are revealed for all 120 day periods but not for the annual average index. The opposite is true for Madang. This result is probably a function of the anomaly trend for individual 120 day periods (Table 7).

Table 7 is of value and may bear implications for likely trends of rainfall at the analysed stations assuming the analogy is true that the climatic conditions of a warm year ensemble represents possible future climatic conditions for a warmer globe. Generally for the annual anomaly index the warm year ensemble indicates positive departures i.e. greater precipitation amounts than the long term mean where cold year ensembles show negative departures. Of significance is the Papua New Guinea annual anomaly which indicates in warm years that Papua New Guinea experiences above average precipitation amounts and therefore following the above analogy Papua New Guinea should receive greater amounts of precipitation given global warming. However attention should be paid to the 120 day period warm/cold year ensemble relationships. For the 0-120 day period Lae shows a significant negative rainfall anomaly for the warm years while Momote and Kavieng demonstrate positive departures. Significant differences for the 121-240 day period are revealed for Lae and Port Moresby both with positive anomalies in warm years. For the 241-366 day period Lae has a significant positive warm year anomaly while Kavieng has a negative anomaly. The annual anomaly index for individual stations reveals only significant differences between warm and cold year ensembles for two stations. These are Madang and Kavieng which both possess positive warm year anomalies.

Table 6. Levels of significance for differences in station warm/cold year rainfall anomaly index

| Station | Period (days) 0-120 | 121-240 | 241-366 | Annual |
|---|---|---|---|---|
| Rabaul | - | - | - | - |
| Lae | 0.05 | 0.025 | 0.10 | - |
| Madang | - | - | - | - |
| Port Moresby | - | 0.025 | - | - |
| Momote | 0.025 | - | - | - |
| Kavieng | 0.01 | - | 0.10 | 0.05 |
| PNG | 0.05 | 0.05 | - | 0.10 |

Note: Days 0 - 120 and 241-366 incorporate the 'wet' season and transitional periods between the 'wet' and 'dry' season. Days 121-240 represent the 'dry' season.

Table 7. Warm/cold year ensemble anomalies trend for 120 day periods

| Location | 0-120 | 121-240 | 241-360 | Annual |
|---|---|---|---|---|
| Rabaul | +/0 | -/0 | -/+ | +/+ |
| Lae | -/+ * | +/- * | +/- | +/- |
| Madang | +/- | +/+ | -/- | +/- * |
| Port Moresby | +/+ | +/- | +/+ | +/+ |
| Momote | +/- * | -/- | -/+ | -/- |
| Kavieng | +/- | -/- | -/+ * | +/- * |
| PNG | +/- | +/- * | -/+ | +/- * |

\+ = positive anomaly
\- = negative anomaly
* = Significant difference between mean anomaly.

From the results presented in Table 7 it is apparent that a great deal of variability exists between individual locations and 120 day periods, and a synthesis of these results is difficult. What is apparent though is that individual stations in some cases show distinct responses in the way of positive or negative anomalies for southern hemisphere warm or cold years. As Papua New Guinea is located in a sub equatorial position, and its climate is influenced by the seasonal movement of the Inter Tropical Convergence Zone, rainfall anomalies are likely to be also influenced by components of the northern hemisphere circulation, especially the behaviour of the northern hemisphere sub tropical high pressure belt. This fact and the fact that this analysis is based on southern hemisphere warm and cold years may account for the variability of the trends shown in Table 7. Additionally, given global warming and Papua New Guinea's location and the likelihood that the present asymmetry of the southern hemisphere circulation will become pronounced and the southern hemisphere will remain cold relative to the northern hemisphere, the cold year ensemble may be more indicative of future trends in rainfall. If this is the case Papua New Guinea would expect to receive less rainfall with global warming.

Synthesis

The above analyses have produced a small degree of convergence of the results for the GCM and atmospheric dynamic - climate relationship approaches although the latter most likely represents an extreme scenario of possible climate change. Both these approaches indicate that Papua New Guinea may experience decreases in rainfall for the dry season months of June to August, with wet season precipitation totals remaining close to their present levels. For other locations east of Papua New Guinea increases in precipitation may be generally experienced but decreases should not be discounted for some areas. Locations likely to be impacted the most are those that presently possess a sub-humid climate and a distinct June to August dry season. Possible decreases in June to August precipitation amounts may result in increased drought stress during these periods. This is likely to be exacerbated by increased evapotranspiration rates associated with increased temperatures.

Results of the warm cold year ensemble analysis show little convergence with results from the other two approaches. What is apparent is the intra-regional variability of the response of rainfall to warm and cold years. This makes any statement on the likely trends of rainfall for the area of interest based on this type of analysis tenuous. If however global warming does result in a unipolar glaciation, with the southern hemisphere possessing a greater pole to equator temperature differential than the northern hemisphere, then the analogy that a warm year ensemble is indicative of future circulation systems given global warming may not hold true. In this case a cold year ensemble may be more appropriate for modelling future trends with net precipitation decreases expected for Papua New Guinea and possibly the rest of the Pacific.

Temperature

Numerical modelling studies indicate that $CO_2$ forced climatic warming will result in greater temperature increases at the poles than at the equatorial regions. For the latter a warming of 2°-3°C has been predicted. Presented in Table 8 are probable future mean annual temperatures for a variety of centres throughout Papua New Guinea.

Probably the greatest impact a 2°C warming will have will be on human activity, especially human comfort. Presently most of coastal Papua New Guinea is classified according to the Terjung classification (McAlpine *et al.*, 1983) as experiencing sultry days and warm nights. Such conditions are considered moderately uncomfortable. Temperature increases of up to 2°C in coastal areas are likely to result in a transition to sultry conditions both day and night, a condition presently experienced in the Bismark Archipelago and Milne Bay areas. A transition to such conditions will render most coastal areas uncomfortable.

This contention is further reinforced by a consideration of the Relative Strain Index (RSI). The RSI is an index of human comfort, and is the ratio of the amount of sweat evaporation needed for comfort to the amount of evaporation possible in the given circumstances. In practice discomfort is experienced with RSI values in excess of 0.3.

Shown in Table 9 are the present and future RSI values for a number of coastal centres throughout Papua New Guinea. Calculations of future RSI values have been based on a 2°C temperature increase

Table 8. Present and future mean annual temperatures Papua New Guinea

| Location | Elevation (m) | Present (°C) | Future (°C) |
|---|---|---|---|
| Ambunti | 50 | 27.4 | 29.4 |
| Goroka | 1565 | 20.1 | 22.1 |
| Lae | 10 | 26.3 | 28.3 |
| Lumi | 535 | 23.8 | 25.5 |
| Madang | 4 | 26.5 | 28.5 |
| Momote | 4 | 27.3 | 29.3 |
| Mt Hagen | 1630 | 18.3 | 20.3 |
| Mt Wilhelm | 3480 | 7.6 | 9.6 |
| Port Moresby | 35 | 26.8 | 28.8 |
| Rabaul | 4 | 27.1 | 29.1 |
| Samarai | 40 | 26.5 | 28.5 |
| Wabag | 1980 | 16.7 | 18.7 |

Table 9. Present and projected* levels of human comfort.

| Location | Feb. | April | June | Aug. | Oct. | Dec. | Annual |
|---|---|---|---|---|---|---|---|
| Ambunti | .33 | .33 | .33 | .34 | .34 | .29 | .32 |
| * | .45 | .43 | .44 | .44 | .44 | .39 | .42 |
| Daru | .35 | .30 | .23 | .21 | .28 | .36 | .28 |
| * | .47 | .41 | .33 | .29 | .31 | .48 | .41 |
| Lae | .34 | .30 | .23 | .20 | .26 | .31 | .27 |
| * | .40 | .40 | .31 | .28 | .36 | .39 | .40 |
| Madang | .29 | .28 | .28 | .27 | .28 | .29 | .27 |
| * | .39 | .39 | .39 | .36 | .38 | .39 | .39 |
| Popondetta | .35 | .30 | .25 | .25 | .28 | .31. | .29 |
| * | .42 | .41 | .35 | .34 | .34 | .41 | .41 |
| Port Moresby | .31 | .30 | .25 | .23 | .28 | .33 | .28 |
| * | .41 | .40 | .32 | .31 | .36 | .43 | .40 |
| Rabaul | .30 | .20 | .30 | .27 | .29 | .29 | .29 |
| * | .40 | .40 | .40 | .36 | .39 | .39 | .40 |
| Samarai | .32 | .25 | .17 | .15 | .19 | .29 | .30 |
| * | .43 | .35 | .25 | .23 | .28 | .40 | .35 |
| Wewak | .29 | .30 | .31 | .29 | .29 | .29 | .30 |
| * | .39 | .40 | .42 | .39 | .38 | .40 | .43 |

* 2°C temperature increase and 7% vapour pressure increase.

and a 7% increase in vapour pressure. These future RSI values are considered to be conservative as a 1°C temperature increase is associated with a 7% vapour pressure increase.

On a mean annual basis most coastal centres in Papua New Guinea presently experience conditions below the discomfort level. Values for Samarai and Wewak however do indicate that some discomfort is presently experienced in these areas. An appreciation of the seasonal march of human comfort is given by the bimonthly values shown in Table 9. This demonstrates that most coastal stations possess great variability in comfort levels with the dry season months of June to August the most comfortable. However a transition to equatorial temperatures 2°C higher than present ones with an associated rise in vapour pressure will drastically reduce the periods of comfort and in some cases result in all year round discomfort. This is demonstrated well for the case of Port Moresby which presently has a well defined period of June to October when conditions are comfortable as rated by the RSI. Equatorial warming of 2°C however will result in these dry season months becoming marginally uncomfortable. The situation will be much worse for Ambunti, Madang, Popondetta, Rabaul and Wewak.

Generally global warming will result in marked changes to the seasonal distribution of comfort throughout the southwest Pacific. Perhaps the major implications of an increase in discomfort levels are for the major coastal commercial centres throughout the equatorial and southwest Pacific. Although some natural acclimatisation to the increased temperatures may offset some of the projected discomfort, greatest impacts will be felt by workers in the primary sectors of the economy. Outside work will become more stressful with perhaps an alteration in the hours of work required so as to avoid the most uncomfortable and stressful times of the day. There will also be implications for the secondary and tertiary sectors of the economy. If an equitable indoor climate is to be maintained for indoor workers a commensurate increase in air conditioning above the present levels is likely to be required. Such requirements are most likely to be greatest in buildings that are presently 'under air conditioned'. Related to this will be an increase in energy consumption for air conditioning and a consequent economic cost.

Warming of up to 2°C will result in an altitudinal shift of mean annual isotherms. As temperatures above 500 m asl. are strongly controlled by altitude, as opposed to physiographic effects at low altitude (below 500 m) sites, and the present mean annual environmental lapse rate is 6°C/km a 2°C warming will result in an altitudinal shift of mean isotherm position by approximately 333 m. Areas at 300-350 m will therefore be subject to a temperature regime similar to that presently experienced at coastal locations. Such an altitudinal shift will have implications for the future altitudinal limits of agricultural production, the health of natural vegetation and mean annual water budgets. (See Hughes & Sullivan, this volume).

Vegetation

As the present distribution of natural vegetation above 500 m appears to be controlled by temperature as evidenced by the well developed altitudinal zonation of major vegetation associations (Pajimans, 1976) a shift in the boundary of upper montane forest may occur with global warming. A return to a vegetation distribution pattern similar to that of the Hypsithermal, as discussed by Bowler *et al.* (1976) and Flenley (1985), may be likely. However the relatively rapid transition, to 2°C warmer than present compared to that during Holocene warming, is expected to have more of a negative impact on the natural vegetation than a positive one. The vegetation may be impacted in two ways. Firstly as previously discussed a mean global warming of 4°C is expected to produce a net reduction in rainfall totals in Papua New Guinea. By mid to late next century rainfall regimes are expected to be significantly different from present ones. While the opportunity may exist for an altitudinal shift in the forest limit due to general temperature increase it is believed that reduction in rainfall amounts will impose sufficient moisture stress to curb any significant altitudinal shift of the forest limit. Secondly due to the projected rapid change in temperature relative to the Holocene, ecotonal areas may experience significant changes in ecosystem dynamics. Generally vegetation in marginal environments, where limiting factors are dominant in determining plant distribution, is expected to experience some stress. The stress magnitude and the degree to which it will affect current patterns can not be determined at this stage without a detailed consideration of the physiology of the major component species of the dominant plant associations occupying marginal areas.

## CONCLUSION

A consideration of the likely climatic response to a global warming has revealed that changes to the meteorological controls of climate are likely. The meteorological controls on climate are expected to be significantly different by the end of the 21st century. By this time the climate of Papua New Guinea and the southwest Pacific is expected to be somewhat different compared to the present. Changes in the meteorological controls will be manifest by possible changes in precipitation amounts and distributions in the southwest Pacific. Areas likely to be impacted severely and subject to increased drought frequency and magnitude are those that presently experience southeast season rainfall minima. This has serious implications for the future allocation of water resources in these areas. These problems are expected to increase with a change of the meteorological controls on climate in the southwest Pacific. Conversely areas that may experience an increase in rainfall amounts will be faced with flood management problems. Increased rainfall amounts may also lead to higher rates of erosion. This has implications for the design of future flood protection works.

Equatorial warming of 2°C will have a number of impacts on vegetation zonation, the vertical distribution of temperature and human comfort. A vertical shift of the position of the mean annual isotherm associated with the present altitudinal limit of agricultural production by 333 m will conceptually result in an increase in the potential area available for agricultural production. However, if there is a net reduction in rainfall amounts commensurate with a change of the meteorological controls on climate, this may offset any future perceived increased levels of agricultural production and the extension of agricultural production zones in present marginal areas.

Human comfort will be significantly affected by an equatorial warming of 2°C. Although some natural acclimatisation may be expected increased temperatures and atmospheric vapour pressures are likely to increase levels of discomfort significantly above present ones. This will be especially true for inhabitants of coastal environments. In coastal built up areas increased levels of human discomfort will have implications for worker productivity, energy consumption and capital expenditure for the maintenance of equitable indoor climates.

The evidence from numerical modelling studies that increased atmospheric $CO_2$ levels will force a change in the mean global climate is mounting. Also the fact that global warming will have significant impacts at the regional scale cannot be denied. For the southwest Pacific although the impacts of a changing global climate will not be as great as those projected for mid to high latitude environments, the likely impacts of a 2°C regional warming and more importantly a mean global 4°C warming with associated implications for the meteorological controls on climate should not be ignored.

The consequences of climatic warming discussed above are considered to be of major significance in terms of their socio-economic impacts. These consequences should be taken into account if a sensible approach to the future utilisation of the southwest Pacific's climatic resources is desired and the response to climatic change planned for.

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# THE EFFECT OF SEA LEVEL RISE ON ATOLLS AND MOTU

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## INTRODUCTION

Coral islands generally occur within 30° North and South of the equator. They are best developed in the Indo-Pacific province and are less extensive in the Atlantic province (Caribbean to West Africa). Coral diversity, and the variety of coral reef structures reflect this, and in the Indo-Pacific the diversity of coral structures increases from west to east towards the central Pacific (Figure 1, after Davies, 1972:71).

In the Indo-Pacific there are more than 300 atolls, and extensive barrier reefs. In contrast, in the Caribbean there are about 10 atolls and two true barrier reefs (McLean, 1977). The shoreline of the Gulf of Eilat supports only fringing reefs (Loya & Slobodkin, 1971). The Seychelles Islands in the western Indian Ocean support fringing reefs and several small atolls (Braithwaite, 1971, 1984; Stoddart, 1984) while the Maldives are made up of a double chain of atolls rising from a submarine ridge (Davies *et al.*, 1971). The Andaman Island group to the east is similarly located on an active tectonic plate boundary and also contains atolls (Stoddart, 1971). Throughout the Pacific there are extensive and diverse reef forms.

Conditions favouring coral growth and reef development are well known, and include warm well-oxygenated water of moderate salinity and low turbidity, which is shallow enough to permit light penetration. Sufficient carbon dioxide for symbiotic algal growth and adequate nutrients are also required (see e.g. Bird, 1984:253; Stoddart, 1969). Most hermatypic coral growth occurs at depths of less than 100 metres (Wiens, 1962:11) and most actively growing reefs which have continued to develop since the Holocene warming and associated sea level rise are built on older limestone deposits dating from Eocene or earlier times (see e.g. Stoddart, 1967, 1969, 1970; Jones & Endean, 1977). Widespread destruction of coral reefs may have occurred in the Atlantic province due to an influx of cold water during Pleistocene glacial phases (Davies, 1972:73), and during this period reefs were substantially cut down to form platforms or terraces on which late Pleistocene and Holocene reef growth has taken place (Wiens, 1962:109; Stoddart, 1982). Present day coral reefs have developed therefore against a background of changing sea level, and most recently, a rising sea level. The effects of continued rise in sea level are here considered with particular reference to the islands (motu or cays) which are developed on reef platforms.

## CORAL REEF FORMS AND ISLANDS

The islands associated with reefs have a variety of forms which reflect the conditions of coral growth and breakdown. Constructional processes involve the upward and outward growth of reefs into the zone of water turbulence. As reef building proceeds, sediments derived from reef erosion become banked up against the flanks of massive reefs (Bird, 1984:254). Considerable quantities of broken reef material may accumulate against the reef flanks and on lagoon floors, from where they are available for redistribution throughout the reef system, and for the building of emergent islands. Reef erosion to produce such debris occurs at both formational and emergent levels (Davies, 1972:71; Stoddart, 1970, 1982), and supplies sand, pebbles and boulders from which beaches and small islands or motu are constructed. Raised or emergent coral erodes severely to produce such debris (Wiens, 1962:18), but although some of the debris which forms motu is derived from emerged reefs, most is not (Bird,

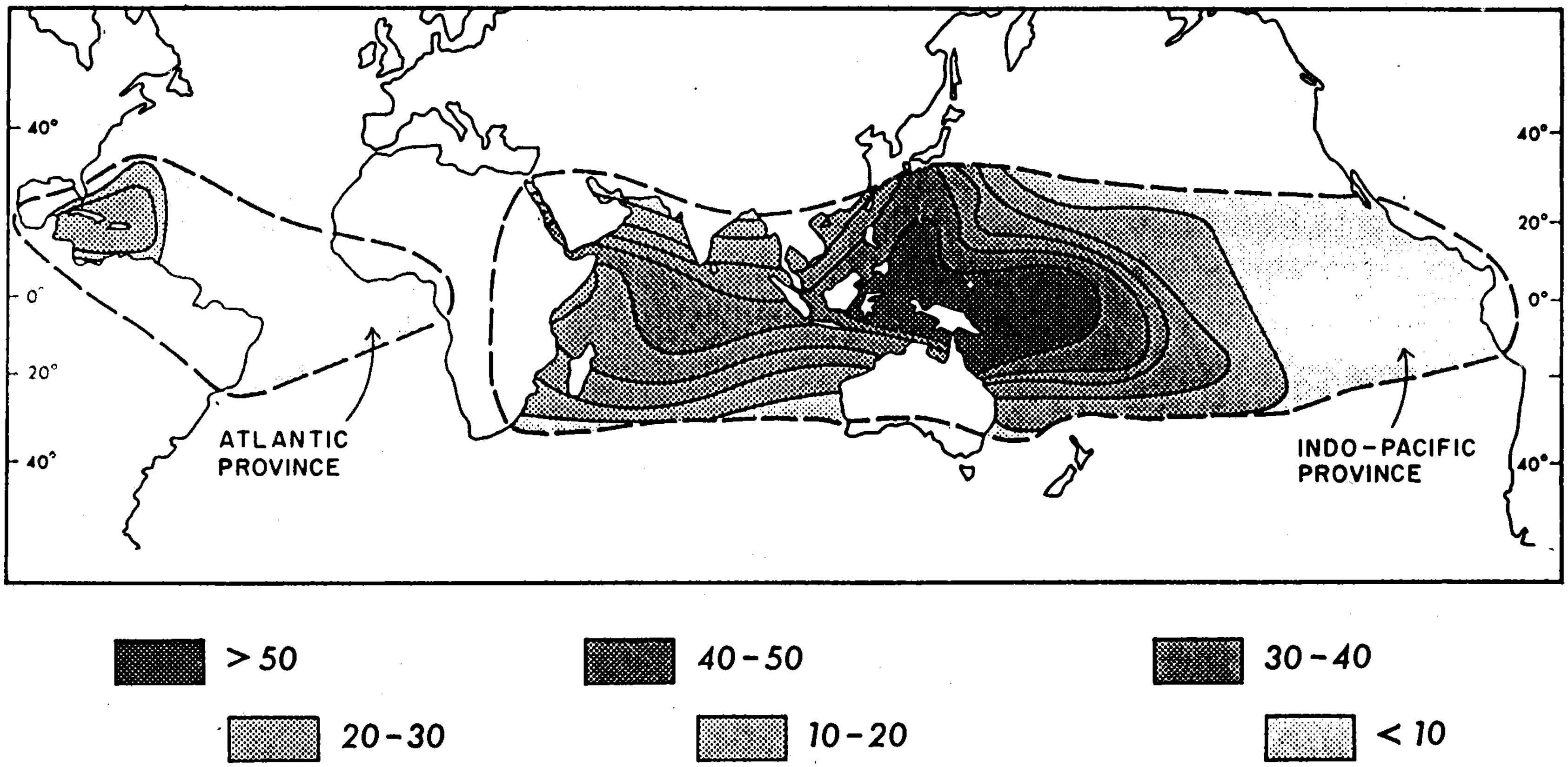


Figure 1. Distribution of reef-building corals (after Davies, 1972:71). Numbers refer to coral genera.

1984:271), and the accumulation of sediment to form low islands does not require any relative shift in sea level.

Coral reefs have been traditionally divided following Darwin's classification into fringing reefs, barrier reefs and atolls. Subsequent more systematic studies of reef island forms however have demonstrated the necessity for an amplification of this classification. One such scheme which takes into account coral reef landforms is that of Davies (1972:72), which is presented here in a slightly modified form.

Coral Landforms With No Central Lagoon

Fringing reefs
Barrier reefs
Platform reefs
Patch or ribbon reefs
Coral pinnacles or knolls

Coral Landforms With a Central Lagoon

Oceanic atolls
Shelf atolls
Compound atolls
Faroes or micro-atolls

While the classification of reef forms into these categories is relatively simple, the classification of low islands or motu is more difficult. Such islands form as the result of sediment accumulation on all types of reef platform, but are found most frequently on patch or ribbon reefs and atolls. Patch reefs tend to form downwind of massive reefs (Bird, 1984:271; Roberts, 1983), in areas of less favourable coral growth conditions, and ribbon reefs occur near the outer margins of barrier reef systems (Orme *et al.*, 1978). Atolls occur in oceanic locations and on outer shelf margins.

## ATOLLS

Wiens (1962:11) noted that atolls are: 'all more or less continuous reefs surrounding a distinctly deeper lagoon with or without lagoon reefs .. which rise from a sea bottom which is too deep for the growth of coral reefs.' Atolls are of three types (Bird, 1984:261; Davies, 1972:72).

(i) Oceanic atolls, with volcanic foundations, formed on submarine basaltic volcanoes of the Central Pacific, on andesitic volcanoes nearer to the continental shelf margins (see e.g. Wiens, 1962:13), or based on oceanic ridges, where sea level rise or tectonic subsidence have led to former fringing reefs developing into ring-shaped atoll reefs;

(ii) Shelf atolls arising from continental shelf areas in water less than 550 m deep;

(iii) Compound atolls - rings which enclose the relics of earlier atolls.

Wiens' definition of atolls excludes reefs without a lagoon, and raised coral islands without a central depression. Atolls however occur at a variety of scales and are highly variable in form. They may have secondary pools, ponds or depressions, and in some atolls former lagoons have become filled with sediment, and are reduced to swamps or bogs. Atolls may be completely submarine features not supporting islands, when they are commonly referred to as banks or shoals (Wiens, 1962:11).

Guilcher (1971) described the development of faroes in the Comoro Islands and the Maldives where these reef forms have also been described by Eibl-Eibesfeldt (1965) and Davies *et al.* (1971). He suggested that faroes developed from patch reefs and that they may develop further to form the foundations of atolls (Guilcher, 1971:66, 86). If Stoddart & Scoffin's (1979) observation that upward growth in faroes or micro-atolls is determined by the lowest tidal water levels, and if water temperature rises do not inhibit coral growth, rising sea levels may in fact lead to the increased growth of faroes or micro-atolls.

In addition to the variation in atoll form, high islands may be surrounded by fringing reef (e.g. Rarotonga), or be encircled by a barrier reef (such as Truk and Uvea), in which case they are described by many writers as 'almost atolls' (Wiens, 1962:16). Such situations demonstrate stages in the development of atolls which are commonly the submerged, raised or partly raised coral fringes to a lagoon. They are highly variable in both form and (where known) their ages of formation. In tectonically active areas where raised atolls occur, the lagoon floor becomes merely a depression, and the landform may not be recognised or classified as an atoll.

Atolls are common in the central Pacific, but do not occur in the Marquesas, nor in the Galapagos Islands where their absence, and the absence of other significant coral landforms, can be readily explained by the upwelling of cold oceanic water (see e.g. Stoddart, 1969). The largest atolls and atoll islands in the Pacific occur in the Marshall Islands of Micronesia and further south along a chain stretching southeast through Kiribati, Tuvalu, Tokelau, the Society Islands and the Tuamotu Islands.

The shape and elongation of atolls varies considerably, but has been shown to reflect basement contours and the lineaments of tectonic zones (Wiens, 1962:18). The living reef tends to grow to windward, and atoll reef platforms are generally widest towards the prevailing wind.

Atoll reefs are made up of a series of concentric zones which vary in form depending on whether they are dominantly windward or leeward. These zones, which were described for example by Wiens (1962:47ff), Eibl-Eibesfeldt (1965) and Stoddart (1969) include.

(i) *Outer slope*. The steeply descending outer slope of the reef below the point of abundant living coral and coralline algae, at about 30 m depth.

(ii) *Reef front*. The upper seaward face of the reef, with abundant living coral and coralline algae. This zone, which slopes down to 15 to 30 m, may include a shelf-like bench or terrace. The form is variable, from smooth profiles to grooved and ridged spur systems.

(iii) *Seaward reef margin*. The edge of the reef platform characterised by an algal ridge cut by surge channels.

(iv) *Reef flat*. The upper reef surface which is exposed or awash at high tide. This surface may support islands. The reef flat sediments are commonly zoned from the outer (seaward) side to the inner (lagoon) margin, across either or both a seaward beach and a lagoon beach. Sediments tend to be coarser (gravelly) on the outer or seaward margins and finer (sandy) on the inner margins. Indurated beachrock is common on reef flat beaches.

(v) *Lagoon reef margin*. This zone is commonly poorly defined.

(vi) *Lagoon slope*. The coral slope into the lagoon, which is highly variable in form, and commonly dominated by soft corals and non-hermatypic forms.

(vii) *Lagoon floor*. The flat to variably undulating base of the lagoon depression. This may have coral and algal knolls or prominences (bioherms).

Atoll diameter and lagoon depth are related. McLean (1977) noted that larger atolls may have lagoon depths in excess of 50 m. In such cases there is generally a depth related sequence of sedimentary facies.

Most atolls have at least shallow reef channels or passages through the coral reefs to the inner lagoons. Deep navigable passages also occur but are relatively rare (Wiens, 1962:32). Passes generally occur on the leeward side of atolls, and patch reefs or reef spurs occur at the lagoon mouths of such passes. These channels or passages are related to the complex interaction between limestone solution, wave action, abrasion, and scour, and may develop from the grooves and surge channels noted on the reef fronts and seaward reef margins of most atolls (Wiens, 1962:121; Roberts, 1983).

When the reef is open sediments may be swept through the channels. In such cases patch reefs and knolls are common in the lagoon (Wiens, 1962:77). Where reefs form a more complete encircling structure, sediments accumulate in the lagoon and coral prominences are less common.

## THE LIVING REEF

As noted above coral reefs are found in areas where mean annual water temperatures do not fall below 24°C; where oxygen levels are high and where light penetration is sufficient for symbiotic algal growth. It is however important to note that the geographic distribution of coral reefs and the geomorphic form of individual reef structures is in part a reflection of the growth form and requirements of the hermatypic coral colonies composing the reef. Coral reef growth is therefore a function of individual colony growth rates, which vary from genus to genus, and locality to locality; combined with the rate at which interstitial spaces are filled by bioclastic sediments, often a function of the growth rates of other biotic components of the reef system.

All reef systems display zonation of their communities with seaward communities differing in composition and diversity from those at the reef crest, on the reef flat and on the lagoonal edges of the reef itself. Each community differs in its rate of upward and outward growth as a function if the combined community growth which reflects the species characterising each zone. Any factor which changes the abiotic factors characteristic of each micro-habitat will affect the zonation and consequently reef growth.

The consolidated reef upon which the living community of corals grow is composed of the lithified skeletons of coral colonies and other organisms, sediments of varying particle size all or most of which may be cemented together initially through the action of encrusting coralline algae and later through the processes of recrystalisation of the calcium carbonate materials. Buddemeier & Smith (1988) estimate that sediments generally account for up to 50% of the total consolidated reef volume. Much of the fine sediment produced in reef areas is derived from algal growth, particularly *Halineda*, which may be responsible for a considerable portion of the interstitial bioclastic sediment in Pacific reef structures.

Sediments are also produced by storm action and by processes of biodegradation through the actions of boring organisms such as sponges, molluscs and other species which weaken living coral skeletons and in the process produce large volumes of fine particulate material. The process of reef formation and maintenance, i.e. reef growth, is a dynamic interaction between the biological processes of coral colony growth and degradation and the production of sediments by reef associated organisms.

It is often assumed that 'coral reefs' may keep pace with accelerated sea level rise simply by upward growth of the coral community, however a limit to upward growth may be reached where sediment production fails to fill the interstices of the coral communities skeletal structures and hence the community itself fails to provide a sufficiently stable base on which the living community may continue to exist. The maximum rates of reef growth discussed by Buddemeier & Smith (1988), for example, represent probable limits for the combined interaction of the two processes. They suggest that Pacific reefs may well not keep up with projected rises in sea level. Any factor which upsets the present balance between coral growth and reef sediment production might therefore be expected to alter the ability of the community to respond to increasing sea level.

Changes in the coral community composition may well occur under the changed environmental conditions predicted to following global warming and sea level rise. The typical zonation patterns described by many authors and outlined above represent sub-communities of algal and coral genera and species adapted to micro-habitat conditions which vary across existing reef structures. A rising sea level might be expected therefore to result in the upward growth of the sea ward reef slope community, a community characterised by massive branching forms, growing below the level of high wave energy. Such forms produce a skeletal matrix which traps and retains little fine sediment thus forming an unsuitable substratum for upward growth of the reef as a whole, unless external sediment and larger materials are periodically added to the community through storm damage.

A factor of more critical importance to coral communities in terms of combined reef growth is water temperature. Not only does temperature limit the global distribution of coral reefs, it can also have significant consequences for the health of the coral community. Most corals in the tropical Indo-Pacific are currently growing at or near their thermal limits of tolerance and an increase in water temperature might be expected to cause significant lowering of growth rates as a consequence of thermal stress. Coral bleaching and death, often associated with other forms of stress is known to occur as a consequence of temperature stress, and the widespread die-off of several coral genera in the Maldives during June, July and August 1987 is thought to have been due to the anomalous high temperatures recorded for the Indian Ocean (1.5°C above normal) at that time (Pernetta & Sestini, 1989).

Under conditions of increased global temperature it might be expected that coral growth rates will be reduced and the community composition changed such that the corals will no longer be capable of keeping pace with increasing sea level rise. Temperature stress may be significantly less important in oceanic atoll systems, where lagoonal water exchange with the surrounding ocean is adequately high, thus maintaining a lower temperature in the lagoon.

For fringing reefs behind barrier reefs, and for micro-atolls and faroes in enclosed atoll structures where water exchange is limited, the problem may be severe. More importantly however, if the global ocean temperature rises beyond the thermal limits for hermatypic coral growth (perhaps 1.5-2°C above present tropical water temperatures) we might expect that tropical reefs will no longer reach an upper limit determined by tidal exposure but rather an upper limit determined by temperature. Sunken or submerged reefs may therefore predominate between 20° North and South of the equator. Clearly there is a need for a detailed evaluation of the current data base relating to thermal tolerance limits of hermatypic corals (Jones *et al.*, 1976) and more detailed data relating to the present water temperature regimes in Pacific atoll lagoons.

Any factor affecting the growth, survival and local distribution of coral genera and species may be expected to cause changes in community growth rates, and hence affect the consolidation and upward growth of the reef as a whole. Once reef growth patterns change, local current regimes are altered and sand movements between sinks change such changes may threaten the cays or motu which rest on reef flats and form the basis for a number of Pacific and Indian Ocean Island States.

## LOW ISLANDS: CAYS OR MOTU

Low islands, known as cays in the Caribbean and motu in the Pacific, are islands built up on a coral reef base, as distinct from high islands which have a core of emergent bedrock. Such islands are common on atolls, where groups of three to five islands commonly reflect the underlying atoll structure. Islands comprising sediments accumulated on reef flats rarely emerge more than a few metres above sea level - maximum elevations on such islands being about 4 m.

Low islands may be formed on at least one end of each reef sector on atolls with channels cutting through the encircling reef, in leeward locations where coral debris can accumulate. On atolls with abundant sediment supply and low energy zones due to wave refraction, numerous islands are developed. Not all atoll reef platforms support cays.

Motu development

Motu are composed of sediments derived from the breakdown of reefs, and are characterised by a sequence of sediments of variable grain sizes (Wiens, 1962:69; Bird, 1984:275). The most conspicuous features of low islands are storm or cyclone wave-generated bouldery beach ridges comprising gravel or boulder ramparts, which may rise more than 6 m above sea level. Storm activity is important in depositing the coarse beachridge sediments which form the basis of cay development.

Following debris deposition, primary colonising plants become established, followed by palms and casuarinas, to form a stable cay. Beachrock cementation at the water table level assists formation. The island configuration may change due to climatic changes (Bird, 1984:275), or during exceptional storms it may change abruptly, or whole cays may be swept away. McLean (1977) noted that in the Indo-Pacific motu are mainly found on windward reef flats, while in the Caribbean sand cays occur more commonly on leeward reef flats.

The sequence of landforms and sediments which are typical of cays and low islands (see Figure 2, after Bird, 1984:275), are a shingle ridge on the windward side, and a sandy flat on the leeward side of the reef flat. On the lee side of reef patches refracted waves converge, preventing debris being swept over the lee side of reef islands, and maintaining the existence of low sand islands. In the northern Great Barrier Reef area Flood & Scoffin (1978:55ff) described a common pattern of reef sediments comprising three facies:

(i) rim deposits of broken coral composed of branching corals on the windward side and massive colonies of corals on the leeward sides of shingle ramparts or boulder tracts;

(ii) a thin blanket of sand-sized coral and algal fragments across the reef flats and lagoons;

(iii) leeward sand cays formed by refracted wave reworking of fine sandy materials from reef breakdown, which may become very stable if they are cemented to form beachrock.

Most of the systematic investigations of low islands and motu have been carried out within the Great Barrier Reef formation in northern Australia, where there are a variety of low island forms. Thom *et al.* (1978:37ff) have presented a model of cay development since the Pleistocene in which they noted that the configuration of the erosional Pleistocene-Holocene surface, the areal extent of that surface and a complex of hydrodynamic and biological factors affect the island form. They also observed that high energy reefal wave conditions have predominated throughout the Holocene, and that such conditions favour the deposition of coarse sediments.

Stoddart *et al.* (1978) proposed a classification of low sandy islands based on size, elevation, sedimentary material and degree of vegetation differentiation. They demonstrated that as such islands increased in size, there is a sorting of sediments into zones, and an associated increase in vegetation diversity. The most complex sand cays tend to occur inshore, not on the outermost ribbon reefs of the Great Barrier Reef complex, and are classified as low wooded islands. Such islands show strongly horizontally sorted sediments, ranging from fine sands to boulders, commonly support a central mangrove swamp, and may have re-cemented beachrock along the shorelines. The complex interaction between mainland and continental island provenance, and the complex ecological controls and interactions between sea levels, mainland stream velocities, sediment loads and colonisers in determining the form of low islands were noted by Orme *et al.* (1978).

The actual location and form of sand cays is determined by local conditions. It has been noted for instance from Heron Island (Flood, 1986) that cays change in shape reflecting regional wind pattern changes, and consequent changes in sand movement. Guilcher noted only four small cays and no beachrock in Comoro reefs, and related the existence of sand islands to sources and relative availability of sand (Guilcher,1971:71-72). The four sand cays were situated near gaps in the barrier, either

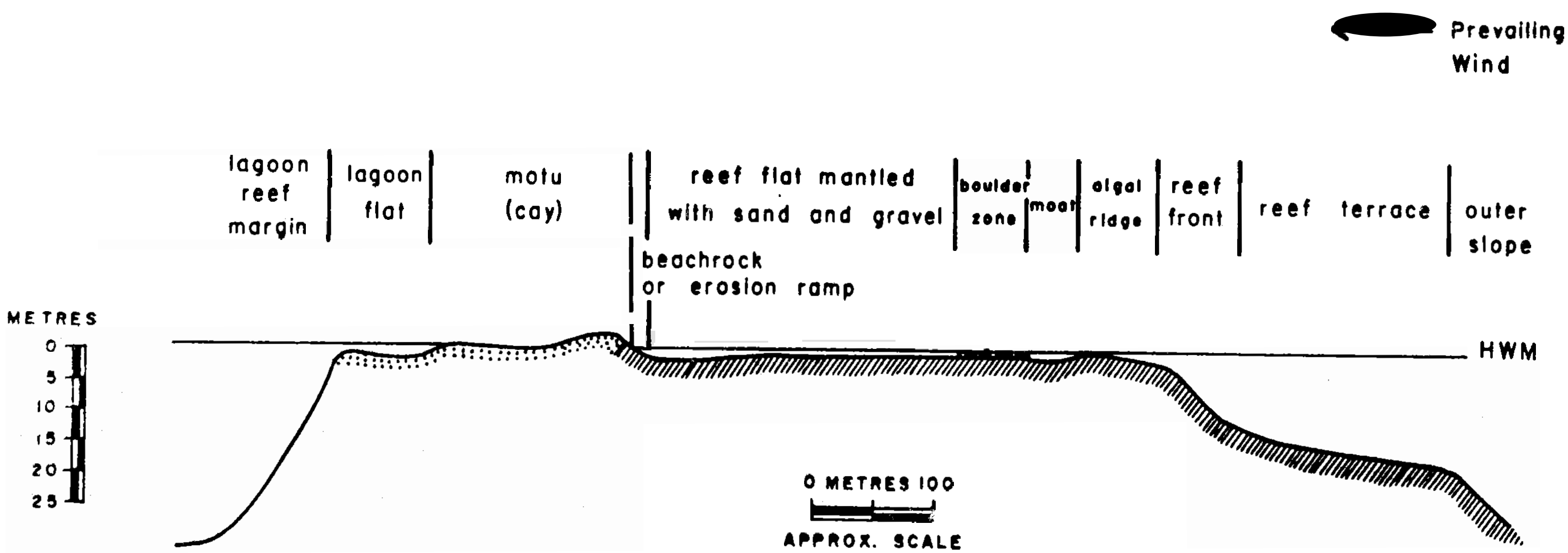


Figure 2. Schematic section through an Indo-Pacific atoll and motu (after Bird, 1984 and Stoddart, 1969)

adjacent to a passage or on the margins of shallower interruptions, and Guilcher suggested that this is related to wave refraction. Longshore drift from any direction is halted by waves refracted as they sweep into the pass, so they beat upon both transverse shorelines. Guilcher also noted that many Pacific motu occur in similar depositional situations.

Estimates of the rate of accretion of calcium carbonate sedimentary products from reefs have been made (Smith, 1978). He noted that reefs and reef sediments were a quantitatively significant global sink for calcium, and about 6 x $10^{12}$ mol. of calcium carbonate are precipitated annually. Of this about 13% is produced in the South Pacific. An unknown quantity of reef material is reduced to clastic sediments annually. The turnover time for the production of such sediments from cycling calcium is estimated at tens of thousands of years (Hatcher *et al.*, 1987), but occurs at a maximum rate on shallow windward reef flats and in enclosed lagoons.

Stoddart (1965), reporting on the re-survey of British Honduras reefs and cays after Hurricane Hattie in October 1961, noted that dead reef debris had been moved onto reef crests and island shores. Fresh shingle and coral rubble had been piled up against the vegetation on the windward side of islands. Some small dunes had accumulated on hurricane deposited sandsheets.

On many atoll motu in the Pacific it has been noted that severe storms have completely altered the position and configuration of the cays - commonly exposing beachrock which is taken as an indication of the location and extent of former cays (see e.g. Baines & McLean, 1976).

Beachrock can also be destroyed by the impact effects of wave carried debris as was noted by Stoddart (1965) during Hurricane Hattie. He also noted that by 1965 this had re-lithified and solidified, enhancing the island's stability. Recovery time from a hurricane was estimated at 20-30 years, and Stoddart noted that cays are in general built up by cyclones rather than destroyed.

In the Papua New Guinean region motu are generally located on atolls, which are in turn concentrated on the margin of the Pacific lithological plate (Scott, 1983). In a survey of cays, Guilcher (1971:72) noted that the barrier extending 300 km eastward off the south coast of Papua New Guinea is poor in cays - Great Daugo (Fishermans) and Little Daugo Islands being the only two he identified.

Water tables and freshwater sources on low islands

Low islands are characterised by the absence of surface water sources. The high porosity of their sand or shingle sedimentary cover, and of the underlying reef limestones generally results in rapid percolation of precipitated water from the ground surface (Wiens, 1962:317). Water is held by capillary action in the soil layers, and basal groundwater is stored in unconsolidated sediments and in the porous limestone. A lens of freshwater fed from the overlying sediments, and roughly proportional to the size of the island occurs in cays or low islands of about 1.4 or more hectares (Wiens, 1962; McArthur & Wilson, 1967:32). Groundwater is fresher towards the lagoon and brackish seaward. While freshwater enters the groundwater storage through infiltration and percolation, seawater enters through cracks and crevices in the reef structure, and infiltrates through the very porous seaward boulder ridges (Wiens, 1962:69,323).

There is a density separation and freshwater lenses float on a seawater base. The position and volume of the lens vary with tidal changes, and with local hydrological conditions. The lens shrinks during periods of low rainfall, and swells following rainy periods. As the head of freshwater spreads out its depth becomes less, resulting in a lens beneath the island surface thickest near the centre and thinning towards the coastal margins.

Guilcher (1971:73) noted that subaerial karst development occurred during Pleistocene low sea level phases in many atoll forms, and Weins (1962:18) and Stoddart & Taylor (1971) similarly recorded active karst development in emerged reefs. The voids so formed are important in funnelling freshwater into vadose or phreatic cavities, with the implication that differences in active cavity form may be attributed to wet/dry climatic fluctuations and to fluvial activity. Limestone porosity is highly variable both spatially and temporally. Marshall & Jacobsen (1985) observed both vadose and phreatic freshwater diagenesis on Tarawa Atoll, and described a repetitive sequence from bores of cemented top (cay rock), which forms a partial aquiclude, unconsolidated sediment, which provides a perched aquifer, and corals and leached limestone of last interglacial age with vadose and phreatic cavities. It is likely that a similar pattern occurs on other atolls.

Groundwater occurrence is controlled by reef geology, tidal fluctuations, precipitation and island and reef geometry, and these variables have been used in models to predict the occurrence of freshwater lenses and their behaviour under conditions of rising sea level. Oberdorfer & Buddemeier (1986) and Buddemeier & Oberdorfer (this volume) noted that island and reef hydrology are heterogeneous, and have provided models for assessing fresh groundwater resources on low islands, and have discussed the likely impacts of potential climatic change and sea level rise on such freshwater lenses.

## THE LIKELY EFFECTS OF RISING SEA LEVEL ON REEF LANDFORMS

### Growth rates of coral atolls and islands

One relevant question in any consideration of the effect of a continually rising sea level is the effect on coral reef growth. Coral reef growth is primarily in response to light availability (Sato, 1985) and is highest just below the surface water layers. Marshall & Jacobsen (1985) noted that coral growth kept pace with sea level rise during the most rapid rises in the early Holocene when rates of accretion were measured at 5-8 m/1000 years.

There have been a variety of estimates of average and maximum rates of both coral growth and vertical reef accretion, and the question of maximum rate of accretion is vital to any projection of coastal process and morphological changes which occur in response to rising sea levels. Wiens (1962:90) noted that on average individual coral colonies grow upwards and outwards at about 1 m/40 years or 2.5 m/100 years. Reefs grow more slowly due to the compounded effects of storm damage and recovery, the interaction between the growth of coral and algal mantles and the rate of clastic sediment production to fill the interstices of the reef platform. He noted normal rates of reef growth of 0.5 to 2 m/100 years (consistent with those recorded by Marshall and Jacobsen), but quoted extreme growth rates (Wiens, 1962:91) of 30 m/100 years.

Buddemeier & Hopley (1988) point out that predictions of reef growth rates must take into account the structure of the reef community, and the likely occurrence of local events such as cyclones or predator attacks, which would temporarily inhibit reef growth. They noted that although rising sea levels generally favour reef growth, this growth may not keep up with predicted sea level rises due to global warming (Buddemeier & Hopley, 1988:4). Buddemeier & Smith (1988) cited predicted sea level rises of 15±3 mm annually over the next century, and commented that this is five times greater than the modal rates of vertical accretion on reef flats (about 1 m/100 years), and 50% greater than currently measured maximum rates, although they acknowledge that Holocene data indicate that vertical reef growth rates of 14 m/100 years are possible. Rates of reef acretion greater than 0.8 m/100 years were noted by Hopley & Kinsey (1988:191) to occur commonly only at depths greater than 5 m, and they suggest higher rates are unlikely to occur on reef surfaces affected by rising sea levels. They also point out that reef growth is unlikely to be sustained if water temperatures reach 30°C (Hopley & Kinsey, 1988:200), which would occur across much of the Pacific with global warming.

As early as 1962, Wiens (1962:134) expressed concern about the fate of atolls and low islands developed on atolls on a world wide scale, should sea levels continue to rise. He described a likely sequence of landform changes which would not change in the light of more recent observations of low islands. Continually rising sea levels will produce gradually rising beach ridges, higher towards the sea, on the lagoonal side of atolls as land pushes inwards towards the lagoon. This will result in a slope from the top of the lagoonal beach ridge towards the central depression, down which sediment will move, gradually filling the central depression and forming islands with swampy interiors. He noted that this effect will be exacerbated on occupied atolls by the digging of taro pits in the swampy depressions.

He also commented that at average Holocene rates of sea level rise, most present land on atolls would be inundated, and most present reef islands destroyed within the next 5,000 to 6,000 years. During the first half of this century however, Wiens (1962:134) noted that the rise in sea level 'has amounted to 2 to 3 inches ... Were the earth's temperatures to increase and the sea level rise at the same rate most atolls would be awash or at least largely comprised of saline swamps within a thousand years.' In commenting on the fate of atoll islands, he noted 'the migration of the land area lagoonward ... will probably end with their (atoll islands) being pushed back across the reef into the depths of the lagoon.'

It should however be noted that such predictions appear to be based on an assumption that coral growth will not keep pace with sea level rise. It is possible that in many situations coral growth will be able to keep pace with even rapidly rising sea levels, perhaps with changed reef composition and form, if such rises occur no more rapidly than 3 m/100 years. This will depend however on a number of biological factors. In such a situation the removal of surface sediments may be followed by the upward growth of coral, and the development of submerged atoll structures.

The social implications of this for populations resident on the motu are nevertheless considerable. Removal or displacement of the low island land is inevitable, even if a later result is the formation of a new island land mass.

Sea level rise - a model of change in atolls and cays

Given the present state of knowledge of the formation and subsequent changes in atolls and low islands, it is possible to develop two simple models of changes which are likely to occur should sea level continue to rise, or to rise then stabilise.

1. *Assuming coral growth keeps pace with sea level rise.*

(i) Low island sediments will be swept either into atoll lagoons in two stages: (a) to give saline swampy depressions, and (b) to give submerged ring-shaped clean coral reefs, with a sediment store in the central depression, or off the leeward margins of patch reefs. In the case of patch reefs on a shallow shelf zone, this sediment will be stored on the leeward side of the reefs.

(ii) Coral growth will be re-established, and there will be an upward and outward growth, resulting in the extension of atoll rings, and possibly the enlargement of patch or ribbon reefs, to form faroes, and of faroes to form incipient atolls.

(iii) These reef flats may bear ephemeral low islands, but such islands are unlikely to establish stable vegetation communities or to maintain a lens of fresh groundwater.

(iv) If the sea level rise slows or stabilises, there will be a re-establishment of cays on atolls, including cays on the leeward side of lagoons due to the supply of stored sediment.

(v) There will be island growth on the leeward side of patch and ribbon reefs and a possible rapid development of cays on the windward side of such reefs if they lie downwind of reefs currently bearing cays.

(vi) The end result will be of a gain in low island land area, but in other than the current locations of low islands, and with the subsequent slow development of freshwater lenses. Biological communities, which may take 20-30 years to re-establish, will regain stability only when the rate of sea level rise falls. Such islands will normally be less suitable for human habitation than they are at present.

2. *Assuming coral growth does not keep pace with sea level rise.*

(i) Atoll islands will (a) become saline swampy islands, then (b) undergo submergence, followed by a lagging upward and outward growth of reef.

(ii) There will be accelerated upward and outward growth of faroes and patch reefs, but at a rate insufficient to support cay development.

(iii) Low islands will be swept from atolls and reefs, which will resume a lagging growth.

(iv) Mainland coastlines which are presently protected from storm waves by offshore atolls and cays will become subject to storm wave erosion as the protective barrier is removed.

(v) The overall effect of this will be a significant loss of land.

In either case, for raised atoll and reef islands, the situations will be highly variable, depending on present elevation, and whether or not these islands support fringing reefs. For all such islands the following changes can be predicted:

(i) There will be a rise in saline water tables.

(ii) Sediments will be swept away by tidal action if sea level rises to their basal layers.

(iii) If coral platforms are submerged there will be a re-establishment of coral growth, as in 1 or 2 above.

## FUTURE RESEARCH

Little is known of the nature and distribution of atolls, or of the form or dynamics of sand cays in Melanesia. Löffler (1977) summarised the form and broad distribution of reefs, and Ollier (1975) and Ollier & Holdsworth (1970) have described some aspects of reef island geomorphology in Papua New Guinea. Little specific biophysical research however has been carried out on the reef islands, and none on cays.

As Buddemeier & Smith (1988) have noted, human beings are now in effect carrying out a large scale geophysical experiment to observe the effects of sea level rise. In order to effectively observe changes, and to predict the far-reaching results of such changes, baseline information is needed for Pacific atolls and motu.

It is therefore proposed that an inventory be carried out, in which motu and atolls are mapped from existing topographic maps, satellite imagery and airphotos. For some countries such data may already exist and should therefore be synthesised. For other countries, particularly in Melanesia, such data are lacking, and in the case of Papua New Guinea, for example, selected atolls in the Manus, Milne Bay or North Solomons Provinces should be investigated to determine: atoll areas and elevations, soil and sediment cover, vegetation cover, population dynamics, land use, gardening methods, and needs, sources and methods of obtaining freshwater. For such sand cays the landforms, sediment depth, vegetation sequences, freshwater sources and nature and extent of beachrock should also be investigated.

These data would provide:

- a baseline assessment from which to monitor changes in land area, shoreline form, vegetation, freshwater availability, soil moisture content and salinity changes, with changes in sea level;
- tests of models developed elsewhere in the Pacific;
- a basis for the prediction of later or exacerbated effects.

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# CLIMATE CHANGE AND ISLAND GROUNDWATER RESOURCES

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## INTRODUCTION

The purpose of this paper is to identify the implications of climate change for island water resources, with particular reference to the groundwater resources of small coral-reef islands. In order to arrive at a set of practical recommendations for assessing vulnerabilities and identifying practical and appropriate response strategies, we first briefly summarise the current state of knowledge and uncertainty about the climate of the future. We then describe the general factors controlling island water resources and how they may be influenced by the predicted climate changes. A more detailed description of the nature and occurrence of fresh groundwater lenses on small islands is followed by a discussion of potential climate change impacts, and finally by a list of actions that can be taken to evaluate and (to the extent possible) safeguard water resources.

## PROSPECTS FOR CLIMATE CHANGE

It is generally accepted that the Earth's climate is or soon will be warming as a result of the Greenhouse effect. The origin and nature of the Greenhouse phenomenon is adequately described elsewhere; for the purposes of this paper we will simply outline the best presently available predictions about the nature of future climate and the rates of change.

The present versions of the large General Circulation Models (GCMs) used to predict future climate suggest that a doubling of the pre-industrial atmospheric carbon dioxide concentration would increase the global average temperature by 3-5°C once ocean temperatures have equilibrated with atmospheric changes (MacCracken, 1988). The 'doubled $CO_2$' is a somewhat arbitrary case used for computer simulations, but it is realistic in the sense that many scientists believe that we are unlikely to avoid reaching Greenhouse effect levels that are equivalent to a doubling of $CO_2$. The atmospheric carbon dioxide concentration is now about 125% of the pre-industrial level. The rates of increase in atmospheric concentrations of other Greenhouse gases - including methane, chlorofluorocarbons and nitrous oxide - are greater than that of $CO_2$, and it is estimated that their combined warming effects will equal the warming due to $CO_2$ before the middle of the next century.

Hansen *et al.* (1988) have attempted to model the rate of temperature rise, taking into account both the effects of Greenhouse gases other than $CO_2$ and the thermal inertia of the oceans. They suggest that global average temperatures could warm at a relatively steady rate to about 0.5 to 3.0°C (most probable value, 1.5°C) above the present value by the year 2050. This will be in addition to the approximately 0.5°C warming that is believed to have occurred between 1850 and 1980 (Jones, 1988).

An issue of particular concern to island nations is the rise in sea level that is expected to accompany the warming - a combined result of thermal expansion of ocean water and the melting of land ice. Titus (1988) has summarised the various estimates that have been made for sea level at the year 2100; they range from <0.5 to >3.0 m above present sea level, but there is general agreement that the most probable range of values is 0.5-1.5 m. The exact pattern of sea level rise is not known, but it seems likely that it will increase gradually, with the highest rates of rise occurring at least a few decades into the 21st century. Although global sea level rise will be very significant in the long term, local sea level effects due to changes in atmospheric pressure and ocean circulation patterns may be dominant over the next few decades.

At more detailed levels of prediction there are very large uncertainties; the single point of agreement is that the future climate will be significantly different from the present for most if not all locations. Although it is believed that warming may be slightly less in the tropics than at higher latitudes, there is virtually no agreement among the different GCMs and palaeoclimate studies concerning factors such as temperature, wind and rainfall at local or regional levels in a warmer climate (Grotch, 1988). Emanuel (1987) has suggested that tropical cyclones might increase in intensity as a result of sea-surface warming; Holland *et al.* (1988) consider it likely that cyclone activity will increase in the central South Pacific, but caution that detailed predictions are not possible. Broecker (1987) has raised the important point that although global averages may change gradually, regional patterns of atmospheric or oceanic circulation may undergo abrupt transitions. It is possible to develop scenarios for climate change (Pittock, 1988) or to use analogues from our present experience (e.g. El Niño conditions: Meehl & Washington, 1986). Such exercises can be extremely useful for assessing vulnerabilities and reviewing possible future needs and responses, but it is extremely important to keep in mind that such scenarios represent possible outcomes and not reliable predictions.

In summary, the climate change predictions that we can currently consider reasonably reliable are as follows.

1. Global average temperatures will increase at a rate between 0.1 and 0.5°C/decade - but local or regional changes may be greater or less and may occur either gradually or abruptly.

2. Global sea level will slowly increase its rate of rise from present values (1-2 mm/year) to values that may reach 10-20 mm/year by the second half of the 21st century. A total increase of 0.5-1.5 m over the next century seems likely, although greater or lesser changes cannot be ruled out.

3. It is reasonable to expect that the range, frequency and intensity of tropical cyclones will generally increase, but we cannot predict probable changes at specific locations.

4. Changes in the patterns of rainfall, winds, ocean currents, and upwelling are likely, but the rates and locations of specific changes cannot be predicted at present.

It is important to assess potential effects of climate change on our resources and societies on the basis of present knowledge. However, much effort is being devoted to climate monitoring and modelling, and we can expect increased understanding over the coming years and decades. It is therefore extremely important that plans and assessments be reviewed and updated regularly in the light of experience and new knowledge. In the sections that follow we will attempt to provide information and recommendations that will be useful in the future as well as at present.

## ISLAND WATER RESOURCES

Before considering the nature of small island groundwater bodies in more detail, we will first examine the components of the basic hydrologic cycle with special reference to islands. This has two purposes: first, to identify those aspects that are sensitive to various forms of climate and sea level change, and second, to identify those that are subject to human manipulation.

Islands vary from those with populations that currently make no use of groundwater, through the various stages of using groundwater either for non-potable supplies (washing, irrigation) or as a reserve supply in dry periods, to those where people routinely withdraw a substantial fraction of their water supply from the ground. Both population increase and economic development tend to increase demand for water, and may also result in actions that affect supply. The possible effects of climate change or variability and human responses must be viewed in the context of future changes in the economic and demographic situation.

The supply to a groundwater body is known as recharge, and on an average basis it is given by:

Recharge = Rainfall - Evapotranspiration - Runoff

As we have already discussed, rainfall may be expected to change with changing climate, but we currently have no reliable predictions about the nature of change. We can also note that there is little that people can do to influence rainfall on a local basis. Evapotranspiration (ET) is the loss of surface water or soil moisture through evaporation and/or plant respiration. It is a complex function of temperature, radiant energy, relative humidity, wind speed, and amount and type of vegetation, but the dependence on temperature is sufficiently strong so that ET losses will very probably increase as temperature rises. Runoff (e.g. surface water flow into the ocean) may be significant for high islands, but is generally treated as negligible for small, low islands.

Rainfall can lead to recharge only if it falls on a land surface, and recharge can create and replenish a potable water body only if there is a suitable aquifer material underlying the land surface. If an island accretes new land area it may eventually support a larger groundwater lens; however, loss of effective land area because of coastal erosion or flooding with sea water may reduce the quality or quantity of potable groundwater. This is a serious concern in view of the predictions of rising sea level and possible increased storm activity.

Recharge is the fresh (potable) water that reaches the island water table after percolating through the soil, and is thus the sole source of supply for the potable groundwater body. A number of other processes may act to reduce the groundwater inventory.

1. Outflow to the ocean - this natural process puts an upper limit on the amount of potable groundwater that can be stored in a given geologic structure; it tends to increase as the inventory of groundwater increases, and may become the underground equivalent of runoff when recharge rates are much more rapid than the rate at which the groundwater lens can reach hydraulic equilibrium with the surrounding ocean. Outflow is probably relatively insensitive to changes in climatic parameters other than the amount and intensity of rainfall. Human effects are also likely to be slight, although major construction, excavation or dredging projects have the potential to alter the hydrogeologic environment of the groundwater.

2. Natural degradation - these are the processes by which mixing of the potable groundwater with ocean water increases salinity and eventually renders the water nonpotable. In most locations tidally-induced oscillations in water elevations cause mixing of fresh and salt water into a brackish 'transition zone' at the bottom and edges of the potable water lens (Oberdorfer & Buddemeier, in press). This is a relatively constant process, and is unlikely to change significantly as a result of either climate change or human intervention (except for large-scale alteration of the physical environment). A less frequent natural degradation mechanism is salt-water intrusion as a result of flooding from higher sea level (e.g., storm surges). It seems probable that this type of occurrence will increase, at least in some locations, as a result of rising sea level and increasing tropical cyclone activity. Human actions that raise or lower the elevations of coastal surfaces can make inland areas more or less vulnerable to flooding, and shorelines can in some locations be 'armoured' to resist erosional losses.

3. Artificial degradation - Human activities can result in the loss of the use of groundwater in a variety of ways, such as contamination with waste, sewage, pesticides or petroleum products, or from poor water management practices that artificially enhance saltwater intrusion (see for example Volker *et al.*, 1985). Population growth increases both the potential for contamination and the pressure for excessive groundwater withdrawal, although these are not directly attributable to climate change.

4. Withdrawal - Human extraction of groundwater is limited in the short term by the amount of potable water present and in the long term by the differences between unavoidable natural losses (outflow, saltwater mixing) and recharge. Although man controls this term in the hydrologic budget, ultimately nature controls the potential size of this term and therefore the extent of water use by man. Climate change can alter the availability of water for withdrawal - by changes in factors such as rainfall, ET and land area - and can also change the demand by modifying human and crop water requirements.

Before proceeding to a more detailed discussion of groundwater lens characteristics, we must note some important differences between small-island groundwater bodies and the aquifers on larger land masses. In the latter situation the sustainable yield (potential withdrawal) of a groundwater body is only somewhat less than the average annual recharge, and there are few practical limitations on the amount of recharge the groundwater body can accept or the time pattern of withdrawal. This is because large-island or continental groundwater residence times are long compared with the small island case, and outflow and natural degradation are typically very small fractions of the total water volume. By contrast, the island groundwater body floats on the surrounding seawater and the aquifer material only extends a few metres above sea level, so there is a severe limit to how much fresh water can be 'stacked up' in the small island lens. Protracted heavy recharge will increase the rate of outflow, providing a subterranean equivalent of runoff loss. Further, the continuous process of saltwater mixing means that the potable lens will shrink if recharge is interrupted; in extreme cases, some islands support potable lenses only during the rainy season (when it isn't needed!). Thus, island groundwater resources will not necessarily increase in proportion to increases in rainfall, and they may be vulnerable to changes in rainfall (recharge) pattern - longer or more frequent dry seasons can cause serious water supply problems even if average rainfall remains the same or increases.

## FRESHWATER LENS OCCURRENCE

Fresh groundwater is present on islands because the geologic material acts as a catchment for infiltrated rainwater, delaying its discharge into the surrounding ocean. Freshwater in ocean islands occurs as a lens of freshwater floating, due to density differences, atop saline ocean water that permeates the porous geologic substructure of the island. In addition to flow produced by mounding of water within the island, tidal variations in the surrounding ocean act as a driving force that produces time-dependent variations and flow within the freshwater lens. Small islands and coastal regions of larger islands are generally most strongly affected by tidal influences because of their physical proximity to the ocean tides.

The traditional conceptual model of island groundwater occurrence has been the Ghyben-Herzberg Lens (Figure 1), which is generally treated mathematically in resource assessments with the Dupuit assumption of horizontal flow (Vacher, 1988; Hunt & Peterson, 1980). This conceptual model probably works well for islands that are relatively homogeneous on a field scale (some large volcanic islands and perhaps raised coral islands are in this category because the geologic materials have undergone similar histories). This type of groundwater body is assumed to have a number of features that are quite important for resource evaluation and management. First, outflow is assumed to occur at the island margin, in or immediately below the intertidal zone (see arrows, Figure 1). Flow is predominantly horizontal, except for a downward component near the centre of the lens. Because of the relationship between fresh water and ocean water densities, the lens contains an amount of fresh water approximately equivalent to a lens depth (below mean sea level) forty times the head (elevation of the water table above mean sea level). Tidal mixing is often considered negligible or small, and generally is treated as significant primarily at the island margins (see the depiction of transition zone width in Figure 1). Water table tidal fluctuations are expected to decrease (and their time lag behind the ocean tide to increase) rapidly as one moves away from the shoreline (Wheatcraft & Buddemeier, 1981).

An alternative to the Ghyben-Herzberg-Dupuit (GHD) conceptual model for low atoll islands takes into account the heterogeneity of the geologic materials and the observed tidal signal response in island wells (Wheatcraft & Buddemeier, 1981; Herman *et al.*, 1986; Oberdorfer & Buddemeier, in press). The recent geologic history of most atolls includes subaerial exposure of the carbonate reef structure during Pleistocene low stands of the sea. If the Pleistocene reefs were exposed in areas of high

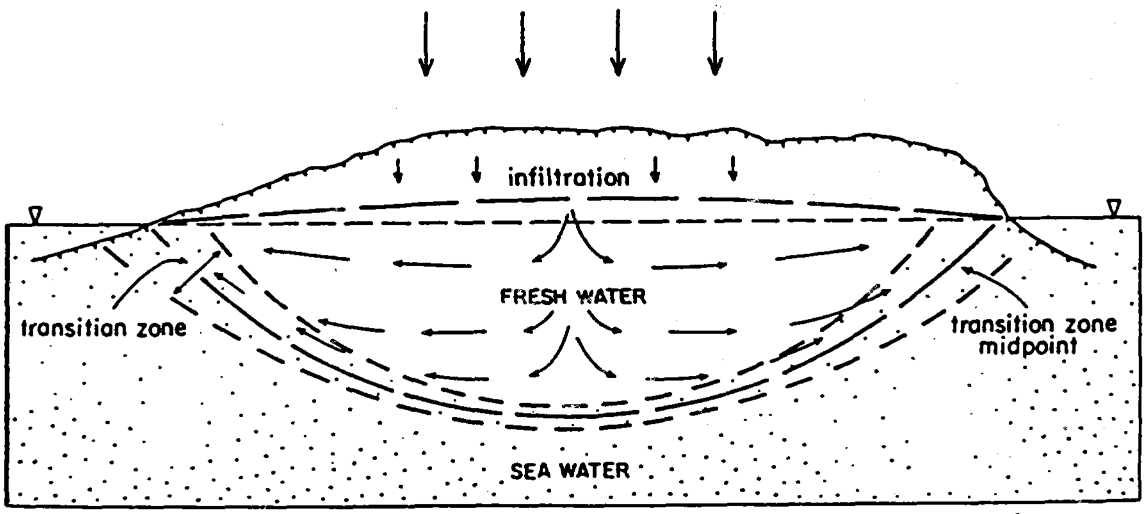


Figure 1. Depiction of a traditional Ghyben-Herzberg lens model of atoll island groundwater in a homogeneous medium. Note the predominantly horizontal water flow, with loss at the island margins. A small transition zone of brackish water occurs at the bottom of the lens, and is protrayed as widening near the margins where tidal mixing is presumably more effective. From Hunt & Peterson (1980).

rainfall, rainwater dissolution of the limestone created a karst topography which, combined with constructional variations, gave the heterogeneous geologic materials a very high and variably distributed permeability. Geologic logging of boreholes on reefs and islands indicates that solution unconformities identified with the most recent Pleistocene low sea level typically occur 7-25 m below sea level in most tectonically stable areas (e.g. Hopley, 1982). Overlying these Pleistocene deposits are semi- to un-consolidated Holocene deposits, primarily sand and gravel-sized coral reef rubble. Where measurements have been made, this Holocene aquifer often has lower permeability (by one to two orders of magnitude) than the Pleistocene aquifer (Wheatcraft & Buddemeier, 1981; Oberdorfer & Buddemeier, 1985), and it is these Holocene materials that retain most of the freshwater.

The hydrodynamic consequences of this two-layer, permeability-contrast system can be inferred from the system shown schematically in Figure 2. The tidal signal is propagated rapidly and efficiently through the high-permeability Pleistocene aquifer and then vertically through the Holocene aquifer over a much shorter distance than the horizontal distance from shoreline (Hunt & Peterson, 1980; Herman *et al.*, 1986). This induces a pattern of oscillating vertical water movement that is inconsistent with the horizontal flow assumptions generally associated with the GHD lens model. From a practical standpoint, the primary mechanism for the 'loss' of potable water from the system is not outflow of freshwater at the island margins, but rather loss to degradation by downward mixing into the saline water below the lens. One important result is that this process creates a very broad transition zone of mixed fresh and saline water, and thus reduces the potable water inventory. In the past, fresh groundwater assessments based solely on the height of the water table above sea level and the Ghyben-Herzberg relationship for density differences have often grossly over-estimated the amount of water resource available because they failed to recognise the extent of the transition zone. It is important to realise that freshwater head is controlled by the integrated total of freshwater in the system and not by the salinity of the water; one metre of pure freshwater and 2 m of a 50% seawater mixture will both produce the same head, but the former is potable and the latter is not. Figure 3 shows vertical salinity contours plotted from a calibrated model of island freshwater distribution (Oberdorfer & Buddemeier, in press). Note that the 50% seawater contour (roughly indicative of the depth of an equivalent amount of pure freshwater) extends nearly to 10 m depth, but that there is essentially no potable water (<<5% seawater) in the system.

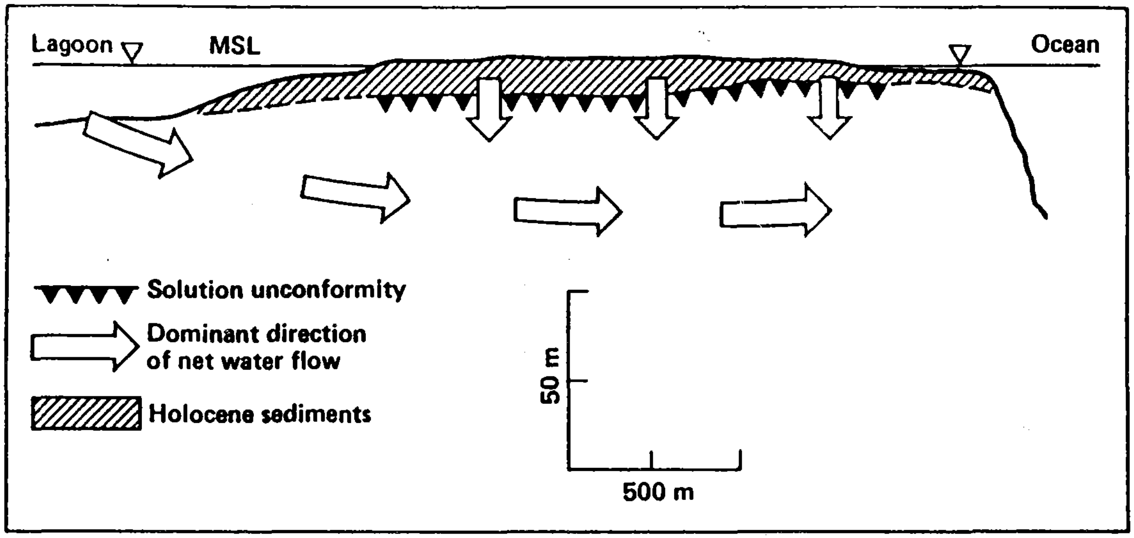


Figure 2. Simplified sketch of a layered-aquifer island. The Pleistocene formation below the solution unconformity is highly permeable and transmits the tidal signal to the bottom of the Holocene aquifer across the entire width of the island. The Holocene sediments are less permeable and contain a thin lens of freshwater that is tidally mixed into the underlying permeable aquifer. The lagoon-to-ocean flow indicated is based on observations of net lagoon-ocean heads at Enewetak Atoll (Buddemeier, 1981).

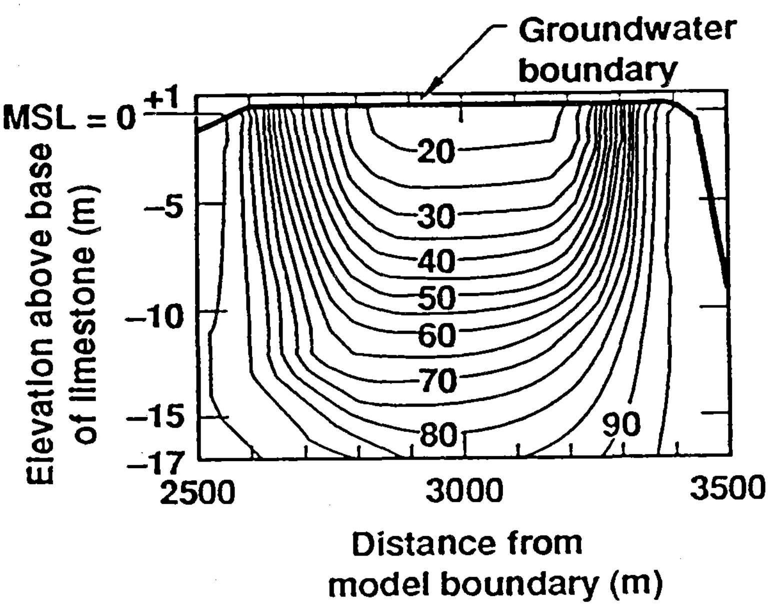


Figure 3. Salinity contours (percent seawater) for a layered-aquifer groundwater system (Enjebi Island, Enewetak Atoll) as modelled by Oberdorfer & Buddemeier (in press) using a calibrated numerical model. Parameters used: present sea level and tide range, recharge = 0.5m/yr (1/3 of mean annual rainfall), and dispersivity = 0.01.

Groundwater bodies that conform to the layered-aquifer model rather than the homogeneous-island GHD model will have other distinguishing characteristics. Perhaps most obviously, there will not be strong or consistent trends in water table tide lag or efficiency as a function of distance from shore (Herman *et al.*, 1986). These parameters, and water table salinity as well, are likely to exhibit much greater spatial variation because of increased sensitivity to heterogeneity in the aquifers. Similarly, the fresh water is not necessarily deepest in the geometric centre of the lens, as would be the normal GHD assumption. Net water flux is not necessarily limited primarily to the shallow island margins, and may be influenced by the hydrodynamically active marine sediment-water systems (Buddemeier & Oberdorfer, 1986; in press). For example, Figure 2 depicts a situation in which a cross-island head due to wave set-up (e.g. 'ponding' in an enclosed lagoon) drives a flow through the permeable Pleistocene aquifer, entraining the freshwater as it is mixed downward by tidal pumping (Buddemeier, 1981).

The magnitude of the water resource available will depend upon complex interactions of a variety of factors, especially those outlined as follows.

Amount of recharge from rainfall

To a first approximation, the greater the rainfall, the greater the amount of recharge. Low rainfall atolls such as Enewetak (rainfall = 1.5 m/yr) may exhibit relatively poor potable water lenses and extreme variation between islands (Buddemeier, 1981), while high rainfall atolls such as Majuro (3.4 m/yr) may have very extensive freshwater lenses (Anthony, 1987; Hamlin & Anthony, 1987).

Surface soils on coral islands typically have such high infiltration rates that very little rainfall is lost to surface runoff. Water that infiltrates, however, may be removed from the ground by evaporation or transpiration by plants; thus, the type and abundance of vegetation can play a role in affecting the magnitude of effective recharge. For recharge to occur, rainfall must exceed evapotranspiration for long enough so that the soil column reaches field capacity (effective saturation) and water flows through the soil pores rather than filling them. Small, intermittent rains (e.g. squall activity) may therefore be less effective in producing recharge than the same amount of rain concentrated in a single sustained storm. Rainfall pattern, as well as amount, influences recharge.

Both recharge efficiency and evapotranspiration may be modified by man as he modifies vegetation, soil type or the distribution of impermeable surfaces such as roads, buildings and airstrips. Such modifications may either enhance or diminish groundwater resources - if the runoff from new construction is directed into the ocean or onto areas of the island that do not support a potable water lens, the water is lost. However, if runoff (from an airstrip for example) is collected and directed to an appropriate infiltration site, the concentrated recharge may provide more groundwater than would exist naturally. In most unaltered island environments, effective recharge of the lens is likely to be somewhere between one-third and two-thirds of the total rainfall.

Island size

Larger island size provides both a larger surface area for infiltration and a larger volume of porous medium for retention of the water. Very narrow strip islands typically do not have a potable water lens. On islands where groundwater flow is primarily horizontal, edge effects - the loss of potable water resources to tidal mixing along the shoreline - would be more predominant, whereas the vertical flow experienced by most Pacific atoll islands reduces the relative importance of edge effects (Oberdorfer & Buddemeier, in press). Reducing island width does reduce the volume of the lens, but not as disproportionately as might be expected with a classic Ghyben- Herzberg lens. Figure 4 compares field data from a variety of atoll islands to assess the degree to which island width and rainfall affect freshwater retention. The moderate correlation ($r = 0.72$) between lens size and the ratio of rainfall to island width supports the contention that rainfall and island size play significant roles in determining recharge, but that other factors are also important.

Tidal range

Greater tidal ranges are likely to generate more vertical flow, resulting in greater mixing of fresh and saline water. While the effect of this will be less noticeable in large, high islands and in islands where horizontal flow dominates, atoll islands with similar structures and rainfall patterns should show an increasingly broad transition zone, and hence less potable resource, with increased tidal range.

Type of geologic material

Higher permeability geologic materials will permit the rapid outflow of freshwater, while lower permeability sediments will retain the water to a greater degree, thus permitting the formation of a thicker lens (Buddemeier & Oberdorfer, in press). Extremely low permeability, however, can make it impractical to extract water from the formation. Finer grained deposits from the lower-energy, lagoonal side of islands can combine relatively high porosity with low permeability and thus create a thicker lens in that portion of the island, and highly lithified formations (such as algal ridge structures) can act as low-permeability barriers to groundwater movement. Because reef and island sedimentary structures are non-homogeneous and stratified over small distances compared with island dimensions, the details of groundwater occurrence will depend on local conditions. Although basic principles can assist in description and understanding, there is no substitute for well-designed local resource surveys.

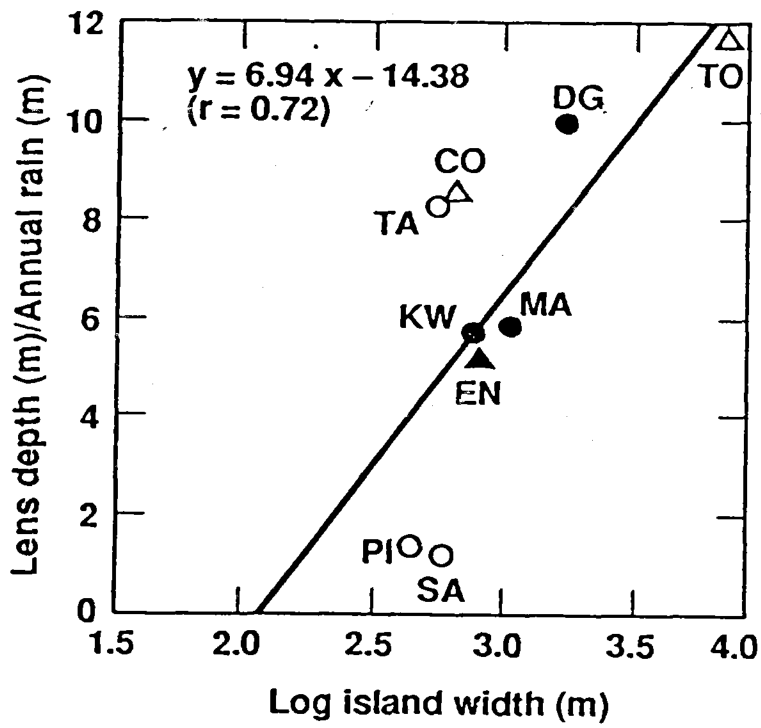


Figure 4. The ratio of fresh water lens thickness (distance from water table to 50% seawater isochlor, m) to mean annual rainfall (m) plotted against log island width (m; minimum dimension at location of freshwater lens). Island data are for Tarawa (TA; Lloyd *et al.* 1980), Pingelap (PI; Ayers *et al.* 1984), Satawan (SA; Ayers & Clayshulte 1983), Majuro (MA; Hamlin & Anthony, 1987), Kwajelein (KW; Hunt & Peterson 1980), Enjebi (EN; Buddemeier & Holladay 1977), Diego Garcia (DG; PRC Toups 1983), and Tongatapu (TO; Hunt 1979). In order of decreasing estimated reliability, lens depth data are based on salinity profiles from nested peizometers (solid circles) and open boreholes (solid diamond) or on values estimated from fresh water head (solid triangle) or surface resistivity surveys (open triangle).

Water quality

Any process that negatively affects the quality of the groundwater has the potential for reducing the water's utility as a resource. Both anthropogenic sources (waste disposal, agricultural practices, saltwater upconing due to overpumpage) and natural contamination (saltwater overwash of islands generated by storm surges, saltwater upconing due to high evaporation from surface ponds) can make the water unfit for use until cleansed either by natural washout or by human intervention.

## CHANGING CLIMATE: GROUNDWATER CONSEQUENCES AND VULNERABILITIES

The variety of scenarios for the consequences to groundwater of climatic change are numerous, both because of local variations in island groundwater resources and because of uncertainties in the exact patterns and magnitudes of climate change. However, basic hydrologic principles in combination with our general knowledge of the directions of climate change permit us to outline the major issues that need attention.

Recharge

Changing rainfall and temperature patterns will alter the amount of water available for recharge. Higher temperatures will cause more evapotranspiration; whether rainfall will increase enough to compensate for this is not currently predictable for specific locations. If recharge or rainfall decrease, islands that currently have small potable portions of their lenses will be particularly susceptible; a decrease in recharge could mean the absence of potable water available for withdrawal after natural losses. If rainfall patterns were to change so that precipitation, regardless of quantity, were to fall during less reliable or shorter rainy seasons, leaving longer periods without rain, then a crisis could occur as both demand and pumpage increased during the dry season and excessive withdrawals were made from a depleting lens. Increased seasonal swings in lens size would be likely to promote additional mixing of fresh and saline water, thus further limiting the resource. Islands most vulnerable to these problems are those that now experience seasonal degradation of water quality or have drought-induced water supply problems. Local assessment of potential problems must consider changes in demand that will result from future population changes, and the potential effects of human alteration of the island vegetation or surface characteristics.

Island size

Over longer time scales of decades or more, rising sea level may be expected to erode coastlines and flood low-lying portions of islands. It is unclear to what extent island accretion will be able to keep up with sea level increases (Hopley & Kinsey, 1988). Decreased island size will mean less surface area for infiltration and potentially a smaller volume of aquifer available for the storage of fresh water. If the population is not reduced in proportion to the changing area, a greater proportion of the island might also then be covered with impermeable surfaces. As noted above, this could either enhance or further diminish groundwater recharge. Vulnerability to climate change will be greatest for islands that are particularly low in elevation or small in area.

Water quality

Decreasing lens size due to either of the effects discussed above would tend also to decrease water quality by making any groundwater development more likely to produce some upconing of saline water. In addition, if the climate were to change so that severe storms became more frequent, then over-topping of the island with salt water by storm surge waves could contaminate the lens more often, while rising sea level would effectively reduce the magnitude of the storm necessary to cause flooding. While in some cases recovery can progress fairly quickly (Oberdorfer & Buddemeier, 1984), storm-contaminated groundwater may be unusable for a period of months or longer. Greater population density (from decreased area as well as from population growth) may intensify the amount of anthropogenic contamination from waste and possibly from the use of more agricultural chemicals to increase productivity.

In spite of uncertainties and the importance of unique local conditions, we can summarise some general guidelines for evaluating the vulnerability of small island groundwater systems to climate change. This summary will then lead into the recommendations made for action in the final section of the paper. Attention to the evaluation, protection and management of groundwater resources may be especially important if:

* groundwater is now relied upon for essential water supplies;
* the existing water supply is marginal or subject to deterioration during dry seasons or droughts;
* there is no reliable information on the extent or quality of the groundwater supply;
* demands for groundwater are expected to increase in the future (and especially if the demands are relatively inelastic);
* the island is relatively small, or has a relatively small groundwater lens;
* the island, and especially its coastline, has relatively low relief above highest high tide level;
* the island is in or adjacent to a region of tropical cyclone activity; and
* there is or will be a significant population or economic resource dependent on the water supply.

While most Pacific islands probably fall into one or more of these categories, such a list can serve to establish priorities for evaluation and planning.

## RECOMMENDATIONS FOR POLICY AND PREPARATION

The potential consequences of climate change are serious, and deserve thoughtful attention. Because environmental change will be relatively rapid, planning and preparation should start now. However, the situation is not an immediate crisis, as some of the effects - particularly global sea level rise - will take decades to have major impacts on any but the most vulnerable localities. During this time we may expect that our understanding of the nature and rate of climate change will improve immensely. We can now say that climate change and rising sea level threaten the low islands of the world, but we do not yet know if they are necessarily doomed. We contend that the prudent course of action is to understand the nature of our essential resources, to evaluate their possible vulnerability to climate change, and to take those actions that will serve both to improve our present situation and to protect us in the future. Careful and conservative management of our resources in the present environment is the most important first step toward preparing for future deterioration, and will permit us to take the most effective advantage of our experience and steadily improving predictive abilities.

We recommend the following policies be adopted and implemented by the appropriate local governments, regional consortia and international agencies.

1. Island groundwater resources should be surveyed and evaluated. Such an evaluation should be sufficiently thorough to determine not only the size of the potable water resource, but also its variability over time, the primary factors controlling size and variability, and the mechanisms by which these factors exert their control (e.g. whether it is more accurately described as a layered-aquifer or a GHD system). Existing survey results should be critically evaluated to ensure that conclusions are not based on unjustified assumptions (e.g. calculation of potable water resource from groundwater elevations alone). Priorities for such surveys or reviews should be based on the degree to which the groundwater is now a critical resource and on the population or economic resource that would be at risk if it were to fail.

2. Islands that draw on groundwater resources should have basic management and monitoring programs so that records are kept of the key variables - rainfall, simple indicators of potable water quantity and quality, and some estimate of water withdrawal.

3. Island topography should be surveyed, particularly with reference to the elevation of the areas that overlie potable water resources and the peripheral areas that separate them from the ocean. The goal of this effort is to identify particularly flood-prone areas that might be readily structurally protected, and to establish a data base against which to evaluate the significance of future improvements in sea level rise predictions.

4. Development, construction and land use, both present and future, should be evaluated for their potential impact on recharge and water quality. Laws or policies should be developed to protect the common water resource.

5. A mechanism should be established for regular review of plans and policies in the light of changing knowledge and predictions concerning climate change.

6. In addition to the foregoing technical and management-oriented recommendations, there are social and political issues that are clearly critical to our adaptation to a changing environment. One such issue is the limitation of population or population density; another is education (at all levels) to prepare people to conserve their resources and adapt to change.

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# THE EFFECTS OF SEA LEVEL RISE ON TROPICAL RIVERINE LOWLANDS

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## INTRODUCTION

Tropical lowlands and coastal floodplains are amongst the most populated and productive lands in the world. They also are highly vulnerable to changes of sea level. Rising sea level will cause river floodwaters to invade floodplains more frequently, as well as causing tidal flooding of estuarine and coastal plains. Both factors affect the ecology and agricultural potential of these lands.

The extent to which tidal and fluvial flooding is increased by a given rise of sea level is affected by factors such as floodplain slope, both downstream and laterally away from the river, and the form of river levees. Flooding also is affected by the extent to which floodplain sedimentation can keep pace with rising tidal and flood levels. Figure 1 illustrates this for a system where tidal effects extend well upstream. In this simple example, it is assumed that the plain between the inland tidal limit and the river mouth lies just above high spring-tide water level (HSWL) in the adjacent river, and that beyond the tidal limit the plain is graded to the level of a standard flood, such as the mean annual flood.

The effects of flooding and sedimentation, given a rise of sea level, are illustrated in Figure 1. Without sedimentation, tidal flooding will extend across all land up to the new high spring tide level (contour h in Figure 1). The degree to which fluvial flooding increases upstream depends on the floodplain slope, and the new position of the high-tide shoreline. Figure 1 shows the position of the new floodplain surface as it would be if sedimentation kept pace with sea level rise. The volume of new sediment, which would be required for the floodplain to keep pace with rising sea level, can be calculated from a series of cross sections.

To estimate the changes which might happen if sea level rises in future, the rate of sediment input to floodplains should be measured. Figure 1 illustrates the simple concept of sedimentation keeping pace with sea level rise. Real cases are likely to be more complex. New sediment is not likely to be distributed uniformly, particularly if its rate of supply is insufficient for the floodplain deposition to keep pace. Further, the tidal part of the river is likely to change, because the channel will adapt to increased flows caused by overbank tidal flooding. This may affect the hydrology and sedimentation within and beyond the tidal reaches.

The problem may be addressed using computer models, based on hydrological and geomorphological processes, and channel hydraulics. In the author's view, our knowledge is inadequate at present to make reliable models, and the actual behaviour of riverine lowlands under various conditions of past sea level changes should be examined. The Holocene period (the last 10,000 years) is most appropriate, as sea level was rising rapidly until about 6,500 years ago, and has been relatively stationary since. Present riverine lowlands evolved during this period, and their behaviour during the rising sea level phase is recorded in shallow subsurface deposits.

Following an outline of the Holocene period, this paper discusses two examples of the effects of Holocene sea level changes on tropical riverine lowlands. These cases are chosen to illustrate the way in which response to sea level rise varies with tidal behaviour as well as sediment input.

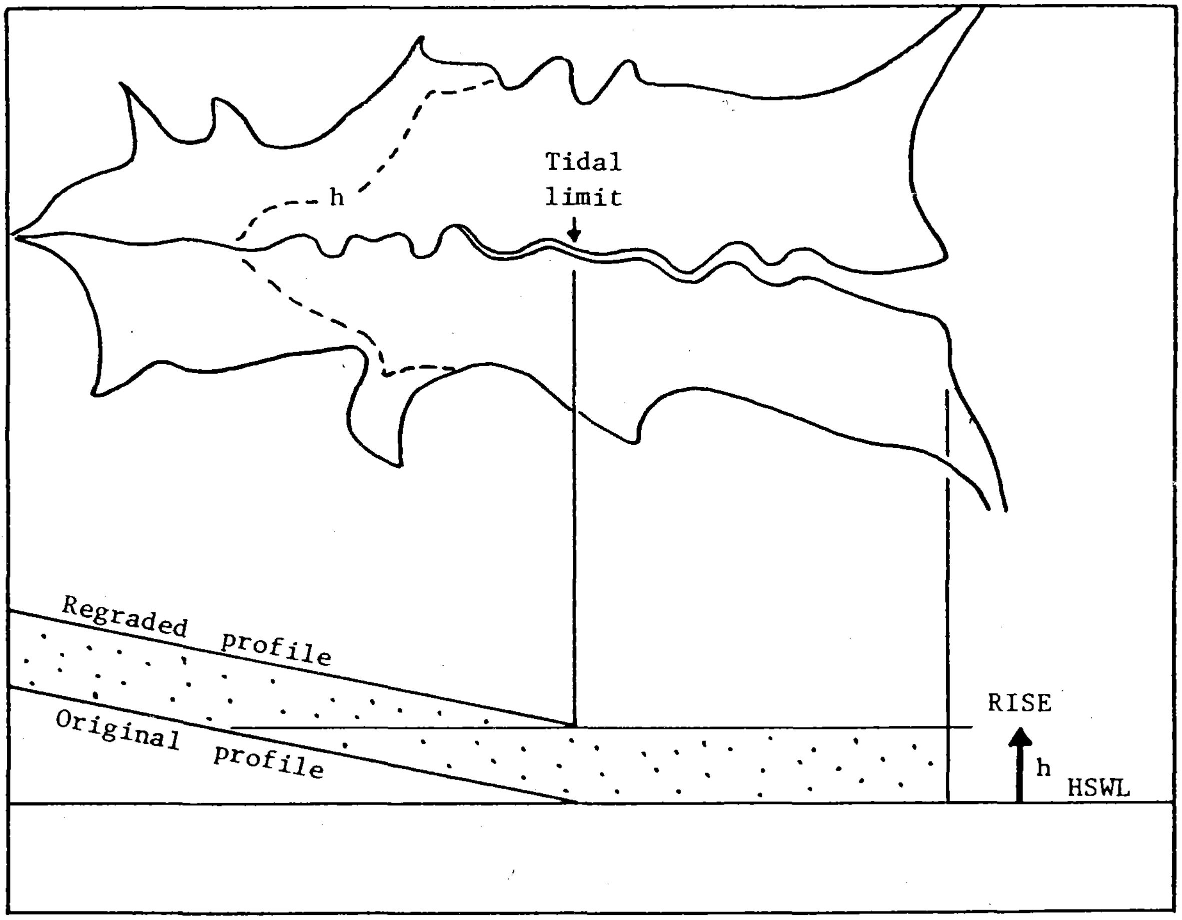


Figure 1. Regrading of floodplain as sea level rises. Map of simple floodplain (top) shows that tidal flooding will extend inland to contour 'h', after sea level rises by h metres, unless sediment is deposited on the plain. Vertical profile (bottom) is shown as horizontal below tidal limit, and sloping upstream of that. Stippled section indicates sediment which must be deposited if plain is to keep pace with rising sea level.

## THE HOLOCENE CONTEXT

The Holocene period (the last 10,000 years) followed the last of the Pleistocene ice ages. Holocene climates have been more similar to those of the present than those of the ice ages. Northern continental ice sheets were retreating rapidly 10,000 years ago and had vanished by about 6,500 years ago. Starting about 17,000 years ago, rising sea level caused by ice melt flooded the continental shelves.

The pattern of sea level change has not been the same throughout the world, and must be considered relative to any given landmass. This is explained geophysically.

(i) The sea surface seeks a figure which is in gravitational equipotential with the solid earth, which includes icecaps on land.

(ii) Changing the mass of water by forming or melting icecaps causes isostatic changes of the solid earth, globally as well as beneath the ice caps themselves.

Both factors were satisfactorily analysed by Clark *et al.* (1978), and by others, and the problem recently has been analysed with considerably higher spatial resolution by Nakada & Lambeck (1988). Data showing the patterns of relative sea level changes for different parts of the world can be found in Tooley & Shennan (1987) and Devoy (1987).

The amount of sea level rise between 17,000 and 6,500 years has been debated, as a world average, but probably amounts to 130 m (Chappell & Shackleton, 1986; Lambeck & Nakada, 1988). It is reasonably certain that sea level rose by about 30 m between 10,000 and 6,500 years, relative to most tropical and sub-tropical lands. Sea level since then has been comparatively stable, although relative to most lower latitude coasts it reached at peak a metre or two above present, in Mid-Holocene times. The magnitude and timing of this peak varies with place (see for example Hopley, 1987), and is generally consistent with geophysical predictions (Nakada & Lambeck, 1988). Selected sea level curves for the last 10,000 years are shown in Figure 2.

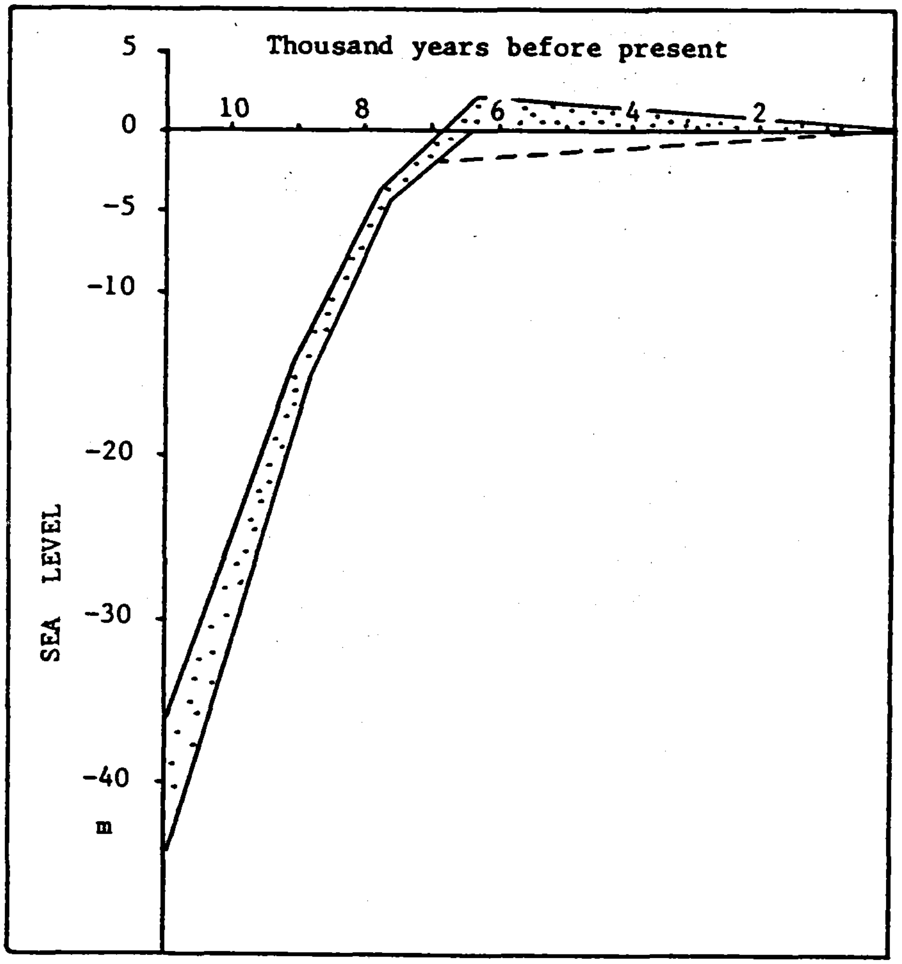


Figure 2. Sea level changes in the last 10,000 years, western Pacific region. The rise before 6,500 years ago is based on southeast Australian data (Thom & Roy, 1985). The stippled zone from 6,500 to the present covers individual curves from northern Australia and data from many Pacific islands (data in Hopley, 1987). A rising curve over the last 6,000 years (dashed line) has been identified in some other part of the world.

The effect of Holocene sea level on riverine lowlands can be considered in two episodes, the first from 10,000 to 6,500 years when it was rising at 0.6 to 1.0 m/100 years, and the second from 6,500 to the present when it has been essentially stable. During the rising phase, the sea transgressed upon land and valleys were drowned, an effect offset to some extent by sedimentation. The rate of sea level rise at that time was similar to the future rise predicted for the greenhouse effect. The sedimentary record of this period is relevant to future problems, because it indicates the patterns of sedimentation which occur when sea level is rising rapidly.

CASE 1: HIGH TIDAL RANGE, LOW SEDIMENT INPUT

This case is represented by rivers in northern Australia, where sediment yield from the land is low by world standards, because of the low relief and great geological age of the landscape. These rivers are tidal for 100 km or more, flowing through floodplains which lie only slightly above high tide levels. The climate is monsoon tropical, with a long dry season. In areas of higher summer rainfall, such as the northern part of Northern Territory, the floodplains include freshwater wetlands which actually lie below highest tide levels, but are protected from tidal invasion by low river levees. Freshwater flow is substantial for a month or two in the wet season, and the lower tidal reaches of these rivers become progressively more saline through the dry season. Tidal currents in the rivers are strong.

It would seem that rising sea level would drown these floodplains to a depth, at high spring tide, equal to the sea level rise. Sediment input from the catchment is very low and floodplain sedimentation is small. However, the Holocene history of these systems shows that the answer is not so simple.

The case of the South Alligator River is reviewed, based on work by Woodroffe *et al.* (1986) and Chappell *et al.* (in press). Figure 3 shows a map of the South Alligator plains and tidal river. The plains are built over muddy sands which were deposited in a long and rather shallow valley during the Holocene. The nature and age of these sediments is known from an extensive program of drilling and radiocarbon dating (Woodroffe *et al.* 1986). Today the plains are covered in sedges and grasses, saturated and partly flooded by freshwater during each wet season. Conditions around 6,000 years ago were very different. Mangrove swamp, flooding with saltwater at every tide, covered most of the South Alligator plains. Its extent around 6,000 years ago is mapped in Figure 3.

It is important to recognise that this mangrove developed when sea level was rising. Deposits beneath the floodplain, shown in cross section in Figure 4, illustrate this. Away from the central river channel sediments, most of the floodplain is underlain by mangrove muds up to 10-14 m thick. Radiocarbon dating shows that most of this accumulated between 8,000 and 6,000 years ago, while sea level rose by 12 m. Mangrove swamp sedimentation throughout the valley virtually kept pace with rising sea level.

The fact that mangrove sedimentation kept pace with sea level is surprising, because sediment input from the South Alligator catchment is small. Understanding the processes involved is important for the question of future sea level rise and its effects. Woodroffe *et al.* (1986) show that catchment sediments probably account for less than 10% of what accumulated when sea level was rising, and suggest that marine muds moved into the valley as the shoreline advanced towards the land. Strong tidal currents, caused by the large tidal range, were an important agent for redistributing sediment. A significant amount of sediment came from widening of the channel itself, as it changed from a relatively narrow seasonal river to a large tidal estuary as the sea invaded. Analysis shows that, with strong tidal flows, the sediment mobilised as the channel widens is then trapped in the system and is distributed onto the plains.

In summary, strongly tidal rivers such as the South Alligator, and others in northern Australia which flow through long floodplains in shallow prior valleys, are now known to have filled with sediment under mangroves when sea level was rising at about 0.6 m/100 years. It is likely that a future sea level rise of similar rate will cause such plains to revert to mangrove, and that sedimentation will approximately keep pace with sea level once this change has occurred. Because the rate of sediment supply from their catchments is low, the change from fresh to saline wetlands seems inevitable.

CASE 2: LOW TIDAL RANGE, HIGH SEDIMENT INPUT

This case is represented by the Sepik and Ramu rivers in Papua New Guinea, where sediment input is high because of high relief and high tectonic uplift rate in the surrounding mountain ranges. Annual rainfall in the lower floodplains is about 2,000 mm, and varies from 3,000 to over 6,000 mm in the mountain catchments. Freshwater discharge is large, and although tidal rise and fall occurs weakly for about 90 km up the Sepik, tidal currents are insignificant. The floodplains include sago swamp, forest, grassland, and extensive wetlands.

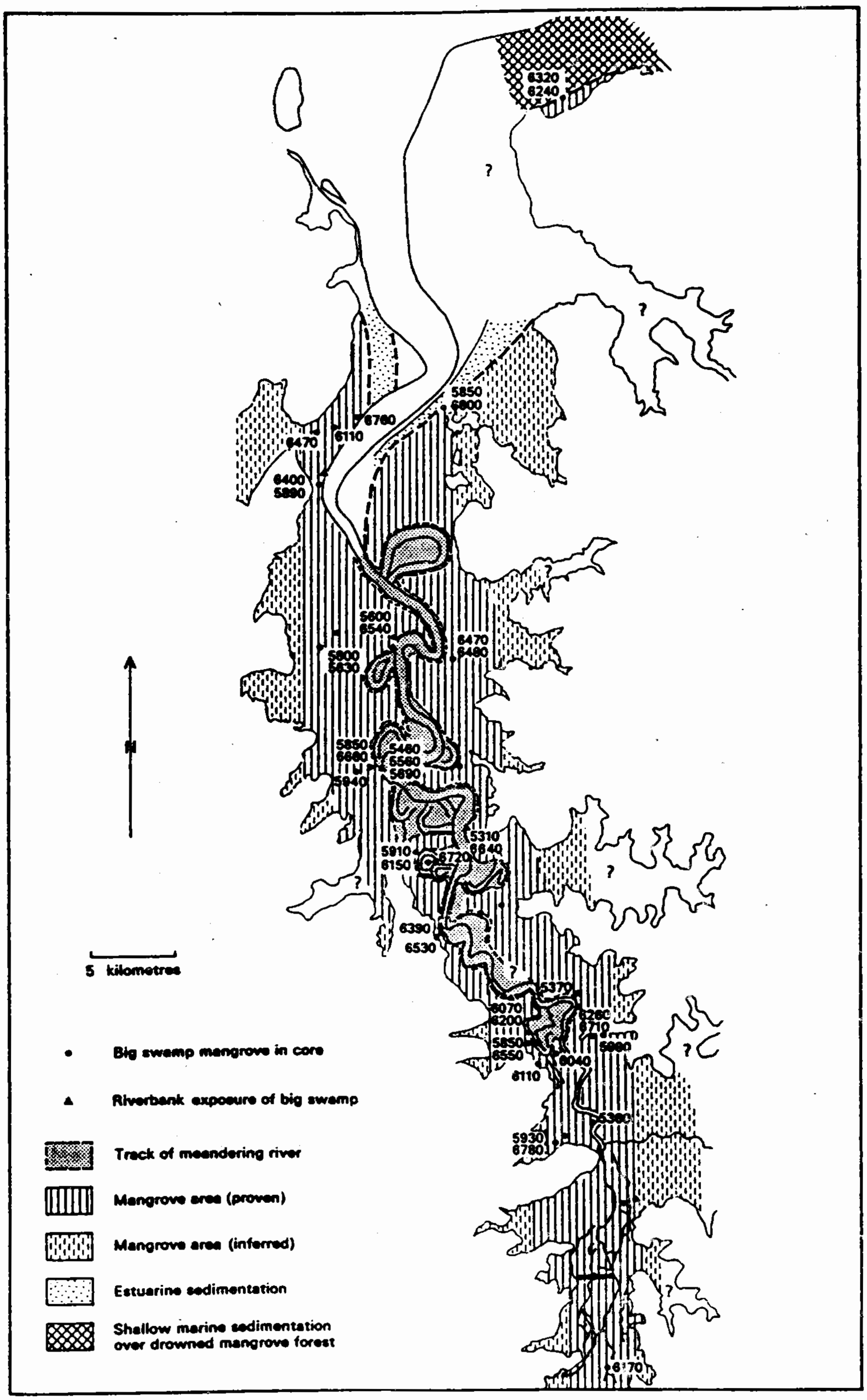


Figure 3. South Alligator tidal river and plains area, northern Australia. The map shows that part of the plains which was mangrove swamp around 6,000 years ago. Radiocarbon ages of these former mangrove swamps are shown. Today the plains, including previous meanders, are freshwater wetlands and seasonally-flooded grassland.

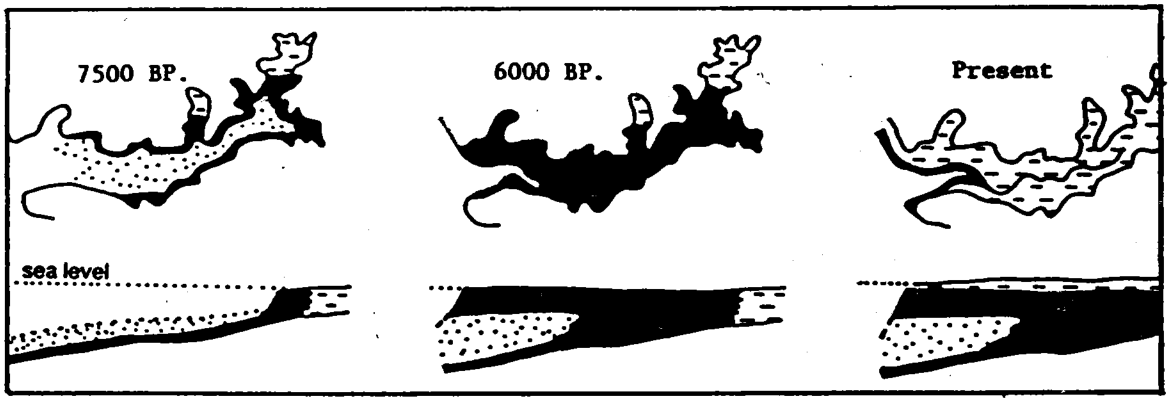


Figure 4. Evolution of the South Alligator plains. When sea level was rising rapidly, 7,500 years ago, the valley was a broad shallow estuary fringed with mangrove. As sea level stabilised, 6,000 years ago, mangrove swamp developed throughout what is floodplain today (see also Figure 3). Mangrove, and subsurface mangrove sediments, are shown in black.

The future question concerns the extent to which river flooding will increase if sea level rises, and the extent to which the sea will invade lowlands near the coast. As tidal effects are negligible, the processes of tidal redistribution of marine and river bank sediment, which were significant in the northern Australia case, will be unimportant. The rate of sediment supply from the catchment, relative to the size of the lowland basin, is the critical factor. Maintenance of the floodplains and their ecology, with rising sea level, depends on sedimentation on the plains.

This is difficult to estimate from measurements of sediment in the river itself. River gauging and measurements of sediment concentrations can provide estimates of sediment supply, but say little about floodplain accumulation. A large part of the sediment load leaves the river mouth and is deposited on the sea bed. In the Sepik-Ramu case there is no continental shelf and much of this material cascades to the deep sea floor offshore. From available data, the maximum possible rate of floodplain sedimentation is roughly 0.3 m/100 years for the lower Sepik plains. This figure assumes that virtually no sediment leaves the river mouth.

The lower Sepik-Ramu basin was invaded by rising sea level in early Holocene times. Figure 5 maps the region, and shows estimated positions of shorelines for 2,000 and 6,000 years ago, which have been identified and radiocarbon-dated at some localities. These former shorelines are now buried by thick floodplain sediments, and have been identified from shallow drillholes, and river bank exposures observed at times of low flow. Summarising, a shallow inland sea was created during the major sea level rise which began 17,000 years ago. This was filled by sediment from the catchment, and receded rapidly when sea level stabilised in the last 6,000 years.

Figure 5 must be interpreted carefully when estimating effects of future sea level rise. The former inland sea is not a scenario for the near future, because it formed towards the end of a major sea level rise. The future problem concerns the beginning of a possible rise. The rate at which the Sepik-Ramu floodplain can build up is the critical factor. One estimate is given by the rate of accumulation during the period when the inland sea was receding rapidly. Coastal regression can have a similar effect on river flooding and sedimentation as a sea level rise (Figure 6a). Radiocarbon ages from freshwater organic peats and marine beds immediately beneath the alluvial sediments provide estimates of the rate of floodplain accumulation during retreat of the inland sea. Figure 6b shows radiocarbon ages through the sediments along the Keram transect, crossing the lower Sepik floodplain (location, Figure 5). These results indicate sedimentation rates of up to 0.3 m/100 years near the Keram River. As this includes levee sedimentation, it will exceed the average rate for the entire plain. However, this figure is similar to the estimate based on direct gauging given above, and suggests a maximum possible rate of sedimentation on the plains. If sea level rises more rapidly than 0.3m/100 years, flooding in the lower Sepik will become more frequent and widespread.

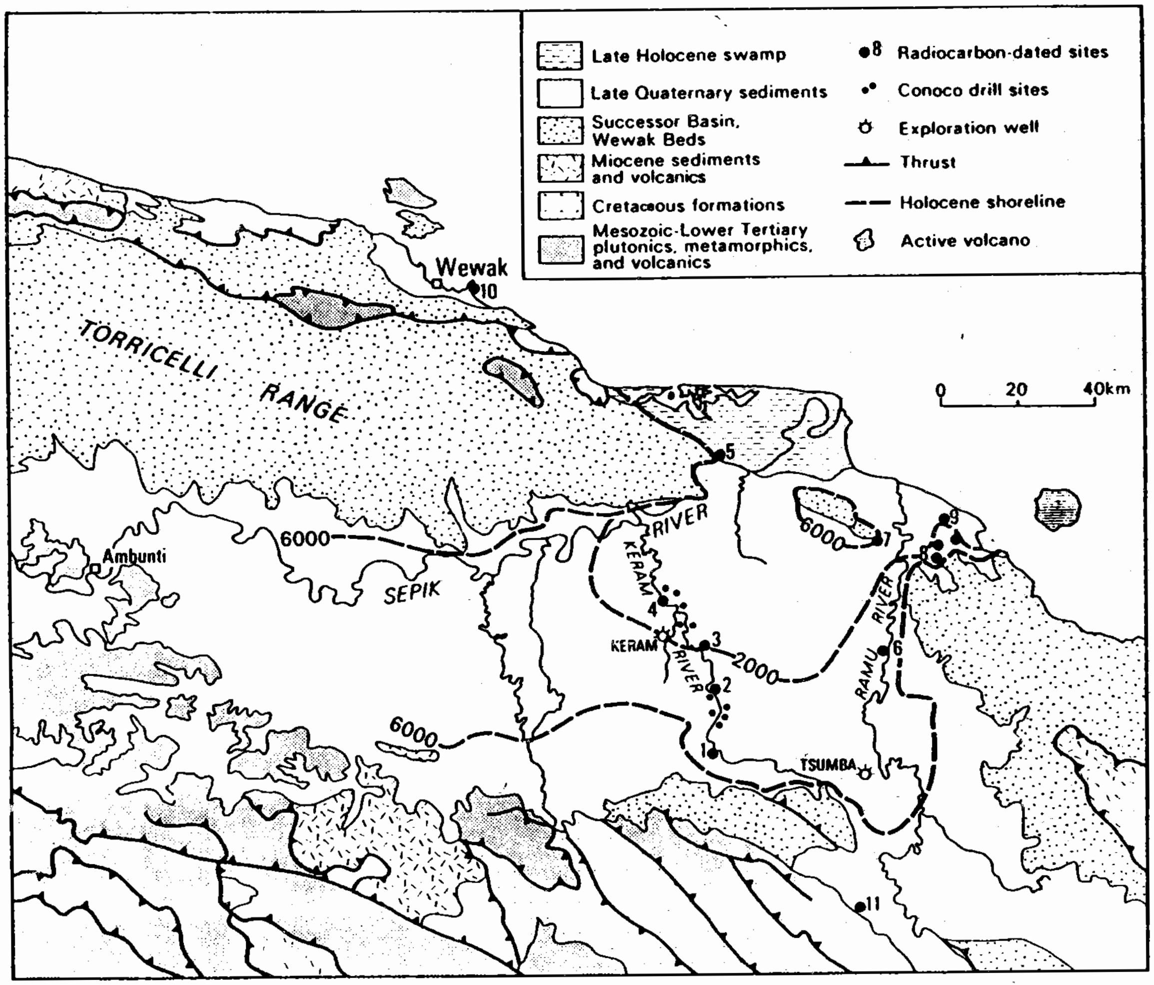


Figure 5. Geology, and Holocene shorelines, in the lower Sepik-Ramu region, Papua New Guinea. A shallow inland sea formed during the period of rapid sea level rise, before 6,000 years ago. This shallow sea receded rapidly when sea level stabilised. Former shorelines are inferred from coastal deposits beneath floodplain sediments; these radiocarbon-dated at some sites. Rates of river sedimentation can be gauged at dated sites.

## CONCLUSIONS

The conclusions of this paper are simple: if we are are to estimate the effects of a possible future sea level rise, the effects of the last major sea level rise should be investigated. This commenced 17,000 years ago and finished 6,500 years ago. The interval between about 8,000 and 6,000 is most relevant for problems of coastal and riverine lowlands, as deposits from this period lie directly beneath the modern lowlands. These studies of the past should be included in any local or regional future-oriented programmes of investigation.

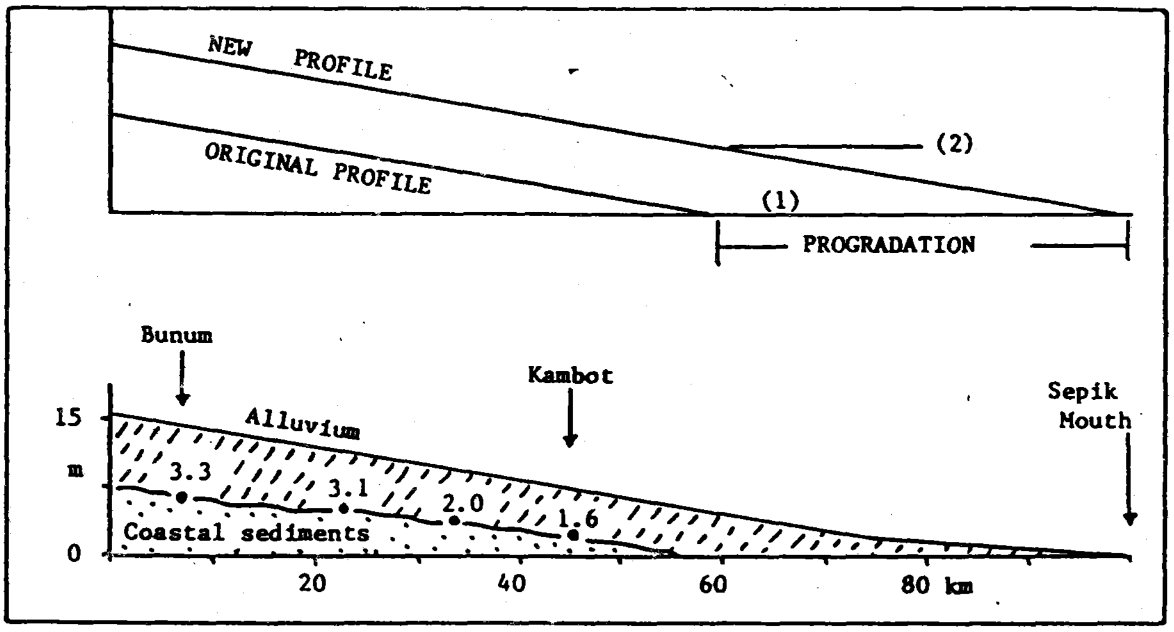


Figure 6. (a) Coastal progradation can have the same effect on river sedimentation as sea level rise. Upper diagram shows that sedimentation from original to new profile is similar to the effect of a rise from level 1 to level 2. (b) Lower diagram shows transition from coastal to alluvial sediments in lower Sepik, on transect from Bunum (locality 1 in Figure 5) to coast near Sepik mouth. Numbers on section show age of basal river deposits, in thousands of years.

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# PLANT ECOPHYSIOLOGICAL INFORMATION FOR CONTINGENCY THINKING IN THE SOUTHWEST PACIFIC IN FACE OF THE GREENHOUSE PHENOMENON

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## SUMMARY

It is suggested that the best way for Southwest Pacific countries to prepare for greenhouse effects so far as plant ecophysiological responses are concerned is to construct or improve relevant information systems which will be valuable whether or not the greenhouse phenomenon materialises.

Standardised plant ecophysiological data-sets should be prepared at an appropriate scale, and these should cover fuelwood, forest, and weed species, as well as crops. In relation to climate data, the information systems should include long runs of actual data so that the effects of climate variability can be assessed. Provision for long runs of synthetic climate data should also be made so that hypothetical scenarios can be examined. Whatever land data are stored should be directly meaningful so far as plant production is concerned.

Given such information systems, a variety of methods can be used for predicting plant performance under different types of greenhouse impact. Some of these methods can be operated manually or merely by eye. However, problems which the expertise or data immediately available may not highlight should not be overlooked. Among those mentioned are losses due to pests and diseases arising from possible increased weather variability, and alteration in soil biology, upon which subsistence food systems heavily depend.

Ten formal recommendations are made. Wherever possible, these favour work which can be decentralised and readily adapted to local needs and perceptions.

## INTRODUCTION

The ASPEI Task Team recommended to the UNEP meeting in SPLIT in October 1988 on impacts of the greenhouse phenomenon that work be done on the geographic distribution, importance, and ecophysiological tolerance of a range of commercial, smallholder, and subsistence crops. This report suggests a strategy for such work.

The strategy is based on the view that the most helpful action would be to create techniques for handling plant information which will be useful whether or not the greenhouse phenomenon manifests itself as feared. This strategy should be relatively easy to pursue because interest in the ecophysiological characteristics of plant species is already strong due to concern about the conservation of food production systems and development of the marketing and processing of plant products.

This report offers a philosophical basis for the work proposed, discusses some simple and some more complex means by which it can be conducted and ten formal recommendations are made. The physiological effects of raised carbon dioxide levels on plant production are not discussed because it is considered (a) that they are unlikely to be negative and (b) that the nature of the benefits which may be obtained are too unpredictable at present to allow for in planning processes.

The relevance of the proposals to more immediate problems of plant production and land-use planning will be readily apparent. However, these aspects are rarely referred to below because that was not the prime purpose of this report.

## CHOICE OF SCALE

Contingency thinking about the impact of the greenhouse effect on plant production in the Southwest Pacific is likely to begin with simple questions such as 'How will yields be affected in the present locations of crop species?' and 'Where might optimal performance occur if conditions do change?'

Following closely upon such questions would be a group which focuses around farming systems, such as 'How might mixes of species be affected by simple effects such as a rise in temperature?' and 'If conditions become more variable for month to month and year to year, would the existing mixes of species cope with that?'.

Behind the second set of questions would come a third set relating to socio-economic considerations, such as 'How readily will producers perceive what is happening to the environment and to their production systems?'. 'How well can they be expected to adapt by using their own experience and resources?', and 'Might some of the effects be so marked that efforts to respond might lead to social conflict in some form?'.

Because these questions range across many people, many places, many factors, and many species, care has to be given in choosing a scale for working on them. For dealing with plant/environment relationships, which this report is almost exclusively concerned with, there are four broad scales or levels to choose from (Hackett, 1983). These levels are defined in relation to the content of general-purpose descriptions of plant species, namely Level A - checklists of names, Level B - dictionary entries, Level C - chapters and articles, and Level D - monographs.

Study of differences between the content of plant descriptions at these levels has shown that Level C is well suited to broad-sweep examination of the type of problem being considered here. The typical Level C description is of course textual and does not lend itself well to direct use in formal studies, but standardised Level C descriptions can be prepared which can serve analytical thinking very well. An example of such a description follows and is used to show that very simple methods of assessment can be quite informative about possible plant responses to potential greenhouse impacts in the Southwest Pacific.

## A SAMPLE PLANT DATA-SET

The data-set for sweet potato shown in Figure 1 was derived from one prepared for a land evaluation project for Papua New Guinea - see Bellamy (1986) and Hackett (1988a). This particular representation of the data-set comes from 'Manual ECOPHYS' (Hackett, 1988b), which is a system for making rapid coarse predictions of performance by hand, using worksheets and look-up tables. In all, Hackett (1988a, 1988b) contain 18 such data-sets for crops grown in the Southwest Pacific - see Table 1 for a list.

Explanation of the origin of the description shown in Figure 1 and the conventions and symbols used in its preparation can be found in Hackett (1988a, 1988b). All that needs to be said here is that (a) as far as possible all such descriptions were built up from expert knowledge of the species, (b) the focus of the format shown here is the limitation rating (LR - 0 to 10), (c) use of Liebig's Law of the Minimum (Browne, 1942; Hackett, 1988a: Chapters 4 & 10) to estimate performance which gave surprisingly good results, and (d) the prediction process was tested many times by 'blind' methods (Hackett, 1988a: Chapter 10).

To illustrate how such data-sets can be used to consider greenhouse effects simply by eye, reference will be made here to a small selection of the factors covered in Figure 1.

Sequential examination of the subsets of data marked '**' in Figure 1 shows the following for sweet potato (Hackett, 1984; 1985).

- If increased rainfall produced poorer soil aeration, yields in many areas would tend to fall unless the growers could compensate in some way

Sweet potato (storage roots)

CROP DATA FOR THE MANUAL PREDICTION SYSTEM

Common name: Sweet potato
Family: Convolvulaceae
Scientific name: Ipomoea batatas (L.) Lam.
Subspecies or cv.:
Product(s): storage roots
Potential rooting depth, PRD (cm): > 200
Quality ratings (0-9): 5,5
Main sources: Hackett (1984, 1985)

******** LIMITATION RATINGS FOR TIME-CONSTANT FACTORS ********

(Class; LR 0-9 for low, median and high chars.; class-code in PNGRIS)

| BS (%) | | | CEC (meq/100g) | | | DEPTH (cm) | | | AERATION / DRAINAGE ** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| < 20 | .!5!. | 3 | < 10 | .!5!. | 3 | < 5 | .!9!. | 4 | Well | .!0!. | 1 |
| 20-60 | .!3!. | 2 | 10-25 | .!3!. | 2 | 5-10 | .!7!. | 4 | Imperfect | 1!3!. | 2 |
| > 60 | .!1!. | 1 | > 25 | .!1!. | 1 | 10-25 | .!5!. | 4 | Poor (swcl) | 5!7!. | 3 |
| | | | | | | 25-50 | .!2!. | 3 | Poor | 3!6!. | 3 |
| | | | | | | 50-100 | .!1!. | 2 | Swampy (mvg) | .!9!. | 4 |
| | | | | | | 100-200 | .!0!. | 1 | Swampy (stg) | .!9!. | 4 |
| | | | | | | > 200 | .!0!. | 1 | | | |

| NITROGEN (% x 100) | | | pH | | | PHOSPHORUS (ppm) | | | POTASSIUM (meq/100g) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| < 2 | .!6!. | 3 | 3-4 | .!9!. | 3 | < 2 | .!8!. | 3 | < 0.1 | .!7!. | 3 |
| 2-4 | .!2!. | 3 | 4-5 | .!5!. | 3 | 2- 5 | .!6!. | 3 | 0.1-0.2 | .!3!. | 3 |
| 4-8 | .!1!. | 3 | 5-6 | .!0!. | 2 | 5-10 | .!3!. | 3 | 0.2-0.4 | .!2!. | 2 |
| 8-20 | .!0!. | 3 | 6-7 | .!0!. | 1 | 10-20 | .!1!. | 2 | 0.4-0.6 | .!1!. | 2 |
| 20-50 | .!0!. | 2 | 7-8 | .!4!. | 4 | > 20 | .!0!. | 1 | > 0.6 | .!0!. | 1 |
| > 50 | .!0!. | 1 | > 8 | .!8!. | 5 | | | | | | |

| SALINITY (mS/cm)** | | | SLOPE (deg) | | | STONINESS (%) | | | TEXTURE | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | .!0!. | 1 | < 2 | .!0!. | 1 | < 1 | .!0!. | 1 | V.fine (swcl) | 5!7!. | 4 |
| 2 | .!1!. | 1 | 2-5 | .!0!. | 2 | 1-3 | .!1!. | 2 | V.fine | 2!4!. | 4 |
| 4 | .!3!. | 2 | 5-10 | .!0!. | 3 | 3-15 | .!4!. | 3 | Fine | .!3!. | 3 |
| 6 | .!4!. | 2 | 10-20 | .!1!. | 4 | 15-30 | .!6!. | 4 | Medium | .!2!. | 2 |
| 8 | .!5!. | 2 | 20-30 | .!2!. | 5 | > 30 | .!8!. | 5 | Coarse | .!2!. | 1 |
| 12 | .!8!. | 3 | > 30 | .!4!. | 6 | | | | Gravel | .!5!. | - |
| 16 | .!9!. | 3 | | | | | | | Rocky | .!7!. | 6 |
| | | | | | | | | | Peats | .!0!. | 5 |

*** LIMITATION RATINGS FOR SOLAR RADIATION (MJ/m2/day): RESPONSE GROUP C3G2 ***

| Units | 0 1 2 3 4 | 5 6 7 8 9 | Units | 0 1 2 3 4 | 5 6 7 8 9 |
|---|---|---|---|---|---|
| Tens 0 | 8 8 7 7 6 | 6 6 5 5 4 | Tens 0 | . . . . . | . . . . . |
| 10 | 4 4 4 4 3 | 3 3 3 3 3 | 10 | . . . . . | . . . . . |
| 20 | 3 2 2 2 2 | 2 2 1 1 1 | 20 | . . . . . | . . . . . |
| 30 | 1 1 1 1 0 | 0 0 0 0 0 | 30 | . . . . . | . . . . . |

From Hackett (1988a) User's entries

Figure 1. Example of a formal Level C ecophysiological data-set as used in "Manual ECOPHYS" (Hackett 1988b). The subsets of data marked ** are referred to in the text of this report.

Sweet potato (storage roots) cont.

LIMITATION RATINGS DUE TO TEMPERATURE ( $^{o}$C) **

Damaging temperatures:

| | Threshold temperatures (TT) Plant parts | TT (deg) | LRs (0-9, cv.) <=TT-2 | TT-1 | TT | TT+1 | >=TT+2 |
|---|---|---|---|---|---|---|---|
| Heat damage, soil | ............ | ..!..!.. | .!.!. | .!.!. | .!.!. | .!.!. | .!.!. |
| " " , air | ............ | ..!..!.. | .!.!. | .!.!. | .!.!. | .!.!. | .!.!. |
| Brief cold , plant | leaves...... | ..! 3!.. | .!9!. | .!9!. | .!6!. | .!3!. | .!0!. |
| Ext. cold , plant | leaves...... | ..! 8!.. | .!9!. | .!8!. | .!6!. | .!3!. | .!0!. |

Rate of development:

Cardinal temperatures (TA - TD) for storage root development:**

TA - ..!10!.. TB - ..!24!.. TC - ..!24!.. TD - ..!34!..

For Papua New Guinea only

| Elev'n (m) | Max/min | DUs | LR (0-8) | Elev'n (m) | Max/min | DUs | LR (0-8) |
|---|---|---|---|---|---|---|---|
| 0 | 33/22 | 44 | 2 | 1800 | 23/13 | 38 | 3 |
| 300 | 31/20 | 51 | 1 | 2100 | 22/11 | 30 | 4 |
| 600 | 30/19 | 52 | 1 | 2400 | 20/10 | 23 | 5 |
| 900 | 28/17 | 53 | 1 | 2700 | 18/ 8 | 15 | 6 |
| 1200 | 26/16 | 50 | 1 | 2850 | 18/ 8 | 15 | 6 |
| 1500 | 25/14 | 44 | 2 | .... | ../.. | .. | . |

Estimated no. of weekly DUs to first harvest (based on 22-week optimum) = 1150

LIMITATION RATINGS (0-8) DUE TO WATER DEFICIT AND SEASONAL WATERLOGGING**

Water deficit response group: sweet pot. stor. rts Growth phases: storage root devel.

LRs (0-8) for AET/PET (%) **

| Tens \ Units | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 8 | 8 | 8 | 8 | 7 | 7 | 7 | 7 | 7 | 7 |
| 10 | 7 | 7 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 5 |
| 20 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 |
| 30 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 |
| 40 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 |
| 50 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| 60 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| 70 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 |
| 80 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 |
| 90 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 |
| 100 | 4 | | | | | | | | | |

(From Hackett 1987, 1988a)

LRs (0-8) for AET/PET (%)

| Tens \ Units | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | . | . | . | . | . | . | . | . | . | . |
| 10 | . | . | . | . | . | . | . | . | . | . |
| 20 | . | . | . | . | . | . | . | . | . | . |
| 30 | . | . | . | . | . | . | . | . | . | . |
| 40 | . | . | . | . | . | . | . | . | . | . |
| 50 | . | . | . | . | . | . | . | . | . | . |
| 60 | . | . | . | . | . | . | . | . | . | . |
| 70 | . | . | . | . | . | . | . | . | . | . |
| 80 | . | . | . | . | . | . | . | . | . | . |
| 90 | . | . | . | . | . | . | . | . | . | . |
| 100 | . | . | . | . | . | . | . | . | . | . |

(User's entries)

Seasonal waterlogging (CRDRDEP = 45 cm) **

(1) If SURP in WATSTAT = 0, LR = 0.

(2) If SURP in WATSTAT > 0,

(a) obtain DRDEP/CRDRDEP (%) from Worksheet 7

(b) if DRDEP/CRDRDEP % < 80, LR = 4!6!.

if DRDEP/CRDRDEP % >= 80 and < 133, LR = 2!4!.

if DRDEP/CRDRDEP % >= 133, LR = 0!0!.

Figure 1. Continued

- If the sea encroached on cropped land by underground seepage of salt, sweet potato would be expected to be reasonably tolerant (though palatability might decline).
- Rise in temperature would hasten rate of development in cool areas but decrease it in areas which are already hot.
- Modest changes in rainfall could have noticeable effects even without any change in seasonality or variability because yield of storage roots of sweet potato is favoured by mild water stress.
- Increase in seasonal waterlogging would not be completely disastrous, but the decline in yield would be substantial enough to require greater energy inputs to mounding and ditching where possible.

Table 1. Crops for which standardised to Level C descriptions were prepared for the PNG land evaluation project. See Hackett (1988a: Chapter 3) for authors and citations.

| | |
|---|---|
| banana | potato |
| cashew | sago palm |
| cassava | sweet potato |
| coconut | tannia (*Xanthosoma* sp.) |
| coffee (arabica) | taro |
| coffee (robusta) | winged bean |
| karuka (*Pandanus* sp.) | yam (greater) |
| mango | yam (lesser ) |
| oil palm | |

(Copies of these descriptions are available from the present author at the Division of Tropical Crops and Pastures, CSIRO, St Lucia, Qld 4067. The description for oil palm remains unpublished.)

Without using formal analysis of data-sets of this type, four more observations can be made.

- Because the optimum temperature for rate of crop development differ between species, a change in temperature will affect species in a mixed cropping system differently, which means that the timing of human activities and food supply would be put out of kilter by a temperature rise unless the growers could move their gardening systems to a higher elevation (such a move might rarely be possible because of social factors or adverse slopes in the higher regions).
- Whether or not human communities could adjust to the temperature changes by movement, there would be a underlying tendency of crops to move of their own accord rather like pieces on a chessboard starting to act independently of the players.
- The tendency of crops to move in this way could raise serious problems for enterprises for which a major capital investment has been made on the 'squares' currently occupied by these crops.
- Special attention would need to be given to food supply in the lowlands because several crops are highly intolerant of salt (e.g. yams), some are intolerant of waterlogging (e.g. cassava), and some may already be close to their limit of tolerance to high temperature (e.g. bananas).

Problems such as these can be productively explored by hand by employing the methods contained in Hackett (1988b), using Hackett (1988a) as a back-up for explanation, references and other requirements. The next section indicates what can be done with computer systems, especially when a geographic information system (GIS) is available.

## USE OF A GEOGRAPHIC INFORMATION SYSTEM

During the land evaluation project for PNG which has been referred to above, a computerised resource information system was created called PNGRIS. Over 4500 resource mapping units (RMUs) were recognised, and for each of these the type of information shown in Figure 2 was stored on personal computers.

Attached to PNGRIS is a facility called PNG ECOPHYS which was written by Ms S.M. Cuddy, CSIRO, Canberra using Level C methods described by Hackett (1988a). This facility allows one to make a coarse prediction of the performance of almost any higher plant species for which one has a data-set of the type shown in Figure 1.

Figure 3 gives an example of the output from PNG ECOPHYS. Detailed explanation of the way such output was arrived at can be found in Hackett (1988a) 1988b), but it can be seen from Figure 3 that PNG ECOPHYS produces an almost transparent statement of the limitations to performance in each RMU and indicates the likely collective impact of the limitations after allowing for seasonal variations.

In relation to greenhouse impacts and other problems or questions, a great benefit obtained from joint use in this way of PNGRIS and PNG ECOPHYS (or similarly matched packages) is the capability to scan quickly across many species and many places. This enables the mind to make an almost instantaneous preliminary estimate of the feasibility of subsistence agriculture and smallholder cashcropping in the areas considered.

For such paired packages to be most useful in relation to greenhouse effects, one needs an ability to create hypothetical climatic scenarios. With PNGRIS, it is already possible to create imaginary RMUS and to examine relatively simple questions such as the implications for oil palm of a change in rainfall or temperature at its current locations. But the creation of new conditions for the whole country or even for just a province is not possible yet on an automatic basis. To generate such a facility would be a major research task because some factors have more than one function in the computer programs and because the present climate database in PNGRIS uses only monthly data and makes no allowance yet for variability. Also, to examine greenhouse impacts, one would have to create lengthy imaginary runs of weather data and devise rules for doing that.

On the brighter side, however, it is already possible to use the existing systems for practice in conceptualising the management problems planners would face. One could suppose, for example, that a particular village will be inundated by the sea and the population will have to move inland or further along the coast. Simply working out the questions needed to be put to a GIS in the face of such a situation leads to valuable training in logic and multidisciplinary thinking. Experience shows that hardly anyone emerges from such an exercise without having their perceptions of the locations and the planning problems considerably enhanced. The opportunities GIS's give in this way for interactive learning represent one of their most valuable qualities.

## CAUTIONARY NOTES

A great danger in planning for greenhouse induced changes will be the tendency for advisers to concentrate on their own expertise and for important questions to drop down the disciplinary cracks between the experts. This section tries to correct for this tendency so far as plant ecophysiology is concerned.

Beginning with climatic considerations, it has to be remembered that in addition to presently overlooking rainfall variability, PNGRIS and PNG ECOPHYS do not consider frost, snow, or cyclones. If climate does become more variable, snap frosts and snowfall could occur more frequently in higher altitude areas of Papua New Guinea even if temperatures rise. Cyclones might become more frequent and they might begin to occur in locations which are currently cyclone-free. To overlook climatic factors

350: 1

PROVINCE 14 East Sepik | RMU No. 350 | LAT. 3 deg 37 min S
DISTRICT 3 Maprik | | LONG. 143 deg 7 min E
AREA 44 sq km

## NATURAL RESOURCES

LANDFORM Mountains and hills with weak or no structural control

ROCK TYPE Coarse grained sedimentary

SLOPE 20-30 degrees — ALTITUDE 0-600 m
MAX TEMP 32-30 degC
RELIEF High 100-300 m — MIN TEMP 23-19 degC

RAINFALL
Annual 1500-2000 mm
Seas'lty <100 mm to 100-200 mm
Deficit Irregular, moderate deficit

INUNDATION No flooding or inundation
Extent Nil

SOIL Tropudalfs
Well to imperfectly drained, moderately weathered soils with finer textured subsoils

Dystropepts
Moderately weathered soils with altered B horizons and low (<=50%) subsoil base saturation values

Ustorthents
Undifferentiated, mostly shallow soils which are subject to seasonal moisture stress

VEGETATION See Land Use
Medium-crowned lowland hill forest

+-----------------------------------------+
| POSSIBLE CONSTRAINTS
| Low seasonal rainfall
+-----------------------------------------+

## SOILS

SOIL 1 Tropudalfs

| | | | |
|---|---|---|---|
| STONINESS | Not stony/rocky (<1%) | | |
| DEPTH | Moderately deep (50-100cm) | | |
| DRAINAGE | Imperfectly drained | | |
| REACTION | Weakly acid to neutral | AVAIL WATER CAPACITY | |
| SALINITY | None | 0-25 cm | Low |
| CATION EXCH | High (>25 meq%) | 0-50 cm | Moderate |
| BASE SAT'N | Moderate (20-60%) | 0-100 cm | Moderate |
| % NITROGEN | Moderate (0.2-0.5%) | MIN RESERVE | Moderate |
| AVAIL P | Moderate (10-20 ppm) | TEXTURE TOP | Fine |
| EXCH K | Moderate (0.2-0.6 meq%) | TEXTURE SUB | Very fine |
| ERODIBILITY | Moderate | ANION FIX'N | No problem |

SOIL 2 Dystropepts

| | | | |
|---|---|---|---|
| STONINESS | Not stony/rocky (<1%) | | |
| DEPTH | Moderately deep (50-100cm) | | |
| DRAINAGE | Imperfectly drained | | |
| REACTION | Acid | AVAIL WATER CAPACITY | |
| SALINITY | None | 0-25 cm | Low |
| CATION EXCH | Low (<10 meq%) | 0-50 cm | Moderate |
| BASE SAT'N | Low (<20%) | 0-100 cm | Moderate |
| % NITROGEN | Moderate (0.2-0.5%) | MIN RESERVE | Moderate |
| AVAIL P | Moderate (10-20 ppm) | TEXTURE TOP | Fine |
| EXCH K | Moderate (0.2-0.6 meq%) | TEXTURE SUB | Very fine |
| ERODIBILITY | Moderate | ANION FIX'N | No problem |

SOIL 3 Ustorthents

| | | | |
|---|---|---|---|
| STONINESS | Moderately stony/rocky (3-15%) | | |
| DEPTH | Very shallow (<25cm) | | |
| DRAINAGE | Well-drained | | |
| REACTION | Weakly acid to neutral | AVAIL WATER CAPACITY | |
| SALINITY | None | 0-25 cm | Very low |
| CATION EXCH | High (>25 meq%) | 0-50 cm | Very low |
| BASE SAT'N | High (>60%) | 0-100 cm | Very low |
| % NITROGEN | Low (<0.2%) | MIN RESERVE | High |
| AVAIL P | Moderate (10-20 ppm) | TEXTURE TOP | Medium |
| EXCH K | Moderate (0.2-0.6 meq%) | TEXTURE SUB | Rock |
| ERODIBILITY | Moderate | ANION FIX'N | No problem |

## LAND USE

'USED' AREA 44 sq km = 100% of total area

POPULATION DENSITY
Total Population 3592
Density on Total Area 82 persons/sq km
Density on 'Used' Area 82 persons/sq km

| LAND USE INTENSITY | sq km |
|---|---|
| High | 25 |
| Low | 19 |

REGROWTH
Mixture of tall and short woody and grass 44

NON-SUBSISTENCE USE

SMALLHOLDER ECONOMIC ACTIVITY
Total Households 868 — Total Villages 14

| Activity | Households No | Households %Total | Activity | Households No | Households %Total |
|---|---|---|---|---|---|
| coffee | 704 | 81 | spices | 7 | 1 |
| tea | 0 | 0 | foodcrops | 657 | 76 |
| cocoa | 284 | 33 | fish | 5 | 1 |
| rubber | 0 | 0 | cattle | 6 | 1 |
| c'nut/copra | 104 | 12 | pigs | 118 | 14 |

## RURAL POPULATION AND VILLAGES

| | | Males | Females | Total |
|---|---|---|---|---|
| Total Population | | 1805 | 1787 | 3592 |
| Dist 3 MAPRIK | Divsn 29 YAMIL | | | |
| 1 ANUNYALIN | | 95 | 93 | 188 |
| 2 AUNYALIN 2 | | 133 | 125 | 258 |
| 8 NAMBENOGWEN | | 74 | 82 | 156 |
| 10 YALAHIN | | 71 | 51 | 122 |
| 11 YAMIL 1 | | 118 | 94 | 212 |
| 12 YAMIL 2 | | 134 | 137 | 271 |
| 13 YAMIL 3 | | 42 | 36 | 78 |
| Dist 3 MAPRIK | Divsn 30 MAPRIK | | | |
| 3 BARANGA | | 39 | 42 | 81 |
| 4 CHERAGUM | | 59 | 80 | 139 |
| 6 JAME | | 159 | 149 | 308 |
| 7 KALABU 1 | | 283 | 314 | 597 |
| 12 LONEIN | | 105 | 87 | 192 |
| 15 NELIGUM | | 261 | 257 | 518 |
| 16 YAMIKUM | | 232 | 240 | 472 |

Figure 2. The description of RMU 350, East Sepik Province, in the PNGRIS

which computer systems do not deal with at present could therefore lead to major errors in contingency planning.

Another group of factors not allowed for in the prediction systems referred to here relates to pests and diseases. For example, it would be of little use to focus heavily on plant ecophysiological responses if the greenhouse effect is likely to cause pests or diseases to become much more active than before.

There is also the question of weeds. These are likely to respond too, but as yet there are no Level C data-sets for weeds.

Important too are lesser crops which may be supplying vital human nutrients or are filling seasonal gaps in food systems. To neglect these crops in favour of the major crops might be unwise.

There could also be a tendency to focus inwards in the face of greenhouse changes so that the cropping resources of the rest of the world are not thought about in a productive way. For example, there is a sweet potato cultivar called 'Papota' in the southern United States and Puerto Rico. Its tolerance of heavy soils and waterlogging might be of even greater value under greenhouse conditions if it saved villagers from moving and thereby saved social tension. Has this cultivar been evaluated yet in the region and has sweet potato germplasm in other centres been reviewed - e.g. that held in China?

One can also ask whether any thought has been given yet to the soil biology which literally holds so many cropping systems together in the Southwest Pacific? How will the greenhouse effect, have an impact on soil processes? Can the Level C model of erosion in agroforestry systems developed by Professor A. Young of ICRAF, Nairobi (pers. comm.) be applied to this problem soon?

Finally, should thought be given to the knowledge of cropping systems held by farmers and gardeners? They have a reputation for being highly adaptable, but what form does their knowledge take, to what degree could it be mobilised in the face of greenhouse induced changes, and what services might be needed to help them understand the phenomena they are dealing with?

## RECOMMENDATIONS

The recommendations put forward below are intended to be relatively cheap to act on, to make best use of existing and shareable resources, and to be useful if greenhouse does not eventuate.

### Geographic information systems (GIS's)

Moves to create GIS's for countries in the Southwest Pacific should be encouraged. Efforts should be made with these GIS's to include or attach long runs of actual weather data and to devise and add systems for creating long runs of synthetic weather data. Descriptions of land and soil recorded in such systems should be as meaningful and user-friendly as possible.

### Plant data-sets

More formal Level C plant data-sets should be prepared, covering fuelwood, forest, and weed species as well as crops. This work can be decentralised. Guided use for this could be made of university students, especially if prediction systems were made available to them for checking purposes. (By late 1989, quicker methods of description than those used for Hackett [1988a] should be available.)

### Location of major commercial crops

The location of major commercial crops should be studied in case greenhouse impacts cause changes to new locations which are distant from the capital-intensive facilities which currently serve them.

Province: 14 East Sepik. RMU 350

| | | Time-Constant | | | | | | | | | | | | SR | Temperature | | | | Max. Water | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Soil & crop | Suitability | LR | BS | CE | DE | DR | NI | pH | AP | EK | SL | ST | TE | SR | BC | EC | HD | RD | WD | WL |
| 633 Tropudalfs | | | | | | | | | | | | | | | | | | | | |
| Banana | Low | 5 | 3 | 1 | 2 | 4 | 1 | 1 | 2 | 1 | 3 | . | 3 | 2 | . | . | . | . | 5 | 6 |
| Banana PNG | Moderate | 4 | 3 | 1 | 2 | 2 | 1 | 1 | 2 | 1 | 3 | . | 3 | 2 | . | . | . | . | 5 | 4 |
| Cassava | Moderate | 4 | 3 | 1 | 1 | 4 | . | . | . | 1 | 2 | . | 3 | 3 | . | . | . | 1 | 1 | . |
| Potato | Nil | 9 | 3 | 1 | . | 4 | . | 3 | 1 | 2 | 2 | . | 2 | 2 | . | . | 9 | . | 3 | . |
| Sago palm | Moderate | 4 | 3 | 1 | 4 | 2 | . | . | 2 | 2 | 3 | . | 2 | 2 | . | . | . | 1 | 5 | . |
| Sweet potato | Moderate | 4 | 3 | 1 | 1 | 3 | . | 1 | 1 | 1 | 2 | . | 3 | 3 | . | . | . | . | 4 | . |
| Tannia | Moderate | 3 | 3 | 1 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | . | 3 | 2 | . | . | . | . | 3 | . |
| Taro | Moderate | 3 | 3 | 1 | 2 | 2 | . | 2 | 2 | 2 | 2 | . | 3 | 2 | . | . | . | . | 7 | . |
| Yam, greater | Moderate | 4 | 3 | 1 | 3 | 4 | . | 2 | 1 | 2 | 2 | . | 3 | 2 | . | . | . | 1 | 2 | . |
| Yam, lesser | Moderate | 3 | 3 | 1 | 3 | 2 | . | 2 | 1 | 2 | 2 | . | 2 | 2 | . | . | . | . | 3 | . |
| 334 Dystropepts | | | | | | | | | | | | | | | | | | | | |
| Banana | Low | 5 | 5 | 5 | 2 | 4 | 1 | 3 | 2 | 1 | 3 | . | 3 | 2 | . | . | . | . | 5 | 6 |
| Banana PNG | Low | 5 | 5 | 5 | 2 | 2 | 1 | 3 | 2 | 1 | 3 | . | 3 | 2 | . | . | . | . | 5 | 4 |
| Cassava | Low | 5 | 5 | 5 | 1 | 4 | . | 2 | . | 1 | 2 | . | 3 | 3 | . | . | . | 1 | 1 | . |
| Potato | Nil | 9 | 5 | 5 | . | 4 | . | . | 1 | 2 | 2 | . | 2 | 2 | . | . | 9 | . | 3 | . |
| Sago palm | Low | 5 | 5 | 5 | 4 | 2 | . | 2 | 2 | 2 | 3 | . | 2 | 2 | . | . | . | 1 | 5 | . |
| Sweet potato | Low | 5 | 5 | 5 | 1 | 3 | . | . | 1 | 1 | 2 | . | 3 | 3 | . | . | . | . | 4 | . |
| Tannia | Low | 5 | 5 | 5 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | . | 3 | 2 | . | . | . | . | 3 | . |
| Taro | Low | 5 | 5 | 5 | 2 | 2 | . | 2 | 2 | 2 | 2 | . | 3 | 2 | . | . | . | . | 7 | . |
| Yam, greater | Low | 5 | 5 | 5 | 3 | 4 | . | 2 | 1 | 2 | 2 | . | 3 | 2 | . | . | . | 1 | 2 | . |
| Yam, lesser | Low | 5 | 5 | 5 | 3 | 2 | . | 2 | 1 | 2 | 2 | . | 2 | 2 | . | . | . | . | 3 | . |
| 143 Ustorthents | | | | | | | | | | | | | | | | | | | | |
| Banana | Low | 6 | 1 | 1 | 6 | . | 3 | 1 | 2 | 1 | 3 | 2 | 2 | 2 | . | . | . | . | 6 | 6 |
| Banana PNG | Low | 6 | 1 | 1 | 6 | . | 3 | 1 | 2 | 1 | 3 | 2 | 2 | 2 | . | . | . | . | 6 | 4 |
| Cassava | Nil | 9 | 1 | 1 | 6 | . | 1 | . | . | 1 | 2 | 4 | 2 | 3 | . | . | . | 1 | 1 | 9 |
| Potato | Nil | 9 | 1 | 1 | 5 | . | 2 | 3 | 1 | 2 | 2 | 3 | 2 | 2 | . | . | 9 | . | 4 | 8 |
| Sago palm | Nil | 8 | 1 | 1 | 8 | . | 4 | . | 2 | 2 | 3 | 1 | 2 | 2 | . | . | . | 1 | 6 | . |
| Sweet potato | Low | 5 | 1 | 1 | 5 | . | 1 | 1 | 1 | 1 | 2 | 4 | 2 | 3 | . | . | . | . | 4 | 6 |
| Tannia | Nil | 7 | 1 | 1 | 7 | . | 2 | 2 | 1 | 1 | 2 | 4 | 2 | 2 | . | . | . | . | 4 | 6 |
| Taro | Low | 6 | 1 | 1 | 6 | . | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | . | . | . | . | 7 | . |
| Yam, greater | Nil | 8 | 1 | 1 | 7 | . | 3 | 2 | 1 | 2 | 2 | 4 | 2 | 2 | . | . | . | 1 | 3 | 8 |
| Yam, lesser | Nil | 7 | 1 | 1 | 7 | . | 4 | 2 | 1 | 2 | 2 | 4 | 2 | 2 | . | . | . | . | 4 | 6 |

PR - Province code
Soil - Greater soil group code
RMU - Resource Mapping Unit
LR - Suitability rating/limitation rating

BS - Base saturation
CE - Cation exchange capacity
DE - Depth
DR - Drainage
NI - Nitrogen
pH - pH
AP - Available phosphorus
EK - Exchangeable potassium
[SA - Salinity (not present in this RMU so omitted from the table)]
SL - Slope
ST - Stoniness
TE - Texture
SR - Solar radiation

[BC - Brief cold; EC - Extended cold (neither present in this RMU so omitted from the table)]
HD - Heat damage
RD - Rate of development
WD - Water deficit (worst month)
WL - Water logging (worst month)

Figure 3. Example of an ecophysical evaluation of a Resource Mapping Unit (RMU) in PNGRIS using PNG ECOPHYS

**PNG-ECOPHYS-CROP/RMU EVALUATION (LIMITATION RATINGS)**

| Water Deficit Calendar | | | | | | | | | | | | Waterlogging calendar | | | | | | | | | | | | If Annual | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| J | F | M | A | M | J | J | A | S | O | N | D | J | F | M | A | M | J | J | A | S | O | N | D | LGS | B | W | NP |
| . | . | . | . | . | . | 4 | 5 | 5 | . | . | . | 4 | 6 | 6 | 4 | . | . | . | . | . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | 4 | 5 | 5 | . | . | . | 2 | 4 | 4 | 2 | . | . | . | . | . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | . | 1 | 1 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | 7.9 | 4 | 4 | 12 |
| . | . | . | . | . | . | 2 | 3 | 3 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | 4 | 5 | 5 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . |
| 4 | 4 | 4 | 4 | 4 | 4 | 1 | . | 1 | 4 | 4 | 4 | . | . | . | . | . | . | . | . | . | . | . | . | 5.1 | 4 | 4 | 12 |
| . | . | . | . | . | . | 2 | 3 | 3 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | 9.6 | 3 | 3 | 12 |
| . | . | . | . | . | . | 5 | 7 | 7 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | 9.2 | 3 | 4 | 12 |
| . | . | . | . | . | . | 1 | 2 | 2 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | 6.4 | 4 | 4 | 12 |
| . | . | . | . | . | . | 2 | 3 | 3 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | 10.6 | 3 | 3 | 12 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| . | . | . | . | . | . | 4 | 5 | 5 | . | . | . | 4 | 6 | 6 | 4 | . | . | . | . | . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | 4 | 5 | 5 | . | . | . | 2 | 4 | 4 | 2 | . | . | . | . | . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | . | 1 | 1 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | 7.9 | 5 | 5 | 12 |
| . | . | . | . | . | . | 2 | 3 | 3 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | 4 | 5 | 5 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . |
| 4 | 4 | 4 | 4 | 4 | 4 | 1 | . | 1 | 4 | 4 | 4 | . | . | . | . | . | . | . | . | . | . | . | . | 5.1 | 5 | 5 | 12 |
| . | . | . | . | . | . | 2 | 3 | 3 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | 9.6 | 5 | 5 | 12 |
| . | . | . | . | . | . | 5 | 7 | 7 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | 9.2 | 5 | 5 | 12 |
| . | . | . | . | . | . | 1 | 2 | 2 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | 6.4 | 5 | 5 | 12 |
| . | . | . | . | . | . | 2 | 3 | 3 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | 10.6 | 5 | 5 | 12 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| . | . | . | . | . | 5 | 6 | 5 | 5 | . | . | . | 6 | 6 | 6 | 6 | . | . | . | . | . | . | 6 | 6 | . | . | . | . |
| . | . | . | . | . | 5 | 6 | 5 | 5 | . | . | . | 4 | 4 | 4 | 4 | . | . | . | . | . | . | 4 | 4 | . | . | . | . |
| . | . | . | . | . | . | 1 | 1 | 1 | . | . | . | 9 | 9 | 9 | 9 | . | . | . | . | . | . | 9 | 9 | 7.9 | 9 | 9 | . |
| . | . | . | . | . | 2 | 4 | 3 | 3 | . | . | . | 6 | 8 | 6 | 6 | . | . | . | . | . | . | 6 | 6 | . | . | . | . |
| . | . | . | . | . | 5 | 6 | 5 | 5 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . |
| 4 | 4 | 4 | 4 | 4 | 1 | 1 | . | 1 | 4 | 4 | 4 | 6 | 6 | 6 | 6 | . | . | . | . | . | . | 6 | 6 | 5.1 | 5 | 6 | 12 |
| . | . | . | . | . | 2 | 4 | 3 | 3 | . | . | . | 6 | 6 | 6 | 6 | . | . | . | . | . | . | 6 | 6 | 9.6 | 7 | 7 | . |
| . | . | . | . | . | 6 | 7 | 7 | 7 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | 9.2 | 6 | 6 | 12 |
| . | . | . | . | . | 2 | 3 | 2 | 2 | . | . | . | 8 | 8 | 8 | 8 | . | . | . | . | . | . | 8 | 8 | 6.4 | 8 | 8 | . |
| . | . | . | . | . | 2 | 4 | 3 | 3 | . | . | . | 6 | 6 | 6 | 6 | . | . | . | . | . | . | 6 | 6 | 10.6 | 7 | 7 | . |

The climatic and water balance data derived from records obtained at the Maprik SDHQ climate station.

LGS - Length of growing season (months)
B - Limitation rating, best planting month
W - Limitation rating, worst planting month
NR - Number of worthwhile planting months

Performance prediction systems

Production and distribution of simple manual and computer-based systems for predicting plant performance should be supported, with rights given to users to make modifications and to see the modified versions. (As mentioned above, PNG ECOPHYS was written in KnowledgeMan language and is tied very closely to PNGRIS. A BASIC version of PNG ECOPHYS is being developed which will permit local adaptation and operation quite separate from GIS's. Ideally, management and economic overlays should be designed for these systems to allow for inputs, costs, and prices. No such overlay exists yet for the systems referred to here.)

Pests and diseases

Since all objects and phenomena can be viewed and understood at different scales, thought should be given to whether pests and diseases can be usefully described at a scale equivalent to Level C in relation to the greenhouse effect. If pests and disease of the Southwest Pacific can be treated in this way, the resulting models of behaviour could then be used locally with crop information and with GIS's.

Cultivars

A review should be made of cultivars available in germplasm centres which may be of help in the face of greenhouse effects.

Soil biology

An assessment should be made of the possible impact of climate changes on soil biology and soil biochemistry. The relevance and availability of simple models for coarse-scale assessment of this problem should be examined.

Cropping systems

Using an appropriate scale, formal description and classification of cropping systems should be fostered with the aim of (a) understanding their components and strategies, (b) assessing their robustness and transferability in the face of greenhouse changes, and (c) identifying needs for particular types of plant material or crop protection to help sustain them in the future.

Informal knowledge-base

It should be considered how a greater understanding of the traditional knowledge-base, decision-making, and person-to-person knowledge-transfer systems used by crop producers in the Southwest Pacific could be harassed in the face of the greenhouse effect.

Time-schedules and budgeting

If these proposals are considered useful, their total implications in terms of time and costs should be assessed before any work is undertaken. To effect this, the proposals could be grouped according to time-horizons, priority and benefits if the predicted greenhouse changes do not eventuate. Spreading of work across agencies and countries should be considered, and the additional cost of undertaking the proposed work should also be defined as well as possible.

## CONCLUDING NOTE

The lack of reference above to the work of FAO and other highly experienced agencies in the sphere of crop description and land evaluation is due solely to the deadline imposed for this report. Hackett (1988a) contains a wide range of references and fully acknowledges the lines of thinking drawn on in this brief review. Recently a global review of agricultural land evaluation and related research activities was made, and the resulting volume (Bunting, 1987) contains pointers which may be of value in the Southwest Pacific in the future.

ACKNOWLEDGEMENTS

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# THE GREENHOUSE EFFECT: THE IMPACT OF SEA LEVEL RISE ON LOW CORAL ISLANDS IN THE SOUTH PACIFIC

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If the greenhouse effect raises sea levels by 1 metre it will virtually do away with Kiribati if what the scientists say now is going to be true. In 50 or 60 years my country will not be there. (President I. Tabai, Kiribati, September 1988)

The environmental change caused by industrial progress in the developed world may slowly drown this unique paradise in its entirety. (President M. Gayoom, Maldive Islands, 1987)

We are an endangered nation. (President M. Gayoom, 1988)

## BACKGROUND

No environmental issue has captured public and private imaginations throughout the world more than the 'Greenhouse effect' has over the past 12 months. Indeed, perhaps no environmental issue has ever stimulated such global interest and spawned such a recent variety of popular and academic accounts of future scenarios, although the term itself was coined before the end of the nineteenth century. There are at least two reasons for this widespread interest: the cataclysmic effects forecast by the prophets of doom and, the uncertainty over the actual effects and future rates of climate change. Scientific studies have increasingly begun to draw important and consistent conclusions about future trends, and point to the regions where the greenhouse effect will cause the most severe problems. This paper examines some of these trends in the context of South Pacific atoll states where the impacts are likely to cause substantial social, economic and political problems, and where such problems may begin to emerge around the start of the next century.

For most coastal dwellers around the globe there will be the option of retreating inland to higher ground. In some countries, especially those with rich agricultural land and dense populations in low deltaic plains, enormous economic and social dislocations can be expected, but the most extreme situation will be faced by small ocean island states occupying low coral islands on atolls. Here high land does not exist and whole populations may be displaced and left country-less. This paper focuses on the four Pacific atoll-states of Kiribati, Marshall Islands, Tokelau and Tuvalu, which are entirely composed of low-relief atolls (Figure 1). It has recently been stated that these states 'will be devastated if projected rises occur and consequently such states may cease to contain habitable land' (Pernetta, this volume 23). The focus is therefore appropriate.

To gauge the extent of the impact we adopt as a convenient scenario a sea level 1 m higher than at present in 50 years time; it is not intended as a prediction of what will happen. In this scenario, average rates of sea level rise for the future (about 20 mm/year) are similar to those documented by geologists during the Postglacial Marine Transgression (PMT), about 18,000 to 6,000 years ago, when the sea rose at an average rate of 12-15 mm/year (Thom & Roy, 1985; Devoy, 1987). Geological data from the past thus provides a basis for modelling future trends (Figure 2).

The paper does not consider in any detail the issues that affect atolls when they are only part of larger multi-island states that include high islands, such as the Federated States of Micronesia (FSM), French Polynesia or the Cook Islands (Figure 1). There are two reasons for this, the first being that it may be possible to divert resources from larger islands with stronger economies to provide special funds and strategies for atoll islands within the same state. This is the case in the French Polynesian atoll chain of the Tuamotus (Connell, 1986: 53-4). Secondly, and more importantly, the existence of high islands or much larger land masses such as in Papua New Guinea and the Solomon Islands provide atoll dwellers

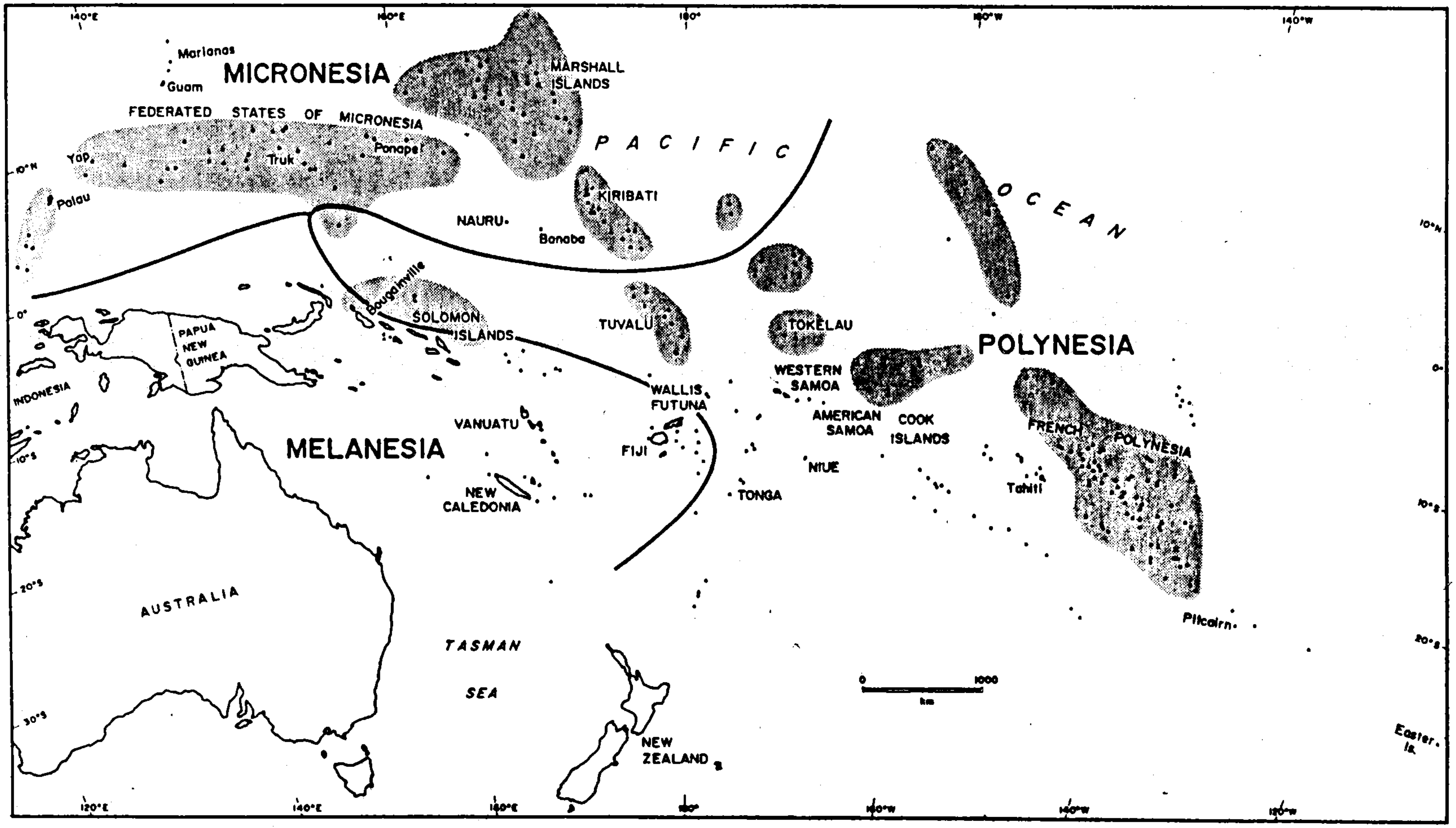


Figure 1. Island regions in the Pacific that are composed principally of low coral atoll islands are shown here stippled.

with migration options within states. Most of the discussion that follows, and particularly that concerning Kiribati and Tuvalu, is also extremely relevant for both the Maldives (for a recent review see Pernetta & Sestini, 1989) and Australia's Indian Ocean Territory, the Cocos-Keeling Islands, whose situations are very similar. The paper reviews past developments and problems in the atoll states and speculates on the potential impacts of climate change on future development strategies.

## ISLAND POPULATIONS

The four atoll states are quite different in language, culture, history and in their physical environment. Tuvalu and Tokelau are part of Polynesia; the Marshall Islands and Kiribati are in Micronesia. The state of Tuvalu consists of nine coral atolls and reef islands with a total land area of no more than 24 $km^2$, spread over a distance of 590 km. Kiribati has 20 populated atolls (including Banaba) and a land area of 700 $km^2$, but more than half of this (363 $km^2$) is on Christmas Island (Kiritimati) some 3,500 kilometres away from Tarawa, the national capital. The Marshall Islands has 24 populated atolls, but most of the population lives in the capital, Majuro, or on Ebeye, close to the American missile range on Kwajalein atoll. The population density in Tokelau (Table 1) is significantly less than in the other three states, partly because of substantial migration to New Zealand, where a majority of Tokelauans now live.

Kiribati is the easternmost and southernmost part of Micronesia. Tuvalu, once the Ellice Islands, is part of Polynesia, and there are indications that colonisation there may have been as recent as the sixteenth century (Munro, 1982:7) not long before the great Spanish explorer, Mendana, sighted at least one

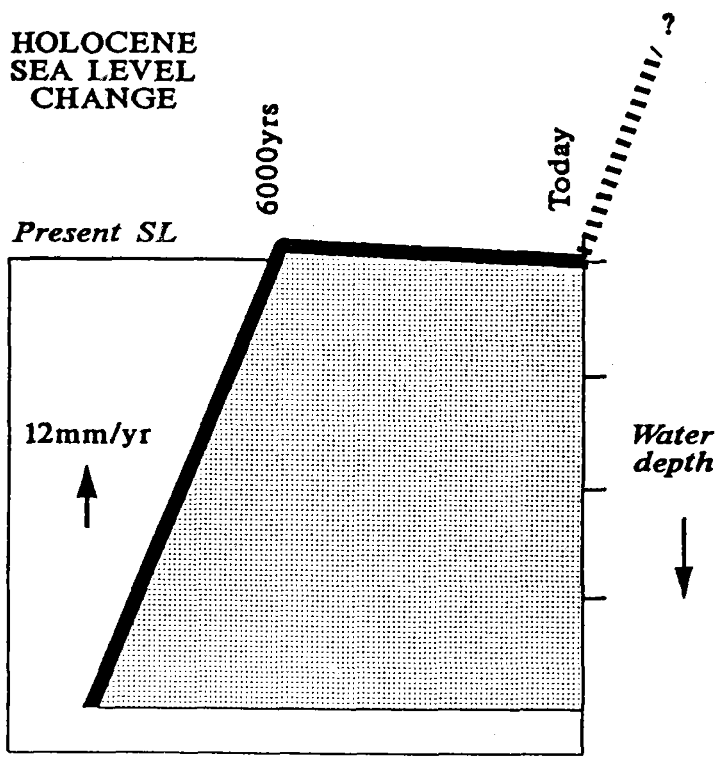


Figure 2. Following the last glaciation, Holocene sea levels rose rapidly (the PTM) to a maximum about 6000 years ago, then stabilised or fell slightly. Predicted greenhouse effects may cause a renewed sea level rise at a similar rate to the PMT.

of the atolls in 1568. Further north Quiros sighted the Kiribati atoll of Butaritari in 1606, but it was not until the 1820s that European contact began to influence the trajectory of development. The Tokelau atoll of Atafu was first sighted by Europeans in 1765, when it was uninhabited, but at second contact in 1791 it was inhabited. Tokelau was severely affected by the Peruvian labour trade of the 1860s which led to a drastic reduction in the population (Maude, 1981). Spanish voyagers reached the Marshall Islands in the seventeenth century and there was considerable contact with traders, whalers and missionaries from the eighteenth century onwards. After the Second World War the Marshall Islands became part of the United States administered Trust Territory of the Pacific Islands. Tuvalu became independent in 1978 and Kiribati in 1979. The Marshall islands has a degree of autonomy, having achieved independence in association with the USA in 1984. Tokelau remains a New Zealand territory and Tokelauans are citizens of New Zealand.

Table 1. Atoll state populations

| | Marshall Islands | Kiribati[a] | Tokelau | Tuvalu[c] |
|---|---|---|---|---|
| Occupied atolls | 24 | 16 | 3 | 9 |
| Total population | 43,335 (1988) | 61,186 (1985) | 1,690 (1986) | 7,349 (1979) |
| Mean atoll population | 1,805 | 3,284 | 563 | 817 |
| Mean population (excluding central atoll) | 719[b] | 2,299 | 563 | 653 |
| Population density (km$^2$) | 242 | 227 | 56 | 287 |

Note: Areas are land areas. Since lagoons provide maritime resources, variable lagoon areas are also important. Populations have grown significantly since the censuses to which these data refer.

a. These data refer to the Gilberts only, thus excluding Banaba and the Line Islands.

b. This figure excludes the populations of both Majuro (including Laura) and Kwajalein (including Ebeye).

c. In 1983 an informal census of Tuvalu was undertaken; this head count gave a total population of 8,364 within Tuvalu, of whom 2,620 were on Funafuti. A formal census is due to be held in 1989.

## THE GREENHOUSE EFFECT

The build-up of industrial gases in the earths atmosphere over the past 30 to 40 years is now well documented (Bolin *et al.*, 1986; Pittock, 1988; Pearman, 1988). The resulting 'Greenhouse effect' is expected to raise temperatures over much of the earth's surface and lead to a rise in the levels of the world's oceans. Initially the latter will come about through expansion of surface waters in the oceans and melting of mountain glaciers (Bolin *et al.*, 1986); not until much later will melting of the polar ice sheets significantly augment the ocean volumes (Budd, 1988).

Because of uncertainty concerning the pattern and extent of future heating of the earth's surface and the rate at which heat will be absorbed by the oceans (Pittock, 1988; Tucker, 1988), rates of expansion of the oceans cannot be determined with any accuracy. Extreme scenarios for the next 50 years range from virtually no change in mean sea level to an elevation many metres higher (Hoffman, 1984; de Robin, 1986). In Australia, values representing an intermediate range of 0.2-1.4 m rise in the next 50 years have been adopted in order to consider possible implications of greenhouse for the future (Pearman, 1988). The period of 50 years was chosen because it is the upper limit of most planning time-scales. The UNEP agreed scenarios for regional reviews are 20 cm by the year 2035, and 1.5 m by 2100.

The basic impact effect of a greenhouse induced rise in sea level is for low lying lands to be inundated and for coasts to erode (Short, 1988; Thom & Roy, 1988). Erosion, as opposed to inundation, is likely to be most severe on shorelines composed of unconsolidated sediment exposed to storm wave attack on high-energy coasts. Here, a gradual rise of mean sea level will progressively lift the zone of flooding, storm wave set-up and surge effects to new levels thus eroding areas hitherto considered safe. Human responses will vary depending on the values of the coastal land under attack and the resources available to provide protective measures (Roy & Thom, 1987). In Pacific atoll states where resources are very limited, the provision of expensive engineering works will not be a commonly available option. A recent expert meeting (UNEP, 1988) stated that 'engineering solutions (such as large dykes and walls) are not likely to represent a realistic long-term solution to the problem of rising sea level, except in very special cases. Social adaptation and land-use change will be the most appropriate responses to sea level rise' (UNEP, 1988 p.161).

## ORIGIN OF ATOLLS

Atolls are accumulations of the remains of calcareous reef-forming organisms usually arranged into a rim around a central lagoon, found in tropical ocean waters within 20° latitudes of the equator. The geological origins and geomorphological features of atolls are reviewed by Sullivan & Pernetta (this volume), but most coral atolls comprise a succession of old weathered limestones that form an irregular substrate on which the most recent (Holocene) deposits have accumulated (see Figure 2 in Wheatcraft & Buddemeier, 1981). Intertidal and shallow subtidal areas that form the atoll rims and reef flats are composed mainly of coarse coral detritus; these deposits reach thicknesses up to 25 m (Wheatcraft & Buddemeier, 1981; Davies & Hopley, 1983), but in some cases, such as Mataiva in French Polynesia (Pirazzoli & Montaggioni, 1986), may be as thin as 2 m. Reef-rim detritus becomes finer towards the lagoon (e.g. Ayers & Vacher, 1986) where the main sediment types are biogenic sands and calcareous muds (Figure 3a and b).

Variations in coral assemblages and growth styles reflect exposure of atoll margins to prevailing trade winds (Wiens, 1962; Hopley, 1982). Typically, atoll rims are higher and narrower and reef flats are better developed on high-energy, windward coasts (Wiens, 1962). Here, storm waves deposit coral rubble that progrades lagoon-ward in washover lobes (Wiens, 1962). Storm ridges and spits of coarse rubble that build above sea level act as nuclei around which grow small islands (motu) (Figure 3c).

Radiocarbon dating studies (Davies & Hopley, 1983; Hopley, 1982; Hopley & Kinsey, 1988; Marshall & Jacobson, 1985) show that, in most cases, upward reef growth lagged behind rising sea level during the Postglacial Marine Transgression (PMT). It was not until one or two millennia after sea level stabilised that reef building corals reached shallow sub-tidal depths; here living corals became vulnerable to storm erosion, at least on windward coasts. Much of the rubble that the storms generated is washed landwards. This rubble together with *in situ* reef becomes cemented in the intertidal zone to create reef flats (Figure 3b), forming the foundation for islands of calcareous sand and coral rubble built above sea level (Hopley, 1987).

## ATOLL ISLANDS

Islands on atoll rims vary enormously in size and shape but all are composed of mixtures of coral/algal rubble and calcareous sand and rarely rise more than 3 m above mean sea level (Wiens, 1962). Cementation in the intertidal and even supratidal zone (Montaggioni & Pirazzoli, 1984) undoubtedly contribute to their stability. However, the occurrence of exposed and eroding outcrops of beachrock/coral conglomerate on the one hand and newly formed boulder ridges and sand spits on the other indicate that islands are constantly changing shape (Wiens, 1962; Hopley, 1987).

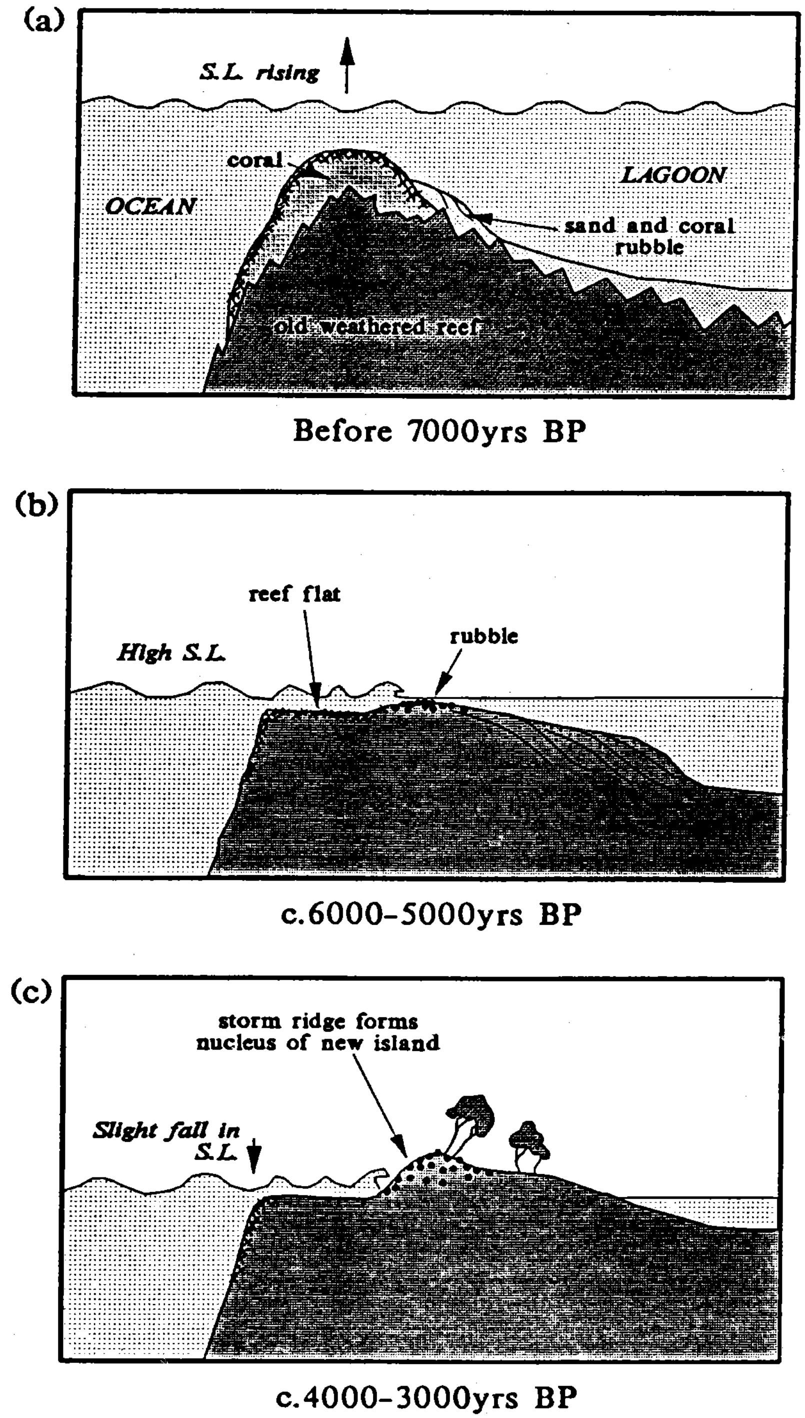


Figure 3. (a) During the PMT, corals colonised old limestone surfaces, but in most cases their upward growth lagged behind the rapidly rising sea surface.
(b) Shortly after sea level stabilised, coral reefs grew up into shallow depths and rubble accumulated to form planar reef flats in the intertidal zone.
(c) A slight fall in sea level during the late Holocene promoted the formation of storm rubble mounds that became the the nuclei for island growth.

The building of atoll superstructures, especially islands, results from a combination of processes of small scale erosion and accretion, that can be observed on a day to day basis, interspersed by catastrophic changes caused by extremely violent storms (cyclones and hurricanes) that occur quite rarely. Series of beach ridges and recurved spits show that islands with these features have undergone a net building or accretionary phase sometime during the last 2,000-3,000 years. In contrast, features that indicate contemporary erosion include tidal channels intersecting islands and 'makatea' surfaces around island margins and on reef flats.

## ISLAND ECOLOGY

The terrestrial flora (and fauna) of atolls is of limited species diversity, especially in comparison with high islands. Wiens (1962) points out that species numbers vary considerably between islands and there seems to be a direct relationship between diversity and island size and rainfall (Wiens, 1962: Table 21, Fig. 91). Some islands are reported to have more than 100 plant species (including many that were introduced by Europeans) but only a few are commonly used for food. The main food crops are coconuts, breadfruit, taro and pandanus. In wetter conditions crops such as bananas are also cultivated.

Swamp taro and *Cyrtosperma* are sensitive to salinity changes and grow in low areas, usually manually excavated (taro pits), in the central depressions of islands; on occasion, notably after storms, salinity causes a substantial reduction in taro productivity (e.g. Levin, 1976; Bates & Abbott, 1958).

The capacity of the islands to support human populations is closely tied to the existence of permanent ground water (Wiens, 1962). Islands about 1.5 ha and 200 m in diameter (Cloud, 1952; Wiens, 1962), contain a permanent lens of fresh water. The volume of this lens is roughly proportional to the surface area of the atoll. Other factors influencing the character and behaviour of the freshwater lens include annual rainfall, permeability of the rocks beneath the island and mixing due to storm or tide induced pressure gradients (Buddemeier & Holladay, 1977; Ayers & Vacher, 1986; Jacobson & Taylor, 1981; see also Buddemeier & Oberdorfer, this volume).

In Kiribati, where ground water is the main source of drinking water on most islands, populations have been forced to migrate temporarily to areas with higher rainfall. On Eauripik cyclone disruption of groundwater supplies has forced bathing in salt water (Levin, 1976). However, the most severe threat to permanent water supplies is not from climatic factors directly, but rather from marine processes that cause coastal erosion and increase the frequence of storm overwash. Figure 4 shows in generalised form, the relationship between the dimensions of the ground water lens and island size, expressed in terms of width, and illustrates the dramatic effect of a 20% reduction in island width which reduces by half the volume of freshwater. Thus any decline in island area has a very dramatic influence on the availability of freshwater supplies.

While coastal erosion is closely linked to raised sea levels in general theories such as that proposed by Bruun (1988), quantitative relationships have yet to be established for coral islands. Clearly, for a given rise in sea level, the amount of erosion will depend on the composition and height of a particular island, its exposure to wave attack and current erosion and the frequency and intensity of storms. Conceivably, in the next 50 years or so, greenhouse effect shoreline erosion rates in the order of 1-2 m/year could reduce the dimensions of some presently inhabited islands to the point where their ground water supplies would no longer support viable ecosystems or permanent habitation .

## THE ATOLL STATES

> Coral reefs with their low sandy islets provide the most limited range of resources for human existence and the most tenuous of habitats for man in the Pacific. The soil is infertile, lacking humus, and fresh ground water is very limited. Maintaining a livelihood is a considerable task for man. (Thomas, 1963:36)

Atoll life, albeit without reference to marine resources, represents a situation where subsistence production was often extremely difficult and the tasks of generating any real surplus even more difficult

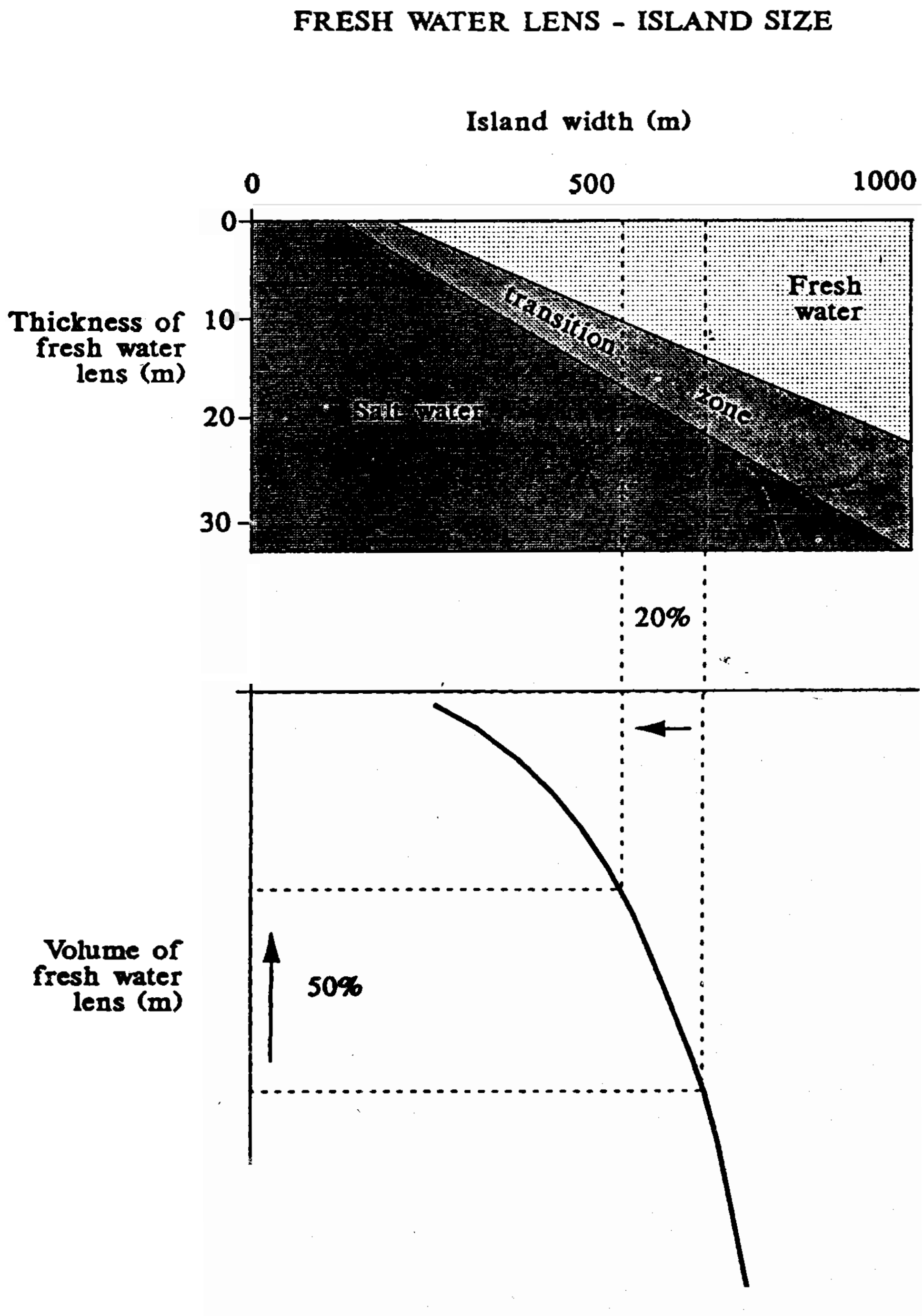


Figure 4. The maximum thickness of the Ghyben-Herzberg lens of freshwater beneath atoll islands increases in direct proportion to island width but the volume of freshwater increases semi-exponentially. Thus changes in island width due to erosion or accretion have a disproportionately large impact on freshwater reserves.

(Bayliss-Smith, 1977:327-8). Atoll life was always far from that portrayed in images of the supposedly idyllic Pacific islands. The nature of society and economy in island groups where hazard, hunger and disease punctuated periods of well-being and where population growth was carefully controlled and wars in pursuit of both land and power were common, especially in Kiribati, the Marshall Islands and Tokelau, was quite different from the Western idyllic view.

Atolls vary enormously in land and lagoon area; in rainfall, and in flora and fauna. Their ability to support human populations differs as does their ability to provide some form of diversified development. Some atolls are small, arid, drought-prone and overpopulated, as in the central Gilbert Islands chain, but where such conditions do not occur the potential for development is often quite different. Nonetheless, in comparison with high islands, the diversity of resources is limited and natural hazards are usually but not always, more severe in their impacts; recurrent hazards such as droughts, hurricanes and tsunamis have had an important demographic and cultural role in the four atoll states (Vayda, 1959). In the past many atolls have been depopulated and repopulated, following episodic events and migrations of various kinds (Alkire, 1978:28-30). In recent times Osborne has provided a vivid description of the dying phases of the small community on Merir atoll, Palau: 'the island is dying .. the women are too old to cultivate taro in any quantity and the men cannot keep the coconut groves clear' (Osborne, 1966:49). Five years later the island was depopulated, with the few survivors having moved to the mainland of Palau, an option only open to atoll dwellers in political liaison with larger islands and states. Generally, atoll populations developed cultural ties with other atolls so that, during periods of population-resource imbalance, their proximity to each other enabled economic exchange, personnel mobility and, on the negative side, warfare and raiding (Alkire, 1978:94).

Beyond these inherent constraints to subsistence production, the modern era has increasingly demonstrated the tyrannies of distance that have restricted contemporary development. Atolls are tiny, with limited resources, often distant from each other and remote from more substantial land masses. Atoll states consequently face a host of development problems, often in more accentuated form than in other island micro-states (Connell, 1988a). These problems include limited skills, small domestic market size, high cost of imports and exports, restricted diversity of exports and substantial administrative costs; leading to large trade deficits, balance of payments problems and considerable dependence on foreign aid and technical assistance. In 1984 for example exports from Tuvalu were valued at A$312,000 and imports cost A$3,965,000; for the Marshall Islands in 1987, US$3.61 million and US$32.25 million; in 1985 for Kiribati, A$6,06 million and A$21.58 million; and in Tokelau in 1984, A$28,000 and A$145,000 respectively. In each case this discrepancy is worsening and atoll states have moved rapidly into situations of extreme dependence on the outside world, primarily for aid, concessional trade and migration opportunities.

Atoll populations are generally small in absolute terms, only the few urban centres have substantial populations and these four atoll states are among the smallest island micro-states in the world. At an early stage in colonial history these resource-poor islands became significantly dependent on the outside world for consumer goods, including foodstuffs (e.g. Munro, 1989). By the 1890s in both Kiribati and Tuvalu, pacification, population growth and changing aspirations had resulted in overseas labour migration being described as 'the only alternative to starvation' (Macdonald, 1982:53) in the sense that population and domestic resources were already recognised to be in some degree of imbalance. Indeed in Kiribati and Tuvalu the Malthusian spectre had been sighted; mid-nineteenth century Tuvaluans 'were genuine Malthusians. They feared that unless the population was kept down they would not have sufficient food' (cited by Bedford & Munro, 1980:3). A century later 'few countries of the South Pacific serve to remind one so well of the so-called 'Malthusian dilemma' as the two countries under consideration with their rapidly expanding population pressing against a limited and non-expanding stock of natural resources' (Fairbairn, 1976:1). The situation was and is marginally better in the less densely populated Marshall Islands and Tokelau.

In every case modern health facilities and medicines have resulted in more rapid natural population increase in most atoll situations; infants are more likely to survive, and diseases are less likely to be fatal, while modern family planning is largely absent in the atoll states. Even during the early 1940s, at a time when the resettlement of Gilbertese islanders in the Phoenix Islands appeared successful, its instigator, H.E. Maude, noted that 'colonisation measures are in fact palliatives only and for more permanent means of population control we must look elsewhere. The ultimate hope for the Gilbertese people probably lies in drastic population control' (Maude, 1968:342). For a time, in the late 1960s, Kiribati appeared to have a successful family planning scheme but it was shortlived, as was the case in Tuvalu. The Marshall Islands now has one of the fastest growing populations of any state in the world; widespread adoption has reduced the perceived need for family planning. As atoll populations increase, the problem of satisfying basic needs (e.g. housing, water and food) from local resources also increases. Although there has been little research on the human carrying capacities of atolls (and it is invariably true that there are possibilities of agricultural intensification, varietal improvement, and fishing development), in a number of cases population densities have reached extremely high levels (Table 1) and development prospects are limited. All atoll residents now demand some cash income for items such as clothes, fish hooks and kerosene). In some exceptional cases, where population densities, as on Eauripik in Federated States of Micronesia (FSM), have increased to the extent that all coconuts produced are eaten rather than marketed as copra (the only possible agricultural export), the constraints are particularly severe (Levin, 1976). In this case, locally generated income is earned almost entirely from handicraft production. Eauripik may be extreme (with a population density of 950 persons/km$^2$ in 1980), but its limited development options reflect the essential problems of atoll development.

Throughout the atoll states, the limited agricultural base of the traditional economy has declined in colonial and post-colonial times. The most dramatic decline has been in the dominant base of that economy, the taro pits, one of the more labour-intensive agricultural systems in the world and and indication of the inherent difficulty of local agricultural production. In urban areas, notably in Majuro, relatively few are now left. Artisanal fisheries have experienced a similar but less dramatic transition, which has followed the depletion of in-shore and lagoon species, indirectly contributing to the necessity for more labour-intensive fishing practices. In every case there appears to have been a decline in local production *per capita*, paralleled by a transition to imported food, especially rice, which has followed changing tastes, preferences, convenience and so on. This transition has been so substantial that in each state, imported foods and drinks now constitute about 35% of all imports by value, a substantial drain on domestic resources. This is most extreme in the Marshall Islands where a recent reliable estimate suggests that 75% of all food consumed in the country is imported (*Marshall Islands Journal*, 13 January 1989).

Limited subsistence agricultural production has been dramatically emphasised since the nineteenth century by the 'coconut overlay' (Bedford, 1980:48) that has transformed the economy of atolls by enabling participation, however limited, in the international economy through copra production and sales. In the Tuamotu atolls of French Polynesia coconut plantation were directly responsible for the complete disappearance of the former agricultural economy (Ravault, 1982). This sole historic domestic source of income, copra production, has continued into the present, although in recent years production does not appear to have grown significantly. Nonetheless, even on the more urbanised islands, including Majuro, copra is still produced because of its capacity for directly generating some cash income. The relative significance of copra incomes for household and national incomes has declined however, especially in the post-war years, as atoll dwellers have discovered that they have a one-crop economy, and that this single crop has a falling price on the world market. Necessary activities, such as coconut replanting, are often postponed indefinitely and copra production offers an increasingly fragile basis for the construction of a modern economy.

Though fish and other marine resources have often been domestically marketed, on a small scale, marine resources have rarely been exported from the atoll states. In recent years, however, there has been some expansion of domestic fishing fleets, often through joint venture operations, and fish have become a growing source of national income, principally in Kiribati and Tuvalu. Much more important has been the leasing of fisheries waters for the fleets of overseas fishing vessels, including, for a brief period, the leasing of Kiribati waters to the Soviet Union (Doulman, 1987; Tabai, 1987a). Through various bilateral and multilateral agreements, fisheries leases now represent a major source of domestic income for the atoll states. Income is however, substantially less than the value of those fisheries. Even the combination of revenue from fisheries and copra does not provide high returns for the atoll states, most of whose national incomes are now externally generated in a non-trade manner.

All atoll states are part of the international economy, and the aspirations of atoll people are generally those of people elsewhere, including; improved services health, education; remunerative employment opportunities, and consumer goods such as imported food, clothes, outboard motors, motorbikes. Although wants are somewhat less than those of occupants of larger islands where imported goods are more familiar, real and perceived differences between places in life-styles, economic opportunity, and the range of available services and facilities have increased, especially since the 1950s (Bedford 1980:47). It is a truism that new aspirations can be less easily satisfied in atoll environments; and equally a truism, that as these aspirations increase, the degree to which they can be satisfied on atolls falls.

## THE MIGRATION OPTION

The combination of higher postwar rates of population increase, the increased desire for consumer goods, the location of higher education facilities and hospitals either on one central atoll or on a high island, and the concentration of formal sector employment there has, in many cases, resulted in migration from outlying atolls to such centres, especially where there is a central high island (Connell 1986:45). The populations of many, perhaps most, atolls are growing at a slower rate than that of the atoll state as a whole, although few atolls have a declining population, and then only the smallest. Throughout the atoll states there have been three migration trends, firstly, the tendency for there to be a growing concentration of population at one point on each atoll, usually the point where there has been some development of services, perhaps in association with a mission station, school or other institution; secondly, the steady increase of the urban population of atoll states and, thirdly, international migration, both temporary and permanent from these states. These two latter trends have more important consequences which are discussed in greater detail below.

On small atolls there are very few prospects for formal sector employment; as population and education levels increase and demand for employment also increases, the employment short fall increases. The extent of emigration especially in youthful age groups is often substantial (Connell, 1986:47) as little local wage employment is available and almost all of this is in the public sector, since the private sector, other than stores, is conspicuous by its absence. In every case public sector employment rapidly expanded in the 1970s, and in Tokelau this caused widespread social changes, disrupted traditional activities and also disrupted the fiction of egalitarianism as, by 1981 on Fakaofo, public service salaries accounted for 82% of all cash income (Hooper, 1982). The impact of the general transition to bureaucratic employment, now the principal target of rural-urban migrants, is discussed in detail elsewhere (Connell, 1983a, b,c,d). Since many atolls are remote from capitals, the costs of transportation (either of commodities or medical services) have increased rapidly as oil prices have increased, and transport services have declined substantially in some areas. Migration becomes a cheaper alternative than remaining. When both population and wants have grown together in environments where local production possibilities are limited, the export of labour has become an important means of meeting basic subsistence requirements, especially food (see also O'Collins, 1988). For example, in 1971:

> The people of Butaritari and Makin [two atolls in northern Kiribati] are becoming increasingly dependent on remittances to pay their taxes and their children's school fees, to buy corned beef and rice for feasts, and to purchase even moderately expensive items at the store. Most of the durable goods on Makin - planks for canoe hulls, canvas for sails, bicycles, sewing machines, radios and even clothing - were brought by returning workers. The export of labour has become the principle means of *maintaining* the local standard of living. (Lambert 1975:220-221; our emphasis)

Migration has thus increasingly become a quest for essentials rather than luxuries.

While out-migration may solve the immediate population and welfare problems of some small, densely populated atolls, it may also increase the problems of destination areas in the atoll states, leading to some of the most difficult and intractable development problems in the South Pacific. Since aspirations to migrate are much the same in most Pacific countries, and infrastructure (principally for health and education) is often highly centralised, migrants have concentrated in a very limited number of areas. The most extreme examples of this are in the Marshall Islands and Kiribati. Tokelau has no 'centre' and much of the administration is actually undertaken from the Office for Tokelau Affairs in

Apia, Western Samoa. In the Marshall Islands, the 1988 census recorded a total population of 43,335 of whom 19,695 were on Majuro (at a density of 2,188 persons/km$^2$); less than 36% of the population were on 'rural' atolls. In Kiribati, the 1985 census recorded a total population of 63,883, of whom 21,392 (33%) were on South Tarawa at an average density of 1,357 persons/km$^2$. The only other atoll state in the Pacific which approaches these kinds of urban concentrations and densities is Tuvalu where the 1979 census recorded a total population of 8,730 (of whom 7,349 were actually in Tuvalu); Funafuti had a population of 2,120 (28.9%) at a density of 770 persons/km$^2$ and this is now substantially greater; Funafuti now has about a third of the national population. In each of these cases urbanisation has been both recent and rapid. The reasons for these urban concentrations are many and, until quite recently, have followed growing economic and social differentials between one central atoll and the remaining atolls. A centralised administration has spawned the centralisation of the service sector, hence most formal sector employment is concentrated in the centre. In Tuvalu, 78% of all those employed in the cash economy were in Funafuti; in Kiribati in 1985 60% were in South Tarawa. The figure for the Marshall Islands (for the two centres) is likely to be even higher than that for Tuvalu. In each case these proportions have grown between the last two census dates, indicating the continued concentration of both the population and contemporary economic activity. This centralisation of wage employment suggests that even where urban unemployment, is growing, the chances of obtaining wage employment appear to be greater at the centre. Social services, the 'bright lights', and a significant proportion of relatives are at the centre, serving as powerful attractions to rural-urban migrants. This centralisation may be compounded by 'urban bias', where financial and technical resources are overwhelmingly concentrated in the urban area.

Inevitably this urban concentration has created problems, many of which are no different from those of much larger urban centres elsewhere in the Third World:

- overcrowding in poor housing conditions with attendant health risks;
- pollution (to the extent that the lagoon in South Tarawa is a potential health risk and was one cause of a cholera outbreak in 1977);
- unemployment (even if disguised by sharing in extended families), the growth of squatter settlements (e.g. Itaia, 1987);
- worsened nutrition (as cash incomes are often inadequate to purchase diets based on imported foods); and
- sometimes higher crime rates and social disorganisation.

Since migrants are not always successful in towns they may be unable, or unwilling, to contribute significantly to the needs of their rural kin. When urban jobs are hard to find, those who earn wages in town may be more likely to redistribute money there than remit to the home atoll. In Lae, in the Marshall Islands, the flow from Ebeye scarcely exceeded the rural-urban flow (Alexander, 1977). More generally, throughout the Micronesian atolls, both 'good' and 'bad' times can usually be distinguished and in the bad times both money and foodstuffs flow to the towns (Alkire 1978:145) or kin may even migrate to urban centres to ensure access to the earnings of their relatives. If bad times in urban areas increase in the future, rural dependence on remittances may inadvertently prompt a reversion toward self-reliance. These urban problems are not unique to atolls, but the small size of the land and lagoon areas, and the problems of achieving economic growth accentuate the basic difficulties

In the atoll states of the Marshall Islands, Kiribati, and Tuvalu there are therefore two related problems: the relative depopulation and economic decline of the smaller, remote atolls and over-urbanisation on the principal atoll. In the absence of overseas migration from atoll states, development prospects would be even more difficult. For Tokelau, migration to New Zealand is a right since Tokelau islanders are New Zealand citizens hence, in terms of ethnicity, a slight majority of Tokelau islanders now live in New Zealand.

> the idea of permanent emigration, involving a severance of many ties with the home island and of seeking one's fortune elsewhere, is well established in Tokelau life and thought. For the past 70 years or so it appears to have been accepted ... that some of nearly every group of siblings must *tahe* ('emigrate') simply because the local resources are seen as insufficient. (Hooper & Huntsman, 1973:403-4)

Migration from the Marshall Islands (and from the Federated States of Micronesia) to the USA is possible under the terms of the Compact of Free Association; indeed the island states were anxious to ensure that such a clause be in the Compact. There are currently few Micronesians in the United States (Connell, 1988b) yet this may well change in the future to the extent that, as for Tokelau, Micronesian residents of the United States may outnumber 'the folks back home' (Marshall, 1979:10-11).

Both Kiribati and Tuvalu specifically train a proportion of the national population for overseas migration through their Marine Training Schools. Apart from overseas seamen (representing 3% and 1% respectively of the *de facto* population of Tuvalu and Kiribati), there were almost 722 (8.2%) Tuvaluans and 1,278 (2%) I-Kiribati employed on Nauru at the time of the last censuses. The number of I-Kiribati on Nauru has declined between 1979 and 1985 and will decline further and will end in about a decade, with the eventual closure of the phosphate mine. Both countries have sought resettlement and overseas employment opportunities and Tuvalu has formally located a handful of workers in New Zealand under existing short-term schemes. In the immediate future, however these two countries do not have long-term overseas migration (or resettlement) opportunities.

Movement overseas both reduces the pressure on local resources and provides a substantial cash flow from remittances. When phosphate mining on Nauru ends, the development problems of Kiribati and Tuvalu will be considerably worsened, because of the loss of remittance income, the increased population pressure on resources as these workers and their families return, and the influence of these returned migrants, hitherto employed in the urban-industrial sector, on the values and attitudes of the national population.

The significance of international migration for Kiribati and Tuvalu is apparent not only in the flow of remittances but also in changing local attitudes to international migration. In pre-war years the colonial administration decentralised part of the population of the more densely populated Gilbert Islands to the Phoenix Islands group to the east (Maude, 1968; Knudson, 1977). At much the same time groups of villagers from Vaitupu in Tuvalu purchased land in Fiji for their own private resettlement (Koch, 1978). Local and colonial perceptions of population density and domestic development prospects were quite similar. For various reasons settlement of the Phoenix Islands was unsuccessful and the settlers were again transplanted, this time to the then British colony of the Solomon Islands, where they and their descendants remain. In Kiribati these settlers are now viewed quite differently from in the past:

> In earlier days they were the unfortunate ones who did not have sufficient land. Now our values have changed. Settling overseas beyond the oceans of our islands is something to be sought after. Why? Because our population is still growing. So now, many consider them, the resettled ones, the fortunate ones and they consider us to be the unfortunate ones. (Schutz & Tenten, 1979:127)

Permanent international migration is increasingly viewed by many atoll dwellers, though certainly not all, as a key solution to many development problems.

Toleration and encouragement of international migration in Pacific atoll states is a function of its impact in reducing population pressure on scarce resources; attitudes to individual freedom of movement and, above all, the substantial flow of remittances that follows international migration. The flow of remittances to Kiribati and Tuvalu and, to a lesser extent, Tokelau is large and increasingly crucial to household and national welfare. Migration and remittances have tended to create an appetite for imported consumer goods, which has driven up wages. The remaining remittances, are, however mainly invested in stores or in the agricultural sector. However rural investment opportunities are normally so few that migration is from a family perspective a more lucrative investment than anything available at home, remittances can only be invested in increased, if not necessarily improved, consumption. Although there are widespread assumptions that remittances emphasise dependency and produce rural stagnation (Connell, 1980) opportunities for emigration and remittances are highly valued by islanders themselves and freedom of movement is given high priority. Migration is often linked or sponsored, with households or extended kinship units planning for and encouraging the migration of particular individuals, to the extent that in the smallest states, such as Tokelau and Tuvalu, Marcus has suggested the emergence of a new institution, the 'transnational corporation of kin', allowing kin groups to colonise and exploit economic opportunities across a wide range of environments (Marcus, 1981). Such behaviour is most apparent where domestic sources of income are least adequate. In all South Pacific states, including the atoll states, there have been no attempts to restrict international migration; rather have there been attempts to gain greater concessionary migration opportunities overseas.

In more dramatic form the growing perception of the household returns from migration has led to increasing fertility rates, as least as documented in the case of Nanumea atoll in Tuvalu, where:

> parents actively hope to produce remittance earners and most feel that this necessitates having more than one son. As one woman said of her only son 'One is not enough. If he goes away to work, there is no one to look after me here. If he stays and cares for me, no one earns any money overseas'. Another woman recognised that her husband had been right to insist that they needed more children ... 'He said that if we had many children we might have a smart one who could go on to school and get good work. He will be our road to money and imported goods'. (Chambers, 1986:2873-4)

This phenomenon has also been observed in other small islands that have become dependent on remittances from migrants (Connell, 1988a:29) and indicates not only that family planning is unlikely to be chosen as a solution to development but that population pressure on resources may worsen in the absence of international migration opportunities.

It is scarcely surprising then that individual migrants and households and also many observers have viewed the future of the atoll states in terms of increased levels of international migration. A relatively recent review by Castle of the possibilities for economic growth in Kiribati and other larger, less remote and better endowed countries in the South Pacific concluded that sustained increases in incomes would essentially be possible only through greater dependence on migration:

> The case of Kiribati exemplifies the dilemma in its starkest form. Even with the most optimistic view of the possibilities for fisheries or further development of the coconut industry, the conclusion must be that continued economic growth from its own resources is impossible.
>
> The acceptance of a no-growth option may be the only realistic option for the small countries.
>
> No-growth need not be synonymous with poverty if the possibility is established for people in stationary economies to migrate either temporarily or permanently It is even more difficult when whole states are placed in the position of having to choose between, on the one hand, restricting opportunities for their nationals to those available within their own boundaries and, on the other, extending the range and choice of opportunities open to individuals by closer integration with larger economies at the possible cost of some attenuation of their national and cultural identity.
>
> [A policy of unrestricted temporary or permanent migration to metropolitan countries] would seem to be the only one that gives the people of the small island countries the chance to choose individual paths of development within the wider world community. (Castle, 1980:135-6)

Specifically contrasting Tuvalu with Tokelau, where Tokelauans can move freely as citizens to New Zealand, Bertram has concluded:

> For Tuvalu, where the British and the local elite together managed to push through a transition to formal independence, the key role for the new state will now be to recruit a new patron and to seek out new opportunities for Tuvaluan labour and capital to penetrate the rest of the world. Closed country models, whether in the political or economic realm, simply do not fit the Pacific of the 1980s. (Bertram, 1987:29)

Denied permanent overseas migration opportunities, unlike almost all other states in Micronesia and Polynesia, Kiribati and Tuvalu have hitherto found opportunities in Nauru and on foreign ships. A future in which these decline or even disappear poses immense problems, not only in rehabilitating and accommodating migrant workers but in coping without their remittances. As a former Australian Commissioner to Fiji and Tuvalu noted: the people of Kiribati and Tuvalu should be seen as 'economic refugees' (Keith-Reid, 1984). It is into that arena that the Jackson Review of Australian foreign aid (Committee to Review the Australian Overseas Aid Program [CRAOAP], 1984) stepped.

The brief 'Executive Summary' of the Review attached sufficient importance to the problems of Kiribati and Tuvalu to give them a special significance denied to all other states except Australia's former colony Papua New Guinea.*

> Kiribati with a population of 60,000 and Tuvalu with a population of 8,000 have special problems. Their remote and minute land areas are heavily populated. They depend very much on remittances from their emigrants and on foreign aid. Their long term development prospects are discouraging. *In view of structural problems which are beyond their control and beyond the reach of aid, Australia should make available limited opportunities for immigration from Kiribati and Tuvalu.* (CRAOAP 1984:8)

The main body of the text scarcely extended on this summary although the Review singled out Tuvalu as having 'a unique combination of minute size, tiny population and an almost total lack of resources. It is a state without internal economic viability, and it will have to remain dependent on remittances and aid' (CRAOAP 1984:171); it was also identified as having additional problems of land shortage, urban drift and high youth unemployment (CRAOAP 1934:171). Kiribati was seen as exemplifying the problems of distance and communications; 'the country consists of islands with a total land area of 690 km$^2$, spread over a sea area of 3.5 million km$^2$ and remote from the nearest developed country market' (CRAOAP 1984:171). Although the Review did not specifically identify other problems in Kiribati those listed for Tuvalu are equally apparent in that country. Urban migration is particularly serious in Kiribati and resulted in the unusual and rather dramatic response of formally allocating unskilled urban government employment by island quotas (Connell, 1983a). Likewise communications problems are at least as serious in Tuvalu, where the withdrawal in 1983 for financial reasons of a limited domestic seaplane service resulted in the departure of Peace Corps volunteers from every island except Funafuti, the capital. Though this aspect of the report was never debated or acted upon in Australia, and the more recent FitzGerald Report (Australian Government, 1988) rejected the possibility of any concessionary scheme for Pacific Islanders, it is indicative of the growing perception of severe development problems in Kiribati and Tuvalu and the role that international migration might play in resolving them. Nonetheless a former Government Economist and Planning Officer of Kiribati has simply stated, 'Emigration, as proposed by the 'Jackson report' is not an answer. This would result only in the removal of the best of one of the country's few resources i.e. its skilled labour, to serve other countries and further frustrate Kiribati development' (Pollard, 1987:6). Though there is some truth in this

* Editors' footnote. The independent state of Papua New Guinea is formed from the Australian colony of Papua (formerly a British colony) and the Trust Territory of New Guinea (formerly a German colony).

view, migration from Kiribati already occurs and there is no obvious shortage of skilled labour that would be solved by reducing migration.

Alongside the contribution of remittances, a further substantial financial support for national incomes of atoll states is overseas aid, welfare payments, subsidies and compensation payments of different kinds. So substantial are aid funds that the atoll states of Kiribati, Tuvalu and Tokelau, alongside Niue and the Cook Islands, have been conceptualised as the Migrant Remittance Aid Based (MIRAB) states, where migrant remittances and aid are the most important bases of the economy and, through these flows, a government bureaucracy has become the principal source of wage and salary employment (Bertram & Watters, 1985). In the Marshall Islands direct external (US) support for the economy is even more substantial. Aid dependence has taken some unusual forms. In 1987 Tuvalu established an aid Trust Fund of A$27 million composed of direct cash donations from Tuvalu's traditional aid donors. This fund is managed by a subsidiary of the Australian bank, Westpac, and if it is successful Tuvalu will be able to live off the annual interest, thus dispensing with conventional annual aid delivery. The money will be invested in a low-risk spread of assets, including fixed-interest funds, equities and property. The fund should enable Tuvalu to clear its recurrent deficit and contribute to long-term financial viability by earning an annual interest almost that of current aid receipts (Fisk & Mellor, 1986). The donors will have some ability to monitor the effectiveness of this fund in contributing to national development. In some respects the Trust Fund is based on the nearby success of the Revenue Equalisation Reserve Fund (RERF), derived from historic phosphate revenue in Kiribati (Bertram, 1986:820; Pollard, 1987). This fund is managed by a London merchant bank, supervised by a Kiribati committee chaired by the Finance Minister. In 1984 Kiribati received external aid of A$13.5 million (vastly in excess of its exports) and received A$5.5 million from the RERF; a further $A512,000 was generated from the lease of a tracking station on Christmas Island. Tokelau received New Zealand aid for the financial year 1985-86 to the value of NZ$3.1 million, and, in 1985, Tuvalu received aid of A$4.6 million. The Marshall Islands received a vastly greater sum than all of these from the United States alone. Only a very small proportion of the national income of atoll states is generated within those countries, through commodity, mainly copra and also postage stamp, exports but is dependent on concessionary external support. However the concessionary trade agreements of the South Pacific Area Regional Trade and Economic Co-operation Agreement (SPARTECA) have proved of no use to countries that manufacture little (Tabai, 1987b) and none of the states has any manufactured exports. Atolls and atoll states have moved a very long way from any semblance of self-reliance. Moreover they have gone beyond the traditional support of coral clusters to dependence on much more distant nations.

## THE IMPACT OF GREENHOUSE EFFECTS

Previous sections have examined the difficulties of development in atolls and atoll states and noted that there has been increasing recourse to migration as the preferred individual and household solution to the challenge of development, whilst the states themselves have tended to become more dependent on overseas aid. Rising sea levels can only worsen the problems of achieving development in atoll states though the extent of the changes will vary temporally and spatially in ways that are not yet predictable. As noted previously there will be climatic changes, in terms of differences in rainfall and storm frequency and rises in air and sea temperatures. Coastal erosion may increase if sea level rise accelerates beyond the upward growth of corals and this erosion will probably be accentuated by the greater frequency of storms. Slowly but inexorably there will be critical environmental changes of an unknown rate and dimension.

In some countries it will be extremely difficult to assess what the impacts will be. The intertropical convergence zone is likely to shift northwards, changing the distribution of zones of upwelling, and hence altering the distribution of fish stocks and thus fisheries. Some areas, including parts of Papua New Guinea and Fiji, may experience a degree of desertification (Baines, 1988; see also McGregor, this volume) At a local level future changes are even more difficult to assess:

> The consequences of changed climate, including raised air and sea temperatures for the physiology of plants and animals and their ecological inter-relationships can only be guessed at at this stage. Ecological processes, too, will change. The fallen leaves and

twigs which are the vegetation litter of forest and grassland, for instance, will decay even faster than now, exposing bare ground more readily to water erosion. (Baines, 1988:9)

On atolls the relatively simple ecosystems enable some conclusions to be made with a greater degree of certainty. A number of specific changes that affect atolls can be separately distinguished and examined in four principal areas. These are, firstly, the drowning of barrier reefs, secondly, the intrusion of saltwater into coastal groundwater supplies; thirdly, the erosion of areas of flat land, and fourthly, storm damage to coastal installations, such as port facilities. Tourism is not a source of income in any of the atoll states under consideration hence the disruption of coastal tourist facilities, which is likely to occur elsewhere, will not be significant, though these problems will certainly discourage any future developments in that area.

The intrusion of saltwater into groundwater lenses will have direct effects on agriculture and on the supply of potable water. The most obvious effects on agriculture will be through increased salinity in taro pits, lower productivity of the taro and hence a greater disinclination to continue with this labour-intensive agricultural activity. Increased salinity is also likely to lead to the decreased productivity of all other crops, including coconuts, pandanus and breadfruits. Although coconuts and pandanus are relatively salt-resistant, increased salinity such as in coastal areas of Thailand (Ealey, 1985), has reduced productivity and killed off palms. There appear to have been no studies of the relationship between salinity and agricultural productivity in the South Pacific region, although no species of fauna or flora will gain from increased salinity. It seems likely that increased salinity will reduce the potability of groundwater which, for most atolls, is currently of considerable significance, although preference is usually given to rainwater for drinking. If increased salinity is combined with any long-term decline in rainfall, as is possible in some areas, the results will be even more serious, since the cost of water purification and desalination is extremely high. On some of the drier atolls, including urban areas such as Majuro, water supply is already a critical problem. (In the extreme case of Nauru water is intermittently imported). If and when groundwater becomes no longer potable human habitation will no longer be effectively possible.

Erosion will both reduce the areas of land on atolls and, because of their minimal elevation, increase the swampiness and salinity of areas that remain above sea level. Areas immediately at risk will be those areas that have previously been reclaimed from the sea, including parts of south Tarawa, and causeways such as those between Betio and Bairiki in Kiribati and in Majuro. This loss of land will directly affect activities and infrastructure, agriculture, housing, roads and airstrips and will inevitably lead to a decline in agricultural production, increased competition for scarce land in urban areas and more disputes over land tenure. (Fortunately, the custom in many atolls, of land tenure being organised by strips across the atoll from lagoon to ocean, is likely to reduce the severity of such conflicts). The loss of land will lead to a related decline in handicraft materials such as wood, pandanus and of firewood, which is already in extremely short supply in urban areas such as Tarawa. Changes to reef ecology may have far reaching impacts on artisanal fisheries.

Impacts are likely therefore to lead to a substantial decline in agricultural production, a possible decline in fisheries production, and a loss of vital water, timber and firewood resources, thus reducing the potential of the few resources in which the atolls and atoll states currently demonstrate a degree of self-reliance. These problems will increase over time, and one extremely pessimistic scenario even suggests that 'it is conceivable that some baselines for territorial seas and Exclusive Economic Zones would have to be altered, decreasing the area of exclusive rights for marine resources and reducing potential income' (Matos & Tiffin, 1988:51; c.f. Pernetta, 1988). These effects will occur alongside continued rapid population growth, and an increase in population pressure on existing resources, unless the changes contribute to increased self reliance in some other area, this will lead to an acceleration of the present process of dependence on metropolitan states. Within countries it is likely to further encourage rural-urban migration in search of the 'fast money' of wages and salaries rather than the increasing unpredictability of agricultural and fisheries incomes.

DEVELOPMENT ALTERNATIVES

There are alternatives to the trends of population migration, dependency and over-urbanisation in the atolls of the South Pacific but climate change will make such alternatives difficult to realise. Marshall (1979:11) has suggested one possibility, that 'outer-island communities may undergo a demographic revitalisation as educated migrants, longing to re-establish their cultural and ethnic roots, forego the urban centres and work towards building a new economic future in their home communities'. While there have always been minority movements to re-establish cultural identity, these have not proved to be an adequate sole basis for development. Where solutions exist they must be in the area of economic development and job provision. Yet even now there are massive constraints.

In Kiribati, a series of policies have been developed in an attempt to achieve more balanced development, including; improved rural education with the inclusion of traditional and practical skills; increased copra prices, by subsidy; the development and expansion of district centres, involving decentralisation of government; and possible resettlement of the distant and sparsely settled Line Islands. The development of the Line Islands, and especially Christmas Island, has recently been given new emphasis in an attempt to decentralise population and development and reduce the high level of urbanisation. Moves to establish vocational education in both Kiribati and Tuvalu have been thwarted by opposition from parents demanding a curriculum that includes the academic training that offers some possibility of urban bureaucratic employment. In each of the atoll states there has been a focus on improved fisheries and agriculture, to increase self-reliance, but success has been minimal; emphasis has moved away from agriculture and marketing infrastructure is minimal. Development plans in each of the states have been exceptionally difficult to translate into practice.

It is improbable that atoll states can ever achieve a significant degree of self-reliance unless totally new models for development are adopted or significant new resources discovered. They are currently incapable of moving away from the present massive dependence on migration, aid and imported goods. The necessary elements of policy redirection are clear: agricultural development policies that stress diversification, food crop production and the use of new varieties of cash and subsistence crops, land tenure reform and the taxation of unused agricultural land; increasing concentration on the exploitation and development of the marine resources that are the only obvious base of both export growth and improved nutrition; transport and energy policies that move away from the use of non-renewable resources; job decentralisation and allocation (along Kiribati lines); improved infrastructure such as wharfs and aid posts; increased emphasis on family planning. Self-reliance entails reducing dependence on imported 'necessities' including foods, oil products, capital equipment, and expertise and this involves changing consumption patterns as well as increasing local productive capacity. Policies would be needed to change living styles at given income levels - using taxes, price policies, advertising, and perhaps rationing. This might also involve increasing national ownership of assets and improving national capacity for negotiating with transnational corporations and metropolitan countries, especially, in this context, those with fishing fleets (c.f. Seers, 1977). In short, self-reliance entails a more selective approach to external influences of all kinds. For atoll states the problems of achieving a greater degree of self-reliance are severe. Self-reliance runs counter to the development trends of the post-war decades, is profoundly unattractive (Bertram, 1987:28), requires stable political authority in what are currently 'soft' states and is inherently unlikely to occur.

A movement toward the self-sufficiency in Atoll States, with a reduction of aid and remittances would be difficult and painful especially for the young as they run counter to perceived trends in metropolitan countries. In most places young peoples aspirations are firmly directed towards the acquisition of modern goods and, as has been argued for the small island of Rotuma, 'with the prestige given to 'foreign' goods, it is doubtful, therefore that Rotumans would want to be self-sufficient, even if that were a possibility' (Plant, 1978:174). In Tikopia Firth (1971:69) states that 'from such a level of dependence on imported goods it becomes difficult to retreat without unease and a sense of deprivation'. In Ponape, too, villagers are not interested in adequate subsistence, nor even 'the right to subsistence' but rather they desire 'continued and increased access to the goods and prestige provided by employment' (Petersen, 1979:37). While these statements refer specifically to small islands rather than atolls, such attitudes are becoming true of most areas within the Pacific, policy prescriptions that focus entirely on self-reliance, are unlikely to be taken in full due to the demands for the prestige associated with modernisation and Westernisation, the difficulties attached to establishing rural projects and the fact that concerted comprehensive policy formation in loosely structured, democratic states is difficult to achieve. Self-reliance is steadily being eroded and the alternative, a more adequate interdependence, is as distant as ever.

The most detailed review of the development prospects of Kiribati and Tuvalu, undertaken a decade ago, was quite pessimistic in its conclusions:

> The economic prospects for the Gilbert Islands and Tuvalu are not promising. No new economic resource other than the sea is likely to present itself ... the islands' remoteness from markets will always create difficulties ... The future appears to lie in maximising returns from existing resources, the export of labour, import substituting, the careful control of government spending and, for the Gilberts, the development of the resources of the islands without indigenous population. (Geddes et al., 1982:5)

But the 'existing resources' of the islands are little more than coconuts and two major subsequent reports (Pitchford, 1981; Green *et al.*, 1979) have cautioned against any real prospects for development in either the unpopulated Phoenix Islands or the even more remote Line Islands; it is a gloomy conclusion. Indeed the Team Report went on to note that:

> Piecemeal tinkering with individual policies might alleviate some conditions but cannot possibly succeed as they are dealing with a complex whole; nothing less than a radical alteration of the whole political economy will suffice that will enable a new economic, social and political structure, firmly rooted in the real pattern of the islands, to emerge. (Geddes *et al.*, 1982:142)

The new leaders, with the notable exception of President Tabai of Kiribati, 'show many of the signs that they may act in the same way as the elite of most other South Pacific governments in recent years - they will pursue the right wing, conventional economic policies of the former British administration and continue with an open laissez-faire economy, welcoming foreign investment capital' (Geddes *et al.*, 1982:154) that they 'need to be austere and moderate in their own tastes and spending, practise restraint in public spending and be able to dampen down local expectations and aspirations that are *no longer* realistic (Geddes *et al.*, 1982:155; our italics). Transformation through tradition may provide some 'grounds for optimism that the islanders will eventually work out their own, indigenous model of development' (Geddes *et al.*, 1982: 156) but this is more likely to be illusory. It will not be a self-reliant future; traditional pre-contact life presented its own problems that cannot now be diminished by appeals to the merits of self-sufficiency. One report on the Tuvaluan atoll of Nanumea indicates, that the 'pouliuli myth', in which traditional Tuvalu culture is considered inferior to western culture and hence local customs belong to 'days of darkness' (Chambers, 1984:272), a view which cannot now be erased. Thus the prospects for greater self-reliance are exceptionally poor and slowly dwindling, under the present political climate.

Some islanders are optimistic about the future, though many statements tend to be exhortatory and idealistic: in Kiribati, 'If there are going to be problems, dangers, or disaster, let us conquer them ... The future is uncertain. But if we remain true to our *kate ni Kiribati* [Gilbertese way] we shall be able to see our way clearly through' (Itaia, 1979:182, 188). Likewise in Tuvalu, 'Tuvaluans have much to be proud of, and can face the future with confidence. They are masters in their own country ... the Tuvaluans of the present, no less than those of the past, accept the challenge of providing as well as they can for those who are to come. Our history contains a message of hope' (Sapoago, 1983:181). No prominent leader has sought self-reliance with such determination as the President of Kiribati, Ieremiah Tabai.

> ... our fundamental conviction [is] that there is no alternative to developing our country so that we can at least stand on our god-given feet. We believe also that any other alternative is no alternative at all, because it would definitely condemn us to perpetual dependence on

others - something that is inconsistent with our national objectives - something that obviously cannot be regarded as development (Tabai, 1987b:4).

However throughout a series of detailed studies conducted in the 1970s there are several expressions of disappointment and pessimism; senior pupils at the Abemama Island School forecasted a future of hardship, insecurity, land shortage and overpopulation, exorbitant store prices and lack of wage employment (Watters & Banibati, 1982:247-9). Characteristically in Kiribati, where traditional attitudes emphasise luck and fate (Geddes *et al.*, 1982:10), there was greater despondency than in Tuvalu. In Abemama this was accentuated by the emergence of an island feeling of relative deprivation in contrast to Tarawa (Geddes *et al.*, 1982:14) and, in both countries, there was a healthy scepticism over the delusions and illusions of development plans.

The views of many island politicians are also much less sanguine. The former Tuvalu Minister of Finance, Henry Naisali, has stated: 'Viability? Never. It's no use pretending we can be, although I hope someone will find a better solution to our future than what I can see at the moment. Foreign investment? Honestly I don't see any foreign corporation investing in Tuvalu' (*Islands Business*, April 1984, p.62). In his inaugural speech after independence the Tuvalu President, Toaripi Lauti, proclaimed: 'All we have is sunshine, wind and a portion of the Pacific Ocean with which to build our nation's development'. Whilst in strikingly similar vein, the President of Kiribati opened the Seventh South Pacific Labour Ministers Conference in Tarawa in July 1981, with the words, 'In Kiribati God was kind to us and blessed us with sunshine, the sea and the coconut'. What may appear pessimism elsewhere is realism here.

Some outsiders are less pessimistic about the future for small island states. Dolman, after an extensive review of development issues in small island states, has queried, 'Is it too much to suggest that small islands, for all the problems and constraints that confront them, could become the laboratory in which alternative development strategies, shaped by the notion of self-reliance, first see the light of day?' (Dolman, 1985:63). For most the answer would be that it is indeed too late, and that self-reliance in the past is very much a myth: 'dependency is sanctioned and encouraged by government action and is culturally a legitimate strategy that is effectively no different from former island network relationships' (McInnes, 1986:132-3). Pollard has reviewed some of the various discussions on the prospects for greater self-reliance in atoll states, concluding that most such states are now well advanced along the 'capitalist road' and 'for some countries perhaps it is too late to change these new ways' (Pollard, 1988:41). Theory does not conform to practice. Despite Kiribati's aim to achieve self-reliance, to the extent of divesting itself of overseas aid, it is apparent that 'countries such as Kiribati will require international assistance for many years yet' (Pollard, 1987:24). For the atoll states the future is increasingly one of dependence, or interdependence, a situation that will be increased and accelerated by climate change.

## CONCLUSION

Atoll development options are naturally constrained by limited land and sometimes lagoon areas, and the simplicity of atoll environments. These options are broadened by the increased availability of new plant varieties, fertilizers, technology, and so on, from outside, but limited by the fact that these may be expensive, and far from simple to organise and maintain. Options have been diminished by changes in aspirations that have resulted in changes in attitudes to traditional agriculture and some loss of essential skills and knowledge for survival and success in environments often threatened by natural hazards. Options will be further reduced, possibly even removed, by climate change.

Questions central to the greenhouse phenomenon are, 'will climate really change in the next 50 or 100 years, by how much, and what will be the impacts?' To expect mankind's past (and ongoing) massive degradation of the world's natural environments not to induce some future change in global climate, is to be irrationally optimistic. There may be geological precedents for different world climates in the past, but there is no precedent for the speed at which present changes to the environment are taking place. It is therefore unrealistic to expect present-day natural systems to compensate for, or accommodate, these impacts without themselves changing to some extent. Inevitably, the worlds climate will change; the extent of that change depends in large part on political, social and technological behaviour in the future.

There is little evidence that our present socio-political systems have the capacity or willingness to control global events such as the unique greenhouse 'experiment'. The majority of the various management options canvassed by Goodman & Jager (1988) recognise the improbability of governments implementing the radical changes needed now to significantly modify the greenhouse effect. Meyer-Abich (1980), in a paper with the the title 'Chalk on the White Wall - On the Transformation of Climatological Facts into Political Facts', suggested that there are three options for response: prevention, compensation and adaptation but concluded that, from a political point of view, prevention and compensation are much less practical than adaptation. Adaptation allows the least marginal action in the present and defers expenses into the future. In addition, adaptation does not require long-term international co-operation or agreement on long-range goals. If adaptation is the most rational political option, the climate problem tends to fade ('Chalk on the White Wall') compared to the already extremely serious problems of development confronting developing countries especially. Thus, at best, climate-oriented policies to cope with climate change would become part of development policies in general.

Uncertainty over the outcome of greenhouse effect has necessarily restricted ability and willingness, nationally and internationally, to respond to the problem through policy formation. Response is least likely in the atoll states where information is least adequate and where planning offices are small and fully stretched to cope with standard recurrent activities. Planning remains in its infancy, finance, data, continuity and technical expertise are limited, environmental planning is almost non-existent and five-year plans (despite a history of 15-year plans in Micronesia) are the extreme limit of long-term planning. Though 'the decision process will not begin until there are more conclusive findings' (Titus, 1987:519) these findings are now sufficiently conclusive, despite their lack of specificity, for some forms of action to be taken now. Even so it is more likely that significant action will not be taken until there is consensus that some local (rather than global) change, can be definitely attributed to greenhouse effect. Atoll states, or other microstates, cannot act individually or collectively to remove or reduce the causes of greenhouse effect, though they can call upon international organisations to act on these causes. An international approach is essential to tackle this global problem though, even at an international level, climatic change is only one element in a complex and integrated set of population, resource, economic and environmental problems. The international context is not discussed here, it is important however to note that greenhouse effect has now become a United Nations priority and UNEP is working towards an international convention for tackling the problem.

For a particular state options of direct action to avoid or eliminate the risk is clearly not possible for climate change impacts, action to reduce vulnerability levels or action to move away from, or abandon, the most risk-prone areas. Climate changes may eventually overwhelm atolls since everything is coastal (in distance and altitude). Conventional measures to reduce vulnerability such as transferring populations, infrastructure and economic activities to higher land are impossible. Other measures, such as the construction of dykes and pumping stations, are extremely expensive especially when a small population is spread over a large number of islands. Similarly there would be no possibility for the transport of material to nourish island growth on the scale that would be required. Even defending the few urban areas, several of which are themselves spread over wide areas, would be a complex and costly operation, and in all probability a pointless exercise. Moreover the finance for projects of this kind would be wholly absent within the atoll states and no aid donor would contemplate aid on the scale that would be necessary, even to strategically important states. Although 'present indications are that by far the most likely responses to the unprecedented historical occurrence of a possible global sea level rise of 1 m by the year 2045 will be high cost 'technical fix' solutions' (Mercer & Peterson, 1988:709) these solutions will simply not be available to atoll states or even other micro-states.

It will be crucial to strengthen the capacity of national planning offices, in relation to environmental matters, to ensure that there are more restrictions on planning in high-risk areas and to enable better monitoring of local changes. Strengthening the ability of governments to undertake conventional planning, in areas such as population planning, will become even more crucial than it already is. Ultimately, however, activities in these areas may turn out to be primarily holding actions, though such actions will reduce risks and ensure greater awareness of the more long-term problem.

Increased emigration must therefore inevitably be seen as one response to climate change, a response that builds on existing trends but that depends almost entirely on the policies of metropolitan states. Nevertheless as the title of a review of the possibility of a concessionary Australian migration scheme implies - Australia's Next Boat People? (Howlett, 1985) - Islanders could ultimately take migration matters into their own hands. Based on the experience of existing migration from the South Pacific to Australia and New Zealand the bulk of potential migrants from Kiribati and Tuvalu would be young, with some education, and would find employment reasonably easily; moreover only a small proportion of the population would initially choose to migrate. Hastings (1984) has concluded that 'it should not be any great economic burden to this country to subsidise a substantial proportion of island peoples - perhaps all of them in a few instances - but should we do?' His concern was that there are grave dangers in selective migration policies and that much larger countries, such as Papua New Guinea and the Solomon Islands, might subsequently demand the same privileges. This was the principal concern of the Australian Department of Immigration and Ethnic Affairs in 1981 when migration policies were being reviewed, and probably of the FitzGerald Committee in 1988. There is then likely to be significant opposition to concessionary migration at the moment though, in time, when the impacts of greenhouse effect becomes apparent this may decline. Concessionary migration schemes may be granted in other potential destinations such as New Zealand or even the United States. They are unlikely within the South Pacific.

Resettlement poses particular problems. In pre-war times the resettlement of Gilbertese to the Phoenix Islands was eventually unsuccessful so that the resettled population was subsequently transferred to the Solomon Islands (Knudson, 1977). Resettlement from atolls has otherwise moved atoll dwellers into very different environments, imposing considerable social, psychological and sometimes economic costs, as they confront a very different economic, political and biological environment. The consensus of the few studies that exist of these kinds of resettlements is that a variety of problems occur as outlined by O'Collins (this volume).

All the evidence suggests that the serious development problems experienced in the atoll states cannot adequately be met even now by internal policies or regional co-operation and that higher levels of aid will not contribute to economic growth (as opposed to improved welfare). This is clearly demonstrated in the case in Niue which has one of the highest levels of *per capita* aid in the world and also one of the highest rates of emigration. Whilst there is much evidence for widespread social and economic disadvantages to high levels of overseas migration, in the smallest states, such as Tokelau, there are substantial gains from migration that cannot be realised by other means. Where expectations of appropriate lifestyles continue to forge further ahead of South Pacific economic realities, the migration response becomes even more probable under the impact of climate change. In historic times atoll dwellers were extremely mobile and far from insular; men and women moved readily between islands in search of new land, disease-free sites, marriage partners, trade goods, and so on. In this way some islands were populated, depopulated, and latter repopulated. Mobility itself was responsible for demographic survival; without mobility, adaptation and change were impossible. It is a phenomenon of contemporary times that South Pacific populations are growing, and political boundaries and policies minimise long-distance migration. Without the flexibility that this kind of resettlement migration provides, the uncertainties and limitations of atoll environments are emphasised and either more permanent migration (usually to urban areas elsewhere) or an uncertain dependence replaces it. The era of great Micronesian and Polynesian voyages may be over but the future may nonetheless lie on distant shores.

Long before the contemporary implications of the greenhouse effect were recognised the choice of appropriate development strategies for atoll states had caused concern. Few world states have ever had such limited prospects for development, have gained so little from contemporary technological change but have nevertheless become so dependent on the outside world. Now it is even more crucial for there to be a focus on development issues in atoll states. Without further substantial external assistance, there is little doubt that people who were once described as real and potential 'economic refugees' will become, in less than fifty years, a new group of 'environmental refugees', or, as suggested elsewhere 'ecological refugees' (Pernetta, 1988). It is extremely unlikely that actions taken within the atoll states alone will allay this gloomy forecast. As suggested by Pernetta (1988) the issue of such 'ecological refugees' must be addressed on a regional basis, single country and bilateral agreements are unlikely to operate satisfactorily under the enhanced stress induced by climate change.

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# SOCIAL AND CULTURAL IMPACT: A CHANGING PACIFIC?

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> Modern folklore would have it that islands are the places where dreams come true. Dreams, however, are deceitful and their relation to reality obscure. (Brookfield, 1980:202)

> Through our ignorance, non-concern, and lack of foresight, we are risking the future of our island ... The dream is already surfacing as a nightmare. What I propose is simply this; that we awake from our slumber, open our eyes to reality and take definite action. (Unpingco, 1975:111)

One of the major objectives of the ASPEI (Association of South Pacific Environmental Institutions) task team, which considered the impact of projected climate change and sea level rise, was to examine the potential impact of such changes on the social and economic life of small nation states in the South Pacific (see ASPEI Task Team Members, this volume:1). Predictions as to the degree and severity of the social and economic impact of these changes vary, not simply because of the differences between the 'worst' and the 'best' scenarios presented by physical scientists. Variations also reflect the wide ranging assessments by social scientists of the reactions of human populations to these changes. There are differing views on the ability of small, vulnerable populations to adapt to yet another threat to their existence as distinct cultural or political entities.

Debates over how people are likely to respond to climate and sea level changes are carried on as forcefully as those over whether the sea level will rise by 20 cm or by 3 m, or whether warming will increase the global average temperature by an average of 2°C or to a greater or lesser degree. Over the next several decades, the real challenge will be to determine realistic alternative courses of action to meet the site-specific needs of different communities or nation states. But, in order to take the 'definite action' which Unpingco calls for, local, national and international decision-makers must be fully informed of the range of possible future impacts. The choices which they then make will often reflect cultural and ideological approaches to basic human needs. For some, the choice may be one of inaction, hoping that the scientific debate on the pace and severity of climate change has been exaggerated. But, as Roberts notes wryly:

> Even when the present media flurry dies down, the world's climate will still be changing, inexorably and at an ever-increasing speed ... what action to take is not a scientific question but a value judgment. (Roberts, 1988:37)

He warns that there is a danger that low income groups and those with less power or ability to influence decision-makers will suffer most. A further argument is that more powerful international forces may well measure physical and social impacts in terms of numbers. How many people will be affected, over what geographic area? The disappearance of small, local or even national entities might seem less important if measured only in strictly economic terms. But the social and cultural costs, and the relationship between these and economic costs, must also be taken into account.

How the people of the South Pacific cope with future changes in their environment will be determined by a complex set of social, economic and political decisions, made over time, both within and outside the Region. Scientific data will provide information that will help identify populations which may be most affected by sea level rise. However, value judgments will inevitably have to be made over issues such as land rights, and rights to marine resources for resettled 'environmental refugees' from small islands or from coastal areas of larger islands. Value judgments will also need to be made as to which community or group of islands should receive the administrative or financial support which may be required if they are to remain where they are, rather than resettle.

This paper will focus on some of the ways in which communities and nation states might respond to the changes which will affect, not only the resources at their disposal, but the ability of people to manage these resources. Because of the wide range of potential impacts, a corresponding range of possible adaptations must also be considered by physical, economic and social planners and by community, national, and international decision-makers.

For some countries or geographic regions within a country, land loss may be so severe that massive out-migration will be the only long term solution. However, for many others solutions may be found which do not involve total separation of groups of people from their traditional homelands. In general planning terms, key questions will be: What range of choices and alternatives do we have? Over what period of time? What warning will we have? Where should we start?

The ASPEI task team examined a number of possible scenarios in which there could well be a considerable amount of choice for 'at risk' populations. In some situations:

> Local populations will need to adjust their management practices to changes in land and marine resources. Traditional methods and local knowledge may not be appropriate and new crops may need to be introduced. External assistance will be needed to train local farmers and extension officers to respond to the changes in their environment. (ASPEI Task Team Members, this volume:11)

On the other hand, as Nunn (this volume:134) concludes, the potential impact for some coral atolls and other low-lying islands will leave little room for alternative management practices and 'permanent settlements may need to be abandoned as sea level rises'.

Given the wide range of environmental settings and of possible responses, it would be foolhardy to attempt to provide a 'blue print' or model for social impact management. Nevertheless, there are a number of general issues related to urban and rural planning and the provision of social services which can be usefully considered. A number of societies in the South Pacific also provide valuable lessons from their own experiences of migration and of voluntary or involuntary relocation.

## THE EFFECT ON EXISTING MANAGEMENT SYSTEMS

Any attempt to predict the likely social impacts of climate change and sea level rise must begin by looking at existing resource management and the social context in which environmental changes will occur. Existing practices have developed over time and as a result of cultural or environmental pressures. Communities have learned to cope and adapt to change, both from within and outside their immediate environment. This suggests that particular social, economic or infrastructural changes cannot be considered in isolation for, as Powell cautions:

> The social base on which traditional management systems operate must be considered. This is generally an integrated subsistence system in which individual roles are assigned and behaviour controlled by social, political and ritual practices and obligations to the group as a whole. (Powell, 1982:125)

### Climate change, productivity and human comfort

Among the socio-economic factors which will have to be taken into account is the way in which changes in temperature affect human productivity. What will be the planning implications of increased average temperatures, in terms of employment, housing, and the provision of education, health or sporting facilities? McGregor concludes that:

> Human comfort will be significantly affected by an equatorial warming of 2°C. Although some natural acclimitisation may be expected increased temperatures and atmospheric vapour pressures are likely to increase levels of discomfort significantly above present ones. This will be especially true for inhabitants of coastal environments. In coastal built up areas increased levels of human discomfort will have implications for worker productivity, energy consumption and capital expenditure for the maintenance of equitable indoor climates. (McGregor, this volume:39)

For many island and coastal communities, changes in life-styles will be necessary if people are to cope with the warmer temperatures. Formal school or work times may need to be adjusted for higher daily temperatures and this may mean a change in levels of productivity. New designs and materials for homes or workplaces may need to be developed. Those who design sporting facilities and sports programmes will also have to take into account higher average temperatures.

Yet, in specific areas, climate change may actually improve general living conditions. Hughes & Sullivan (this volume) suggest that, in some respects at least, the changes may be beneficial for those in the highlands region of Papua New Guinea. Increased production of both subsistence and cash crops could occur as rising temperatures make it possible for some crops to be grown at higher altitudes. With an increased resource base, previously marginallv productive areas may be able to sustain a greatly increased and healthier population. On the other hand, changes in the distribution of disease vectors, such as mosquitoes, may lead to an increased incidence of malaria, filiarisis and dengue fever (ASPEI Task Team Members, this volume:5).

Health, education and community services

Health, education and other services will need to be strengthened to cope with changing community needs. The psychological and social stresses which may be experienced by those most affected will also have to be taken into account. Individual or group identity is maintained through a sense of continuity, of links with the past. What will be the impact on individual or group identity if customary practices can no longer be followed - if sacred sites and ancestral burial grounds are abandoned or disappear?

An important question is: how do we prepare the next generation for the changes in the environmental resource base which may occur?

School syllabuses will need to be revised to include information on the possible effects of global warming in general and the local changes in the environment which have occurred and which are likely to occur in the future. This updating and revision of text books will be necessary at all levels and will require increased input from physical and social scientists as more evidence becomes available on the pace and type of changes which are taking place.

Planners, administrators and political decision-makers will all require greater access to information. This means that government and non-government agencies must begin to include this information and its planning implications in training programmes for those who will be involved in administration and management in the future.

Just as teachers and health workers will need to be reoriented to the changes which are taking place in their societies, urban and rural planners will also have to re-assess long term plans to ensure that infrastructural, economic and social developments take into account the potential impacts.

Disaster preparedness will need to include consideration of possible changes in building regulations, and in the siting and construction of wharves and bridges. Communities may need to develop early warning systems for hurricanes or the increased danger of local flooding or land slips. Severe erosion may endanger previously stable slopes where, as the ASPEI Task Members (this volume:4) noted 'land use practices are not designed to reduce soil loss'.

Health services and health education

Training of health workers and community health education programmes will also need to be revised if they are to keep pace with new factors which will affect the health of local populations. As noted earlier, malaria or other insect borne diseases may become endemic in areas where these were previously unknown or only a minor problem (ASPEI Task Team Members, this volume:5). Methods of waste disposal will have to be monitored to ensure that previously acceptable practices do not pose a threat to human populations.

Changing community health and cultural practices is a slow and difficult process. In a society where people normally bury their dead, it may be unthinkable to question whether this practice should continue. Yet, in island communities where changes in underground water levels are taking place and where the amount of land available for survival needs may be diminishing, the unthinkable may have to be considered and new solutions found which will be acceptable to the community.

Traditional health practices frequently make use of local plants or other resources and the availability of these resources may alter. In some situations, particular plants or trees could become more abundant or new species of plants enrich the local resource base. At the same time, other medicinal or sacred plants may become scarce or disappear entirely.

Nutritional changes

Climate warming and increased salinity in atoll acquifers and coastal swamps will bring about changes in the type and quantity of food resources. Nutritional adaptations will have to be made by local communities and there are implications also for the marketing and distribution of produce, within and between countries and regions of the world.

What are the likely adaptations which will have to be made? Once again there is no simple answer. For some groups, there may be a significant loss of land or of particular staple food crops. For others, improved food resources may actually mean a richer and more varied diet. Changes in subsistence food resources may lead to changes in agricultural methods and in household management practices. The introduction of sweet potato into what is now Papua New Guinea is an oft-quoted example of how earlier communities adopted a new food crop and how this affected their entire way of life. In more recent times, communities in areas where taro was the major root crop have had to change to other root crops when taro blight destroyed food gardens.

In many communities throughout the Pacific, cassava has taken over as a major staple and has displaced yams and taro which had been cultivated traditionally (see Thaman & Thomas, 1985 for a discussion of the new and important role of cassava). In addition, introduced Western foods are now predominant and preferred items in daily diets even where traditional crops are still grown. McCutcheon documents for Palau (1985:184) that: 'Taro remains an important symbolic element in a customary feast, but rice is usually served as well'. In the highlands of Papua New Guinea 'tinned fish and rice' are now bought with money earned from wage labour or from the sale of cash crops such as coffee or pyrethrum, and similar changes have occurred throughout the Region.

Yet, in areas where seasonal variations in the availability and quantity of food supplies create significant food shortages, management practices may involve decisions regarding who should eat first or who should go hungry. Higher levels of malnutrition have been reported among a number of island communities where population increases have put additional stresses on available food resources. In discussing the cultural 'value judgments' which will influence the management decisions which may have to be made, Payne observed that:

> Failure to meet the additional challenge of a bad year, with a concomitant shortage of food which coincides with peak labour needs, introduces a degree of uncertainty about the sustainability of the family in the future. This is important because malnutrition of any one member of a family may be either the result of such a chance event occurring, or the

initiating event which starts off a sequence of effects, ending with the death of several members, or perhaps with a decision to sell land, or to move, or even the destruction of the whole family. (Payne, 1985:79)

The uncertainty that periodic severe food shortages might indeed threaten the sustainability of the family was a major reason given by Carteret Islanders for their decision to resettle (O'Collins, this volume:247-270). In addition, those who decided to migrate to the Atolls Resettlement Scheme on Bougainville Island produce surplus food which is shipped back to the home islands to supplement the food produced there. [Food shortages continue to threaten the survival of those who remain on the Carterets. In March 1989, storms and high seas inflicted heavy damage on food gardens and the National Disaster Centre, in addition to providing emergency food supplies, discussed with the North Solomons Provincial Government the possibility of evacuating the islanders to Bougainville.]

Other groups may be able to develop strategies for more intensive use of existing land or adopt new crops or obtain food resources from outside the area which will sustain the population over time. Whatever decisions are made, it is clear that site specific solutions to nutritional needs will, as Brown points out (1985:238) 'have to be compatible with practices at the local level'. For example, in areas of low population density on mainland Papua New Guinea, appropriate management strategies may be quite different from those suitable for small islands. Pernetta and Osborne conclude that in a sparsely populated area such as the Fly River floodplain:

> The effects of sea level rise on the people living in the area are likely to be small. They are thoroughly accustomed to coping with dramatic fluctuations in water level, populations are low and food is abundant. (Pernetta & Osborne, this volume:215)

In other areas, where communities have only recently moved down to the coast, the affect of sea level rise may also be minimal, particularly if they have retained rights to land or natural resources further inland. For any impact assessment, the important site-specific variable will be the relative balance between the needs of the population, changing resource base, and people's access to resources.

Population pressure on existing resources

Prior to colonial contacts in the Pacific, many relatively isolated communities appeared to have been able to maintain populations at fairly stable levels. Available evidence suggests that culturally acceptable birth control practices were common throughout the Region and served to maintain a balance between population levels and available food resources. In some situations this was a rather fragile balance and migration histories are often linked to stories of environmental disasters. In his discussion of atoll populations, Bayliss-Smith points out that:

> ... the more extreme solutions of famine and emigration may operate only after the occurrence of disruptions to the 'normal' carrying capacity of the environment following such natural disasters as hurricanes and droughts. At other times some regulation of numbers occurs, enabling the population to remain below the level where food supplies become exhausted. (Bayliss-Smith, 1975a:293)

Following colonial contact, introduced diseases and labour migration threatened the population/resource balance which had been maintained, albeit somewhat precariously, throughout the Region. New contacts with the outside world brought devastating diseases which threatened the survival of many communities. Later, as Western medicine and health services were introduced, the decline in population was arrested. However, the accompanying breakdown of traditional birth control practices meant that fertility and infant survival rates increased, although food resources remained unchanged, or even declined. The depopulation and repopulation of Ontong Java (Bayliss-Smith, 1975b) reflects a similar demographic history to that of the Carteret Islands (O'Collins, this volume:247-270). [For further discussions of demographic changes in Pacific island populations see Carroll (1975), and Bayliss-Smith & Feachem (1977).]

In some communities, the carrying capacity of available land or marine resources has not been fully realised. Methods of resource utilisation, and ways in which land was divided between different sub-groups, may have been appropriate adaptations in the past. Today, however, as Nason (1975) indicates, changes in resource management techniques will be needed if the existing (or shrinking) resource base is to support a growing population. This is not a new experience for many societies and it is important not to underestimate the capacity of local populations to adapt to new challenges or periodic disasters. While accepting that 'arid drought prone, or overpopulated atolls are certainly marginal habitats', Bayliss-Smith (1977:327-328) has cautioned Western observers not to underestimate the balance which has so often existed: 'between resources and population, and the degree of fluctuation in productivity following droughts or hurricanes'.

A study of Bellona Island in the Solomon Islands (Christiansen, 1975) illustrates how small communities adapt to their environments and cope both with natural disasters and with those which are created by influences from outside their own system. Increasingly however, outside forces, whether accompanied by improved health services or new economic or technical innovations, have upset the balance between people and resources. This author questions whether:

> ... the improvement of the carrying capacity via the development of subsistence techniques will enable the increasing population to take their sustenance from the island or will force them to migrate. Or will a new form of population check reappear? (Christiansen, 1975:157)

In discussing the effect of sea level rise on coral and high islands, Sullivan (this volume:218-223) points to the serious potential impact for the densely populated Trobriand Islands where major loss of land at low elevations and fragmentation of island land masses will increase population pressure on the remaining area. As with other South Pacific societies, population management, as it was practiced in the past, appears to no longer exist and introduced family planning methods have not been adopted to any significant degree.

While some attempt has been made to develop appropriate alternative methods of birth control, population growth rates in excess of 3% have been recorded for a number of South Pacific countries or regions within countries. Any attempt to resettle over-crowded communities will need to take into account population growth rates as resettlement may not really ease the situation to any significant degree. The planned re-settlement of Carteret Islanders, for example, was based on original estimates which failed to take into account average family size. Many families have six or more dependent children and methods of spacing or limiting births are not commonly practiced (O'Collins, this volume:260).

<u>Migration, partial resettlement and permanent relocation</u>

> Each man must have some place, some land which belongs to him, which is his territory. If he does not control any land, he has no roots, status or power. In the extreme case this means he is denied social existence. (Bonnemaison, 1984:1).

The affect of sea level rise will inevitably be that a number of geographic communities or sections of a community will have to move to another location. In some situations, this may be a gradual process, but with important economic and social consequences, both for those who leave to form a new community and those who remain behind. Even for those groups whose relocation is only to nearby higher areas away from the coast, the economic and social impacts may be significant. Much will depend upon their relationship to other groups, the existence or acquisition of rights to land or to the use of other resources in the new area, and the affect which the shift in residence will have on economic productivity and lifestyles.

There are numerous examples of past migrations which have resulted in partial or permanent resettlement of Pacific island peoples. In some situations, as with the Carteret Islands, incoming migrant groups appear to have displaced or overwhelmed existing communities. In colonial and post-colonial times partial migration and resettlement has often been prompted by economic incentives or natural disasters. A collection of studies edited by Lieber (1975) distinguishes between 'exiles' who are unable to return to their homeland and 'migrants' who may have retained links with the home community, even if these ties have been weakened by time and distance. In many cases, the permanent nature of the new community may be denied as people prefer to think of themselves as 'temporary' migrants. In his description of one long-term migrant community, Tonkinson observed that:

> People in Maat continue to maximise their options by successfully exploiting the basic ambiguity of being temporary sojourners who are in fact long-term absentees or migrants - culturally Ambrymese on the one hand but locationally Efatese and firmly integrated into the urban economy on the other. This balancing act is not without strains and has implications for the maintenance of their present identity. (Tonkinson, 1985:141)

In some circumstances, partial or total resettlement will be a gradual process, involving increased out-migration of disproportionate numbers of younger members of the community. As Morauta (1984) has shown from her study of an area of high out-migration in the Gulf Province of Papua New Guinea, those who are left behind are more likely to be older, less economically active, and consequently more dependent on external support. In situations of increasing economic and social dependency, the amount of external support required may mean that the complete relocation of the remaining community becomes inevitable.

The decision to relocate is unlikely, however, to be accepted by all sections of the group as many will be extremely reluctant to abandon their ancestral land. Even when relocation has already taken place, this is not always a permanent and unchanging decision. Cultural and historic ties with the home island persist, despite what appears to outsiders to be the impossibility of returning 'home'. Where relocation has taken place because of external pressure and without a real decision to do so by the people, deep-seated group feelings of ambivalence and resentment are likely to persist.

## BIKINI AND ENEWETAK ATOLLS: A BITTER STRUGGLE FOR CULTURAL SURVIVAL

The negative consequences of externally planned resettlement are most dramatically and tragically illustrated from the experiences of the people of Bikini and Enewetak Atolls. Their 'temporary' relocation was to enable their islands to be used as nuclear test sites. The permanent damage and persistent contamination which resulted meant that they were unable to return home after the tests ended. Kiste described the physical, mental and social problems faced by the Bikinians in 1948 when they were moved from Bikini to Rongerik, then to Kwajalein and finally in Kili.

> No one fully appreciated the magnitude of the adjustments the islanders would have to make if they were to resettle on Kili successfully. Bikinians had always depended on the rich marine resources of their lagoon and had never devoted much time or effort to agriculture. (Kiste, 1977:88)

The Americans who planned this resettlement assumed that the Bikinians would be able to easily adapt to a new more agriculturally intensive way of life and there appeared to be little or no real understanding of the magnitude of the problem of adapting to a strange physical and social environment. In the decades that followed, the reality of relocation has profoundly changed the way in which this group deals with the outside world. They have also, not surprisingly, developed a 'deeply felt identity as a victimised people'(Kiste, 1985:117).

The magnitude of the change which had been forced on the Bikinians was replicated for the people of Enewetak. Prior to the commencement of nuclear testing and their relocation to Ujilang Atoll, the Enewetakese lived a self-contained isolated existence, heavily dependent upon marine resources and on the small land holdings which were passed on by parents to their children.

> The people had an almost mystical attachment to their land, and their ties to it were deep. They could trace the history of their holdings back about a half-dozen generations .... an individual's identity was, at least in part, defined by one's *wato* [land holding] and one's island of residence. (Kiste, 1987:19)

Once again, relocation did not take into account the needs or wishes of the people. They were given no choice but to accept the alternative location provided for them, an atoll previously considered unsuitable for habitation:

> Ujilang is 124 miles southwest of Enewetak. It had been inhabited by a Marshallese population, but in the late 1800s a typhoon decimated the atoll and killed all but a handful of its people, most of whom were moved to the southern Marshalls. (Kiste, 1987:21)

In 1980, after petitions to the United Nations, compensatory payments and prolonged legal action, Enewetak was returned to its people. However, the damage which had been inflicted meant that only some of the atolls could be inhabited with reasonable safety. The social and economic consequences of the contamination and environmental destruction will continue to be felt for many years to come.

## RESETTLEMENT AND CULTURAL IDENTITY: LESSONS FROM THE PAST

It would be easy to conclude that these are unique cases which, although devastating in human terms, are unlikely to be repeated in the post-independence Pacific. Yet, there are lessons for national and international planners which can be gained from an appreciation of the problems experienced when people are uprooted from their familiar environment. Even when people appear to have been 'fairly' compensated or to have been consulted regarding alternative possibilities for relocation their initial helplessness in the face of superior forces creates a deep and lasting sense of grievance and loss of cultural identity.

In their history of the British phosphate industry in the Pacific, Williams & Macdonald (1985) describe the various proposals regarding alternative homelands for the people of Nauru and of Ocean Island. In the final outcome, Nauru became an independent nation state while the Banabans settled on Rabi Island in Fiji. This island had been purchased on behalf of the Banabans but there was disagreement as to whether it should be seen as a complete or partial relocation of the people from Ocean Island. Although considerable discussions and negotiations did occur, the islanders felt that they were dominated by the overwhelming force of the administrative planning system. The ambivalent feeling of Banaban leaders was reflected in their rejection of the administrative officer appointed to supervise their resettlement.

> The official in question had, in fact, been chosen by Rotan and other Banaban leaders to supervise the resettlement scheme. Within months he had been rejected and was soon to be removed ... The fundamental issue was simple: the Island people(or at least their educated leaders) wished to be treated as equal human beings ... [and were] ... uncertain of their rights over the land they still owned, and what was due to them financially in this new situation. (Williams & Macdonald, 1985:345)

Before dismissing these examples as merely representative of colonial attitudes and not relevant for planning considerations today, it is useful to compare the experience of the Bikini, Enewetak and Banaban people in the 1940s with problems experienced by the Carteret Islanders on the Atolls Resettlement Scheme in Papua New Guinea in the 1980s. The establishment of this scheme in the North Solomons Province of Papua New Guinea was prompted by political and bureaucratic concern that communities living on a number of low-lying atolls were becoming increasingly dependent upon outside aid for their survival. The Carteret Islanders responded enthusiastically and a number of families have settled at the Scheme.

Despite their initial positive response, many settlers have complained about what they perceive as a lack of assistance from the project co-ordinator and government extension officers. A sense of discomfort that they are no longer in control of their environment and are dependent on outsiders appears to be a major cause for the dissatisfactions which are expressed. As one settler explained:

> ... people were afraid they would lose their rights to the little land that was available on the islands and ultimately be left without land rights at all. While he could see that eventually they would have to leave their islands and it was better to put pressure on the Provincial Government to take immediate action to secure agricultural land for cash crop development, others had become tired of waiting. Waiting in a sense, just as they had waited back on the Carterets for the Atolls Enterprise to come, bringing supplies. (O'Collins, this volume:267)

## CONCLUSION: PLANNING FOR AN UNCERTAIN FUTURE

This paper has outlined some of the likely social and cultural impacts which should be considered in future local, national and regional planning for populations affected by climate change and sea level rise.

Local populations will need to adjust their life styles and management practices in relation to levels of comfort, education and health needs, and changes in land and marine resources. Traditional methods and local knowledge may not be appropriate and new strategies for making maximum use of available resources must be developed. External assistance will probably be required to enable both residents and urban and rural extension workers to respond appropriately to changes as they occur.

In some situations this may actually lead to innovative and more productive use of the existing resource base. For example, if mariculture and aquaculture techniques were successfully introduced to an atoll lagoon this may make it possible to sustain larger populations. It may even be possible to export food surpluses to less productive areas. More intensive sustainable management practices may make it possible for relatively small areas of land to support existing populations. More imaginative changes could involve the development of new varieties of seaweed, of taro which can be grown in a more saline water lens, or rafts on which food crops can be grown in the lagoon.

While, as Nunn (this volume:146) concludes, 'forward planning would offset the enormity of the impact', for many groups 'there appears to be no feasible way of avoiding the impact of future sea level rise'. For a number of island communities, partial or complete relocation may be the only long term solution.

There is often a temptation to think only in stark alternatives such as 'fight or flight': stay while the water engulfs one's homeland or abandon completely the land of one's ancestors. Often the process will be mixed with some possibility of changing land usage for those who remain, some movements back and forth between a re-settlement area or areas and the homeland and some permanent relocation.

The experience of the Carteret Islanders (O'Collins, this volume:247-270) has shown that it may not be possible to fully anticipate the massive change in lifestyle which will occur following the move from a self-contained isolated island home. For some communities or larger groups, relocation has and will mean a gradual abandonment of cultural identity and even their very existence as an independent nation state. Planners will have to be aware that each situation will have to be assessed over time and that there is no model which can completely predict the future impact of climate change and sea level rise on particular peoples. This gives added weight to the conclusion by Brookfield and Bedford that:

> The real meaning of population and environmental planning is therefore the need to anticipate, or at least allow for, the unexpected. This is true at all levels of planning, but is of greatest significance in translating plans to small areas, and to individual projects. (Brookfield & Bedford, 1980:222)

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# POTENTIAL IMPACTS OF PROJECTED SEA LEVEL RISE ON PACIFIC ISLAND STATES (THE COOK ISLANDS, FIJI, KIRIBATI, TONGA AND WESTERN SAMOA): A PRELIMINARY REPORT

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## INTRODUCTION

The work discussed in this first of two reports is the result of investigations by the University of the South Pacific team in co-operation with governmental contacts in urban centres as follows: Suva, Labasa and Savusavu (Fiji), Apia (Western Samoa), Nuku'alofa and 'Ohonua (Tonga) and Tarawa (Kiribati). Interviews with government officials and others in appropriate positions were carried out by all researchers. Copies of the instructions given to student assistants engaged in data source identification, data acquisition and interviewing can be obtained by writing to the author at the Department of Geography, University of the South Pacific, P.O. Box 1168, Suva, Fiji.

Most authorities believe that sea level will rise over the next hundred years perhaps by as much as 3.5 m as the result of the so-called 'greenhouse effect'. The consequences of this sea level rise on Pacific islands will be substantial and should be the subject of some forward planning. The aim of the work reported below was to seek some indication of the nature of these effects. Since the project was initiated only in November 1987, the results reported are not as wide-ranging or as detailed as those which would eventuate from a longer-term study.

The most visible and probably the most immediate effect of sea level rise on Pacific island coasts will be in terms of land loss. This is also one of the easiest effects to predict accurately and thus formed a large part of the work carried out.

## METHODS OF INVESTIGATION

Over such a short time period as was set for the preliminary investigation no field surveys to produce original data were contemplated, and the main source of information was maps at suitable contour intervals. Linear interpolation between existing contours and map datum, supplemented by a particular investigator's knowledge of the area covered by the map, allowed the construction of four contours each representing a time-dependent scenario of future sea level rise as follows.

(a) Contour at 20 cm (0.2 m) or 0.67 feet (8 inches); the medium scenario for the year 2025.

(b) Contour at 50 cm or 1.5 feet (1 foot, 8 inches); the high scenario for the year 2025.

(c) Contour at 1.5 m or 5 feet; the medium scenario for the year 2100.

(d) Contour at 3.5 m or 11.5 feet; the high scenario for the year 2100.

For this work, it was necessary to find maps with an existing contour interval equal to or less than 5 m or 15 feet in order to allow linear interpolation to proceed and the contours named above (a-d) to be constructed. Once contours at these intervals had been constructed, it was possible to quantify impact in terms of the area of land loss. To do this, student researchers counted squares on graph paper of specified size between each constructed contour and map datum; squares were converted to square kilometres or metres by the senior researchers using maps scales. Each area was then divided on the basis of land-use types to enable the quantitative impact to be presented in terms which are readily convertible to measures of economic impact. These methods are detailed in the instructions given to students and the results are discussed below.

DATA SOURCES AND DATA ACQUISITION

The biggest problem encountered in this study was finding suitable maps. Ministries of Lands and Surveys in the various countries of the study region yielded little suitable material. Among the urban areas investigated, only Nuku'alofa and Suva apparently had map coverage at 1:1,000 with suitable contour intervals. No maps of rural areas in any of the countries under study could be found at suitable scales, although unpublished geomorphological maps made for other purposes allowed some useful studies of small islands in Fiji to be made. Had more time been available, approaches to some of the large 'resorts' along the inlands' coasts may have been profitable in this context, as may have been contact with consulting architects and engineers, based both within and outside the region, who have worked on particular projects.

In many cases, the map datum and method of contour construction were not specified on the map so careful checks were carried out to ensure that the contours were realistic. Where map datum was unspecified, it was assumed to be mean high water; on most islands in the region under study, this level is approximately 0.5 m above mean sea level, the most common global map datum.

On few maps was it possible to calculate the 0.2 m and 0.5 m contours. In urban areas, the presence of sea walls commonly rendered these contours coincident with map datum.

The precision of data resulting from square counting within areas bounded by constructed contours and map datum is dependent in the final instance on the accuracy of the original map and the precision with which the existing contours were constructed. In many cases it is not possible to assess this meaningfully although an accuracy rating is given for all the results as a rough guide to data quality.

Much time was spent by project investigators searching through vast collections of unpublished maps, often uncatalogued, and visiting various governmental and non-governmental agencies in the hope of finding suitable material. The time spent in this activity would not need to be repeated were this project to be continued in more detail in the future since optimum data sources have been identified. In Fiji, Tonga and Western Samoa, these were the Ministries of Lands and Survey (or similar). A comprehensive search of the Kiribati government archives in Tarawa by a student researcher revealed no suitable maps, although it is possible that such are kept elsewhere, in New Zealand or Australia for example.

The maps used in this study were, in most instances, made freely available to researchers, and it is a pleasure to acknowledge the help, co-operation and interest of the various bodies concerned.

RESULTS

The results of the work on land loss and other impacts of sea level rise are presented below as a series of separate case studies. The land-use catergories used in Table 1-13 are defined as follows -

(a) Agricultural (including grasslands).

(b) Forest (including areas of widely-spaced trees, such as coconut palms, not otherwise classifiable).

(c) Mangroves (including swampy areas not otherwise classifiable).

(d) Residential (including settlements with wide-spaced houses not otherwise classifiable).

(e) Industrial.

(f) Commercial.

(g) Others (as specified).

Most of the case studies described below were chosen because they are representative of a particular set of geographical conditions and the conclusions drawn concerning the impact of future sea level rise may therefore be applied to similar situations. The case studies and the situations they typify are as follows -

Rarotonga, Cook Islands

High volcanic island with extensive coastal plain fringed by a beach ridge: only a fringing reef offshore (similar to Moorea and Tahiti Nui, French Polynesia, Savai'i in Western Samoa, Kadavu in Fiji).

Beqa, Fiji

Small volcanic island with narrow coastal plain, highly variable offshore reef configuration.

Cicia, Fiji

Small volcanic island with peripheral (*makatea*) limestone; only a fringing reef offshore (similar to Lakeba in Fiji, Rurutu in the Austral Islands, Mangaia and Aitutaki in the Cook Islands).

Moala, Fiji

Large volcanic island with narrow coastal plain and both fringing and barrier reef offshore.

Vatoa, fiji

Moderate height limestone island with upland agriculture and variable offshore reef configuration (similar to Niuatoputapu, Tonga).

Vatulele, Fiji

Low limestone island with lowland, often swampland, agriculture; variable offshore reef configuration (similar to many true atolls, also Vava'u and Tongatapu in Tonga).

Labasa, Fiji

Town at delta head threatened both by shoreline retreat and impounding of sediment in narrowly-constricted valleys (similar to many smaller settlements on Viti Levu and Vanua Levu in Fiji, and on Upolu in Western Samoa).

Savusavu, Fiji

Town developed along narrow coastal plain threatened by impounding of steep narrow valleys at its rear as well as shoreline retreat (similar to many settlements on Viti Levu and Vanua Levu in Fiji, and in parts of Vanuatu and Solomon Islands).

Tarawa, Kiribati

Ribbon atoll (similar to most others in Tuvalu and Kiribati, the northern Cook Islands, and the island motus of French Polynesia and elsewhere).

Nafanua, Tonga

Artificial harbour threatened from rear but considerable protection afforded already by naturally steep cliff character of the shoreline (similar to cliffed limestone coasts elsewhere in Tonga, on Tongatopu and Vava'u for instance, in the southern Cook Islands and eastern Fiji).

Nuku'alofa, Tonga

Large urban centre to be considered a case by itself.

Apia, Western Samoa

Large urban centre to be considered a case by itself.

Cook Islands - Rarotonga

Suitable contour maps of the Cook Islands were not sufficiently detailed to allow anything other than the construction of the 1.5 m contour (Figure 1, Table 1), and data quality is not high. Undoubtedly higher-quality data could be found on the island itself.

Rarotonga is a high volcanic island with a comparatively narrow, intensively farmed and densely populated coastal plain. This is fringed by a beach ridge reaching 4-5 m above sea level, which is important in preventing inundation of the inner parts of the coastal plain, where most development is located. Much of the area below 1.5 m is agricultural, a large amount of staple food crops being grown here in swamp areas.

Although 17.11% of the lowland area on Rarotonga lies below 1.5 m, far greater amounts of land would be lost were sea level to rise this much because of lateral erosion of the largely unconsolidated and/or permeable materials of which this coastal plain is composed. A rise in sea level causes shoreline disequilibrium. Equilibrium will be restored through lateral erosion which would be needed if the original (pre-sea level rise) equilibrium shoreline profile were to be established at a higher level.

Fiji - Beqa Island

Data sources for Beqa (Figure 2, Table 2) are reasonable and have been supplemented by direct field observation. Beqa is a small high volcanic island with a very narrow coastal plain in most places. The coincidence of villages with area of future inundation indicates the critical shortage of low, flat land, which will obviously be exacerbated as sea level rises.

The low areas at the heads and along the sides of bays are mostly mangroves and not extensively used for agriculture at present. The amount of inundation shown in these area for different scenarios is unlikely to be realised since most of the island's large rivers debouch into these bays and sea level rise will greatly increase sedimentation therein, perhaps causing the bays to become infilled.

Villages on Beqa will all, with the possible exception of Rukua, suffer from the effects of sea level rise; 79.41% of them would be inundated by a 3.5 m rise. A substantial acreage of gardens and forest, mostly coconut palms, is also threatened. The solutions are obviously a gradual change from lowland to upland village sites and increased utilisation of the agricultural potential of upland areas.

Inundation of the offshore reef (not shown in Figure 2) will cause increased wave attack along the island's south and southeast coasts. Most of the Beqa lagoon lies off the island's northwest coast and changes in lagoon circulation caused by sea level rise will have serious consequences for fishing.

Fiji - Cicia Island

Form-line maps of Cicia supplemented by field data were sufficient to allow construction of the 3.5 m contour (Figure 3, Table 3), which is coincident in most places with that at 1.8-2.5 m. This point represents the shoreline established 4-6,000 years ago when the sea first reached its present level after the long Holocene postglacial transgression.

Over 75% of Cicia's settlements would be affected by a 3.5 m rise. Only the higher parts of Tarakua and Mabula, which are overflow settlements from the original sites on the crowded coastal plains, would be relatively untouched.

The central part of Cicia is volcanic but the island is fringed in places by uplifted reef limestone (the makatea of Polynesia), areas which are already undermined and would be further affected by future sea level rise. Increased sedimentation would be accommodated in what are presently the middle reaches of the main valleys, inland from the west coast and Lomati village. The major commercial copra plantation at Tokalau will be lost completely even if the sea rises only 1.5 m.

Those parts of the coastal plain which are under greatest threat from compensatory lateral erosion associated with sea level rise are southwest of Mabula, behind Naceva-Tokalau and between Lomati and Tarakua.

Table 1. Impact of future sea-level rise on Rarotonga, Cook Islands, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Rarotonga is 66 sq.km (see Figure 1). The last column on the right refers to the 1.5m scenario only. Accuracy rating for Rarotonga data is medium to low.

| Type of land loss | Scenario 0.2 | 0.5 | 1.5 | 3.5 | % total in each category |
|---|---|---|---|---|---|
| Agricultural | ? | ? | 0.83 | ? | ? |
| Forest | ? | ? | 0.31 | ? | ? |
| Mangroves | ? | ? | 0.20 | ? | ? |
| Residential | ? | ? | 0.58 | ? | ? |
| Industrial | ? | ? | ? | ? | ? |
| Commercial | ? | ? | ? | ? | ? |
| Others | ? | ? | ? | ? | ? |
| Total land loss | ? | ? | 1.92 | ? | |
| % total land area | | ? | 2.91 | ? | |
| % total lowland area | | ? | 17.11 | ? | |

Sources of data: Lands and Survey Department, Cook Islands, 1982, 1:15,840 topographic map of Rarotonga, 3rd edition

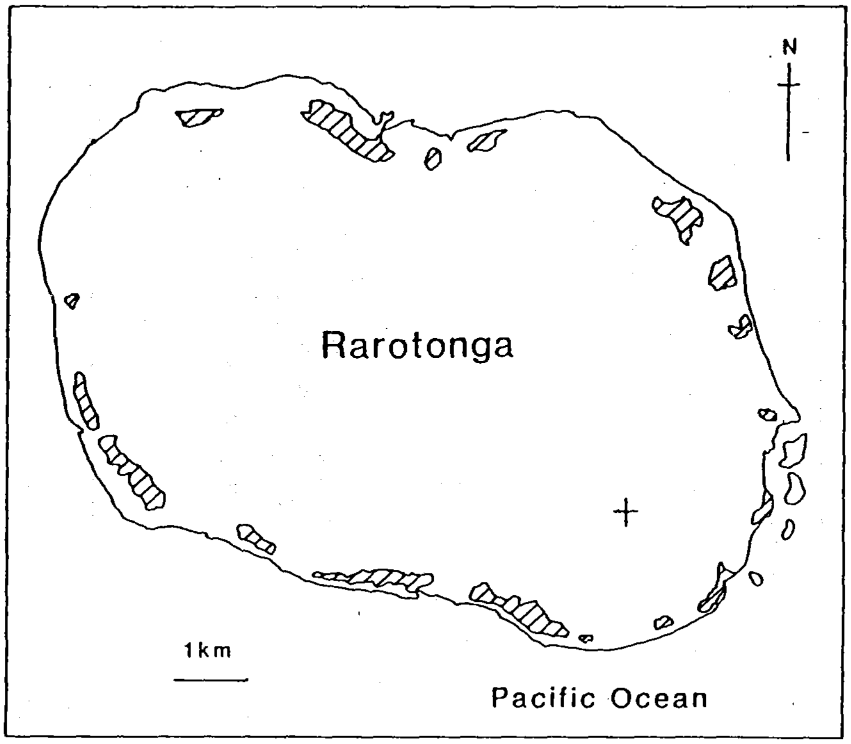


Figure 1. Island of Rarotonga in the Cook Islands showing land below 1.5m (stipple). The cross marks the point 159°45'W, 21°15'S. The main population centre is Avarua in the centre of the north coast with the international airport just to its West. The island is surrounded by a fringing reef.

Table 2. Impact of future sea-level rise on Beqa island, Fiji, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Beqa is 36.26 sq.km (see Figure 2). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Beqa data is medium.

| Type of land loss | Scenario 0.2 | 0.5 | 1.5 | 3.5 | % total in each category |
|---|---|---|---|---|---|
| Agricultural | ? | ? | 0.04 | 0.40 | ? |
| Forest | ? | ? | 0.15 | 0.29 | ? |
| Mangroves | ? | ? | 0.82 | 0.82 | 100.0 |
| Residential | ? | ? | 0.13 | 0.27 | 79.41 |
| Industrial | 0 | 0 | 0 | 0 | 0 |
| Commercial | 0 | 0 | 0 | 0 | 0 |
| Others - sand | ? | ? | 0.15 | 0.42 | 80.0 |
| Total land loss | ? | ? | 1.29 | 2.20 | |
| % total land area | ? | ? | 3.56 | 6.07 | |

Sources of data: Department of Lands, Mines and Surveys, Fiji, 1961, 1:50,000 topographic map (Viti Levu sheet 22); field survey, P.D. Nunn (1988)

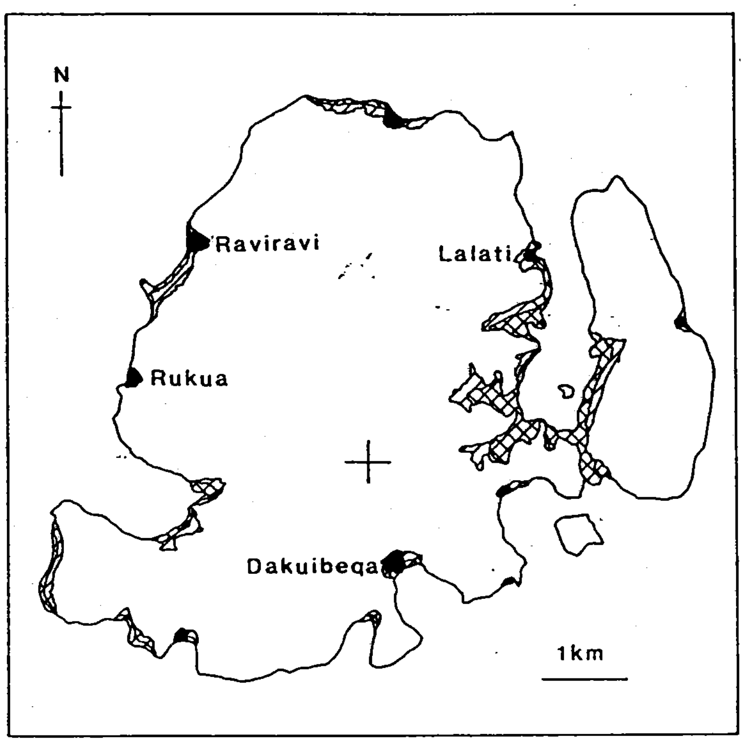


Figure 2. The island of Beqa (Mbengga) in Fiji showing the land below 3.5m (stipple), land below 1.5m (cross-hatch), and settlements (solid). The cross marks the point 178°08'E, 18°24'S. The island is surrounded by a fringing reef ton the South and East, and a barrier reef to the North and West.

Table 3. Impact of future sea-level rise on Cicia island, Fiji, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Cicia is 34.6 sq.km (see Figure 3). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Cicia data is medium.

| Type of land loss | Scenario 0.2 | 0.5 | 1.5 | 3.5 | % total in each category |
|---|---|---|---|---|---|
| Agricultural | ? | ? | 0.2 | 0.6 | 8.0 |
| Forest | ? | ? | 0.35 | 1.71 | 30.0 |
| Mangroves | ? | ? | 0.95 | 0.95 | 100.0 |
| Residential | ? | ? | 0.2 | 0.5 | 76.6 |
| Industrial | 0 | 0 | 0 | 0 | 0 |
| Commercial | 0 | 0 | 0.05 | 0.3 | 80.0 |
| Others - sand | ? | ? | 0.12 | 0.77 | ? |
| Total land loss | ? | ? | 1.87 | 4.83 | |
| % total land area | ? | ? | 5.40 | 13.96 | |

Sources of data: Department of Lands, Mines and Surveys, Fiji, 1958, 1:31,680 map (2 inch series); unpublished geomorphological maps and field notes by P.D. Nunn and S. Lutubula, 1986

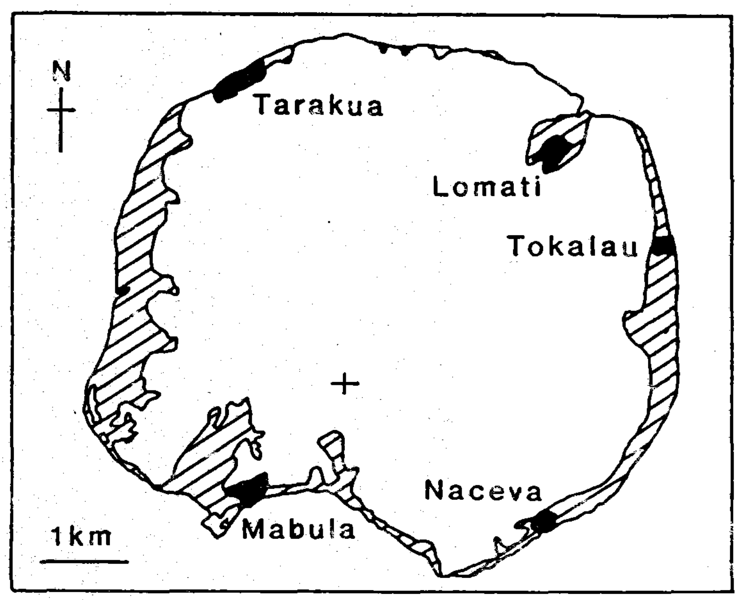


Figure 3. The island of Cicia (Thithia) in eastern Fiji showing the land below 3.5m (stipple) and settlements (solid). The cross marks the point 179°20'W, 17°45'S. The airstrip is built on reclaimed land below 1.5m in the central part of the island's West coast.

Moala Island

Mapping of shorelines on Moala (Figure 4, Table 4) depended heavily on unpublished field notes and geomorphological maps, and data quality, although variable, is quite good. Moala is a large, high volcanic island with only a narrow coastal plain in most places, from which most villages have spilled over onto higher ground.

Outside the villages, most of the narrow strip of coastal lowland is used intensively for agriculture and a significant amount of copra would be lost were sea level to rise 1.5 m. Many villages depend on copra plantations located outside settlements, such as southeast of Vadra, for cash income.

Much of the rest of the island's cash income comes from *yagona* (*Piper methysticum*) and staples such as yam (*uvi*) which are grown in the island's cooler, higher parts. These are the usual growing areas for these important crops on other small Pacific islands and their availability could be seriously curtailed by the rise in temperature of 1.5°-5.5°C which is the primary predicted consequence of the 'greenhouse effect'.

The presence of both a barrier and fringing reef around Moala means that the coastline is well protected at present from aggressive coastal erosion. The effects of the removal of this protection would be analogous to those where there are presently gaps in the reef, such as west of Naroi.

Very few maps exist of Vatoa (Figure 5) but a reasonable picture has been built up from sources cited (Table 5). The island is presently well protected by reef which lies close to its southeast-facing coasts and fringes a lagoon off Raviravi.

Vatoa is composed wholly of limestone and reaches a maximum height of around 45 m. Most of the direct land loss resulting from sea level rise will be in the main copra-growing areas, which will affect the island's cash economy. Although a little upland agriculture is practised at present, this must clearly be increased to counter the effect of land loss, although the lithology is not conductive to intensive cultivation.

Erosion on the island's limestone (southeast-facing) coasts will increase greatly as sea level rises. On the (northwest-facing) sandy coasts, this will be preceded by removal or redistribution of existing beaches.

It appears possible that Vatoa is one kind of island where permanent settlement may have to be abandoned as sea level rises.

Fiji - Vatulele Island

Unpublished geomorphological maps of Vatulele were of great assistance in constructing the 1.5 m and 3.5 m contours (Figure 6 and Table 6). Vatulele is a low (maximum height 36 m) limestone island with a fringing reef close to the cliffed west coast and a barrier reef some 2-3 km off the low east-facing coast.

A 1.5 m sea level rise would not produce substantial land loss directly owing to the presence of a coastal dune ridge parallel to and adjoining the east coast. Those areas which would be affected directly would be the marshy flats inland where *taro* (*dalo*) and other staples are grown in comparative abundance. Most of the island's worked copra resources lie atop the dune ridge which would be unaffected directly.

The picture is obviously more severe for a 3.5 m sea level rise which would inundate the dune ridge, the island's main settlements and most of its present agriculturally-productive area. As with Vatoa, this might result in permanent settlement on Vatulele being abandoned.

The effective removal of reef barriers would amplify the already high-energy erosional regime of the island's west coasts and would cause accelerated retreat of the east coast. For these reasons, the shorelines shown in Figure 6 should be regarded as conservatively drawn; they represent the theoretical starting point of a rapidly adjusting (retreating) shoreline profile.

Table 4. Impact of future sea-level rise on Moala island, Fiji, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Moala is 62.12 sq.km (see Figure 4). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Moala data is medium to high.

| Type of land loss | Scenario 0.2 | 0.5 | 1.5 | 3.5 | % total in each category |
|---|---|---|---|---|---|
| Agricultural | ? | ? | 0.17 | 0.29 | 15.0 |
| Forest | ? | ? | 0.25 | 0.58 | 9.0 |
| Mangroves | ? | ? | 1.92 | 1.92 | 100.0 |
| Residential | ? | ? | 0.20 | 0.34 | 39.53 |
| Industrial | 0 | 0 | 0 | 0 | 0 |
| Commercial | 0 | 0 | 0.04 | 0.04 | 90.0 |
| Others - sand and rock | ? | ? | 0.20 | 0.71 | ? |
| Total land loss | ? | ? | 2.78 | 3.88 | |
| % total land area | ? | ? | 4.48 | 6.25 | |

Sources of data: Mineral Resources Division, Fiji, 1976, Geology of Moala, Matuku and Totoya; unpublished geomorphological maps and field notes, P.D. Nunn, 1986-1987.

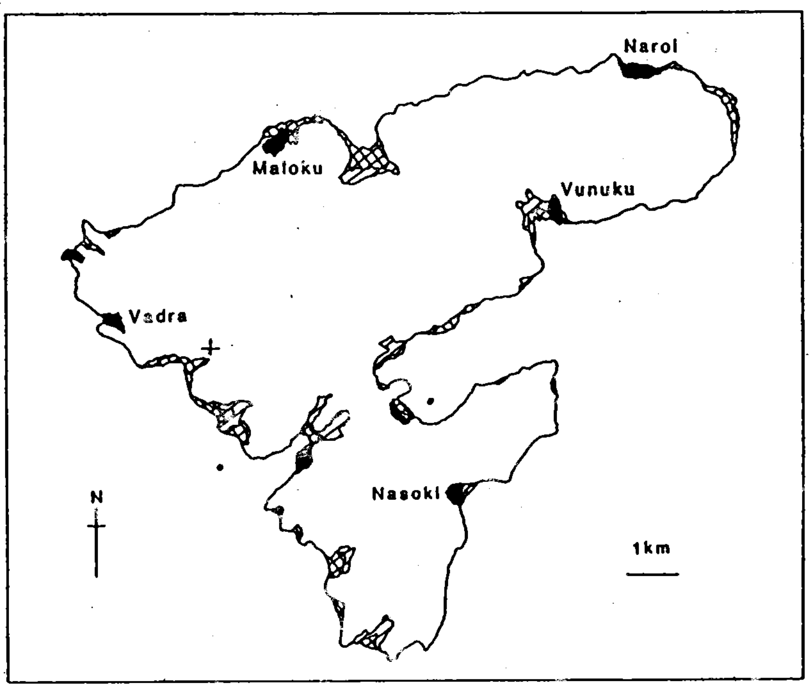


Figure 4. The island of Moala in Fiji showing the land below 3.5m (stipple), the land below 1.5m (cross-hatch) and the villages (solid). The cross marks the point 179°52'E, 18°36'S. The airstrip is on the easternmost extremity of the island, all below 3.5m. A fringing reef and barrier reef are continuous around most of the island.

**Table 5. Impact of future sea-level rise on Vatoa island, Fiji, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Vatoa is 4.45 sq.km (see Figure 5). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Vatoa data is medium to low.**

| Type of land loss | Scenario 0.2 | 0.5 | 1.5 | 3.5 | % total in each category |
|---|---|---|---|---|---|
| Agricultural | 0 | 0 | 0 | 0 | 0 |
| Forest | ? | ? | 0.39 | 0.61 | ? |
| Mangroves | 0 | 0 | 0 | 0 | 0 |
| Residential | ? | ? | 0.04 | 0.09 | 64.29 |
| Industrial | 0 | 0 | 0 | 0 | 0 |
| Commercial | 0 | 0 | 0 | 0 | 0 |
| Others | | | | | |
| - sand | ? | ? | 0.02 | 0.04 | ? |
| - bare rock | ? | ? | ? | 0.18 | ? |
| Total land loss | ? | ? | 0.45 | 0.92 | |
| % total land area | ? | ? | 10.11 | 20.67 | |

Sources of data: L.E.A. Patterson, 1967, Topographical Survey of Vatoa Island, Sth Lau Group (1:4,800).

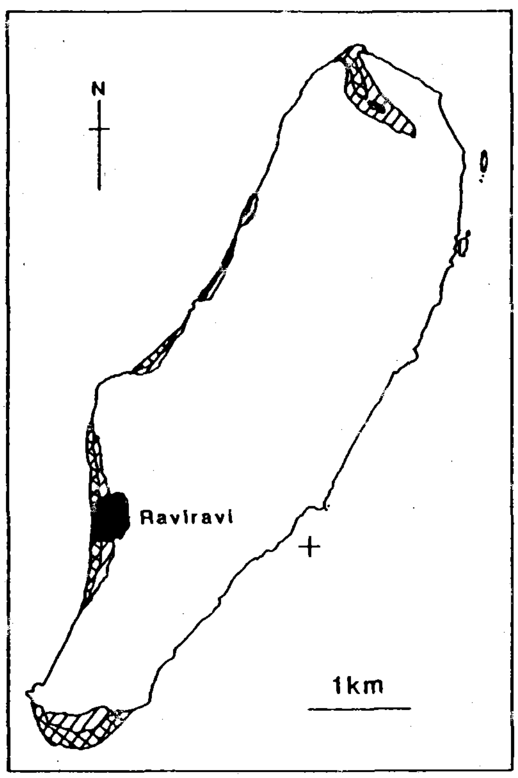


Figure 5. The island of Vatoa in southeast Fiji showing the land below 3.5m (stipple), the land below 1.5m (cross-hatch), and the villages (solid). The cross marks the point 178°13'W, 19°50'S.

After decades of getting drinking water from shallow wells, often contaminated with sea water, each village on Vatulele has recently switched to rainwater roof-catchments, which is clearly the type of move similarly-situated island communities should make.

Fiji - Labasa town

Labasa is the largest urban centre on Vanua Levu island in Fiji and has important functions as a port, primarily for export of cash crops, especially sugar cane. Labasa (Figure 7) is located close to the head of a large delta, the productive parts of which are protected by a number of sea walls. Three large river systems - the Wailevu, Labasa and Qawa - empty into this delta and in their alluvial valleys bounded by the lowest break of slope in Figure 7, most of the sugar cane in the immediate area is grown. Figure 7 shows the 1.5 m and 3.5 m contours reconstructed as permitted by map coverage of the area.

The Wailevu, Labasa and Qawa have been contributing sufficient sediment to the Labasa coast to enable it to prograde over the last few millennia. Were sea level to rise, the main effect in terms of land loss would be the landward movement of the present shoreline. This would also cause river sediment and water to become impounded in the Wailevu, Labasa and Qawa valleys, an effect which would leave the site of Labasa itself virtually uninhabitable. It would also adversely affect the productivity of the valleys which, like so many along Viti Levu's north coast, provide the main element in the island's cash economy. As sea level began rising in the area, the first noticeable effect would be an increase in large-magnitude flood frequency in the valleys, which would cause increased annual failure of the sugar cane and short-term enrichment of the alluvial carpet.

The impact in terms of land loss on Labasa town itself (Figure 8, Table 7) was determined from detailed land-use mapping on good quality base maps. Nearly 90% of the town would be inundated in the 3.5 m scenario, but the site would obviously be abandoned long before the sea level reached that height, for reasons stated above. With such a large coastal frontage, abandonment of the site appears the only feasible option. The high ground immediately to the north of the present town would be suitable for relocation.

Fiji - Savusavu town

Savusavu is located on the southern side of Vanua Levu island, across from Labasa (see above). It is smaller than Labasa, although of proportional importance to its hinterland, and stretched along a narrow coastal plain. As such it is typical of many settlements on islands where there are no extensive coastal flats available for settlement. It should be noted that data in Table 8 referring to Figure 9 are in square metres, not square kilometres as with the other tables.

Although nearly half the town would theoretically be inundated were sea level to rise 3.5 m (Table 8), the impounding of sediment behind the landwards-retreating shoreline would cause greater problems to the town area presently lying above 3.5 m. These would be manifested as an increase in the extent and frequency of large-magnitude floods and mass movement events such as landslides.

Kiribati - Tarawa atoll

Although no direct original information about the impact of future sea level rise in Kiribati could be obtained, owing to a lack of primary sources, it is clear that Tarawa atoll, where the capital Bairiki is situated, exemplifies the island type.

Since most mid-ocean (oceanic) atolls do not rise much above 3.5 m, the impact of a sea level rise of that magnitude on land area will clearly be greater than for any other case study presented in this report. The small size of the motus, or sand-reef islets, will render artificial shoreline protection prohibitively expensive.

Table 6. Impact of future sea-level rise on Vatulele island, Fiji, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Vatulele is 31.57 sq.km (see Figure 6). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Vatulele data is medium to high.

| Type of land loss | Scenario 0.2 | 0.5 | 1.5 | 3.5 | % total in each category |
|---|---|---|---|---|---|
| Agricultural | ? | ? | 0.19 | 0.95 | 31.1 |
| Forest | ? | ? | 0.52 | 1.65 | 26.77 |
| Mangroves | ? | ? | 0.01 | 0.03 | 100.0 |
| Residential | ? | ? | 0.03 | 0.34 | 96.0 |
| Industrial | 0 | 0 | 0 | 0 | 0 |
| Commercial | 0 | 0 | 0 | 0 | 0 |
| Others - sand and bare rock | ? | ? | 0.33 | 0.73 | c40.0 |
| Total land loss | ? | ? | 1.08 | 3.70 | |
| % total land area | ? | ? | 3.42 | 11.72 | |

Sources of data: Government of Fiji, 1986, 1:50,000 topographic map, FMS 31 M 30, Government Printer, Suva; unpublished maps and field notes, P.D. Nunn, 1985-1987

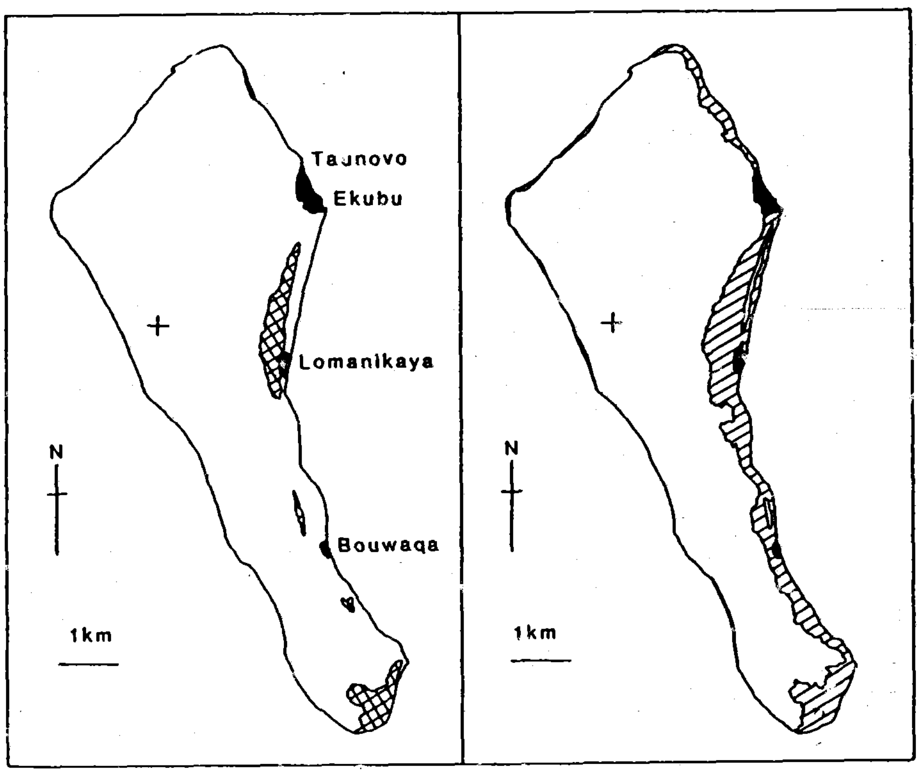


Figure 6. The island of Vatulele in Fiji showing the land below 1.5m (cross-hatch in left-hand diagram) and the land below 3.5m (stipple in right-hand diagram). Villages are shown as solid shading. The cross in both diagrams represents the point 177°37'E, 18°32'S.

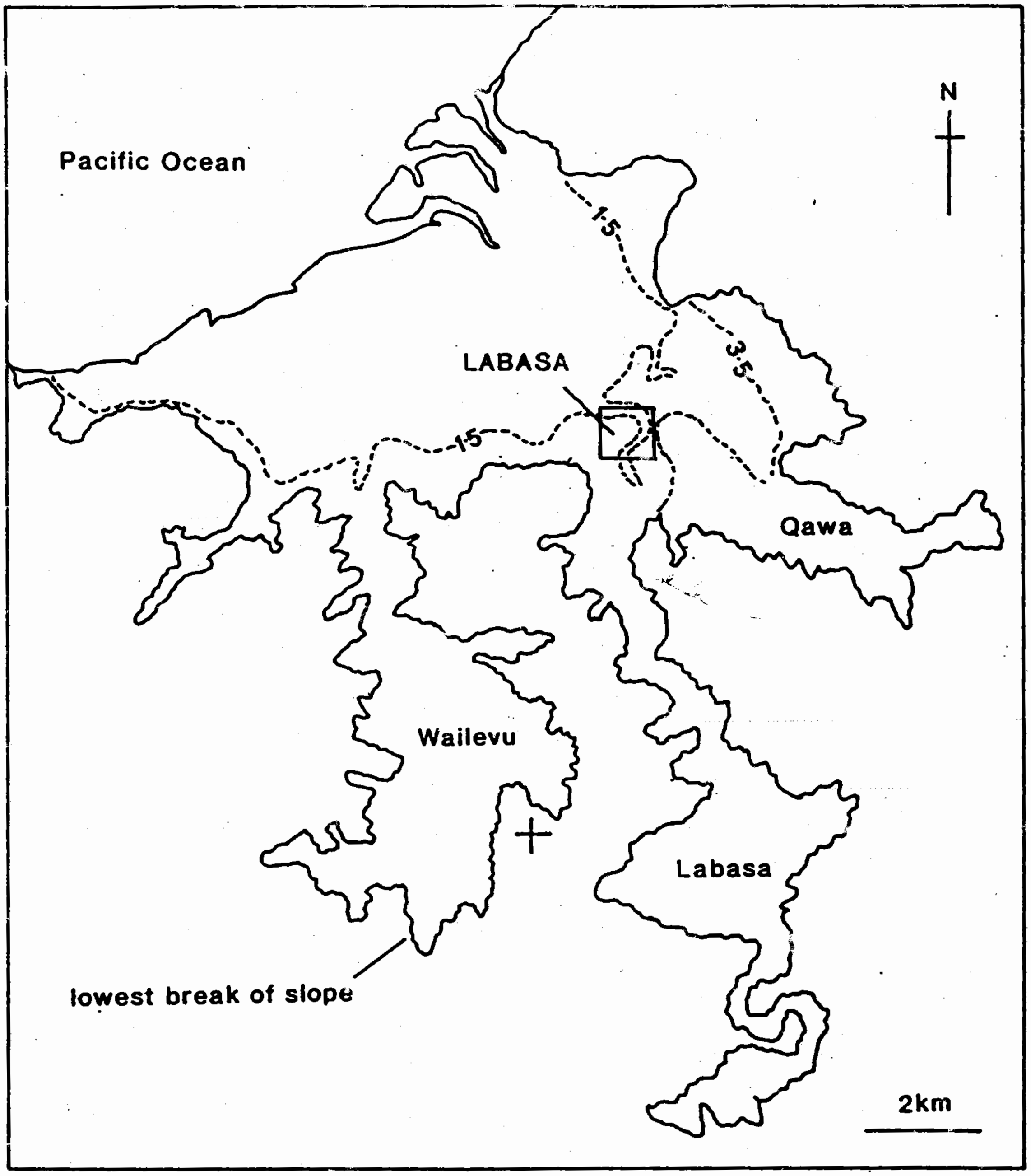


Figure 7. The Labasa area, northern Vanua Levu, Fiji, showing the 1.5m and 3.5m shorelines, and the three main valleys feeding the delta, bounded by the lowest slope break, which represents the approximate upper limit of alluvium and intensive commercial cultivation. For details of Labasa town, see Figure 8. The cross represents the point 179°21'30'E. 16°30'S.

Table 7. Impact of future sea-level rise on Labasa town, Vanua Levu, Fiji, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Labasa is approximately 0.28 sq.km (see Figures 7 and 8). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Labasa data is high.

| Type of land loss | Scenario 0.2 | 0.5 | 1.5 | 3.5 | % total in each category |
|---|---|---|---|---|---|
| Agricultural | 0 | 0 | 0 | 0 | |
| Forest | 0 | 0 | 0 | 0 | |
| Mangroves | 0 | 0 | 0 | 0 | |
| Residential | ? | ? | 0.015 | 0.054 | |
| Industrial | ? | ? | 0.002 | 0.006 | |
| - port-related | ? | ? | 0.031 | 0.048 | |
| Commercial | ? | ? | 0.010 | 0.104 | |
| Others - services | ? | 0.002 | 0.019 | | |
| - open space | | ? | 0.004 | 0.006 | |
| - education | | ? | 0.008 | 0.014 | |
| Total land loss | ? | ? | 0.072 | 0.251 | |
| % total land area | ? | ? | 25.71 | 89.64 | |

Sources of data: Ministry of Lands, Fiji, 1968, Plans of Labasa and surrounding area (1:1,584); supplementary information by B. Masianini.

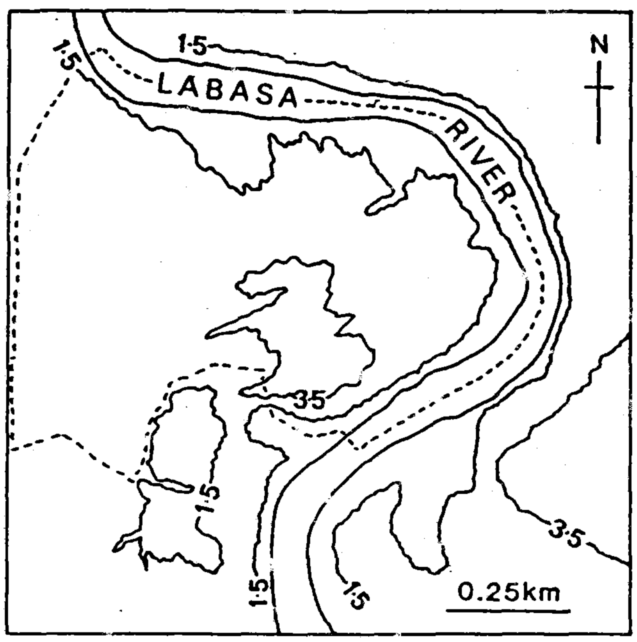


Figure 8. Labasa town, Fiji (see also Figure 7) showing the 1.5m and 3.5m contours. The river flows northwards, the broken line represents the town boundary.

Connections between motus, such as the Betio-Bairiki causeway on Tarawa, will be increasingly subject to severe erosion and periodic inundation as sea level begins rising and may quickly be rendered unusable.

The inundation of the atoll reefs offshore will result in greater wave energy on the shoreline and a reduction in the supply of reef-rock debris to the shoreline; both effects will cause a sharp increase in the erosion of the ocean-facing sides of motus.

The high reliance of atoll communities on groundwater for drinking and for agriculture, especially in pits dug down into the freshwater lens, must be lessened if the sea level rise is not to necessitate abandonment of the atolls within the next 50 years; reduction in volume of the lens will otherwise have disastrous effects.

The scenarios of impact on atolls are the most severe discussed and it is recommended that immediate plans for resettlement are drawn up by the appropriate authorities.

Tonga - Nafanua harbour

The harbour here (Figure 10) is largely artificial and was constructed to serve the needs of the island of 'Eua, of which 'Ohonua is the largest settlement. The design of the harbour with a wharf 2 m in height appears able to accommodate a sea level rise with less problems than elsewhere (Table 9), a conclusion which applies elsewhere on 'Eua on account of its generally cliffed coast.

Flooding along the river valley to the southeast of the wharf is already a problem and one which would be exacerbated by the sea level rise. The commercial centre of 'Ohonua would be largely untouched by a 3.5 m sea level rise.

Tonga - Nuku'alofa

Owing to the availability of suitable maps, the study of Nuku'alofa is one of the most detailed case studies in this report. Nuku'alofa (Figure 11) is the capital of the Kingdom of Tonga and is situated on the low-lying northern side of Tongatapu island, which is composed entirely of limestone and superficial deposits.

As can be seen from diagram N1 (Figure 11, Table 10), most of the 0.2 m and 0.5 m sea level rise scenarios would not apparently affect the central part of Nuku'alofa on account of existing sea walls, although once these have been overtopped, severe effects in terms of land loss on the commercial district and one of the most important cultural areas in Tonga will ensure. However since the town is based on raised limestone, penetration of sea water may render the sea walls functionless.

The major port area of Nuku'alofa (Figure 11, diagram N2, and Table 11) is also bordered by a seawall, but this will not prove as effective a barrier to inundation and most of the map area would be inundated if sea level rose 3.5 m. This area includes many hydrocarbon storage facilities and facilities for the manufacture of many light industrial and other products.

A representative area of suburbs in Nuku'alofa (Figure 11, diagram N3, and Table 12) was also examined. The coastline here is not seawall-protected and the 0.2 m and 0.5 m shorelines have been traced through the mangroves and debris which comprise most of it. As with area N2, nearly half this area would be inundated by a 1.5 m sea level rise, nearly all by a rise of 3.5 m.

The highest parts of Tongatapu lie in the island's south and southwest and, if the sea level begins to rise, it seems likely that relocation of Nuku'alofa in these directions will have to take place. It seems imperative however to determine the effects of sea level rises of various magnitudes on shoreline retreat, much of which will come about in response to not as a direct manifestation of sea level rise. Owing to the low-lying and exposed character of Tongatapu's north coast, its preservation in its present condition will become increasingly expensive and probably increasingly ineffective.

Table 8. Impact of future sea-level rise on Savusavu town, Vanua Levu, Fiji, expressed as square metres of land loss for different scenarios identified by the sea level in metres above present. Total town area of Savusavu is approximately 0.1 sq.km (see Figure 9). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Savusavu data is high.

| Type of land loss | Scenario 0.2 | 0.5 | 1.5 | 3.5 | % total in each category |
|---|---|---|---|---|---|
| Agricultural | 0 | 0 | 0 | 1200 | - |
| Forest | 0 | 0 | 0 | 0 | - |
| Mangroves | 0 | 0 | 0 | 0 | - |
| Residential | 0 | 0 | 0 | 4688 | |
| Industrial | 0 | 0 | 0 | 6720 | |
| Commercial | 0 | 60 | 3120 | 16640 | |
| - mall | 0 | 0 | 0 | 1120 | |
| Others | | | | | |
| - civic | 0 | 416 | 1856 | 5568 | |
| - open space | 0 | 5968 | 9136 | 10400 | |
| Total land loss | 0 | 6444 | 14112 | 46336 | |
| % total town area | 0 | 5.95 | 13.03 | 42.79 | |

Sources of data: Ministry of Lands, Suva, 1967-1970, Topography of Nasavusavu (2 chains to an inch); local information by B. Masianini.

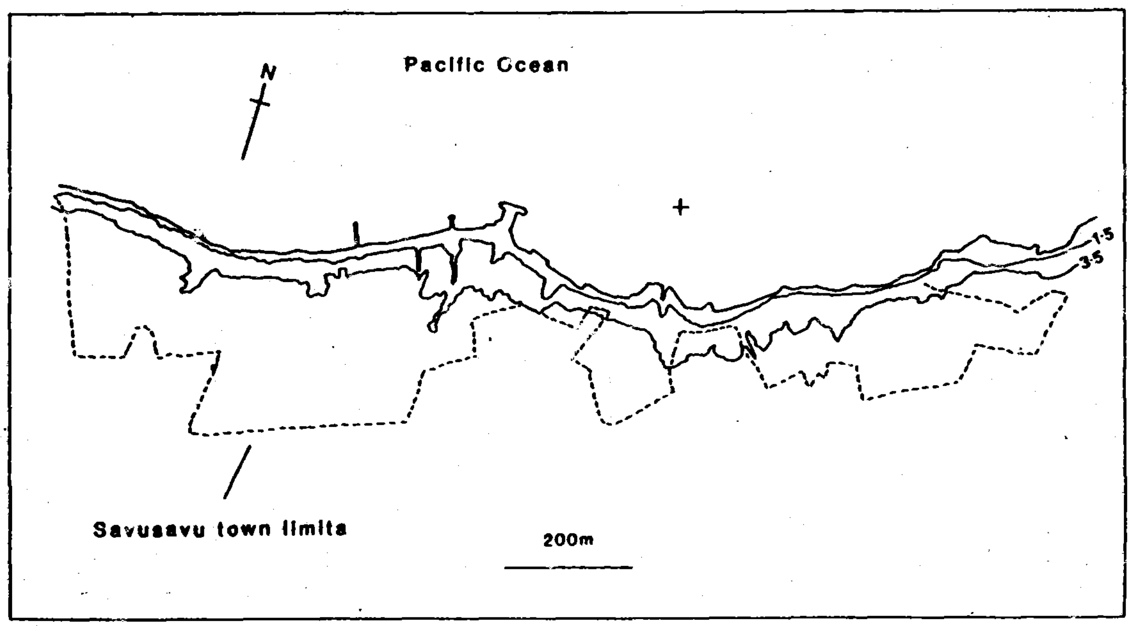


Figure 9. Savusavu town, Vanua Levu, Fiji, showing the 1.5m and 3.5m contours and the town limits (broken line). The cross represents a point 179º20'E, 16º46'30'S.

Table 9. Impact of future sea-level rise for Nafanua Harbour, 'Ohonua, 'Eua island, Tonga, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of the map is 0.245 sq.km (see Figure 10). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Nafanua data is high.

| Type of land loss | Scenario ---------------------- | | | | % total in each category |
|---|---|---|---|---|---|
| | 0.2 | 0.5 | 1.5 | 3.5 | |
| Agricultural | 0 | 0 | 0 | 0 | |
| Forest | 0 | 0 | 0 | 0 | |
| Mangroves | 0 | 0 | 0 | 0 | |
| Residential | 0 | 0 | 0 | 0 | |
| Industrial | 0 | 0 | 0 | 0 | |
| Commercial | 0 | 0 | 0 | 0.003 | |
| Others - sand and bare rock | 0.009 | 0.015 | 0.07 | 0.094 | |
| Total land loss | 0.009 | 0.015 | 0.07 | 0.097 | |
| % total land area | 3.67 | 6.12 | 28.57 | 39.59 | |

Sources of data: Central Planning Department, Tonga, 1981, Nafanua Harbour (1:1,000); additional information by S. Afeaki.

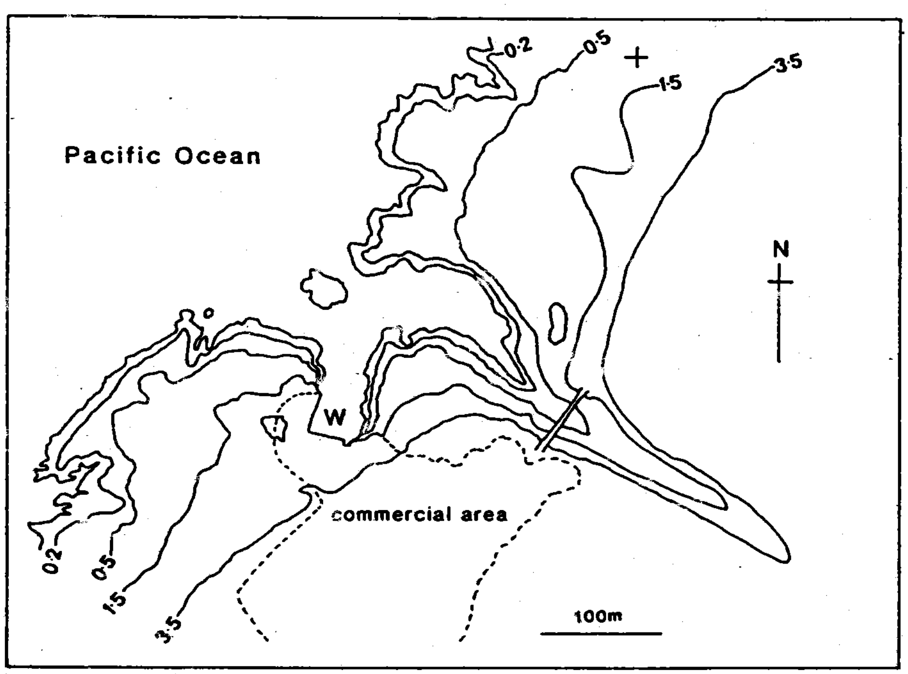


Figure 10. Nafanua harbour, 'Ohonua, 'Eua island, Tonga, showing contours at 0.2m, 0.5m, 1.5m and 3.5m. W marks the wharf which rises to around 2m above sea level. The cross marks the point 174°57'W, 20°20'S.

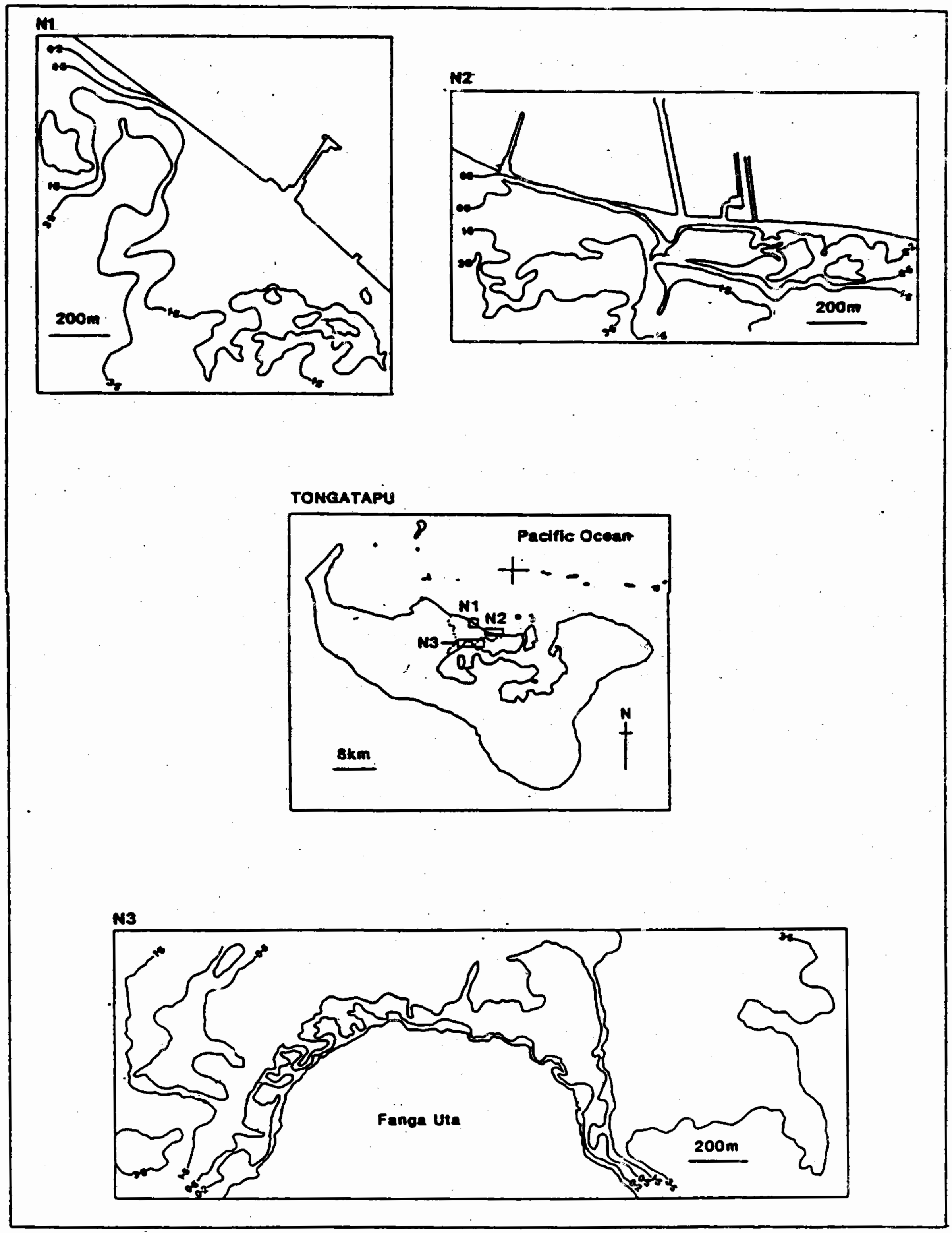


Figure 11. Nuku'alofa, Tongatapu island, Tonga. The location of Nuku'alofa is given in the central diagram, showing the island of Tongatapu; Nuku'alofa is bounded by the broken line, the cross represents the point 175°10'W, 21°05'S. The three squares; N1, N2 and N3 located in the diagram represent case studies of central Nuku'alofa, the port area and a representative suburb respectively.

Table 10. Impact of future sea-level rise on central Nuku'alofa, Tongatapu island, Tonga, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of the map (N1) is 0.81 sq.km (see Figure 11). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Nuku'alofa (N1) data is high.

| Type of land loss | Scenario 0.2 | 0.5 | 1.5 | 3.5 | % total in each category |
|---|---|---|---|---|---|
| Agricultural | 0 | 0 | 0 | 0 | |
| Forest | 0 | 0 | 0 | 0 | |
| Mangroves | 0 | 0 | 0 | 0 | |
| Residential | 0.011 | 0.011 | 0.011 | 0.011 | |
| Industrial | 0 | 0 | 0 | 0 | |
| Commercial | 0.009 | 0.019 | 0.129 | 0.421 | |
| Others | | | | | |
| - Royal Palace | | 0 | 0 | 0.052 | |
| - Royal Tombs | | 0 | 0 | 0.043 | |
| - park | | 0 | 0 | 0.03 | |
| Total land loss | 0.02 | 0.03 | 0.14 | 0.557 | |
| % total land area on map | 2.47 | 3.70 | 17.28 | 68.77 | |

Sources of data: World Health Organisation, 1:1,000 map of Nuku'alofa, Tongatapu, Tonga 1981; local detail by S. Afeaki and V. Tiseli

Table 11. Impact of future sea-level rise on the main port area of Nuku'alofa, Tongatapu island, Tonga, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of the map (N2) is 0.78 sq.km (see Figure 11). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Nuku'alofa (N2) data is high.

| Type of land loss | Scenario 0.2 | 0.5 | 1.5 | 3.5 | % total in each category |
|---|---|---|---|---|---|
| Agricultural | 0 | 0 | 0.002 | 0.113 | |
| Forest | 0 | 0 | 0 | 0 | |
| Mangroves | 0.008 | 0.008 | 0.008 | 0.008 | |
| Residential | 0.008 | 0.035 | 0.130 | 0.288 | |
| Industrial | 0.004 | 0.061 | 0.064 | 0.080 | |
| Commercial | 0.005 | 0.019 | 0.053 | 0.055 | |
| Others - school and church | 0.018 | 0.051 | 0.073 | 0.166 | |
| Total land loss | 0.04[illegible] | 0.174 | 0.330 | 0.710 | |
| % total land area on map | 5.51 | 22.31 | 42.31 | 91.03 | |

Sources of data: World Health Organisation, 1:1,000 map of Nuku'alofa, Tongatapu, Tonga 1981; local detail by S. Afeaki and V. Tiseli

A more detailed assessment of the potential impacts of sea level rise on Nuku'alofa is presented in the case study by Spenneman *et al.* (this volume).

Table 12. Impact of future sea-level rise on the Fanga - Havelu-Loto-Mataika suburb of southern Nuku'alofa, Tongatapu island, Tonga, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of the map (N3) is 2.12 sq.km (see Figure 11). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Nuku'alofa (N3) data is high.

| Type of land loss | Scenario 0.2 | 0.5 | 1.5 | 3.5 | % total in each category |
|---|---|---|---|---|---|
| Agricultural | 0 | 0 | 0 | 0.01 | 100.0 |
| Forest | 0 | 0 | 0 | 0 | |
| Mangroves | 0.020 | 0.048 | 0.048 | 0.048 | 100.0 |
| Residential | 0.045 | 0.285 | 0.890 | 1.828 | |
| Industrial | 0 | 0 | 0 | 0 | |
| Commercial | 0 | 0.003 | 0.003 | 0.003 | |
| Others - school and community centre | | 0 | 0 | 0.011 | |
| Total land loss | 0.065 | 0.336 | 0.941 | 1.90 | |
| % total land area on map | 3.07 | 15.85 | 44.39 | 89.62 | |

Sources of data: World Health Organisation, 1:1,000 map of Nuku'alofa, Tongatapu, Tonga 1981; local information by S. Afeaki and V. Tiseli

## Western Samoa - Apia

Apia (Figure 12, Table 13), the capital of Western Samoa, occupies a narrow coastal plain fringed partly with mangroves, around a harbour which lies opposite a prominent break in the reef. Most of the mangroves would be inundated were sea level to rise slightly, but if this increased to 1.5 m, then most of the commercial centre of Apia would be inundated, including the peninsula leading to Mulinu'u Point, where the government buildings and many large hotels are situated. A 3.5 m sea level rise would not add much to this picture although the dispersal of sediment and water coming down the steep, narrow valleys of the Gasegase, Mulivai and Vaisigano rivers behind the town would become increasingly problematical. The solution to the latter may be to pipe the discharge of these rivers away from the town.

## CONCLUSIONS AND RECOMMENDATIONS

It is clear that, if the sea level rises in the next 50-100 years as predicted, the economic consequences for Pacific island nations will be enormous. However, in many cases, forward planning would offset the enormity of the impact, although in other cases, primarily those of presently-inhabited atolls, there appears to be no feasible way of avoiding the impact of future sea level rise.

Table 13. Impact of future sea-level rise on Apia, Upolu Island, Western Samoa, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Apia is 7.8 sq.km (see Figure 12). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Apia data is medium to low.

| Type of land loss | Scenario 0.2 | 0.5 | 1.5 | 3.5 | % total in each category |
|---|---|---|---|---|---|
| Agricultural | 0 | 0 | 0 | 0 | |
| Forest | 0 | 0 | 0 | 0 | |
| Mangroves | ? | ? | 0.570 | 0.570 | |
| Residential | ? | ? | 0.481 | 0.730 | |
| Industrial | ? | ? | 0.160 | 0.231 | |
| Commercial | ? | ? | 1.406 | 1.994 | |
| Others | ? | ? | ? | ? | |
| Total land loss | ? | ? | 2.617 | 3.525 | |
| % total land area | ? | ? | 33.55 | 45.19 | |

Sources of data: Department of Lands and Survey, Western Samoa, 1983, Topographical map of Western Samoa (Upolu Sheet 19), 1:20,000; supplementary information by R. Lafaele

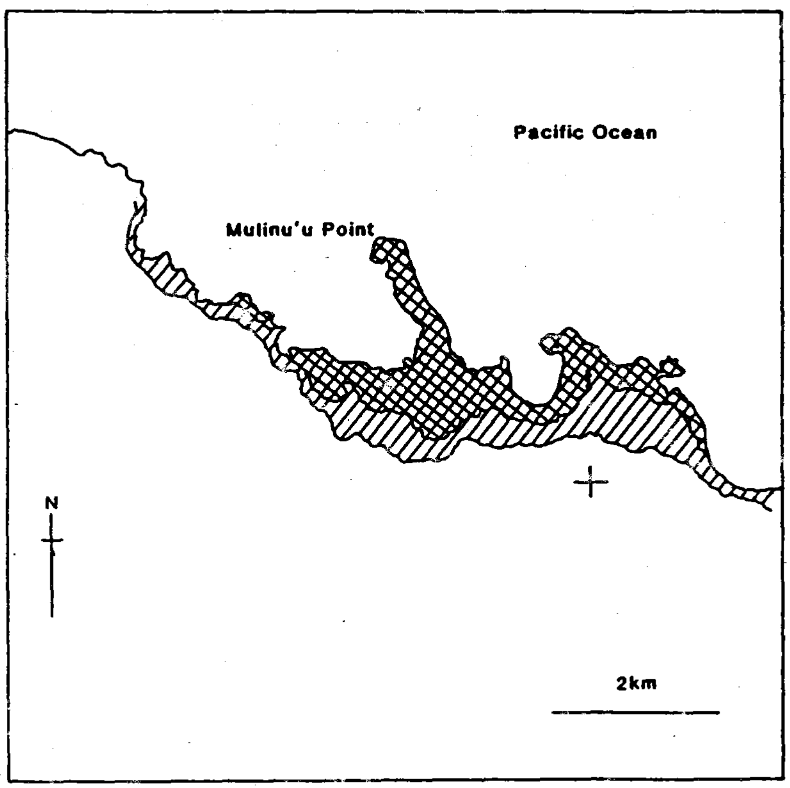


Figure 12. The coast of Apia, Upolu Island, Western Samoa, showing the area below 3.5m (stipple) and the area below 1.5m (cross-hatch). The central parts of Apia are located in the central third (in an east-west sense) of the shaded areas, most residential areas lie to the south. The cross marks the point 171°45'W, 13°50'S.

In all cases, foreknowledge is not enough; farsighted and maybe unpopular decisions need to be taken soon. Some specific recommendations are as follows:

> that a more in-depth study of the potential impact of future sea level rise on Pacific islands be carried out as a priority;
>
> that quantitative data on sediment and water discharge of major rivers close to important settlements be gathered and input into models which are able to predict landscape response to both sea level rise and temperature rise;
>
> that contingency plans be drawn up for the movement or relocation of major Pacific island settlements to areas where they will not be affected by future sea level rise;
>
> that Pacific island governments form a joint consultative body to reach decisions based on available data.

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It should be noted that participation in this project does not imply agreement with its major findings nor the conclusions drawn by the other participants. Ultimate responsibility for the contents of this report lies with the team leader.

# RECENT COASTLINE CHANGES AND THEIR IMPLICATIONS FOR FUTURE CHANGES IN THE COOK ISLANDS, FIJI, KIRIBATI, THE SOLOMON ISLANDS, TONGA, TUVALU, VANUATU AND WESTERN SAMOA

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## AIMS OF THIS INVESTIGATION

The first part of this study, reported elsewhere (Nunn, 1988a; this volume) gave details of the impacts of sea level rises of 0.2 m and 0.5 m (the medium and high scenarios for the year 2025 - Hoffman, 1983) and 1.5 m and 3.5 m (the medium and high scenarios for the year 2100 - Hoffman, 1983) for a selection of coastal environments in the South Pacific region. The environments selected are listed in Nunn (this volume:129) and the results summarised in Table 1.

When this first part of the study had been completed it was felt that rather than continue to examine the future impacts of global warming, the priority for the island Pacific was to gather information concerning recent environmental changes, themselves possibly the effects of global warming, then to use these as examples to illustrate likely future impacts, especially those other than straightforward land loss, on which the first part of this study had concentrated.

The second part of this project had the following aims.

(a) To examine how sea level had changed along South Pacific coasts since 1900. Such information is urgently needed because no long-term tide gauge data are available for the region. The nearest are in Honolulu, Hawaii and New Zealand, and interpolation across such large distances is a poor substitute for direct measurement within the area.

(b) To record and analyse the important environmental changes associated with recent sea level changes in order that future changes may be anticipated with more certainty than has hitherto been possible.

(c) To combine the information obtained from (a) and (b) above with that from the first part of this project in order to produce a summary of likely future impacts of global warming on the region's coasts and a series of priorities for future research and planning.

## METHODS OF INVESTIGATION

The aims of research were to be fulfilled by administering a questionnaire in the local language/dialect to the elderly inhabitants of coastal settlements throughout the South Pacific. The questionnaire (interview sheet) was divided into three parts. Students who were to administer the questionnaire were familiarised with it through lectures in Suva and a practice session at the island village of Serua about 50 km west of Suva. Copies of the interview sheet used in this study can be obtained by writing to the author at the Department of Geography, University of the South Pacific, P.O. Box 1168, Suva, Fiji.

The first part of the questionnaire was intended to gather background data on the settlement. The student was required to draw a map, explain what type of shoreline fronted the settlement (hard rock, sand beach, cliff or other), whether any artificial structures (e.g. seawalls, groynes, harbour facilities) existed, describe what sort of vegetation occurred along the shore and whether any had been planted specifically for purposes of coastal protection, give details of present tidal range horizontally and vertically, and to discuss the character and disposition of coral reefs offshore.

Table 1. Summary of results of impact in terms of land loss on selected coastal environments in the South Pacific (see Nunn, this volume; Nunn, 1988a). Numbers in parentheses are percentages of the total island, urban or map area where appropriate. All data are in km$^2$.

| Site | Total land loss by year and scenario | | | |
|---|---|---|---|---|
| | 2025 (medium) | 2025 (high) | 2100 (medium) | 2100 (high) |
| Apia | - | - | 2.6 (33.6) | 3.5 (45.2) |
| Beqa | - | - | 1.3 (3.6) | 2.2 (6.1) |
| Cicia | - | - | 1.9 (5.4) | 4.8 (14.0) |
| Labasa | - | - | 0.1 (25.7) | 0.3 (89.6) |
| Moala | - | - | 2.8 (4.5) | 3.9 (6.3) |
| Nafanua | <0.1 (3.7) | <0.1 (6.1) | 0.1 (28.6) | 0.1 (39.6) |
| Nuku'alofa[1] | <0.1 (2.5) | <0.1 (3.7) | 0.1 (17.3) | 0.6 (68.8) |
| Nuku'alofa[2] | <0.1 (5.5) | 0.2 (22.3) | 0.3 (42.3) | 0.7 (91.0) |
| Nuku'alofa[3] | 0.1 (3.1) | 0.3 (15.9) | 0.9 (44.4) | 1.9 (89.6) |
| Rarotonga | - | - | 1.9 (2.9)[4] | - |
| Savusavu | - | <0.1 (6.0) | <0.1 (13.0) | <0.1 (42.8) |
| Suva[5] | <0.1 (0.2) | 0.1 (0.5) | 4.1 (22.9) | 7.9 (44.4) |
| Tarawa | - | - | - | - |
| Vatoa | - | - | 0.5 (10.1) | 0.9 (20.7) |
| Vatulele | - | - | 1.1 (3.4) | 3.7 (11.7) |

1 Central Nuku'alofa
2 Port area
3 Suburb of Fango - Havelu - Loto - Mataika
4 17.1% of the total lowland area
5 Peninsula urban area only

The second part of the questionnaire was based on the extended interviewing of elderly persons. The criteria which interviewees had to satisfy was that they had been born in the village or had moved there, perhaps from an adjacent, now abandoned, settlement, when they were very young. The age(s) of the person(s) from whose memories the questions in the second part were answered was recorded and the average age used to calculate rates of shoreline changes based on these and data acquired in the third part of the questionnaire (see below).

Following an explanatory statement translated by the student researcher, questions were asked about drinking water sources and quality, changes in ease/difficulty of fishing off the village front, changes in the dependence upon seafood in normal diets, changes in the potential of the offshore reefs as sources of food, changes caused by tropical cyclones (hurricanes) to the coastline, perceived changes in tropical cyclone frequency, perceived changes in precipitation and temperature, seismic character of the area (already known, but here clarified for purposes of identifying the tectonic nature of the island), and changes in sea level. The latter enquiry comprised a series of questions asking about changes in low tide and high tide levels (in case sea level change was explainable solely by changes in tidal range) since the time when interviewees were young, changes over the last five years, changes in settlement pattern, and a series of questions designed to confirm the direction of sea level change and acquire details of the character of this change (e.g. whether it was unidirectional, uniform or variable). Questions were also asked about why informants thought sea level had (not) changed (in case a local factor was well-known), what will happen in future, whether relocation of the settlement had been considered and what obstacles there were, if any, to this.

Students were instructed not to take the questionnaire to the interviews they conducted but to fill in the answers to the questions when the interviews were concluded. The negative effect which the sight of the questionnaire would be likely to produce on elderly inhabitants of rural villages was considered to far outweigh the chances of students answering the questions erroneously.

The third part of the questionnaire required the elderly informants to indicate approximately where the low tide level had been in their youth. Student researchers were then required to measure the horizontal and vertical distances between old low tide land and present low tide level in order to get measures of net lateral sea level change and net vertical sea level change.

## QUALITY OF THE RESULTS

The use of social-scientific research tools such as questionnaires in the gathering of natural-scientific data is uncommon and poses a series of unique problems. The principal of these is the imprecision with which measurements are made in this way; comparatively large error margins, perhaps 10% are to be expected, and, clearly, in some cases it is possible that measurement is even of the wrong sign. The recognition of such problems is made doubly difficult by variation in ability and experience of student interviewers, the variation in recall ability of elderly interviewees, and the complexity of particular coastal environments.

Although the data have been 'cleaned' by removing observations which, upon discussion with the student interviewers, were clearly erroneous or misinterpreted, some errors undoubtedly remain hidden. It is believed that by discussing the results on the bases of national and regional averages, the effect of such errors will be minimised and a true, albeit generalised, picture will emerge of recent shoreline changes in the South Pacific.

Although scientific terms were kept to a minimum in interviews, it is possible that errors have crept into the results because of translation difficulties and a lack of understanding of questions by elderly informants. Such problems, however, appear to have been minimal: student interviewers reported enthusiastic and co-operative responses from interviewees in practically every instance.

It is believed that the results presented below are generally of a high quality and, although their deficiencies must not be overlooked, of a reasonable degree of applicability to a region where data of this kind can be obtained by no other means.

## RESULTS - RECENT SEA LEVEL CHANGES

Most coastal settlements were selected for this survey because they are located on tectonically stable islands or parts of islands: in other words, those places where the land level is neither rising or falling, at least at not such a rapid rate as to negate the interpretation which could be placed on shoreline changes. By way of checking this assumption, 11 settlements were selected in tectonically unstable areas where, because of regional lithospheric plate movements, uplift is occurring at comparatively rapid rates. These places were selected on the islands of Ambrym, Malakula and Malo in Vanuatu and on Niuatoputapu in Tonga. At none of these places was a recent sea level rise reported, probably because the land is being uplifted at much faster rates than sea level has been rising.

Data referring to recent sea level changes were obtained from 59 settlements, including the 11 in unstable areas. The raw data are listed in Table 2 and are summarised below and in Table 3 for each island nation represented. Rates of shoreline and sea level change were calculated using the average age of interviewees in each coastal settlement (see above).

Rates of lateral inundation are probably the most accurate of those data obtained which refer to sea level change and therefore the best for intra-regional comparison. Rates of vertical sea level change have been greatly exaggerated as the result of a number of factors, the most important of which is undoubtedly erosion (tidal scour) of the old low tide level once it was abandoned and a new low tide level at a higher elevation established. Such data would also be particularly susceptible to measurement error. They are, however, useful in that they confirm the overall trend of sea level change in the area and reveal much about the type and efficacy of nearshore and coastal processes in particular places. They are also useful in a comparative sense.

**Table 2. Data referring to the magnitudes and rates of recent sea level change recorded from coastal villages in the South Pacific.**

| Country | Island | Village | a | b | c | d | e | f |
|---|---|---|---|---|---|---|---|---|
| Cook Islands | Rarotonga | Avatiu | 54 | + | 5.00 | 9.26 | 0.40 | 7.40 |
| Cook Islands | Rarotonga | Nikao | 67 | + | 5.00 | 7.46 | 0.75 | 11.19 |
| Fiji | Beqa | Dakuibeqa | 82 | + | 5.00 | 9.76 | ? | ? |
| Fiji | Beqa | Nawaisomo | 44 | + | 5.00 | 11.36 | ? | ? |
| Fiji | Beqa | Rukua | 79 | + | 5.00 | 6.33 | ? | ? |
| Fiji | Beqa | Soliaga | 59 | + | 7.00 | 11.86 | 1.40 | 23.73 |
| Fiji | Gau | Lamiti | 68 | + | 60.00 | 88.24 | 1.50 | 22.06 |
| Fiji | Gau | Malawai | 72 | + | 21.00 | 29.17 | 1.35 | 18.75 |
| Fiji | Lakeba | Nasaqalau | 67 | + | 1.00 | 1.49 | 0.70 | 10.45 |
| Fiji | Lakeba | Vakano | 80 | + | 1.00 | 1.25 | 0.65 | 8.13 |
| Fiji | Matuku | Qalikarua | 69 | + | 22.00 | 31.88 | 2.00 | 28.99 |
| Fiji | Totoya | Tovu | 63 | + | 13.23 | 21.00 | ? | ? |
| Fiji | Viti Levu | Culanuku | 64 | + | 2.00 | 3.13 | ? | ? |
| Fiji | Viti Levu | Galoa | 64 | + | 2.00 | 3.13 | ? | ? |
| Fiji | Viti Levu | Namoli | 49 | + | 2.75 | 5.61 | 0.55 | 11.22 |
| Fiji | Viti Levu | Natunuku | 48 | + | 2.00 | 4.17 | 0.45 | 9.38 |
| Fiji | Viti Levu | Navutu | 55 | + | 2.25 | 4.09 | 0.40 | 7.27 |
| Fiji | Viti Levu | Viseisei | 51 | + | 3.75 | 7.35 | 0.60 | 11.76 |
| Solomon Islands | Choiseul | Kakalokasa | 77 | + | 22.0 | 28.57 | ? | ? |
| Solomon Islands | Choiseul | Pangoe | 60 | + | 4.00 | 6.67 | 1.20 | 20.00 |
| Solomon Islands | Choiseul | Zaru | 57 | + | ? | ? | 0.60 | 10.53 |
| Solomon Islands | Kolombangara | Ghatere | 70 | + | 7.50 | 10.71 | 1.50 | 21.43 |
| Solomon Islands | Kolombangara | Habere | 65 | + | 5.00 | 7.69 | 1.50 | 23.08 |
| Solomon Islands | Kolombangara | Hunda | 63 | + | 7.00 | 11.11 | 1.50 | 23.81 |
| Solomon Islands | Kolombangara | Iriri | 51 | + | 7.50 | 14.71 | 1.50 | 29.41 |
| Solomon Islands | Malaita | Gwango | 62 | + | 3.00 | 4.48 | ? | ? |
| Solomon Islands | Malaita | Mana'abu | 64 | + | 4.00 | 6.25 | ? | ? |
| Solomon Islands | Malaita | Ngorigiafau | 69 | + | 3.00 | 4.35 | 1.30 | 18.84 |
| Solomon Islands | New Georgia | Bareho | 77 | + | 4.00 | 5.19 | ? | ? |
| Solomon Islands | New Georgia | Tobe | 79 | + | 1.00 | 1.27 | ? | ? |
| Solomon Islands | Santa Isabel | Ligara | 72 | + | 21.65 | 30.07 | 1.50 | 20.83 |
| Solomon Islands | Santa Isabel | Tataba | 75 | + | 27.50 | 36.67 | 1.00 | 13.33 |
| Solomon Islands | Tikopia | Ravenga | 84 | + | 5.50 | 6.55 | ? | ? |
| Solomon Islands | Tikopia | Rofaea | 74 | + | ? | ? | 0.80 | 10.81 |
| Solomon Islands | Vangunu | Bisuana | 60 | + | ? | ? | 1.20 | 20.00 |
| Solomon Islands | Vangunu | Rukutu | 90 | + | 5.00 | 5.55 | 0.95 | 10.56 |
| Solomon Islands | Vella Lavella | Barakoma | 68 | + | 1.00 | 1.47 | 0.80 | 11.76 |
| Solomon Islands | Vella Lavella | Buleana | 75 | + | 1.50 | 2.00 | 1.30 | 17.33 |
| Tonga | Lifuka | Koulo | 83 | + | 7.00 | 8.43 | 5.00 | 60.24 |
| Tonga | Lifuka | Pangai | 68 | + | 8.00 | 11.76 | 7.50 | 110.29 |
| Tonga | Niuatoputapu | Falehau | 59 | - | 12.00 | -20.34 | 1.26 | -21.36 |
| Tonga | Niuatoputapu | Hihifo | 58 | - | 10.00 | -17.24 | 1.45 | -25.00 |
| Tonga | Niuatoputapu | Vaipoa | 60 | - | 14.00 | -23.33 | 1.50 | -25.00 |
| Tonga | Vava'u | Ovaka | 71 | + | 10.00 | 14.08 | 0.85 | 11.97 |
| Tonga | Vava'u | Pangaimotu | 86 | + | 5.00 | 5.81 | 0.46 | 5.35 |
| Tuvalu | Nukufetae | Savave | 83 | + | 15.00 | 18.07 | 2.40 | 28.92 |
| Vanuatu | Ambrym | Baiap | 69 | - | 72.00 | -104.35 | 0.50 | -7.25 |
| Vanuatu | Ambrym | Sameou | 45 | - | 200.00 | -444.44 | ? | ? |
| Vanuatu | Malakula | Marven | 50 | - | 20.00 | -40.00 | 0.30 | -6.00 |
| Vanuatu | Malakula | Milip | 70 | - | 29.00 | -41.43 | 0.20 | -2.86 |
| Vanuatu | Malakula | Vorles | 67 | - | 18.00 | -26.87 | 0.30 | -4.48 |
| Vanuatu | Malo | Amalo | 44 | - | 8.00 | -18.18 | 0.14 | -3.18 |
| Vanuatu | Malo | Atariboe | 59 | - | 7.00 | -11.86 | ? | ? |
| Vanuatu | Malo | Samarada | 70 | - | 15 | -21.43 | 0.50 | -7.14 |
| Vanuatu | Pentecost | Laone | 64 | + | 5.00 | 7.81 | 0.60 | 9.38 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Western Samoa | Savai'i | Avao | 59 | + | ? | ? | 1.90 | 32.20 |
| Western Samoa | Savai'i | Faga | 71 | + | 1.00 | 1.41 | 1.15 | 16.20 |
| Western Samoa | Savai'i | Iva | 59 | + | ? | ? | 0.80 | 13.56 |
| Western Samoa | Upolu | Satalo | 69 | + | 70.00 | 101.45 | 3.00 | 43.48 |

Key to columns:
a Time span over which sea level behaviour was observed, that is the average age of the village informants.
b Direction of sea level change over time span, that is rising (+) or falling (-).
c Maximum shoreline inundation or emergence (m) in a lateral (earth-surface parallel) sense at average high tide level.
d Maximum rate of lateral inundation (cm/year) calculated from a and c. Rates of shoreline emergence as indicated by negative figures.
e Maximum vertical rise or fall of sea level (m) at high tide level.
f Maximum

Two sets of observations were made in the Cook Islands, both on Rarotonga (see Nunn, this volume:129 for environmental analogues). At both places, sea level has been rising for 67 years at least. This has caused coastal inundation at an average rate of 8.4 cm/year and vertical sea level rise at an average apparent rate of 9.3 mm/year.

Of sixteen sets of observations from Fiji, six were from the east and west coasts of the main island of Viti Levu, the remainder from nearby islands and representative islands in the distant Lau group. Sea level has been rising in Fiji for at least 82 years. This has been manifested by coastal inundation at an average rate of 15 cm/year and vertical sea level rise at an average apparent rate of 15.2 mm/year. Of note is the shoreline at Lamiti on Gau island which has retreated 60 m in the last 68 years. These are tectonic reasons to suppose that the high rate of apparent sea level rise at Qalikarua on Matuku (29 mm/year) may have been amplified by local subsistence.

Twenty observations were obtained throughout the Solomon Islands, excluding those islands which are believed to be least tectonically stable (Guadalcanal and San Cristobal). Observations were distributed fairly evenly throughout the rest of the group with three from Choiseul, two from Santa Isabel, three from Malaita, two from outlying Tikopia in the far east of the group, and ten from various islands in the New Georgia archipelago. Sea level has been rising throughout the Solomon Islands for at least 90 years. This has caused coastal inundation at an average rate of 10.8 cm/year and vertical sea level rise at an average apparent rate of 18 mm/year. Rates of sea level rise exhibit surprisingly similarity throughout the Solomon Islands. High rates of inundation on the north coast of Santa Isabel (Ligara and Tataba) may have been amplified by local subsidence.

Of seven observations obtained for Tonga, three were from the unstable island of Niuatoputapu. Excluding those data, the remainder from the stable (in the short term) coasts of Vava'u and Lifuka (in the Ha'apai group) indicate that sea level has been rising for at least 86 years. The average rate of lateral inundation has been 10 cm/year and the average apparent rate of sea level rise has been 47 mm/year. If the data from Lifuka are excluded, the latter rate becomes 8.7 mm/year which is believed to be more realistic for the group as a whole. It is suspected that profound changes in lagoon currents resulted from sea level rise at the Lifuka sites resulting in lagoon-floor scour: sand mining may also have contributed to the high figures obtained here. All sites on Niuatoputapu indicate a relative sea level fall resulting in lateral shoreline extension at an average rate of 20.3 cm/year and an average apparent sea level fall at a rate of 23.8 mm/year, which, interestingly, is considerably higher than rates inferred from archaeological studies of the island.

Only one observation came from the atoll nation of Tuvalu. This was from the island of Nukufetae from which it appears that sea level has been rising for 83 years, causing lateral inundation at a rate of 18 cm/year and an apparent sea level rise of 29 mm/year. These results are regarded as less reliable than the rest because they derive from only one place. Also, atoll coastlines are notoriously changeable environments with erosion and shoreline retreat on one coast commonly being matched by coastal progradation on another nearby.

Although data were collected from nine sites in Vanuatu, eight sets of these were from the unstable islands and only one set, from Pentecost (Laone village), was from an apparently stable coastline where sea level has been rising for 64 years at least. A rate for lateral inundation of 7.8 cm/year and an apparent rate of sea level rise of 9.4 mm/year was calculated for Laone but these figures may have been reduced considerably in magnitude by uplift. Of the unstable coasts in Vanuatu, all record a relative sea level fall over the last 70 years at least. An average rate for coastal extension of 88 cm/year is obtained as is an average apparent sea level fall at a rate of 5.2 mm/year. The highest rates of coastal extension occur on Ambrym island and are probably correlatable with the highest uplift rates among the islands sampled.

Four observations were made in Western Samoa, one on Upolu and three on Savai'i. Sea level has been rising in Western Samoa for at least 71 years. This has caused an average rate of lateral shoreline inundation of 51.4 cm/year but this figure is based on only two data and is greatly influenced by that for Satalo where a rate of inundation of over 100 cm/year was recorded. This is the highest rate recorded in this survey and reflects the gentle sea floor gradient offshore of Satalo. The average apparent rate of sea level rise is 26.4 mm/year in Western Samoa.

It is believed that the corrected regional averages in Table 3 are accurate and regionally applicable figures given the constraints of the study and the methods used. The figure of 10.4 cm/year for the average rate of inundation along stable coasts could be used as a basis for planning. The figure of 14.5 mm/year for sea level rise has, as stated above, been greatly amplified by sea floor scour and other processes. This rate of apparent vertical sea level rise (14.5 mm/year) is high compared with rates obtained from tide gauges along the region's periphery: at Honolulu, Hawaii, a rate of 0.7 mm/year has been recorded since 1900 (Pirazzoli, 1986); at Wellington, New Zealand, a rate of 1.6 mm/year has been recorded since 1900 (Hannah, 1988); and at Pago Pago in American Samoa, a 30-year record indicates a rate of 2 mm/year (from data in Pirazzoli, 1986).

## RECENT COASTLINE ENVIRONMENTAL CHANGES

Supplementary data collected during the survey described above are listed in Table 4. These data derive from 75 coastal settlements, including all those from which data listed in Table 2 and described in the preceding section originate. Of these 75 sites, 12 are located in tectonically unstable areas and have experienced a relative sea level fall recently. The remainder have been affected by sea level rise.

These data (Table 4) characterise the types of shoreline protection found throughout the region and, as such, can be used as the basis for recommendations concerning artificial structures. Details about changes in well usage and well water quality were also collected, as were data relating to perceived changes in mean annual precipitation and mean annual temperature recently. Information was also derived about obstacles to settlement relocation. The results are summarised below.

### Artificial structures along the shoreline

Out of 63 settlements which have experienced a sea level rise recently, 33 (52.4%) had no presently effective form of artificial protection against shoreline erosion, although many had once erected structures but these had been made redundant by sea level rise. Of these 63 settlements, 12 (19%) had seawalls made of cement, sand and stones, but these were not as wholly impermeable as a concrete wall would be. Many had deteriorated since initial construction, and most were the result of local-area (settlement) initiatives rather than national (central government) sponsored projects. Thirteen (20.6%) of these settlements had seawalls made of loose stones, commonly coral blocks, piled on top of each other. Such seawalls were wholly the result of local initiatives and had frequently proved ineffective in preventing shoreline erosion for more than a year. Lines of sticks, commonly bamboo and coconut palm were used for shoreline protection in four (6.3%) of these settlements. Rubbish and debris piled up on the shoreward side of such lines of sticks gave additional protection but this did not amount to a markedly effective combination. Groynes had been used in two (3.2%) of the settlements to trap sand and thus replenish the eroding beach. In both these sites, one on an atoll, the exercise had been successful over one or two decades. A concrete seawall built with central government funds existed in only one (1.6%) of the 63 rural settlements which had experienced a sea level rise recently.

Table 3. Data characterising sea level rise in the South Pacific

| Nation | Rate of inundation (cm/year) | Rate of apparent vertical sea level rise (mm/year) |
|---|---|---|
| Cook Islands | 8.4 | 9.3 |
| Fiji | 15.0 | 15.2 |
| Solomon Islands | 10.8 | 18.0 |
| Tonga[1] | 10.0 | 8.7[2] |
| Tuvalu[3] | 18.0 | 29.0 |
| Vanuatu[4] | 7.8 | 9.4 |
| Western Samoa | 51.4 | 26.4 |
| Regional (uncorrected[6]) | 17.3 | 16.6 |
| Regional (corrected) | 10.4 | 14.5 |

1 Excluding data from Niuatoputapu
2 Excluding data from Lifuka
3 Based on only one observation
4 Excluding data from Ambrym, Malakula and Malo, and thus based on only one observation
5 Based on two greatly differing figures
6 All data listed are used
7 Unrepresentative data from Tuvalu and Western Samoa excluded
8 Unrepresentative date from Tuvalu excluded

It is clear from these results that much effort is being used in constructing artificial structures in the region, but that these are invariably of an inappropriate design or made of unsuitable materials so become rapidly ineffective. It must be possible to draw up and distribute throughout rural settlements in the region, plans for seawalls built to last longer than those at present being constructed which can be made locally with the minimum of professional expertise and cost. The use of groynes in beach replenishment should be encouraged, as should the building of artificial structures to protect the shoreline. In the midst of this, however, one must not lose sight of the likelihood that artificial structures can provide only short-term protection and that the longer-term solution in most cases appears to be relocation of settlements inland and/or higher up.

Natural forms of shoreline protection

Although many Pacific island coasts have natural protection against erosion, these data were collected with reference only to those types of vegetation which had been planted deliberately by local people along the coastline in order to try and prevent or reduce the rate of shoreline erosion.

Out of the 63 settlements which had experienced a sea level rise recently, 37 (58.7%) had planted nothing to try and stop associated shoreline erosion. Of these 37, 23 (36.5%) also had no artificial structures (see above) so represent settlements where nothing was being done in December 1988 - February 1989 to try and prevent shoreline erosion and any other effects of sea level rise. In most cases this is not the result of indolence but of ignorance about the options available for particular shoreline environments and their likely efficacy. Again, this is an area where appropriate instruction is called for.

Of those settlements which had planted natural coastal protection, seven (26.9% or 11.1% of the total experiencing a rise in sea level) had planted grass and shrubs, 25 (96.2% or 39.7%) had planted trees, and one (3.8% or 1.6%) had planted mangroves. Trees, particularly saltwater-tolerant species, are the most successful forms of protective vegetation but are not, as widely believed, wholly effective. An example of the front of the school at Ucunivanua on Viti Levu's east coast in Fiji was documented by Nunn (1988b) who found that 15 m of shoreline retreat, representing a loss of 3,500 $m^3$ of material, had occurred in 30 years since saltwater-tolerant trees (*Ficus benjamina* and *Casuarina equisetifolia*) had been planted. There is clearly potential for greater education about the effective species for particular shoreline environments in the South Pacific and perhaps even the distribution of seeds and seedlings from national centres.

Table 4. Supplementary data relating to recent environmental changes experienced in coastal villages in the South Pacific.

| Country | Island | Village | a | b | c | d | e | f | g |
|---|---|---|---|---|---|---|---|---|---|
| Cook Islands | Rarotonga | Avatiu | 2 | 2 | n/a | n/a | + | - | 0 |
| Cook Islands | Rarotonga | Nikao | 5 | 1,2 | - | - | 0 | + | 0 |
| Fiji | Beqa | Dakuibeqa | 0 | 2,3 | n/a | n/a | - | + | 2 |
| Fiji | Beqa | Naceva | 1 | 1,2 | n/a | n/a | - | 0 | 1 |
| Fiji | Beqa | Nawaisomo | 1 | 0 | n/a | n/a | 0 | 0 | 2 |
| Fiji | Beqa | Rukua | 1 | 2 | - | 0 | + | + | 2 |
| Fiji | Beqa | Soliaga | 2 | 0 | 0 | 0 | 0 | 0 | 2 |
| Fiji | Gau | Lamiti | 0 | 2 | n/a | n/a | - | + | 1 |
| Fiji | Gau | Malawai | 1 | 2 | n/a | n/a | - | + | 1 |
| Fiji | Gau | Nacavanadi | 1 | 1,2 | n/a | n/a | - | + | 1 |
| Fiji | Lakeba | Nasaqalau | 0 | 0 | n/a | n/a | + | + | 0 |
| Fiji | Lakeba | Vakano | 0 | 0 | n/a | n/a | + | + | 0 |
| Fiji | Matuku | Levukaidaku | 0 | 0 | 0 | + | - | + | 0 |
| Fiji | Matuku | Qalikarua | 1 | 1,2 | n/a | n/a | - | + | 0 |
| Fiji | Totoya | Dravuwalu | 0 | 0 | + | 0 | - | + | 2 |
| Fiji | Totoya | Ketei | 1 | 1 | - | - | - | + | 0 |
| Fiji | Totoya | Tovu | 2,4 | 0 | n/a | n/a | - | + | 0 |
| Fiji | Totoya | Udu | 0 | 0 | - | 0[1] | + | + | 0 |
| Fiji | Viti Levu | Culanuku | 0 | 2 | - | - | + | + | 0 |
| Fiji | Viti Levu | Galoa | 0 | 2 | - | - | - | + | 0 |
| Fiji | Viti Levu | Naivuruvuru | 0 | 0 | 0 | 0 | + | + | 0 |
| Fiji | Viti Levu | Namoli | 1 | 0 | - | - | + | + | 2,3 |
| Fiji | Viti Levu | Natunuku | 0 | 0 | - | - | 0 | 0 | 2 |
| Fiji | Viti Levu | Navutu | 1 | 0 | - | - | 0 | 0 | 3 |
| Fiji | Viti Levu | Ucunivanua | 1 | 0 | - | - | + | 0 | 1 |
| Fiji | Viti Levu | Viseisei | 1 | 0 | - | - | - | + | 2 |
| Kiribati | Tarawa | Bikenibeu | 2 | 0 | - | - | - | + | 0 |
| Solomon Islands | Choiseul | Kakaiokasa | 0 | 0 | n/a | n/a | + | + | 0 |
| Solomon Islands | Choiseul | Pangoe | 0 | 0 | n/a | n/a | 0 | 0 | 0 |
| Solomon Islands | Choiseul | Zaru | 0 | 0 | n/a | n/a | 0 | + | 0 |
| Solomon Islands | Kolombangara | Ghatere | 2 | 2 | n/a | n/a | + | + | 0 |
| Solomon Islands | Kolombangara | Habere | 0 | 0 | n/a | n/a | + | + | 0 |
| Solomon Islands | Kolombangara | Hunda | 0 | 2 | n/a | n/a | + | - | 0 |
| Solomon Islands | Kolombangara | Iriri | 2 | 0 | n/a | n/a | + | + | 0 |
| Solomon Islands | Malaita | Gwango | 2 | 2 | n/a | n/a | + | + | 0 |
| Solomon Islands | Malaita | Mana'abu | 3 | 1,2 | - | - | - | + | 0 |
| Solomon Islands | Malaita | Ngoaigiafau | 2 | 2 | n/a | n/a | - | + | 0 |
| Solomon Islands | New Geogia | Bareho | 0 | 0 | n/a | n/a | 0 | + | 0 |
| Solomon Islands | New Georgia | Tobe | 0 | 0 | n/a | n/a | + | + | 0 |
| Solomon Islands | Santa Isabel | Ligara | 3 | 0 | n/a | n/a | 0 | + | 0 |
| Solomon Islands | Santa Isabel | Tataba | 0 | 2 | n/a | n/a | + | + | 0 |
| Solomon Islands | Tikopia | Namo | 0 | 0 | n/a | n/a | + | 0 | 0 |
| Solomon Islands | Tikopia | Ravenga | 2 | 0 | n/a | n/a | - | - | 2 |
| Solomon Islands | Tikopia | Rofaea | 2 | 2 | n/a | n/a | - | + | 0 |
| Solomon Islands | Vangunu | Bisuana | 0 | 2 | n/a | n/a | - | 0 | 2 |
| Solomon Islands | Vangunu | Rukutu | 2 | 2 | n/a | n/a | - | + | 0 |
| Solomon Islands | Vella La Vella | Barakoma | 0 | 0 | n/a | n/a | 0 | + | 0 |
| Solomon Islands | Vella La Vella | Buleana | 0 | 0 | -2 | -2 | 0 | + | 0 |
| Solomon Islands | Vella La Vella | Ugamba | 0 | 2 | n/a | n/a | - | + | 0 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Tonga | Lifuka | Koulo | 3 | 2 | - | 0 | 0 | + | 2 |
| Tonga | Lifuka | Pangai | 3 | 1,2 | - | 0 | 0 | + | 0 |
| Tonga | Niuatoputapu | Falehau3 | 0 | 0 | - | + | 0 | - | n/a |
| Tonga | Niuatoputapu | Hihifo3 | 0 | 0 | - | + | + | - | n/a |
| Tonga | Niuatoputapu | Vaipoa3 | 0 | 0 | - | + | + | - | n/a |
| Tonga | Tongatapu | Kolovai | 0 | 0 | - | 0 | + | + | 0 |
| Tonga | Tongatapu | Niutoua | 0 | 0 | 0 | 0 | 0 | + | 0 |
| Tonga | Tongatapu | Taiafo'ou | 2 | 0 | n/a | n/a | 0 | 0 | 0 |
| Tonga | Vava'u | Ovaka | 0 | 2 | - | - | - | + | 2 |
| Tonga | Vava'u | Pangaimotu | 0 | 0 | 0 | - | + | 0 | 2 |
| Tuvalu | Funafuti | Alapi | 0 | 0 | - | 0 | + | - | 0 |
| Tuvalu | Nukufetae | Savave | 1,4 | 0 | - | - | 0 | + | 1 |
| Vanuatu | Ambrym | Baiap3 | 0 | 0 | - | 0 | - | + | n/a |
| Vanuatu | Ambrym | Sameou3 | 0 | 2 | - | - | 0 | + | n/a |
| Vanuatu | Ambrym | Tarrak3 | 0 | 0 | - | 0 | + | 0 | n/a |
| Vanuatu | Malakula | Marven3 | 0 | 1,2 | - | 0 | + | + | n/a |
| Vanuatu | Malakula | Milip3 | 3,4 | 1,2 | - | + | - | + | n/a |
| Vanuatu | Malakula | Vories3 | 3 | 1,2 | n/a | n/a | - | 0 | n/a |
| Vanuatu | Malo | Amalo3 | 0 | 0 | - | 0 | + | + | n/a |
| Vanuatu | Malo | Atariboe3 | 0 | 0 | n/a | n/a | + | + | n/a |
| Vanuatu | Malo | Samarada3 | 3 | 0 | 0 | + | + | + | n/a |
| Vanuatu | Pentecost | Laone | 0 | 0 | - | 0 | + | + | 0 |
| Western Samoa | Savai'i | Avao | 2 | 0 | n/a | n/a | 0 | - | 0 |
| Western Samoa | Savai'i | Fago | 0 | 0 | n/a | n/a | 0 | 0 | 0 |
| Western Samoa | Savai'i | Iva | 0 | 0 | - | - | + | - | 0 |
| Western Samoa | Upolu | Satalo | 0 | 2 | - | - | + | + | 0 |

Key to columns:
Note that details of the length of time to which answers refer are given in Appendix 1, column 4

- a Artificial shoreline protection: 0 - none, 1 - cement, sand and stones, 2 - stones and/or coral blocks, 3 - sticks, 4 - groynes, 5 - concrete seawall
- b Natural coastal protection planted deliberately: 0 - none, 1 - grass and shrubs, 2 - trees, 3 - mangroves
- c Change in the number of wells used for drinking water: 0 - still the same number in use, "+" - more in use, "-" - less in use, n/a - not applicable, drinking water has never come from wells
- d Change in the quality of drinking water from wells: 0 - no change, "=" - quality improved, "-" - quality deteriorated, n/a - drinking water has never come from wells
- e Change in the annual amount of rainfall: 0 - no change, "+" - more rainfall today than before, "-" - less rainfall today than before.
- f Change in the annual temperature: 0 - no change, "+" - hotter today than before, "-" - cooler today than before
- g Nature of obstacles in the way of moving the village to higher ground: 0 - no obstacles, 1 - cultural obstacles, 2 - physical obstacles, 3 - legal problems (e.g. land tenure)

Notes:
1 Depends on tidal condition
2 Refers to a lake in the village used for drinking water
3 Place which has experienced a relative sea level fall recently

## Well usage and well water quality

Of those 63 settlements which have experienced a sea level rise recently, only 29 had once depended and/or presently depend on well water for drinking. Twenty three of these 29 (79.3%) reported that the same number were still in use now compared with the time when elderly informants were young (on average, 66 years ago), and one (3.4%) reported that more were now in use.

There are of course many reasons for changes in well usage and many settlements which reported declining usage had received alternative forms of supply such as piped water or rainwater storage tanks. In many cases, however, the decrease in dependence on wells for drinking water had to do with the deteriorating quality of that water, and 16 of the 23 (69.6%) reported that well water quality has got worse recently. In many of these cases, it is possible that this had to do with pollution of the freshwater lens or water table as sea level rose. The exact number experiencing this effect is indeterminate from the data collected in this project.

It is interesting that in those islands which are being uplifted, and thus experiencing a relative sea level fall, five out of 10 (50%) settlements which use wells for drinking water report that the quality of that water has improved over time and only one out of 10 (10%) note that water quality has deteriorated recently. This suggests that relative sea level change is strongly correlated with changes in well water quality which, in turn implies that a major cause of deteriorating quality of well water along South Pacific coasts recently has been the regional sea level rise.

Perceived changes in precipitation and temperature

No data of sufficient duration have been analysed to give an accurate picture of recent precipitation and temperature trends. Another problem in the South Pacific region is that data of sufficient duration are available in only a few places and their distribution is too irregular to yield a true picture of regional changes.

Questions were asked in this survey about changes in precipitation and temperature but it is admitted that the results are open to many interpretations and may be regarded as among the most dubious of the data collected in this survey. Results are summarised in Table 5.

In terms of precipitation, it is interesting that, excluding nations with two or less data, all agree that overall it has become wetter (precipitation has increased) with the exception of Fiji. However, the closeness of the totals for those respondents favouring wetter or drier conditions today undoubtedly indicates the lack of a clear regional trend and a considerable degree of intra-regional variation.

Temperature changes appear to have been more clearly perceived with the great majority of respondents in those nations with more than four data believing that it has become hotter recently. The geographical distribution and the strength of this majority suggests that it may reflect, in part, an actual regional trend. As such, it agrees with global temperature trends (e.g. Jones, *et al.*, 1986).

An attempt to overcome such a suggestion was made by analysing radiosonde temperature data for the South Pacific which show an undoubted recent temperature rise in the lower troposphere (Table 6).

Tropospheric warming in the South Pacific is probably matched in broad terms by ground and sea-surface temperatures in the region. Although insufficient long-term data are available from the islands, the former trend is supported by ground temperature analyses for New Zealand, 'a rise having been experienced throughout the whole region during 1935-1979, temperatures climbing by 1°C over these years' (Salinger & Gunn, 1975:397). Sea-surface temperatures in the South Pacific have risen by 0.5-1.0°C since 1912 (Folland *et al.*, 1984).

Possibilities of settlement relocation

Although most coastal communities studied in this survey had discussed the possibility of relocating their settlement elsewhere as a response to sea level rise and associated shoreline erosion, none contemplated such a move in the immediate future although many settlements had been migrating slowly inland for decades.

The possibility of settlement relocation is undoubtedly set to increase in the future so questions were asked about the nature of obstacles, if any, in the way of moving settlements to a new site, inland and/or higher, at present. Forty three settlements which had experienced a sea level rise recently (68%) had no barriers to relocation. Cultural obstacles to relocation were paramount only in Fiji and Tuvalu (9.5% of total); being applicable to 21% of settlements in Fiji. Physical obstacles were the most important in only two places (3.2% of total).

This type of information is important because it illustrates the magnitude and variety of problems which may face settlements within the region desiring to relocate on the same island in the future. Problems appear most acute in Fiji and it may be appropriate for a comprehensive review of these to be made now.

Table 5. Perceived changes in precipitation and temperature in the South Pacific. Figures expressed as percentages of total respondents

| | Precipitation | | Temperature | |
|---|---|---|---|---|
| Nation | Wetter today | Drier today | Hotter today | Cooler today |
| Cook Islands[1] | 50 | 0 | 50 | 50 |
| Fiji | 33 | 50 | 75 | 0 |
| Kiribati[2] | 0 | 100 | 100 | 0 |
| Solomon Islands | 41 | 32 | 77 | 9 |
| Tonga | 40 | 10 | 50 | 30 |
| Tuvalu[1] | 50 | 0 | 50 | 50 |
| Vanuatu | 60 | 30 | 80 | 0 |
| Western Samoa[3] | 50 | 0 | 25 | 50 |
| Region (uncorrected)[4] | 41 | 32 | 69 | 12 |
| Region (corrected)[5] | 42 | 36 | 75 | 8 |

1 Based on only two data
2 Based on only one datum
3 Based on only four data
4 All data used
5 Data from Cook Island, Kiribati, Tuvalu and Western Samoa excluded.

Table 6. Decadal temperature trend for the tropospheric layer defined by pressures 500-850 hPa (approximately 1-5 km above the Earth's surface) in South Pacific (data from Karoly, 1988).

| Time period | Rate of temperature change (°C per decade) | | |
|---|---|---|---|
| | Fiji | New Caledonia | Tahiti |
| 1950-1969 | 0.0 | ? | +0.6 |
| 1966-1985 | +0.5 | -0.1 | +0.2 |
| 1950-1985 | +0.2 | +0.3 | +0.4 |

## CONCLUSIONS

There can be no doubt that sea level has been rising in the South Pacific, at least from the Solomon Islands in the west to the Cook Islands in the east, for at least the past 70-90 years. This sea level rise has already brought about a multiplicity of environmental changes along a variety of coastline types. It seems certain that such changes will not only continue in the future but will become amplified if the rate of sea level rise experienced over the last few decades increases, as it is widely predicted to do.

The apparent reluctance of Pacific island governments to recognise this and the related problems of global warming is not the result of indifference or indeed ignorance but may be seen as the response to the lack of any unequivocal statement from regional advisory bodies. This coupled with the unbalanced and contradictory articles which have appeared in the daily and other press of the Pacific islands, has undoubtedly led government decision-makers to question the need for immediate action of any kind.

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# THE POTENTIAL IMPACTS OF PROJECTED CLIMATIC CHANGE AND SEA LEVEL RISE ON TONGATAPU, KINGDOM OF TONGA

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## ABSTRACT

This study addresses the potential impacts a rise in relative sea level may have on the island of Tongatapu, Kingdom of Tonga. These impacts are both beneficial and detrimental to the well-being of the Tongan people.

Much of Nuku'alofa is located on the ground of a former lagoon entrance, which had become closed during the late Holocene. Because of intensive archaeological survey and excavation work, the history of this entrance is fairly well understood and projections can be made as a basis for discussion of the effects of a future rise in relative sea level.

It can be foreseen that the pressure on land resources will increase exponentially, caused by natural population growth, inundation of gardened land and inundation of residential areas, which will need to be relocated.

The corals of the fringing reefs are likely to re-colonise presently abandoned reef flats and to commence reef growth rapidly. If the projected sea level rise is equal to or less than 8 mm/year then we can expect that the present reef conditions can be maintained and no major change in the wave action on the shore will be experienced.

This study provides only a general outline of present knowledge and identifies short-comings in the data base, which should be filled in with further research to strengthen the projections.

## INTRODUCTION

### The assumed scenario

Given the general considerations made in the 1st report of the ASPEI task team and in Buddemeier and Oberdorfer (this volume), the continuation of global warming of the atmosphere seems certain to occur and the sea level is certain to rise. No accurate prediction as to the speed and magnitude of the sea level rise can be made. Various scenarios of the effects of the global greenhouse gas generated climatic change have been put forward. A study by U.S.National Research Council Carbon Dioxide Assessment Committee (1983) estimated a possible rise of 0.7 m +/- 0.25 by the year 2075. The NRC Committee on Engineering Implications of Changes in Relative Mean Sea Level (1987) has used three scenarios for the year 2085 (i.e.

almost 100 years): a rise of 0.5 m, 1.0 m and 1.5 m. For the purposes of the present study these same three scenarios have been used.

The study

Based on the data available to date, this study attempts to predict the potential impacts a rise in relative sea level would have at these three heights. It reconstructs the extent of the new shore-lines in the Nuku'alofa township area and discusses the potential impact of the inundation on human habitation, sanitation, natural resources, and archaeological heritage.

The data

The data used in this study derive from various sources, mainly geology, coastal morphology, and archaeology. The sea level data utilised here, most of which are as yet unpublished, have been accumulated by the authors during past and present research projects and consultancies (Spennemann, 1986a-e, 1987a, in prep a.). The other data have been drawn from personal observations and from consultancy reports held in the Central Planning Department in Tonga.

The study area

The islands of Tonga are situated in the South West Pacific some 780 km east of Fiji, ~900 km southwest of Samoa and ~2,200 km northwest of New Zealand. They comprise 171 islands, of which about 36 are currently inhabited. The modern political boundaries, as defined by King Taufa'ahau Tupou I (1797-1893) and amended by Taufa'ahau Tupou IV (1918 - ), cover the area from 15° to 23° 30' S and from 173° to 177° W (Tongan Government Gazette 2 [55] 24.8.1887). The archipelago extends in a NNE-SSW direction and is commonly divided into four groups (from north to south): the Niuas (Niuatoputapu and Niuafo'ou), the Vava'u Group, the Ha'apai Group and the Tongatapu Group. Eighty-five km southwest of Tongatapu is the isolated, now uninhabited, island of 'Ata.

The detailed discussion on the following pages will be limited to Tongatapu, and especially to the area of Nuku'alofa township (Figure 1), as this is the most highly populated island and the one for which most data exist. Several observations and conclusions from this discussion can be applied to other islands in Tonga and beyond.

## THE GEOLOGICAL AND GEOGRAPHICAL BACKGROUND OF TONGATAPU

The Tongan islands lie on the mostly submarine Tonga-Kermadec Ridge, which is a major bathymetric feature extending over 1,300 km from New Zealand to west of Samoa, formed by the subduction zone of the Pacific plate sliding under the Indo-Australian plate. The islands are of three types, running in two parallel chains along the Tonga trench, which extends at times to a depth of 10,500 m.

1. An eastern chain of islands, sitting on the relative shallow forarc platform, consists of reefal coral limestone underlain by older volcanic rocks (Tongatapu, Ha'apai, Vava'u). In some instances the underlying volcanic rocks are exposed, such as on Nomuka and 'Eua.

2. A western chain of active volcanoes sits on the Tofoa Ridge and is separated from the chain of coral limestone islands by a trough up to 1,800 m deep (e.g. Tofoa, Late, Kao).

3. A chain of active submarine volcanoes, which erupt spasmodically and form unstable islands consisting of volcanic ash and pumice (e.g. Fonuafo'ou [Falcon or Jack-in-the-box Island], Metis Shoal) coincides with the chain of visible volcanoes.

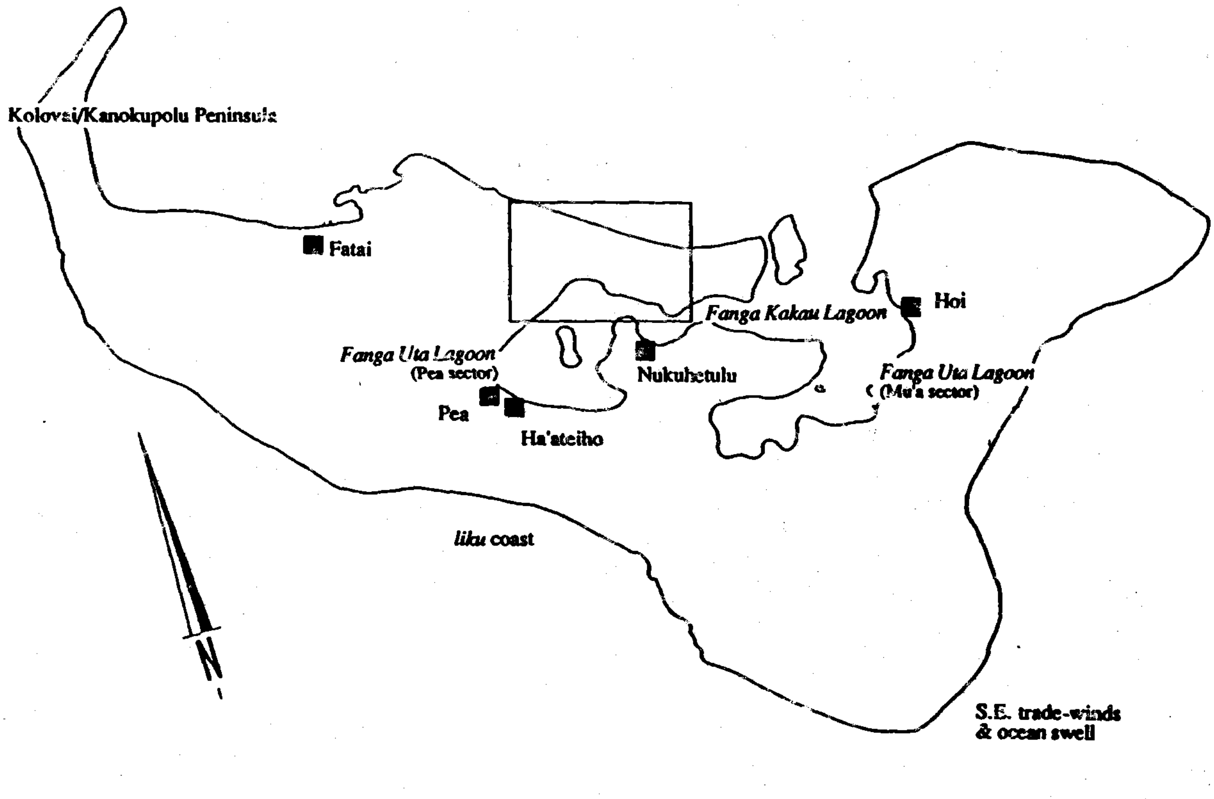


Figure 1. Map of Tongatapu, Kingdom of Tonga, showing the locations mentioned in the text. The frame indicates the location of Figures 2 to 6.

Geology of Tongatapu

The limestones of Tongatapu are reefal in origin and of (?) Pliocene to Recent age. As various oil exploration wells have shown, the limestones vary in thickness from 150 m on the north to about 250 m on the south side of the island. The core of the island underlying the reefal limestone is formed by Miocene volcanoclastics, which have been cored to a depth of 1,500 m.

Morphologically the island is low-lying and undulating, with occasional higher knolls. The highest elevations are in the southeast and nowhere do these exceed 65 m. From the southeast the island slopes gently down to the northern mangrove-fringed coastline. For the most part the coast is cliffed (*liku* coast), the highest (up to 35 m) being found in the south. The central part of the island is occupied by a shallow lagoon (Fanga 'Uta) which, except for a channel at its northeast margin, is entirely enclosed by land. The island is surrounded by a recent coral reef which varies in width from a few metres in the south to over 7 km on the northern shore; here a shallow reef flat extends out to sea.

Penetrating rainwater has washed out numerous caverns and caves in the reefal limestone, creating a karst landscape with dolines. These caves are most accessible in the eastern part of Tongatapu, whereas the formations in the western part are mainly subterranean and have been only occasionally exposed in the course of quarrying.

Six soil series have been distinguished: three of them derived directly from andesitic volcanic ash or tephra (Lapaha, Vaini, Fahefa); one from re-deposited tephra (Fatai), and two derived from marine deposits (Nuku'alofa [coastal sand], Sopu [lagoonal deposits]). The volcanic soils exist in various phases depending on the degree of erosion and weathering. The tephra layers increase in thickness from the east (~1.5 m) to the west of the island (where they may reach up to 5.5 m), indicating that they were deposited against the prevailing winds from volcanic sources west of Tongatapu. The source or sources have not been identified so far, but may well be one or more of the spasmodically erupting submarine volcanic vents, since pieces of basalt scoria of up to 1 cm diameter recovered from the western part of Tongatapu indicate a source close by. The tephra soils are very fertile, while the soils derived from marine deposits are generally rather poor (Lee & Widdowson, 1977; McGaveston & Widdowson, 1978; Widdowson, 1977).

Table 1. Population of Nuku'alofa and Tongatapu (compiled from Fiefia, 1966 and Mulk, 1986)

| | Total numbers | | | Increase in % | |
|---|---|---|---|---|---|
| | 1966 | 1976 | 1986 | 1966-1976 | 1976-1988 |
| Tonga, total | 77,429 | 90,085 | 94,535 | 16.35 | 4.94 |
| Tongatapu, total | 47,920 | 57,411 | 63,614 | 19.81 | 10.80 |
| Nuku'alofa, total | 15,685 | 21,327 | 28,899 | 35.97 | 35.50 |
| | | | | | |
| Kolofo'ou | 8,081 | 9,081 | 10,039 | 12.37 | 10.55 |
| Ma'ofanga | 2,376 | 3,636 | 4,807 | 53.03 | 32.21 |
| Popua | ------ | ------ | 618 | ----- | 6180.00 |
| Tukutonga | ------ | ------ | 220 | ----- | 2200.00 |
| Nukunukumotu *) | ------ | 40 | 47 | 4000.00 | 17.50 |
| 'Oneata *) | ------ | 10 | 5 | 1000.00 | -50.00 |
| Other islets *) | ------ | ------ | 46 | ----- | 460.00 |
| Kolofo'ou, total | 11,245 | 12,767 | 15,782 | 13.53 | 23.62 |
| | | | | | |
| Kolomotu'a | 4,359 | 5,595 | 6,419 | 28.36 | 14.72 |
| Haveluloto | 1,299 | 2,243 | 3,066 | 72.67 | 36.69 |
| Tofoa/Kolua | 425 | 772 | 2,300 | 81.64 | 197.92 |
| Hofoa | 404 | 601 | 608 | 48.76 | 1.17 |
| Puke | 198 | 277 | 403 | 39.90 | 45.49 |
| Sia'toutai **) | 345 | 306 | 321 | -11.70 | 4.90 |
| Kolomotu'a, total | 7,161 | 9,794 | 13,177 | 36.77 | 33.93 |

*) In the 1966 census possibly not counted as a separate entity.
**) Sia'toutai is a church college. Thus the number of inhabitants is relatively stable.

## Demography

The basic demographic characteristics of Nuku'alofa are detailed in Table 1. It should be kept in mind, however, that during the last decade an increasing number of adult Tongans has moved overseas in search for employment. This has left a disproportionately high percentage of older people and children resident in Tonga. As of 1987, approximately 30,000 Tongans were thought to be living in Auckland, 20,000 in Sydney, 20,000 in Honolulu and 30,000 on the west coast of the USA. This has slowed down the actual population growth in Tonga, resulting in a nett growth of about 5% in the last intercensal period (1976-86). Despite this, the increase in the population on Tongatapu has been twice as high as the nation-wide increase and the increase in the population of Nuku'alofa has been 13 times higher (35.5%). The growth rate of Nuku'alofa has been stable in the last two inter-censal periods (Table 1). This clearly reflects the increased attraction of the capital Nuku'alofa, draining the outer islands, and although we can assume that the emigration of Tongans overseas will continue, the influx of people into Tongatapu and especially into Nuku'alofa will also continue, if not increase. Providing sufficient housing is already a problem in Nuku'alofa and will become even more so if the population influx continues (see Connell & Roy, this volume, for a discussion of this problem in atoll states).

## Land use patterns

### On Tongatapu

Except for the mangrove forests along the northern shore and the lagoon, a small strip of land along the southern, cliffed coastline, and aside from some patches of secondary forest in the vicinity of Fua'amotu airport, the entire area of Tongatapu has been allocated to families and is used for gardening or habitation. A family based swidden agriculture cycle prevails, although cash crops are grown on an increasing basis. Most garden allotments (*kau 'api uta*) are intensively gardened with three to four planting seasons (commonly yams, *Dioscorea alata*; giant taro, *Alocasia macrrhiza*; taro, *Colocasia* spp.; sweet potatoes, *Ipomea batatas*; and manioc, *Manihot esculenta*) and a three year fallow period. The settlement pattern on Tongatapu consists of nucleated villages, most of which are located at or near the coast. The houses are erected within a town allotment (*kau 'api kolo*), which by law is 0.16 ha in size, but in practice is at least twice to three times as large. The dimensions of the '*api kolo* in the villages are larger than in the densely populated towns, such as Nuku'alofa or Mu'a.

### In the Nuku'alofa area

The Nuku'alofa township area consists mainly of built-up areas. Mangrove forests and swamplands are located in the extreme west and east at Sopu/Hala-'o-vave and Popua/Tukutonga. Some of this land has been surveyed and allocated for habitation. Settlement of these areas is presently in progress (see below). Most of the Government buildings and offices of foreign representatives are erected in the town centre along the shore front, Taufa'ahau and Queen Salote roads. A small industrial complex, the Small Industries' Centre (SIC), is erected in the east of Nuku'alofa. Few less densely built up areas exist in the highly populated areas of Nuku'alofa. Two Pleistocene (?) patch-reefs have been used as quarries to obtain coral limestone for use as aggregate, for concrete and for road metal. The Ma'ofanga quarry, next to the SIC, has been mined to surrounding ground level, and the other quarry (Pili quarry) has been quarried almost down to the groundwater table. Two further patch-reefs bracket the centre of Nuku'alofa: Sia-ko-Veiongo in the west is used as a troposcatter transmitter station and Holohi'ufi in the east is the residence of the New Zealand High Commissioner. The Royal Palace grounds are located at the foot of Sia-ko-Veiongo. The centre of Nuku'alofa is dominated by a large area reserved as the cemetery of the Royal family (*mala'e kula*).

## HOLOCENE SEA LEVEL CHANGES - A LOOK INTO THE PAST AS A WINDOW INTO THE FUTURE

### The pre-Holocene shorelines of Tongatapu

The most recent and extensive work on the geology of Tongatapu was carried out by Taylor in 1976 (Taylor, 1978; Taylor & Bloom, 1977). Taylor identified five geological formations visible as terraces and, based on radiometric dating and the analysis of wave-cut solution notches on the cliffed side, interpreted the morphology of the island as due to reef formations around a palaeo-island situated in the southeast. Taylor argued that reefs developed on the leeward side of the palaeo-island in response to the prevailing southeastern trade winds. While the southern windward shoreline of Tongatapu is constantly being eroded, the northern leeward side is aggrading. An understanding of these long-term processes is necessary for an understanding of the development of the Holocene shoreline and thus the genesis of the present reef system, as well as to anticipate the changes to the shoreline and the island's response to this change which might be brought about by a rising relative sea level.

The Holocene shorelines - change in relative sea level

The reconstruction of the Holocene shorelines followed three different approaches (for a more detailed assessment see Spennemann, in prep. a) the identification of raised coral reefs, b) the identification of wave-cut solution notches; and c) the analysis of soil patterns.

Corals

Raised coral microatolls were first noted in the Nuku'alofa area by Labilladiere in 1793, who remarked that the sea level must have been higher at one stage (Labilladiere, 1800: II 154). Bourrouillh & Hoang (1976) sampled them in 1974 and provided 230Th/ 234U dates) of 6200 +/- 300 BP and 7600 +/- 800 BP*. Taylor (1978) re-sampled these coral heads in 1976 and confirmed the previous dating using both Uranium series and radio-carbon dates. As Taylor could document, these corals originally occupied an inlet to the lagoon which is now completely silted up. Figure 2 shows the topography of Nuku'alofa based on recent surveying work: the old entrance can readily be identified by the contours. The tops of the coral heads in question are between 1.2 and 1.5 m above present mean sea level (MSL). At Kolonga on the northeast coast of Tongatapu, the Holocene corals were again identified 1.5 m above present MSL, and yielded a similar date. Based on these data, Taylor argued for a relative late Holocene fall of sea level of a magnitude of 2.2 +/- 0.3 m.

Wave-cut solution notches

Ladd & Hoffmeister (1927) described the southern reef platform of Tongatapu, now about 3 m above MSL, and argued for a relative fall of sea level at an undefined point in time. Taylor (1978) also discussed these platforms and the wave solution notches on the southern *liku* coast. Solution notches as such are undatable unless an *in situ* reef has grown subsequently in the notch. Though the Tongan notches, cannot provide any conclusive evidence as to the time of their formation, they may well provide evidence for the maximum relative sea level attained. Taylor identified two series of solution notches, one at about 2 m above the Mean High Water Level at Spring Tides (MHWS) and the other between 3 and 3.7 m. It seems very unlikely that these notches would have survived intact since the Pleistocene highstand, and they are thus likely to be of Holocene date. This could indicate a maximum Holocene highstand of 3.7 m above MHWS, but, as Taylor points out, considerable height variation (up to 1 m) can exist on one and the same continuous notch on Tongatapu. In conclusion we can say that, while the likelihood of a Holocene highstand of ~2 m above present MHWS is supported by the evidence of notches, a higher sea level, possibly as much as 3.7 m, is within the range of probability.

The pedological evidence

The pedological maps for Tongatapu indicate two basic types of soils: those developed on tephras and those developed on marine deposits. The soil map (Gibbs, 1972) shows that most of the Nuku'alofa peninsula consists of the latter deposits. The lack of tephra in these areas may indicate that the tephra was deposited at a time when these areas were permanently or semi-permanently (inter-tidally) under water or that the tephra has subsequently been stripped. Based on the degree of weathering, the younger tephra showers are estimated to have fallen between ~5000 and ~10,000 BP (Orbell, 1977a,b).

*All dates referred to are either calendar dates expressed in AD or BC, or radiometric dates referred to as BP (Before present, i.e. before 1950). Where radiocarbon dates have been expressed as calendar dates, this means they have been corrected for $^{12}C/^{13}C$ fractionation, ocean reservoir effect (where applicable) and atmospheric $^{14}C$ fluctuation (.i.e. the dates have been calibrated, using the program CALIB, version 2.0, Stuiver & Reimer, 1986).

Based on the available data we can advance the following scenario of events for Tongatapu:

~8000 BP (~6000 BC): Highest dated Holocene sea level, higher than 2.2 m above MHWS, possible as high as 3.7 m above MHWS.

~6600 BP (~4600 BC): The former lagoonal entrance at Nuku'alofa is dry at low tide, causing the *Porites lobata* coral heads to die off. This decreases wave action in the bight and alters the currents. The former lagoonal entrance begins to silt in. The sea level is 2.2 m higher than today.

~5000 BP (~3000 BC): Some corals on the reefs and (present) mudflats northwest of Nuku'alofa die off. The sea level is at least 0.5 m higher than today.

~2400 BP (700/500 BC): The lagoonal mouth is almost completely sealed off at high water level. The sea level is slightly higher than it is today. The water exchange in the lagoon becomes restricted and the salinity of the lagoon decreases.

~1800 BP (200 AD): The former lagoonal mouth at Nuku'alofa is completely blocked at MHWS. The shoreline is as high as it is today. The passage connecting the western pocket of the lagoon with the eastern pocket and ultimately with the sea begins to silt in due to decrease in water exchange, a process which is still continuing today.

since ~1800 BP (200 AD): Minor adjustments only.

Change in the palaeo-environment

The pedological map for the southern end of the Pea sector of Fanga 'Uta lagoon shows the area covered with Vaini and Fahefa soils, both of tephra parent material. A deposit of marine-derived the Sopu soils is located along the shoreline, attaining a maximum width of about 500 m. Most of the Sopu soils belong to the loamy phase, with a small elongated pocket of sand located at the south-western distribution area of the marine deposits. Given the location of this sand pocket, directly opposite the former lagoonal entrance at Nuku'alofa, it is likely that it has been formed as an active beach (storm beach ridge?). Shells recovered from this beach buried underneath an archaeological site have shown that the beach formed between 7200 and 6300 BP, which agrees well with the dates obtained from the corals in Nuku'alofa.

Evidence from shells contained in prehistoric shell middens indicates that over time the lagoonal environment was steadily changing from open water conditions to the present-day lagoon. This can be documented by the relative proportion and size distribution of two environmentally sensitive shellfish species, *Anadara* and *Gafrarium*. While *Anadara* which is dependent on an unrestricted flow of seawater and is very sensitive to changes in the salinity of the water, gradually died out, *Gafrarium*, which prefers sheltered environments and which can survive more brackish conditions, became more abundant (Spennemann, 1986c, 1987a). Detailed investigations have shown that, although the overall environmental change was linear, it occurred in a series of minor fluctuations with more open water conditions giving way to sheltered conditions and *vice versa* (Spennemann, unpublished data).

## THE IMPACTS OF A POTENTIAL SEA LEVEL RISE

### Type of inundation

When discussing the effects of a relative sea level change on Tongatapu, two types of inundation need to be distinguished: the inundation caused directly by the rise in relative sea level ('direct inundation'), that is, by the sea level at the coast, and the related rise of the groundwater table in the inland areas ('indirect inundation'). Because of the permeability of the coral limestone, any rise in relative sea level will cause a corresponding rise in the groundwater table, floating on the seawater. This rise in the groundwater table will cause the inundation of low-lying areas which are bounded by higher land. Thus, in the case of Tongatapu, a heightening of the coastal protection walls is no recipe against rising sea level, but may help to alleviate the effects of tidal movements.

In addition to these two basic types of inundation, a third effect needs to be taken into account which causes temporary inundation of land lying up to 0.5 m above MSL. It is possible for extensive sheet-flooding to occur after torrential rainfall, especially in the case of the low-lying areas, as for example in Ha'ateiho village, where shallow puddles thus created can extend over several hundred square metres, evaporating over time. Groundwater fluctuations have been monitored for the reclaimed tidal flats at Sopu (Straatmans, 1954), where it has been documented that 75 mm of rainfall caused the groundwater table to rise by 375 mm the next day. Commonly the groundwater level would have attained its pre-rainfall level after 6 to 7 days. It can be anticipated that a rise in relative sea and groundwater level will create this effect in areas so far unaffected, making them inhospitable and unusable for a variety of agricultural purposes.

Extent of inundation

Before discussing the extent of inundation caused by a rise in relative sea level, it is worth examining the reference level to which the data are related.

Mean sea level, mean high water level springs and the groundwater level

The following analysis is based mainly on detailed contour plans for Nuku'alofa. In the course of the Nuku'alofa Urban Sewerage and Drainage Project (Belz, 1984) a detailed spot levelling of Nuku'alofa township was undertaken by L. Belz. The individual level data were plotted onto air photographs at a scale of 1:1000. These contour data, kept at the local WHO office, were copied in 1986 by one of the authors (DHRS) onto another airphoto at a scale 1:5000, which forms the basis of Figures 2 to 6. The contours do not refer to metres above MSL, but to metres above the old Ministry of Lands, Survey and Natural Resources (MLSNR) datum, which is 0.914 m above the British Admiralty chart datum and 0.156 m above present MSL. Thus all contours plotted in Figures 2 to 6 are in fact 0.156 m higher than originally stated. This discrepancy was discovered after the contours had been traced, and cannot be amended without going back to the original data. Given the quite uneven topography of the area, it seemed advisable to refrain from linearly interpolating the accurate 0.5, 1.0 and 1.5 m (above present MSL) contours and to use the 0.65, 1.15 and 1.65 m contours instead.

As mentioned, these data refer to mean sea level, however, tidal range must be taken into account when discussing the areas affected by direct inundation. This tidal range, however, is different inside the lagoon and at Nuku'alofa harbour. The mean high water level at spring tides is 0.6 m above MSL at Nuku'alofa harbour, which means in practical terms that at spring tides (twice about every 4 weeks) an area 0.6 m above MSL becomes inundated. For the purpose of this study, local effects of currents and accumulation of water due to wind pressure will be excluded. These factors obviously need to be taken into account in any future, more detailed investigation.

The lagoonal mean sea level (henceforth 'MLL') is about 0.10 m above MSL (at the Peace Corps Office, at the lagoonal shore of Nuku'alofa), which is mainly due to effects of moating and restricted water exchange. Mean Lagoonal Water Level at spring tides is about 0.15 m above MLL. Any change in MSL at Nuku'alofa harbour is expected to have effects on the MLL, but the extent of this is unclear at present (see section 'Impact on the water regime of Fanga 'Uta lagoon').

Whereas the water level of the lagoon is less exposed to tidal fluctuations than the sea level at Nuku'alofa harbour, the level of the ground water table is even more stable. Tidal fluctuations, albeit very small, can be noted (Hunt, 1979), but can be ignored for the present assessment. While the table of the groundwater lens in central Tongatapu is about 0.45 m above MSL, it is only ~0.05 m above MSL on the Nuku'alofa peninsula, a difference which can be neglected at the present level of detail. Thus the level of the ground water lens in Nuku'alofa can be equated with MSL for the purposes of the present study.

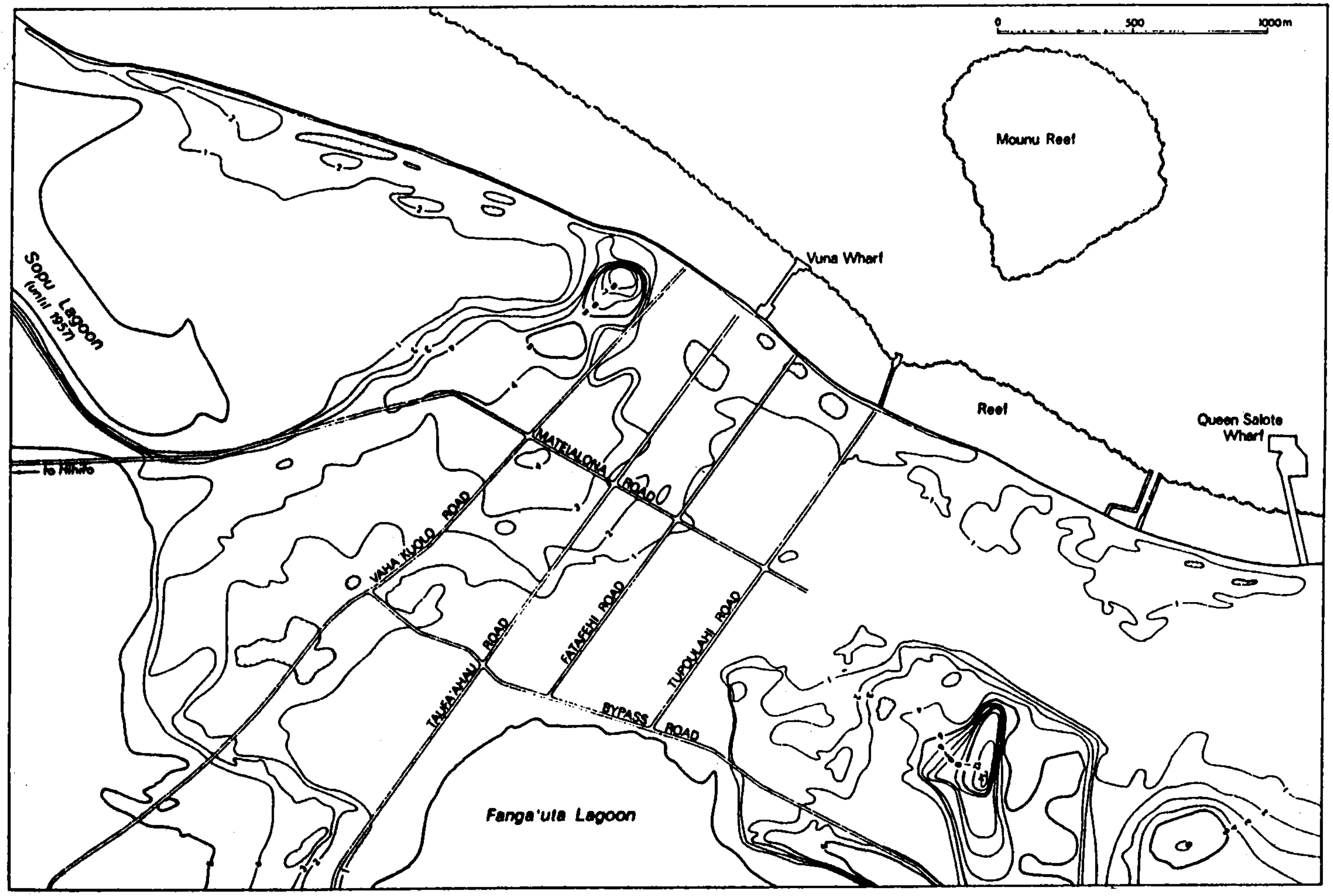


Figure 2. Height contours of the central part of Nuku'alofa. (Compiled from individual spot heights taken by L. Belz)

Nuku'alofa township area

The future development of the coastline at Nuku'alofa can be well illustrated by a series a figures showing the development of the Holocene lagoonal entrance at Nuku'alofa at 0.5 m intervals (Spennemann, in prep.a). We will first show the historical development of the lagoonal entrance with falling sea level down to the present situation and will then, by inverting the series, predict future developments.

At a relative sea level of 2 m above present MSL (Figure 3e-f), a wide open passage is perceptible, flanked by a complex patch reef to the west (the core of which is Sia-ko-Veiongo [Mt. Zion]), which develops into a promontory at the 4 m contour. During the Holocene highstand of at least 2.2 m (see above), the initial situation must have been rather similar. On the leeward side, i.e. to the west of the promontory, sand banks were deposited at the time the sea level had fallen to height of 2 m above MHWS. When the sea level had dropped to 1.5 m above MHWS, these sandbanks formed a narrow but continuous beachridge (chernier) and also extended to the east of the promontory (Figure 3d). Water exchange into Fanga 'Uta was still unrestricted. However, a further drop in sea level to the 1 m mark (Figure 3c) created an entirely new situation: the western beachridge was considerably expanded and the sandbanks east of the promontory had enlarged and merged into larger units. The flow of water into the bay was now restricted. High energy water flow directly from the north was no longer possible; all water came through the small inlets between the sandbanks along the predominately east-west trending passage. This change in the direction of the water flow must have caused a severe alteration in current patterns inside the bay. The southwestern coast of the present lagoon would have experienced strong wave action from a northerly direction in the times prior to the sea level having attained a height of 1 m. After the sea level had dropped to that level the currents would have assumed a more circular fashion, turning south of Kanatea Island into quieter waters. This is corroborated not only by the bathymetry of the lagoon (Kimmerer, 1984:12), but also by the pedological map of the southwestern shore, which shows substantial sand deposits (Sopu soil, sandy phase), deriving from an active beach, which are bordered towards the present shoreline by loamy deposits indicating a quieter depositional environment. It can also be expected that the rate of silting-in would have accelerated at this stage. Once the sea level had dropped to a height of 0.5 m above MHWS, the former passage was virtually closed off and no more water exchange took place.

In postulating the effects of rising relative sea level this sequence is all but inverted. However, the silting changes which took place over the past 2,000 years will have some additional effect, and the issue of moating will be discussed further below.

Extent of inundation by the '0.5 m' rise scenario. Were the relative sea level to rise by 0.65 m, then the shaded areas in Figure 4 would be inundated. Direct inundation would mainly affect the lagoonal shore and would interrupt the Nuku'alofa bypass road. The lagoonal embayment would reach far inland, right into the centre of Ngele'ia. Indirect inundation, caused by rising groundwater, would cause the flooding of a large area behind the radio station, a large area at Fanga, a small area near Pahu, and a small area behind the cable & wireless station (for a tracing of the 0.65 m contour on an airphoto, c.f. Belz, 1984). The central residential and business areas of Nuku'alofa would remain unaffected. Outside the mapped area, parts of Houmakelikao, most of Tukutonga and large parts of Popua would be inundated directly and indirectly. The inundation at Sopu would cause the flooding of most of Hala-'o-vave, Hala'ano and most of the compound of 'Atenisi University. The extent of the flooding at the lagoonal side cannot be estimated beyond reasonable doubt due to effects of moating (see section 'Impact on the water regime of the Fanga 'Uta Lagoon').

Extent of inundation by the '1.0 m' rise scenario. The extent of inundation at the 1.15 m scenario is much greater (Figure 5). The entire central residential and business section of Nuku'alofa would be inundated, and, at least at high tide, a lagoonal inlet would be created. The inundation would cover Fanga, Pahu, most of Ngele'ia, Kolofo'ou and northern Ma'ofanga. Houmakelikao, for which no exact levelling data exists, would most likely also be flooded entirely, along with the remainder of Popua, Tukutonga and Patangata. Were it not for the coastal protection wall, the sea-front would be broken up into a line of small islets, upon which part of the government buildings would stand. Also the Roman Catholic church of Ma'ofanga and the Fakafanua centre would remain on dry ground. A relative sea level rise of 1.15 m would

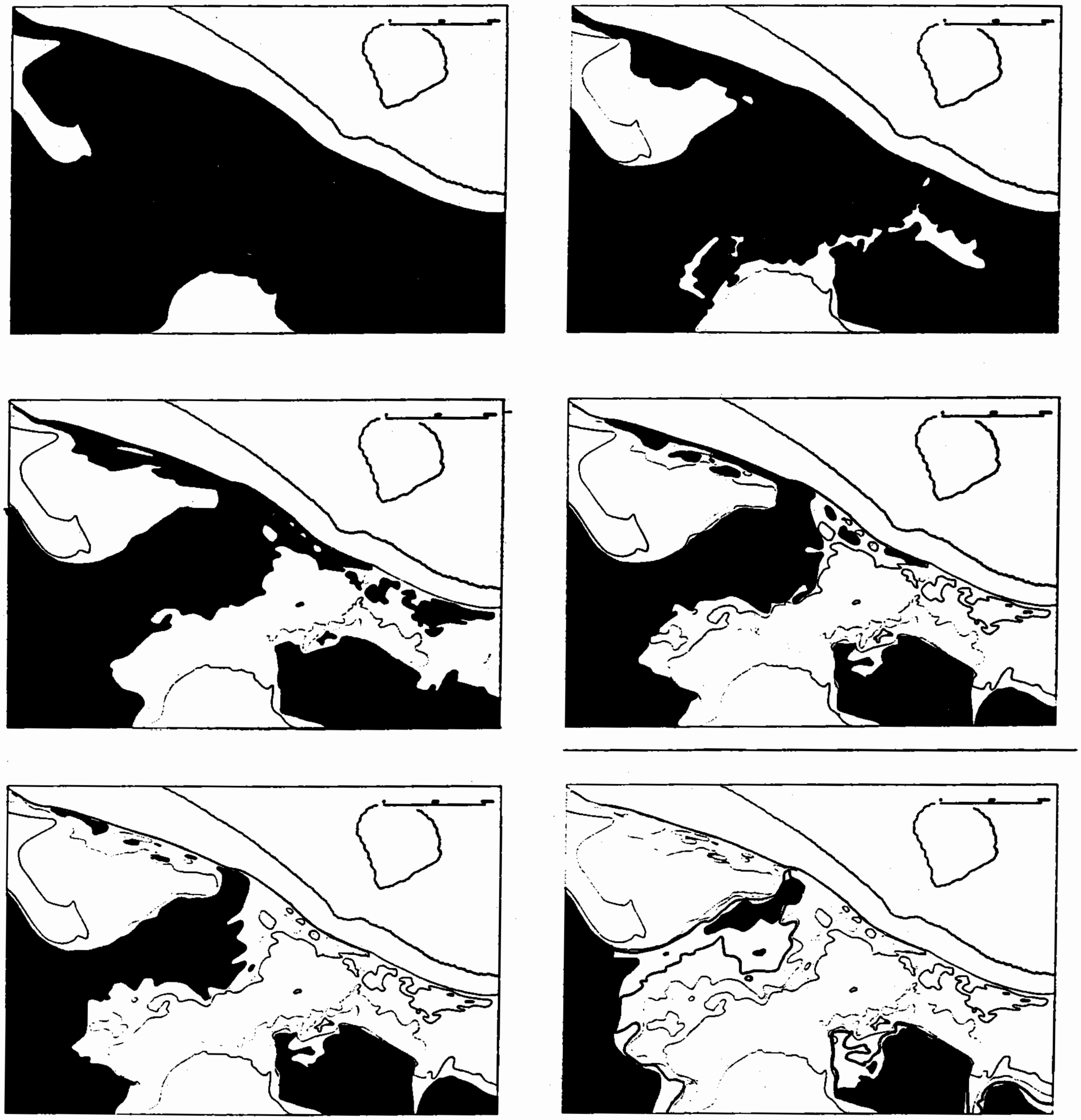

Figure 3. Re-opening of the old lagoonal entrance in the streets of Nukua'lofa with rising relative sea level. For locations of roads see contour plan Figure 2. Land is shown in black.

a - The present shoreline (black), before the reclamation of the old Sopu lagoon in 1951.

b - The extent of the shoreline (black) at a sea level of 0.5 m above present MSL.

c - At a sea level of 1.0 m above present MSL. d - At a sea level of 1.5 m above present MSL.

e - At a sea level of 2.0 m above present MSL. f - At a sea level of 4.0 m above present MSL.

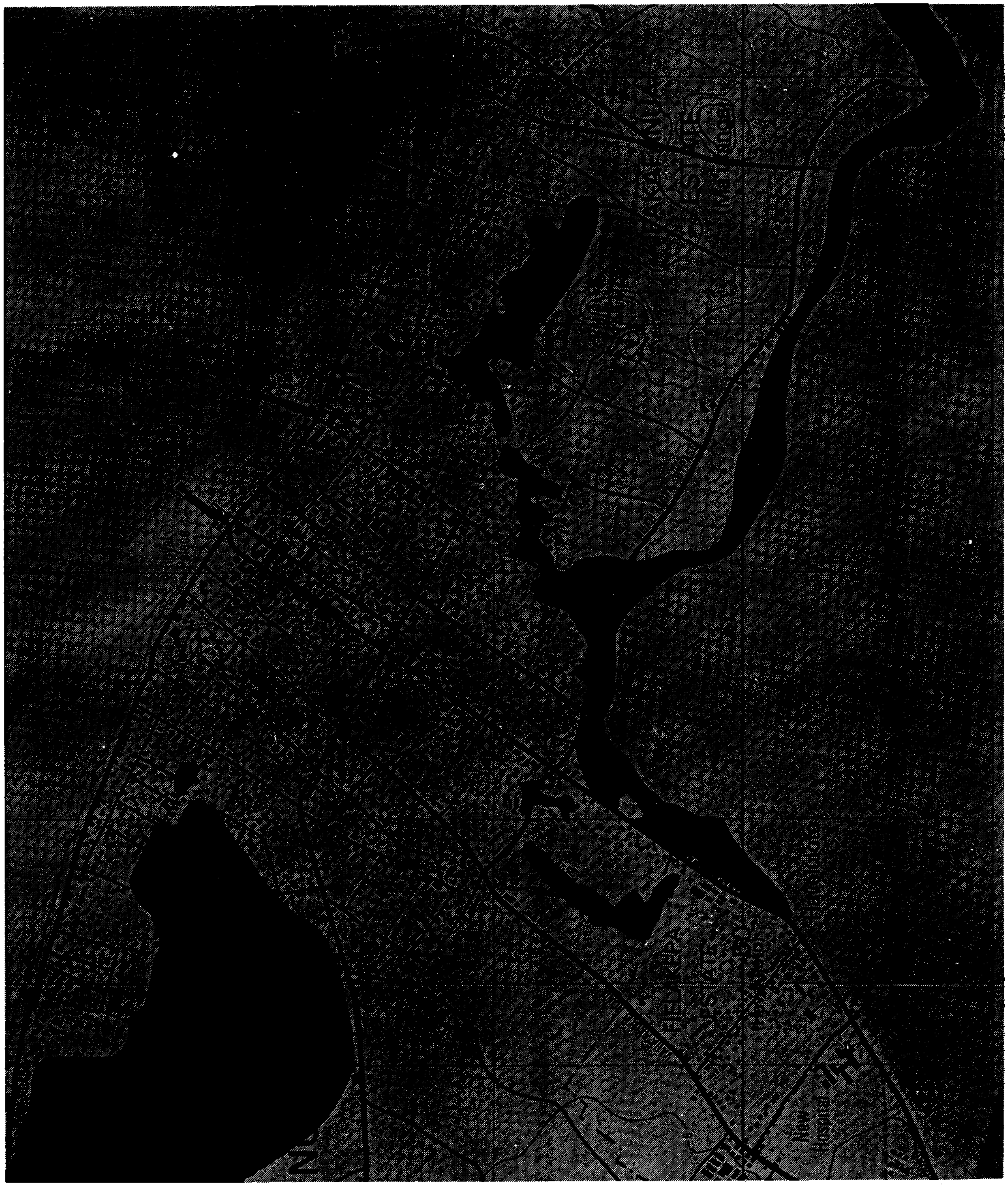

Figure 4: Extent of inundation at a relative sea level rise of 0.5 m above present MSL. Contouring: after WHO data; basemap: Topographic map 1:25,000, sheet 21.

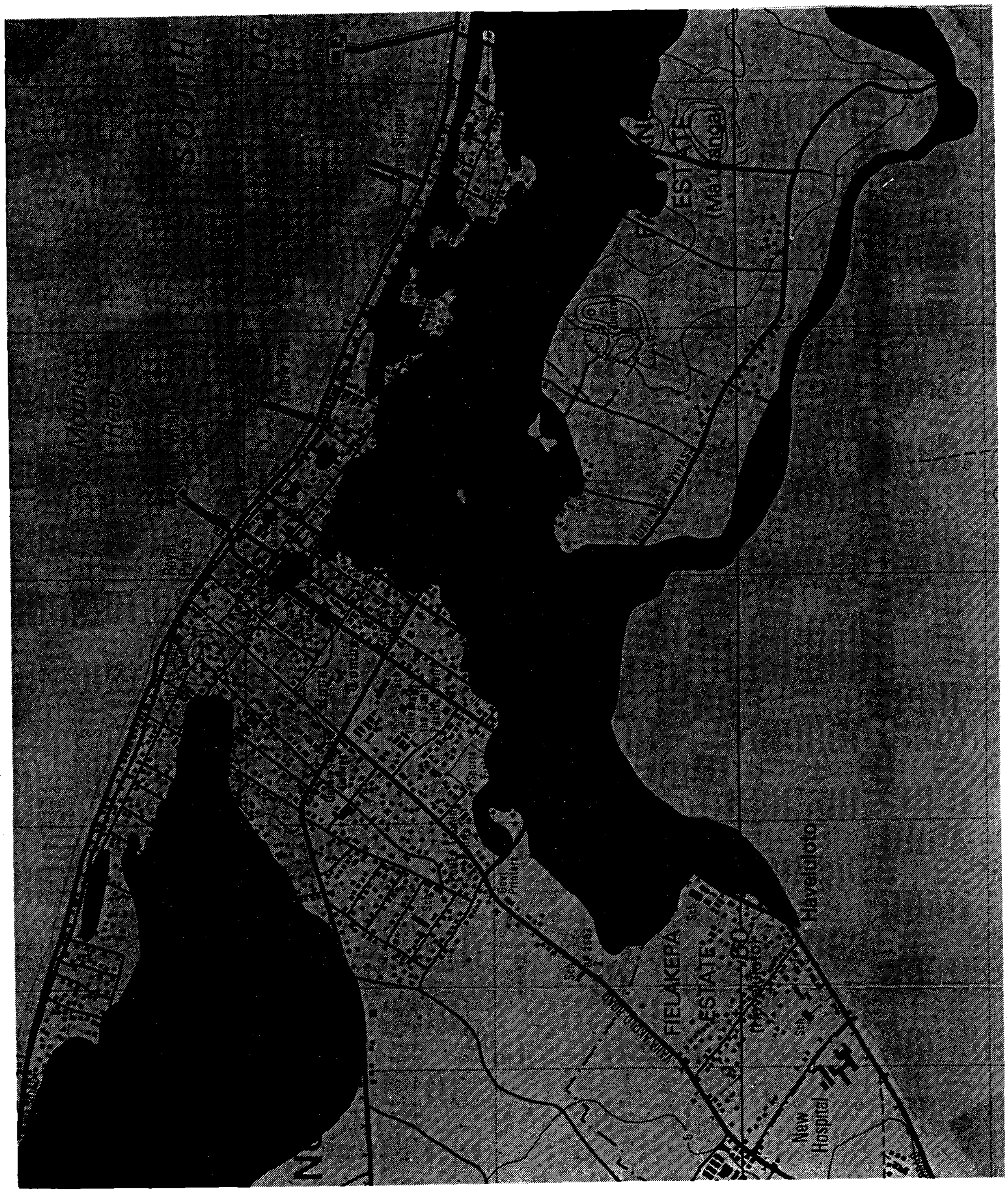


Figure 5. Extent of inundation at a relative sea level rise of 1.0 m above present MSL. Contouring: after WHO data; basemap: Topographic map 1:25,000, sheet 21.

effectively create an island out of the southern part of Ma'ofanga, which would include the area of the SIC. The newly erected Tongan National Centre would also be severely affected by a 1 m rise. The former compound of the USP, the Government Printery and the area of Taufa'ahau road north of Mangaia would be largely unaffected. The inundation of Sopu would extend almost to the southwestern foot of Sia-ko-Veiongo.

Extent of inundation by the '1.5 m' rise scenario. The most serious of the three scenarios, a rise in relative sea level by 1.65 m (Figure 6) adds only small areas to the areas already inundated by the 1.0 m scenario. The additional areas would be the Palace grounds, The Government Printery, Fakafanua Centre, Roman Catholic Church of Ma'ofanga and most of Taufa'ahau road. The ground west of the compound of the USP and the *mala'e kula* would still not be inundated.

The Nuku'alofa waterfront

The foreshore protection wall cannot stop the indirect inundation of low-lying areas behind the wall, as this inundation will result from the rising groundwater table, but it will greatly reduce tidal movement, as can be documented by the closed off part of Sopu lagoon. Given the tidal range of +/- 0.6 m, this gives a great amount of protection. Thus the wall will prevent the formation of a new lagoonal entrance, along the lines of the Holocene entrance, which would dramatically alter the tidal and current patterns inside Fanga 'Uta lagoon.

Sopu reclamation

A good illustration of how the environment of low-lying areas might change with a relative rise in sea level is the old Sopu lagoon. Until 1951 this was an embayment at Sopu, west of the centre of Nuku'alofa, which consisted mainly of tidal flats. The area was blocked off by a dam to stop the influx of sea-water and to allow for sedimentation due to surface run-off and for gradual desalinisation of the area. The sea-wall actively reduced the tidal range inside the closed-off part of the lagoon and the area turned brackish. Several plantation trials were undertaken to assess the suitability of the land for growing various food plants such as sweet potatoes and giant taro. Some plants, especially giant taro, did well in the first year, but became overgrown by weeds in the following seasons. Due to the storm effects of cyclone 'Isaac' in 1982, the dam was breached at various places and sea-water again flooded the area, causing the die-off of all salinity-sensitive plants, and effectively causing reversion of the area to the 1951 status. The suitability of the area for root crops, the main Tongan staple food, has been reduced to nil (Straatmans, 1954; Nor, 1983; Wolterding, 1982).

The Kolovai-Fatai mudflats area

The northern shoreline of Tongatapu, from Hofoa, directly west on Sopu, to Kolovai at the western tip of Tongatapu, is a low-lying area, bordered by extensive mangrove stands. Seaward of the mangroves are extensive intertidal sand and mudflats, reaching 3 km out to sea. The land slopes gently to the sea, with most being below 1 m above HWL. The only clearly visible shoreline is the ~2 m contour, which can be easily recognised in most areas about 300 to 500 m inland from the present high water mark. A large scale loss of gardening land can be predicted in this area. An increase in relative sea level would cause a retreat of the shoreline and would cause the mangrove community to migrate inland. Although mangroves commonly grow slowly, the environment would be likely to remain similar to the present setting, were it not for increasing destruction of mangroves for fire-wood. The mangroves are being cut back at an increasing rate especially in the vicinity of the villages, which is particularly damaging as mangroves act as a sediment trap stabilising the shoreline.

The offshore islets

The northern shore of Tongatapu is protected by a fringing coral reef, which has grown to the present mean water spring tide level (MLWS). A rise in relative sea level is likely to have beneficial effects in the short term as the corals are likely to quickly colonise reef platforms which are now dead in the centre

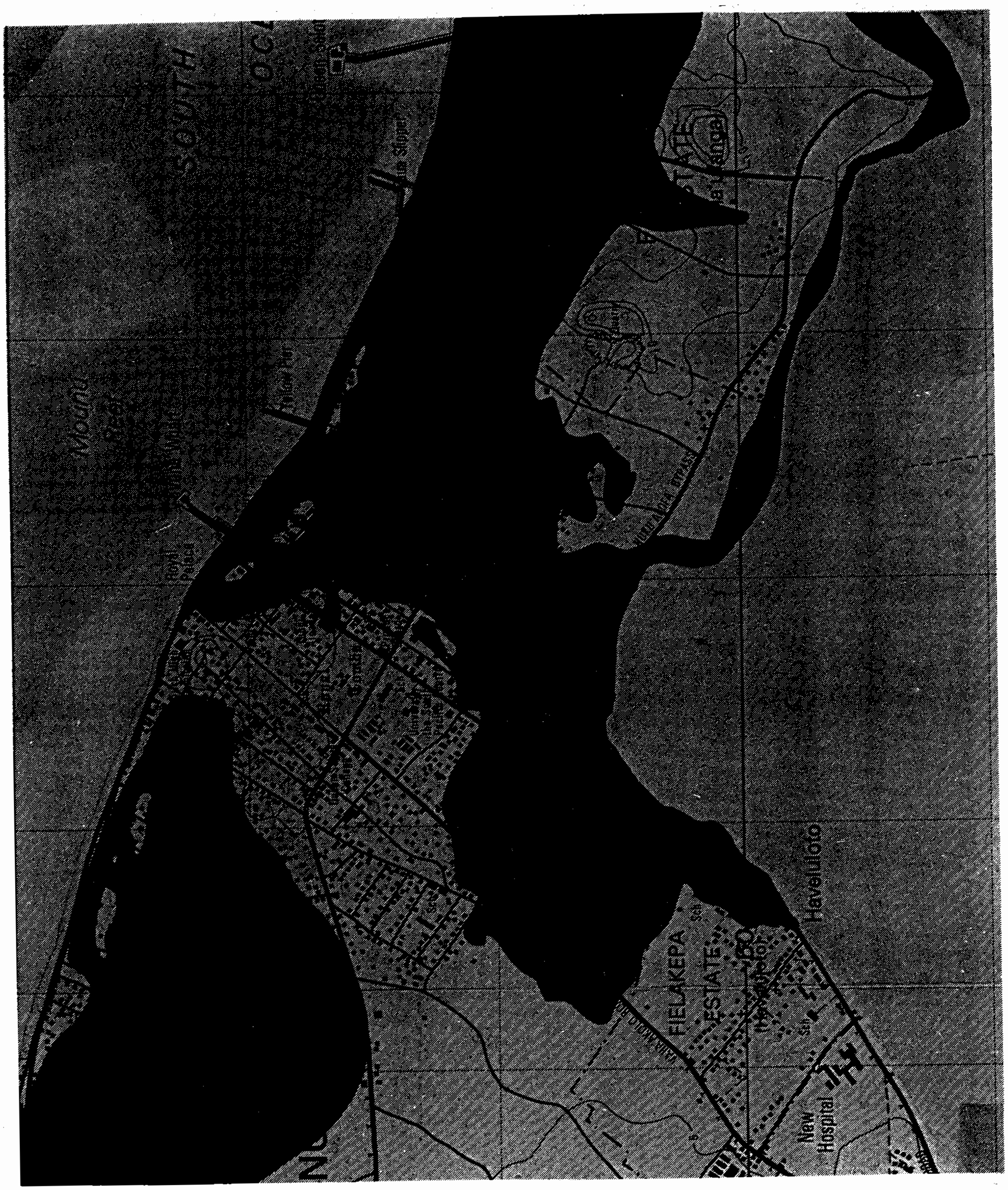


Figure 6. Extent of inundation at a relative sea level rise of 1.5 m above present MSL. Contouring: after WHO data; basemap: Topographic map 1:25,000, sheet 21.

(c.f. similar projections for the Great Barrier Reef: Hopley & Kinsey, 1988). It can be expected, however, that reef growth on areas with soft substrate will not take place for some time. The potential effects of this reef growth largely depend on the rate of sea level rise; if the rise is in excess of 8 mm/year, which is about the growth rate corals may reach under optimal conditions, then the coral may not keep up with the rise but will have to catch up at a later stage, if and when the sea level has stabilised. The history of Holocene sea level change has shown that corals could not keep up with rising relative sea levels of 12.3 mm/year (J. Ellison pers.comm.), but had to 'catch-up'. In the three scenarios evaluated by the 'NCR Committee on Engineering Implications of Changes in Relative Mean Sea Level' (1987) a linear increase of sea level over the next 100 years, would occur at rates of 5, 10 and 15 mm/year respectively. While coral may well be able to keep up with a sea level rise in the 0.5 m scenario (5 mm/year), it is unlikely to be able to keep up in the other scenarios.

This has implications for the assessment of the wave energy, since lessened protection by an increasingly submerged fringing coral reef will result in an increased impact of waves on the northern shore of Tongatapu, which in turn may bring about erosion of the shore.

Another issue concerns the sand cays situated on the fringing reef. Most of the islets offshore of Tongatapu are low-lying, with a maximum height of less than 5 m. While some consist of a raised Pleistocene (?) reef, such as Velitoa Hihifo, Velitoa Hahake, Motutapu, Fukave and Nuku, the majority are sand cays, such as Fafa, Malinoa, Pangaimotu, Makaha'a, Oneata, Manima, Polo'a, Alakipeau, Tufaka and Tau. An increase of relative sea level will cause increased erosion, especially on the windward sides. Most of the islets are wedge-shaped with a slightly degrading, cliffed eastern and southeastern side and an aggrading gently sloping western shore. A comparison between the situation of 1957 and that 30 years on has shown that up to 30 m of shoreline have been lost on some of the islands, most of it due to cyclonic storm surges (Spennemann, 1987b). The effects of cyclone 'Isaac' have been studied by Woodroffe (1983) who could document that in numerous instances the loss of high ground has been substantial compared with the situation 15 years earlier (Stoddart, 1975). Although coastal degradation usually leads to aggradation at the leeward side, the land so formed is commonly very low-lying and prone to tidal flooding and flooding by cyclonic surge. The speed of this erosion is very likely to increase due to increased wave action. Some islets, such as Monuafe (~0.6 m above MHWS) are likely to be completely destroyed and converted into intertidal sand banks. While increased reef growth will bring about an increased amount of detritus, which will most likely be deposited at wave node points, where the sand cays are located, it is also likely to occur predominantly in the intertidal level. Thus the likely scenario is that the islets will in fact expand in area but will be dramatically reduced in height. Those small sand cays which have a deep drop-off on their lee-ward side, such as Pangaimotu, can be expected to experience a net loss of sand. This scenario assumes that the coral reef growth is capable of keeping up with the increase of relative sea level. If this is not the case, then the wave pattern can be expected to change, which in turn may bring about the re-deposition and relocation of the sand cays. The flexibility of the present configuration of sand cays can be high-lighted by the appearance and disappearance of a small sand cay, Iniu, between Pangaimotu and Manima, which at the time of d'Entrecasteaux's visit to Tonga (1793) had become vegetated, but which has disappeared again since (Labillardiere, 1800: II 113-134).

The re-deposition or re-formation of sand cays, with perhaps an increased area but a decreased overall height, will have severe repercussions on the suitability of such sand cays for human habitation. While at present the larger of the sand cays are capable of sustaining a human population by providing them with a ground water lens, the overall loss in height will put this lens at risk. The lower height implies an increased vulnerabilty of the islets to wash over during a cyclonic tidal surge, which, aside from creating structural damage to habitation, will cause the salinisation of the freshwater lens to the point of unsuitability for human consumption.

The southern and south-eastern (*liku*) shore

The southern and southeastern shore is by and large cliffed facing the southeastern oceanic swell pounding against the shore. Several pocket beaches exist in the south, while large beaches exist in the east. Due to coralline algae thriving in the constant spray, the fringing reef has grown above HWL and has formed moated pools. With rising relative sea level it can be expected that coastal retreat will occur and that the beaches will be shifted inland. In some places the pocket beaches are very narrow with a steep cliff face at the back, so that an increase in relative sea level may result in a net loss of sand at that location. As with the corals on the northern fringing reef, rising sea level can be expected to be beneficial, at least in the short term, and to revitalise coral growth.

The Fanga 'Uta lagoon

The future of the lagoon is a very complex issue, which needs to be studied separately and in much greater detail than was possible in the framework of this report. The data available (Ludwig, 1980, Zann *et al.*, 1984) are insufficient to provide a detailed prediction. Given the sensitivity of this issue, only a few general comments will be made.

Fanga 'Uta lagoon consist of two pockets, the Nuku'alofa-Pea sector and the Mu'a-Longoteme sector, which are connected by a narrow arm, the Fanga Kakau lagoon. A wide lagoonal entrance connects the Mu'a-Longoteme sector with the sea. At present, a coral reef at the lagoonal mouth restricts the water exchange and prevents any vessels larger than launches from entering the lagoon. Another restriction to the tidal flow occurs at the eastern entrance to Fanga Kakau lagoon, which is rapidly silting in. Both passages seem to have become increasingly blocked over the past one hundred years, as previously large (up to 40 m long) double-hulled sailing canoes were regularly entering the lagoon to be berthed at locations, in both pockets of the lagoon, such as Pea in the west and Mu'a in the east.

A rise in relative sea level can be expected to increase the tidal flushing of both lagoonal pockets, which is currently quite restricted in the Pea sector (Table 2), leading to a mean residence time of the water of more than 20 days.

Table 2. Measured (*) and estimated tidal range of Fanga 'Uta lagoon, Tongatapu

| | Locality | Tidal range | Reference |
|---|---|---|---|
| 1 | Haveluloto | 0.35 * | R.Carter, pers. comm. |
| 2 | Kanatea area | 0.20 * | Braley 1979 |
| 3 | Peace Corps Office | 0.30 * | Belz 1984 |
| 4 | off Ma'ofanga | 0.13 * | Zann, *et al.* 1984 |
| 5 | off Folaha | 0.17 | Connell *et al.* 1985 |
| 6 | Mata'aho Islet | 0.20 | Connell *et al.* 1985 |
| 7 | Kauvai | 0.79 * | Zann, *et al.* 1984 |
| 8 | Tatakamotonga | 0.79 | Connell *et al.* 1985 |
| 9 | off Hoi | 0.85 | Connell *et al.* 1985 |
| 10 | off Nukunukumotu | 0.85 | Connell *et al.* 1985 |
| 11 | Nuku'alofa wharf | 1.20 * | Admiralty Tide Charts 1977 |

Without computer modelling, the extent of the flooding at the lagoonal site cannot be estimated. Due to effects of moating, the lagoonal mean water level (MLL) at the Peace Corps Office is presently about 0.10 to 0.15 m above MSL at Nuku'alofa sea-front. An overall rise in relative sea level of the order of 0.5 m would increase the tidal flushing of the lagoon and thus the tidal range, but would also reduce the effect of moating. Hence it is quite feasible that to some extent these two effects would cancel each other out. However, it is quite within the range of expectations that reef growth at the present lagoonal entrance will be revitalised to such an extent that the reef will keep up with sea level rise of 5 mm/year (0.5 m scenario). If this is the case, then the tidal pattern in the lagoon is not likely to change dramatically, but may be expected to stay roughly within the present limits.

It should be kept in mind, however, that an overall increase of relative sea level will also increase the level of the groundwater lens, which will cause inundation of low-lying areas. This will cause severe problems especially at the lagoonal shores of Nuku'alofa (see above) and for the villages of Pea and Ha'ateiho, large parts of which are in marginal areas. A good indication of future problems is the fact that large parts of these villages are frequently inundated following torrential rainfall. To a lesser extent the villages of Nukuhetulu, Foloha, and Hoi will be similarly affected.

Although largely beyond the scope of this paper, the point should be raised as to what extent an increase of tidal flushing of the lagoon would be beneficial or actually desirable. Overloading of the Pea sector with nutrients, derived from sewerage and other effluents, has already caused excessive sea-grass growth in the southernmost part of the sector and has resulted in the die-off of several mollusc species, which up to then had provided an important food resource for the population (see below 'Impact on natural resources'). If both the restriction of water exchange and the influx of nutrients continue, algal blooms and a collapse of the lagoonal ecosystem are possible. This is compounded by the cut-back of mangroves for firewood mentioned for the Kolovai-Fatai area which occurs at an even greater rate at the shores of Fanga 'Uta lagoon. In a single year, between mid-1986 and mid-1987, the mangrove community at Ha'ateiho was cut back on a wide front for about 10 m. Construction of habitation at marginal areas has further compounded the effect: at the lagoonal shore of Nuku'alofa it has caused the destruction of almost the entire mangrove community in the area. At the new settlement of Popua (founded 1982) the previously largely intact mangrove forest has been reduced to a fraction of its previous extent.

Impact on human habitation

Nuku'alofa: direct impact

If the relative sea level rises as assumed in the three scenarios actually occur then approximately the following areas in central Nuku'alofa, (i.e. between Sopu in the west and the Shell depot in the east), will be inundated: an area of 0.83 $km^2$ in the case of a rise of 0.65 m; 3.30 $km^2$ in the case of a rise of 1.15 m; and 4.34 $km^2$ in the case of a rise of 1.65 m. The extent of impact under the three scenarios is likely to be as follows:

Potential consequences of the '0.5' m scenario. As can be seen from Figure 3, a rise in relative sea level of 0.65 m will result in extensive inundation at the lagoonal shores, will interrupt the Nuku'alofa bypass road and will create inundated and wet areas in the centre of Nuku'alofa, splitting the centre of Nuku'alofa from southeastern Ma'ofanga. Although the connecting roads can be built on raised shoulders, it can be imagined that the wet areas will impede the communication flow and might create a division between Kolofo'ou/Ngele'ia and southeastern Ma'ofanga, which does not exist at present.

Potential consequences of the '1.0' m rise scenario. A relative sea level rise of 1.15 m would cause the inundation of a large part of central Nuku'alofa, caused by the raised groundwater table. In addition, torrential rainfalls will turn areas which are marginally above sea level into quagmires. Since this scenario affects most of the residential, business and administrative districts, it will also affect the efficiency of the government departments. Several government buildings are likely to be inundated: the Electric Power Board, the Tonga Telecom station, Ministry of Works, and the radio station A3Z. Not only will access to the buildings remaining on higher ground become more problematic, but they will also be more and more isolated and exposed to wind forces as surrounding buildings on lower ground will be given up and salinity sensitive trees, such as mango (*Mangifera indica*) or breadfruit (*Artocarpus altilis*), will die off. Even coconuts (*Cocos nucifera*) cannot exist in standing salt water (see below). The southeastern area of Ma'ofanga will be isolated, and access to it will need to be by boat, by bridge or by raised road. The foreshore protection work should prevent any opening of the old lagoonal entrance and should prevent a dramatic change in current patterns inside Fanga 'Uta lagoon. The bypass road from Queen Salote wharf to the SIC will be interrupted and will require to be raised onto a dam. The area which harbours at present the large BP and Shell tank farms located at Touliki will be inundated, as well as, possibly, the coconut processing plant.

Potential consequences of the '1.5' m rise scenario. The increase in the extent of inundation compared with the '1.0' m scenario is comparatively marginal, but it will affect most of the remaining government departments, such as the Ministry of Lands, Survey and Natural Resources, the Treasury, the Tonga Development Bank Building (with Crown law office and Central Planning Department). It should be pointed out that with the '1.5'm scenario, a storm surge is very likely to wash over the top of the Nuku'alofa foreshore protection wall.

Nuku'alofa: indirect impact

A perusal of the demographic data presented in Table 1 clearly indicates that the population of Nuku'alofa has been growing at a much higher rate than the rest of Tonga. The growth of Nuku'alofa has predominantly taken place in new settlement areas, such as Popua or Tukutonga, or in existing settlements located on the outskirts of Nuku'alofa, such as Tofoa and Haveluloto. This growth pattern, which takes up more and more horticultural/agricultural land, has obvious implications for the future. Given the limitation of the availability of arable land compared with the steadily growing population, the pressure on arable land is likely to increase anyway, regardless of the extension of villages. The extension of villages due to population growth adds further pressure. If the central and low-lying parts of Nuku'alofa, mainly Kolofo'ou, Fasi, Ngele'ia and (northern) Ma'ofanga, become inundated by the rising groundwater table, then the people likely to move out of the area will increase even further the pressure on agricultural land surrounding Nuku'alofa.

A simple arithmetic approximation puts this into perspective: In 1969 Nuku'alofa spread across approximately 5.27 $km^2$ (excluding Sia'toutai, Hofoa and Puke) and the population density was ~3,178 persons/$km^2$. By 1987 the area occupied by housing or industrial premises had grown to approximately 9.40 $km^2$ with a population density of 3,039 persons/$km^2$ (figures obtained from air photography and field surveys. As can be seen, the population density has stayed relatively stable although the residential area had almost doubled. Under the three scenarios used, 0.83, 3.30 and 4.34 $km^2$ of garden land will need to be re-allocated to accommodate the people who will have to leave their inundated land. Based on an average population density of 3,100 people/$km^2$, this involves the relocation of approximately 2,500, 10,000 or 13,500 people. It should be borne in mind that these figures are for central Nuku'alofa only, and do not include the people living on the low-lying areas of Popua and Tukutonga (at present ~850 people) who will be affected by a sea level rise at the 0.65 m level and who will require resettlement.

The case of low-lying areas

The areas most prone to impact by even a limited rise in relative sea level are those low-lying areas which at present can be considered marginal for settlement or other uses. Three outstanding examples will be given.

Hala-'o-vave and Hala'ano. Two settlements which are located on low-lying ground south of Sopu. Most of the terrain belongs to the Holocene precursor of the Sopu lagoon, and most of the ground is less than 0.5 m above MHWS. This area has seen some severe (temporary) inundation in the recent past, from which some data can be drawn. During the flooding caused by the storm surge created by cyclone 'Isaac' large parts of these two settlements (up to 300 m inland) were inundated and temporarily reverted to swamp. The inundation caused the Ministry of Health to remove the people to higher ground for fear of an outbreak of epidemic diseases. Although the villagers were offered permanent allocation of land on higher ground at the other end of the town (at Popua, see below) only a few families decided to move.

'Atenisi University. The campus of 'Atenisi University is erected on swampland adjacent to Hala-'o-vave. Large parts of the campus are swampy after heavy rainfall. Reclamation has been undertaken on site partly by excavating ponds and using the excavated material as fill and partly by bringing in coral gravel as fill.

Popua/Tukutonga. After cyclone 'Isaac' struck in 1982, several families, who had lost their homes, were given new land at Popua, east of Nuku'alofa. In 1987 over 600 people lived there. This area consists mainly of mangrove swamp flooded, or at least soaking wet, due to the raised groundwater table at spring tides. A tongue of firm land covered with volcanic ash-derived soil extends into the mangrove swamp. The initial housing in this area was located entirely on the firm and perennial dry land. A raised roadway connects this settlement area with the northern coast road. However, the population in this area has grown very rapidly due to new arrivals and some squatting, so that large tracts of new 'land' had been surveyed and allocated, which consist entirely of mangrove swamp. Some housing has already been erected in this newly allocated area, and infill processes are in progress, using coral rubble, sawdust and soil (Figure 6).

In all three cases the elevation of the land is 0.5 m above MHWS. Most of the ground is already turned into a quagmire after heavy rainfall, when the ground is soaked with water and surface water remains until it evaporates. Any increase in relative sea level will cause constantly swampy conditions.

Aside from these three areas, in recent years more and more houses have been built on the margin of the lagoon. Some of the area on which these houses have been erected is submerged during the wet season (about December to April), and swampy or dryish during the dry season. In the usual development of such housing, a building is erected on a artificially raised ground, while the surrounding area of the *'api kolo* is left at or below water level. Once sufficient funds have been obtained, the infilling is resumed.

It is of course technically and financially feasible to heighten the land area of these suburbs, keeping pace with the increasing sea level. However, one major aspect in the decision-making process about the fate of this marginal housing is the cost efficiency of such a measure. The main limitation on Tongatapu is the availability of fill material, be it coral gravel, coral sand or soil. The latter commodity is the scarcest on the island, since coral gravel can be obtained by quarrying the remaining patch reefs, and coral sand can be mined in dune formations and particularly offshore (c.f. Tiffin, 1982; Gauss *et al.*, 1983). Soil, and especially topsoil, however, is in limited supply, and usually only available when a new quarry is opened and the surface is stripped of its soil cover. Regrettably, in recent years the quarrying of prehistoric monuments has started (see below), which has enormous repercussions for the historical heritage of Tonga. But even this volume of soil is very limited.

In the normal course of events the land to be raised is filled with coral gravel and covered with soil. While the coral gravel fill underneath the building is commonly compacted, the fill surrounding the house is not. Thus the soil gradually disperses between the crevices left by the coral aggregate, creating a net loss of topsoil cover. Ideally, the coral gravel fill should be compacted as well, or covered with coral sand to fill the crevices and then covered with topsoil.

If it can be positively shown that the relative sea level will rise to 0.5 m in the near future, then a large amount of fill will be needed to maintain the present land level at the marginal habitation locations, let alone to improve the present situation. As shown above, any increase of relative sea level is also likely to severely affect the central district of Nuku'alofa. It can be anticipated that large amounts of fill will be needed to maintain the *status quo* in central Nuku'alofa until the rise in relative sea level has exceeded 0.7 m above present MHWS and very large tracts of Nuku'alofa become swampy. In the light of this, and in the light of the limited soil resources, the option to abandon, or at least to suspend, further settlement of these marginal areas should be considered. Options exist to create canal estates in these areas (Connell *et al.*, 1985), that is, to dig deep channels and to utilise the excavated material as fill to raise the level of the surrounding terrain.

Other areas

Three other areas where some impacts might occur warrant mention.

Kolovai-Fatai. Save for the villages on the Kolovai-Kanokupolu peninsula, all the villages are located well above the 2 m mark so that no impact on human habitation would be felt in this area. On the peninsula, the low lying parts of the villages of Kolovai, Kanokupolu and Ahau are likely to be affected by a rise of relative sea level in the magnitude of 1 m.

Southern and southeastern shore. None of the villages is built directly on the shore and no impact on human habitation can be anticipated, however, numerous burial grounds are located at the backs of the beaches. With increasing relative sea level, these burials may be washed out by the tides or by storm surges, which may eventually make necessary the abandonment of these cemeteries for further interment.

Off-shore islets. It is conceivable that eventually the utilisation of the offshore islets as tourism resorts will have to be abandoned, as these islets may be prone to be over-topping by cyclonic tidal surges.

Impact on the treatment and disposal of sanitary wastes (by Lloyd H. Belz)

The treatment and disposal of sanitary wastes - the situation in 1988

To date, no municipal sewage collection system exists in Nuku'alofa. A few pour-flush and pit latrines exist but the majority of sewage disposal systems are on-site and utilise septic tank soil absorption systems. The reasons for the use of on-site sewage disposal systems is the low elevations of Nuku'alofa, and the undesirability of sewage collection systems which are completely or partially under water. The exceptionally high level of maintenance such systems would require to prevent infiltration are simply not practical in a developing nation (Belz, 1984). The principle of sewage disposal employed at present is to get the effluent into the ground and keep it there so that natural bacterial degradation over time can neutralize and purify the wastes. The prevention of pollution of the ground water is a goal beyond the present financial capabilities of the people, and has no significant impact on the public health of the people, given that the low-lying areas are situated on the edges of the ground-water lens (see below), generally where no drinking water is procured.

The effects of rising groundwater level on sewage disposal systems

The only areas that will be seriously affected by the rise in sea level will be those areas in which the components of sewage disposal systems will be all or partially inundated. Any areas where the groundwater level (mean sea level plus 0.1 m) rises to within 1 m from the surface will be affected to some degree. As the water level rises and advances up the sloping shorelines in affected areas, it will inundate existing sewage treatment facilities. This advance will take on a different character in the Sopu swamp from that in the general Nuku'alofa areas bounded by the lagoon, such as Popua, Pahu and Havelu.

A gradual rise in the groundwater level, such as will occur in Sopu, will gradually reduce the ability of the soak-away to function: tidal effects will not be great in this area.

A more serious effect will be experienced when a gradual rise of water level is accompanied by tidal action, as will occur along the edges of the lagoon. The effect of the tides will accentuate the impacts of higher sea level and render the soak-away non-functional much sooner than the general rise in water level would indicate. The degree of loss of function of the soak-away will generally be associated with the maximum levels reached by the tide. As soon as the effluent is prevented from going into the ground by the high tide water level, the effluent will puddle on the ground, completely destroying all the function of the soak-away. Even before the effluents begin to puddle on the ground the rise and fall of the ground water will create a laundering effect of the soak-aways. This exchange of water in the soak-away will ultimately result in much greater amounts of nutrients being flushed into the lagoon and, even with the increased circulation in the lagoon by the greater amounts of water being exchanged every day, will result in a much greater possibility of algal blooms in the lagoon. Some of the effects of this nutrient pollution could be reduced by mangrove or plant screening but it is doubted that, given the past record of mangrove destruction, that this could be achieved. There would be problems with the necessity of advancing the screen as the water level rose. Further physical elevation features, with the tendency to form drainage channels, would probably make this procedure too difficult to be used.

In the study of the effects of inundation on the sewage disposal system the effects on the septic tank and the soak-away must be considered separately.

* The functions and operation of the septic tank will not be affected by the rise in the ground water until the ground water level reaches either the inlet or the outlet pipe. When the groundwater either enters the tank or prevents the effluent from leaving the tank, because of its higher surface elevation, the septic tank can no longer function and the system must be abandoned.

* The soak-aways' ability to function will normally be impaired and then nearly completely destroyed while the septic tank is still functioning perfectly. Several functions of the soak-away must be considered here:

i) the disposal of the effluent by allowing its passage into the ground.

ii) the biological treatment of the effluent destroying any pathogens.

iii) the disposal of the effluent in an acceptable manner from a quality of living point of view. This means disposal with no smells, breeding of mosquitoes, effluent contact or exposure to animals, no unsightly conditions or pollution of the environment.

The exact effect of the rising ground water table on the capacity of soak-aways both in their ability to handle the volumes of effluent, and to reduce the outflow of bacteria and nutrients, can only be guessed at. The characteristics of the soil and the resultant mat or slime barrier that is formed at the drainrock-soil interface limits the amount of effluent per unit area that can be handled. The high ground water soil absorption systems that are in use in the high ground water areas in Nuku'alofa at the present time have the lower portions of this rock-soil interface under water or under water tidally. The soak-away is a combination of the hole surrounding the septic tank and the existing ground surface surrounding the septic tank. The actual functioning of the above and below water portions, on a unit process basis, is unknown. It is quite possible that the underwater section of the soak-away when subjected to tides cannot develop a slime mat because of the continual backflushing. If this is the case the tidal soak-aways could handle materially more volume per unit area.

<u>Summary</u>

In the affected areas the most serious effect of the rise in the ground water will be the destruction of the sewage treatment systems ability to keep the septic tank effluent in the ground. This will allow tidal sloshing and exposure of raw effluents. This exposure of the effluents to human and animal contact will destroy the effectiveness of the systems as they now exist, forcing the development of alternate methods for the safe disposal of human sanitary wastes or the abandonment of the areas so affected. There is little question that alternate methods of safely disposing of human sanitary wastes can be developed, just as the high ground water sewage disposal systems currently being utilised were developed. Sewage collection systems have already been developed which are partially or completely submerged in water. Were such a piped collection system to be constructed, however, the maintenance problems could be expected to worsen in direct proportion to the increasing submergence of the piping. If the people choose to, or are forced to, live on the land which is gradually being inundated, and adapt to the changing conditions, a real challenge will be presented to sanitary engineers to develop a system to protect the public health of the affected people. However, the development of the processes, appropriate both in terms of their maintenance potential at a local level and financial expenditure required, will take time and is likely to be expensive.

<u>Impact on groundwater resources</u>

Tongatapu, being a coral limestone island at most 65 m high, with a coral base up to 250 m thick, possesses a fresh water lens (Ghyben-Herzberg lens) floating on top of salt water with a higher specific gravity (1.025 compared with 1.0 g/cm3 for fresh water). The ground water lens reaches a thickness of about 20 m at the centre of Tongatapu and seeps out at the edges of the island. The lens is entirely recharged by rainfall. Due to the permeability of the soil, almost no surface run-off occurs and streams do not exist. Despite the high permeability, at most 25% of the rainfall reaches the fresh water lens (Hunt, 1979; Lao, 1979; Pfeiffer & Stach, 1972; Spennemann, in prep. b).

Because of the relatively small size of Tongatapu, coupled with the overall lack of high mountainous ranges which would act as barriers, no predictable orographic rainfall patterns exist. Rainfall is highly localised, caused by rain-loaded clouds producing rain wherever they are pushed by the winds, a pattern of intra-island variation in rainfall noted by Kennedy (1959:23). This situation is exacerbated on the small islets and sand cays off Tongatapu, where the likelihood of rain, and thus groundwater recharge, is even smaller. During most of 1987 rain fell on the islet of Fafa, although it rained quite heavily on Pangaimotu (4 km south east) and the mainland. Such a highly localised rainfall distribution today endangers the commercial success of holiday resorts, which are forced to rely on the ground water lens, or in its absence, to ferry drinking water from the mainland.

As already mentioned, the groundwater resources of the off-shore islets are likely to be reduced due to the reduction in size (above HWL) and height of the islets. The level of the freshwater/seawater interface in the sand/coral base will rise with the sea level. Since there will be less supra-tidal land area available, the freshwater lens will be smaller, and since it continuously flows out to the sea, it will also be shallower and in many areas closer to the surface. Those islets which will increase in area are likely to become much lower, and thus more prone to cyclonic/storm surges washing over the islet and contaminating the groundwater lens with salt-water. Since the groundwater lens is recharged solely by rainfall it will take a considerable time for the groundwater lens to recover. These anticipated effects are also predictable for several islands in the Ha'apai group, making them more reliant on the collection and storage of rainwater. But as can be shown by the example of Fafa, the supply of rainwater is not predictable, so that it is well within the range of expectations that several of the islets will become incapable of sustaining a human population.

Impact on natural resources

Marine environment

One of the beneficial aspects of the projected sea level rise would be the creation of new intertidal areas and lagoonal embayments, which will become the habitat of several shell-fish and crab species, which in turn will be available for human consumption. This is important as the present *Gafrarium* populations show evidence of human over-exploitation (Spennemann, 1986c; 1987a). Wolterding (1983) has described the effects of the loss of shellfish beds in the former Sopu lagoon on the subsistence economy of Hofoa and Sopu villages, which ultimately led to increased, and damaging, pressure on the fish and shellfish resources of the fringing reef.

If the flushing in the lagoon increases, it will have effects on the survival of shellfish species. If the archaeological data of the past Holocene sea level change are any guide, we can expect a reversal of the processes studied so far (Spennemann, 1987c, Spennemann, in prep. c). If the sea level rise is below 0.5 m, we may expect an increasing salinity of the lagoon, which will permit *Anadara antiquata* (Tongan: *kaloa'a*) to expand their habitat from the lagoonal mouth further into the lagoon. At the same rate as *Anadara* expands, *Gafrarium tumidum*/*Gafrarium pectinatum* (Tongan: *to'o*) will decrease. Since the latter shellfish species is the smaller of the two, we can expect an increase in the available shellfish production. We can also predict that the increased tidal range will lead to better flushing of the lagoon and to a reduction in the concentration of nutrients and pollutants in the Pea sector. Based on this, we can also expect that *Gafrarium* will return to their previous habitats in the Pea sector of the lagoon.

Increased flushing of the lagoon is also likely to have beneficial effects on the breeding of fish in the lagoon, provided that breeding grounds in the mangroves are not entirely destroyed.

Impact on gardening land

The impact on gardening land consists of direct land loss due to inundation and flooding, and of secondary effects such as a higher moisture loading and increased salinisation in the newly created marginal areas, reducing the suitability of the affected land for gardening purposes.

Temporary inundation due to heavy rainfall results in a temporary elevation of the ground-water table. Commonly the groundwater level would have attained its pre-rainfall level after 6 to 7 days. It can be anticipated that a rise in relative sea and groundwater level will also create this effect in areas so far unaffected, making them also unsuitable for agricultural purposes in the traditional, manner. Various fruit-trees, such as mango and breadfruit, are very sensitive to (permanent) standing water of any kind and will die off. Coconut palms and *Pandanus*, which can survive a flooding of their roots with fresh water, will show a stunted growth and a greatly reduced yield. In addition, a salinisation of the soil of these new marginal areas is likely to occur during the dry season, when the capillary action of the soil draws up groundwater with a higher salt content than before. This excess salt will eventually be deposited on the surface (predicted by Straatmans, 1954).

However, a possibly beneficial aspect of the fresh-water inundation of some areas will be that it will be feasible to grow swamp taro (*Cyrtosperma*) in those areas, as well as in areas with slightly brackish water. It would be even conceivable to set up proper swamp taro gardens, by artificially deepening the inundated or marshy areas and using the excavated soil as fill elsewhere.

Another application to be investigated would be the establishment of fresh-water aquaculture (for example for the fish *Tilapia*), set up in artificially deepened areas inundated by the rising groundwater table.

Since all land on Tongatapu, save for the patches of forest at the airport, has already been allocated as garden land, a shortage of land is predictable on the basis of the natural population growth. The shortage of land is expected to increase if large tracts of presently gardened land become unusable because of rising sea level, for example in the area between Fatai and Masilamea at the northwestern shore of Tongatapu. This pressure on the land resources will increase even further, as people may need to be relocated from inundated or swampy areas and additional garden land needs to be converted into housing areas.

The increase in temperature is likely to bring about some changes in the growth patterns of vegetation in general and of agricultural crops in particular, as the average soil temperature will also be affected. An overall increase of 2 to 3°C is likely to create on Tongatapu a climate similar to Vava'u, while the climate of Vava'u will resemble more the present climate of Niuatoputapu. This change in the temperature regime is likely to have beneficial effects on some crops and detrimental effects on others.

Impact on archaeological sites

In the case of impacts on the Tongan cultural heritage, which forms a unique part of the world cultural heritage, the increase in relative sea level will have severe implications because the future of most archaeological sites is at risk. Two types of damage can be forecast: i) direct damage caused by inundation and increased tidal activity and; ii) indirect damage caused by the destruction of sites as a result of counter-measures to stop inundation of land areas.

Direct damage

Several important archaeological sites are located in low lying areas, such the *sia heu lupe* (pigeon-snaring mounds) at Popua, Sopu and Fatai, the beachrock quarries at various beaches of Tongatapu and on offshore islets, and the large scale 16th (?) century land reclamation site at Mu'a.

*Sia heu lupe*. The rulers of Tonga, the *Tu'i Tonga* erected circular artificial platforms in the mangrove swamps to catch wild pigeons. These sites, which are not very numerous and which belonged to people from the top of the social pyramid, are sometimes interconnected with raised walkways, which are about 0.2 m above present ground level. Some of these sites are already under threat by the present extension of Popua township and the ongoing infill of land, which is resulting in the levelling and obliteration of some sites.

Beachrock quarries. A common type of archaeological site is the beach-rock quarry, from where stone slabs were procured for the construction of the stone-faced chiefly and royal tombs in various parts of

Tonga. On Tongatapu these quarries exist mainly on the offshore islets (e.g. Pangaimotu, Motutapu, Fafa, Makaha'a) and at Ha'atafu, Niutoua and Ha'ateiho (southern coast). A rise of relative sea level is likely to have two effects on the beach-rock quarries: (i) submerging them under water, and thus obliterating them from view; and (ii) a change in sedimentation patterns might bring about the deposition of sand on top of the quarries, causing a new formation of beach rock, obliterating the traces of the quarries altogether.

Wharf at Mu'a. The wharf at Mu'a is an artificial land fill, which took place during the 15th or early 16th century. It is a low-lying area on the seaward side, partly faced with large beach-rock slabs, from which protrudes a large pier constructed of stones, the only one of its kind in Tonga.

The increased wave action, caused by a higher sea level and a lessened protection by the fringing reef (see above), will dramatically increase shoreline erosion on the windward sides of many of the offshore islets of Tongatapu and will increasingly destroy archaeological sites. A comparison between the archaeological situation of 1957 and that 30 years later has shown that up to 30 m of shoreline have been lost on some of the islands, most of it due to cyclonic storm surges (Spennemann, 1987b). This process is likely to continue with increased speed. In addition, a rise in relative sea level will increase the frequency of tidal washing across entire islets. It can be anticipated that most of the archaeological sites on the offshore islets will be either completely destroyed or severely damaged.

Indirect damage

A relative rise in sea level will result in a heavily increased need for land fill to heighten the ground level. At present, coral rubble is obtained for fill of low-lying areas at the lagoonal water front. About 0.3 to 0.5 m of coral gravel is applied, upon which a 0.2 to 0.4 m thick layer of topsoil is heaped. To some extent this topsoil is quarried from the top areas of newly opened quarries, but also from archaeological sites, notably house and burial mounds. This process, which has started very recently, is likely to continue. Since the mounds form the major source of information about the Tongan cultural heritage between the end of the Lapita period (about 200 AD) and the early European contact (late 18th century AD), we can anticipate that the destruction of the mounds will lead to a complete wipe-out of 1500 years of Tongan history. The opening of new limestone quarries, as well as the opening of sand quarries for the procurement of fill material, is also likely to severely affect the archaeological heritage (c.f. Spennemann, 1986d, 1986e). In order to retain as much agricultural land as possible, it can be anticipated that the growth of villages along the shorelines will continue. As 'safe' sites will be required in the future, the new settlements will have to be placed on elevations higher than 2 m above HWL. This, however, is the location of the sites of the Lapita culture, which represents the first human occupation of the Tongan archipelago (~1300 B.C. to AD200). In the present 'normal' course of village extensions, numbers of these sites have already been destroyed, but we can anticipate that most, if not all will be destroyed in the course of future house construction.

It is very likely that those prestigious archaeological sites, such as the langi and the Ha'amonga, which form tourist attractions (Spennemann, 1987d, 1987e), will survive the primary and secondary destruction, but that most other sites will be either destroyed or severely damaged, resulting in a tremendous loss of Tongan national heritage.

## OTHER POTENTIAL IMPACTS OF CLIMATIC CHANGE OTHER THAN SEA LEVEL RISE

### Other environmental impacts

Rainfall

Tongatapu is too small and too flat to develop clearly defined micro-climates and therefore the rainfall intensity varies without any regularity throughout the island. The long-term annual mean for Nuku'alofa station is 1,716 mm/year. The long-term mean monthly rainfall varies from a peak of 235 mm in March to a low of 93 mm in June. However, the standard deviations are between 65% and 111% of the monthly means, indicating a very high variability. The wet season usually lasts from January to April, but since the rainfall is highly erratic and unreliable, large-scale variations may occur. The humidity is high (annual mean 76%). During the months January to April the humidity is at its maximum and reaches a monthly mean of 80%. The evaporation and evapotranspiration are relatively high.

In the Tonga-wide perspective the intensity of rainfall decreases from north to south. The annual rainfall intensity is highly variable as can be seen by the large standard deviations. Based on the standard deviations it seems as if the rainfall is more erratic in the northern part of the group than in the south. It can be expected that an increase in temperature of 2°C will lead to an increased rainfall and also increased evapotranspiration on Tongatapu. An increase of 2°C would provide Tongatapu with the present temperature regime of Vava'u and Vava'u with that of the Niuas. As the Tongan rainfall is entirely oreographic, we can expect an increase of rainfall on Tongatapu, due to the shifting climatic belts, possibly up to the present rainfall level of Vava'u.

The rainfall level of Vava'u may also increase, possibly up to the present level of the Niuas. This increase in precipitation may result in an increase of erosion. Presently numerous erosion gullies can be seen on Vava'u, where roads have been cut through old terraces, and where the sides have not been protected by applying topsoil and planting a grass-cover. The low-lying islands of the Ha'apai group will have a smaller groundwater lens, as discussed above, but the rainfall may increase. Thus it is likely that a greater chance of rain water catchment for human consumption will develop.

Table 3. Long-term annual mean precipitation (mm) throughout the Tongan Archipelago (after Spennemann, in prep. b).

| Island | Latitude | Mean | 1 σ | No. of years |
|---|---|---|---|---|
| Niuafo'ou | 15° 34' S | 2,567.31 | 1,256.78 | 17 |
| Niuatoputapu | 15° 57' S | 2,366.08 | 834.90 | 41 |
| Vava'u | 18° 40' S | 2,304.31 | 871.60 | 41 |
| Ha'apai | 19° 48' S | 1,763.12 | 507.20 | 41 |
| Tongatapu | 21° 15' S | 1,716.19 | 447.45 | 72 |

Cyclones

The known tropical cyclones (i.e. sustained wind speeds in excess of 117 km/h for 10 minutes, with reported wind speeds up to 230 km/h) which have affected the Tongan Group since 1830 total 108 (until 1982), giving a mean expectancy of 0.71 cyclones/annum. In Tonga the main cyclone season lasts from November until April, with a distinct peak during January, February and March. The annual cyclone expectation is almost the same for all individual island groups of the Tongan chain, although the Tongatapu Group is hit slightly more often than Ha'apai and Vava'u. Taking the tropical storms of gale force (i.e. sustained wind speeds in excess of 88 km/h) into account, the Vava'u group is most hit, followed by Ha'apai and Tongatapu (for references see Spennemann, in prep. a). The southern cyclones originate in the zone between 10° and 20° S and their paths run normally northwest to southeast, although they occasionally may run from south to north. Although the normal cyclone paths run west of Tonga, and most frequently hit the Fiji group, the El Nino/Southern Oscillation (ENSO) phenomenon of the cyclic re-occurring gradual warming of the central Pacific alters these paths, which then affect the Tongan group more frequently. If we use the ENSO phenomenon as a rough approximation of what might happen with an overall increase in global temperature, then we can assume that it will also alter the cyclone belts, shifting them southward. Thus the most populated of the Tongan islands, Tongatapu, is likely to be much more seriously affected by cyclones and gale force winds. Since the performance of modern European-style housing during cyclones has been rather poor in the past (Oliver & Reardon, 1982; Intertect, 1982), steps need to be undertaken to ensure future cyclone-proof housing.

Social consequences

Land tenure

It can be expected that any relocation programmes undertaken by the government may be met by apathy and reluctance to move. As can be documented by the case of the flooding of Hala-'o-vave in the wake of cyclone Isaac in 1982, many families refused to accept new land on higher ground and preferred to remain at their original places, although it was pointed out to them that such a flooding could happen again.

Increasing population, inundation of gardening land and relocation of residential areas will dramatically increase the pressure on the limited land resources. It can be anticipated that this increased pressure may lead to the utilisation of land by more people and thus to a shortening of the fallow period in the swidden cycles and to a greater exhaustion of the soil nutrients. In addition, some social tension can be anticipated between those families who still have land and those who have lost their land.

Health

Health problems can be anticipated if residential land, which is now dry, turns swampy, as housing in such areas presently causes for example a higher rate of respiratory problems (Rew, 1979). In addition, the average temperature is likely to rise, which in conjunction with a high groundwater table and temporary, rain-induced flooding, will provide breeding grounds for mosquitoes, a fact already observed as a consequence of the closure of Sopu lagoon (Wolterding, 1982:11). Increased mosquito numbers and more favourable living conditions for species not yet present (such as *Anopheles*) may provide the environment for vectors and result in an increase in diseases such as dengue fever and possibly even malaria (c.f. similar projections for Australia: Liehne, 1988).

Tourism

As most of the tourist resorts are located on the offshore islets, they are prone to any effects of relative sea level change. Aside from geographical alterations of the islets, the resorts may well become more dependent on imported drinking water as the groundwater lenses become reduced in size.

Whereas most of the present resorts, with the exception of the resort on 'Atata, do not represent vast capital expenditure, a rise in relative sea level should be taken into account in the location of new resorts and hotel buildings. The topography of Tongatapu is highly diverse at a micro level, which permits small scale alterations of settings in order to achieve maximum security. A case in point is the planned 'Crown Prince' Hotel directly east of Holohi'ufi at Popua. While the present location at the beachfront is only about 0.6 m above HWL, a location about 200m inland has an elevation of approximately 1.2 to 1.5 m above HWL.

IMPLICATIONS FOR GOVERNMENT PLANNING

Given the fact that a significant rise in relative sea level is likely to occur in the foreseeable future, some points follow which have to be taken into consideration in future planning.

* Tongatapu is a coral limestone island. Any increase in the relative sea level will result in an increase of the level of the groundwater table.

* Most of the present capital and administrative centre is below 1.0 m above MSL. Thus at some stage in the future it can be anticipated that the groundwater level at Nuku'alofa will rise above present street level;

* Quite some time before this happens the foundations of the buildings will be immersed in water, which may cause erosion of some structures.

For the following discussion it is assumed that there is no desire by government or the community to relocate the entire capital. Thus it follows that:

* Although it is economically viable to erect most buildings on lower ground, for which the capital expenditure will be written off after 30 years, it should be asked whether this is a suitable strategy for public buildings, as it would create a legacy of higher costs for the future.

* It would be advisable to erect all new public and government buildings on higher ground, preferably higher than 2 m above HWL.

* Possible locations would be in the area east and southeast of the *mala'e kula*.

* The selection of such a location would, in the immediate future, apply to the proposed new Parliament house and, possibly, the new Palace.

* The construction of new Government buildings on higher ground also implies that the focal point of Nuku'alofa may be shifted gradually away from the presently prestigious waterfront to higher grounds.

* Higher grounds, however, may be occupied by housing. The present pressure on housing in Nuku'alofa is certain to increase as both the overall population increases and as more and more people leave the outer islands for the amenities of Nuku'alofa.

The available land-fill on Tongatapu consists of coral, sand (quarried from the beaches or offshore) and soil. While coral limestone can be procured on Tongatapu in a fairly unrestricted manner, and while coral sand may be quarried offshore, the availability of soil and especially fertile topsoil is limited. While it is technically feasible to infill large areas of marginal and swamp land, it is to be asked whether the utilisation of limited soil resources as landfill is justifiable in view of the long-term development of the Tongan nation as a whole, since:

* Increasing water-level will require further infill to maintain the *status quo*.

* It can be anticipated that every new heightening of the ground level will be accompanied by a new layer of soil, preferably topsoil.

* Thus the allocation of mangrove swamp for habitation, as is current practice in areas of Popua and Hala-'o-vave needs to be re-assessed. These areas cannot be maintained as future habitation areas unless a large expenditure is made for a drastic programme of infilling, consideration should be given to suspending future expansion of these settlements.

* However, there are viable alternatives, such as the development of canal estates, which could provide a solution.

The anticipated change in climatic conditions is likely to have the following negative impacts:

* An increase in sea-surface temperature is likely to shift cyclone belts southward. Thus Tongatapu, the most populated island, is likely to experience a higher frequency of cyclones.

* In consequence of this, and the rather poor cyclone performance of current modern housing in Tonga, the Government may want to stress the need for cyclone-proofing of all modern housing.

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* The increased rainfall level in Vava'u can be expected lead to an increase in erosion, especially in road-cuts and the like. This danger of large scale erosion can be averted by measures such as applying topsoil onto the sides of the cuts and planting a protective cover of grass thus arresting surface run-off.

In the case of Tongan cultural heritage, which forms an important part of the world cultural heritage, the increase in sea level will have severe implications, as outlined above. The government may need to undertake affirmative action to protect the heritage where possible.

## OUTLOOK

The case study presented here has identified some of the problems Tongatapu may be faced with, if the sea level rises in the near future. Although broad outlines can be sketched for the three scenarios, the data base is generally too limited to permit more detailed and reliable predictions. Obviously more work needs to be done to place these predictions on a more secure footing. This applies particularly to the assessment of the impact on the lagoonal environment, the impact of climatic change on agriculture and the potential impact on social conditions.

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# THE IMPACTS OF POSSIBLE GLOBAL WARMING GENERATED SEA LEVEL RISE ON SELECTED COASTAL ENVIRONMENTS IN PAPUA NEW GUINEA

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## INTRODUCTION

Based on a conservative estimate of an overall rise in world-wide sea level of 1 m by the year 2050, an attempt was made to assess the overall effect of such a sea level rise on the coastline of Papua New Guinea. This was done by mapping a new shoreline on the basis of existing topographic maps at a scale of 1:100,000 with a contour interval of 40 m. These maps, the largest scale series available for the whole of Papua New Guinea, were used for this exercise. For a very few areas where larger scale maps or additional contour information is available such sources were also used.

Cloud-free LANDSAT satellite imagery of Papua New Guinea is available, covering about half the coastline. This imagery was used, together with some air photographs and personal knowledge of the coastal zone to determine the general form of the coastline. From these data a 1 m contour line was interpolated between the present shoreline and the near-shore 40 m contour position. In general on rocky cliffed or sloping (erosional) shorelines the 1 m level was interpolated approximately 1/40 of that distance inland. On coastal areas where a narrow coastal plain (either erosional or depositional) exists between the shoreline and any near-coastal hillslope zone, the 1 m contour line was interpolated 1/20 of the distance inland to the 40 m contour line.

It is clear that given the resources available for this preliminary study, our re-construction is a crude estimate of any likely future coastline. In the following discussion reference is made to length and types of coastline which will be affected, rather than to areas likely to be inundated.

It is immediately apparent that inundation of coastal environments will be a widespread phenomenon in Papua New Guinea, the extent of which will be dictated by physical features such as underlying structure, existing landform, slope, the distribution of deposited sediments, and the local water table levels.

Coastlines were classified into three broad categories according to the degree of inundation -

Negligible where there was no discernible land area likely to be inundated by a 1 m rise in sea level, mapping on a scale of 1:100,000. Such areas, which are generally rocky shorelines affected by recent tectonic uplifts or controlled by terrestrial hillslope processes, will in fact suffer a shoreline regression of less than 20 m in these circumstances.

Moderate where the total land area likely to be inundated was discernible when mapped at a scale of 1:100,000, but comprised either discrete land areas each of less than 1 $km^2$, or a coastal strip of any length along the shoreline, but less than 500 m wide.

Severe where contiguous land areas in excess of 1 $km^2$, or strips of coastline more than 500 m wide would be affected by inundation.

## RISING SEA LEVEL: OVERALL GEOMORPHIC EFFECT

The results of the coastline reconstruction are summarised in Figure 1.

The total length of the Papua New Guinea coastline, including the provincial islands, when measured on 1:100,000 scale maps, is 17,100 km (Table 1). Of that total length, approximately 4,500 km will be affected either moderately or severely, as defined above, that is about 26% of the entire coastline of the country will be affected to varying degrees by significant inundation.

### Landform types affected

In considering the effects of the predicted sea level rise on coastal landform types, the exercise has been carried out without attempting to predict the changes which may occur on active coral reefs, and the consequent effects on nearshore wave environments.

Five landform types or complexes were identified as areas which would suffer particularly from a 1 m rise in sea level. These are:

- deltaic floodplains;
- sand barrier and lagoon landform complexes;
- coral atolls and cays at sea level;
- raised coral islands;
- high islands.

#### Deltaic floodplains

These make up most of the coastal zone of Papua New Guinea which would be affected by a major sea level rise. They occur at the mouths of all the major rivers entering the Gulf of Papua, and at the mouth of the Sepik and Ramu Rivers (see e.g. Löffler 1977; Petr 1983; Percival & Womersley, 1975). This landform complex is therefore relatively very widespread along the southern coastline of the Papua New Guinea mainland, where it accounts for more than 40% of the coastal length, and less important on the northern coastline, or the coastlines of the major islands, where it makes up less than 10% of the shore lengths.

These are depositional landform complexes, with fluvial and coastal depositional processes contributing sediments to the landform complexes. Such areas are likely to suffer major impact due to inundation. Water tables within these landform complexes are high, and should sea level rise by a metre extensive areas of flat-lying land on the deltaic floodplains will be subject to liquefaction due to rising watertables, and consequent episodic coastal erosion. In addition, the offshore waters in the Gulf of Papua are relatively shallow, and a 1 m incursion of sea water will place a proportionally high weighting adjustment on this part of the shoreline, compared with the adjustment likely in deeper water off the north coast and surrounding the Bismarck Arc islands. Shorelines along the Gulf are thus likely to submerge further with the incursion of sea water, exacerbating the effect of the sea level rise.

Such areas are mainly covered with mangrove of swamp forest (Petr 1983; Percival & Womersley, 1975), and the effects on this landform type are discussed with special reference to the Purari delta area by Osborne & Pernetta (this volume).

#### Sand barrier and lagoon coasts

The sample area chosen to exemplify this coastal type is the coastline in the Murik Lakes area, East Sepik Province. As will occur for deltaic floodplains, a 1 m rise in sea level will have a profound effect on many of the depositional features which make up this landform complex, and will necessitate the re-location of villagers whose land will be affected. This is discussed by Hughes & Bualia, this volume, with special reference to populations and land type (see CSIRO and DPI 1987).

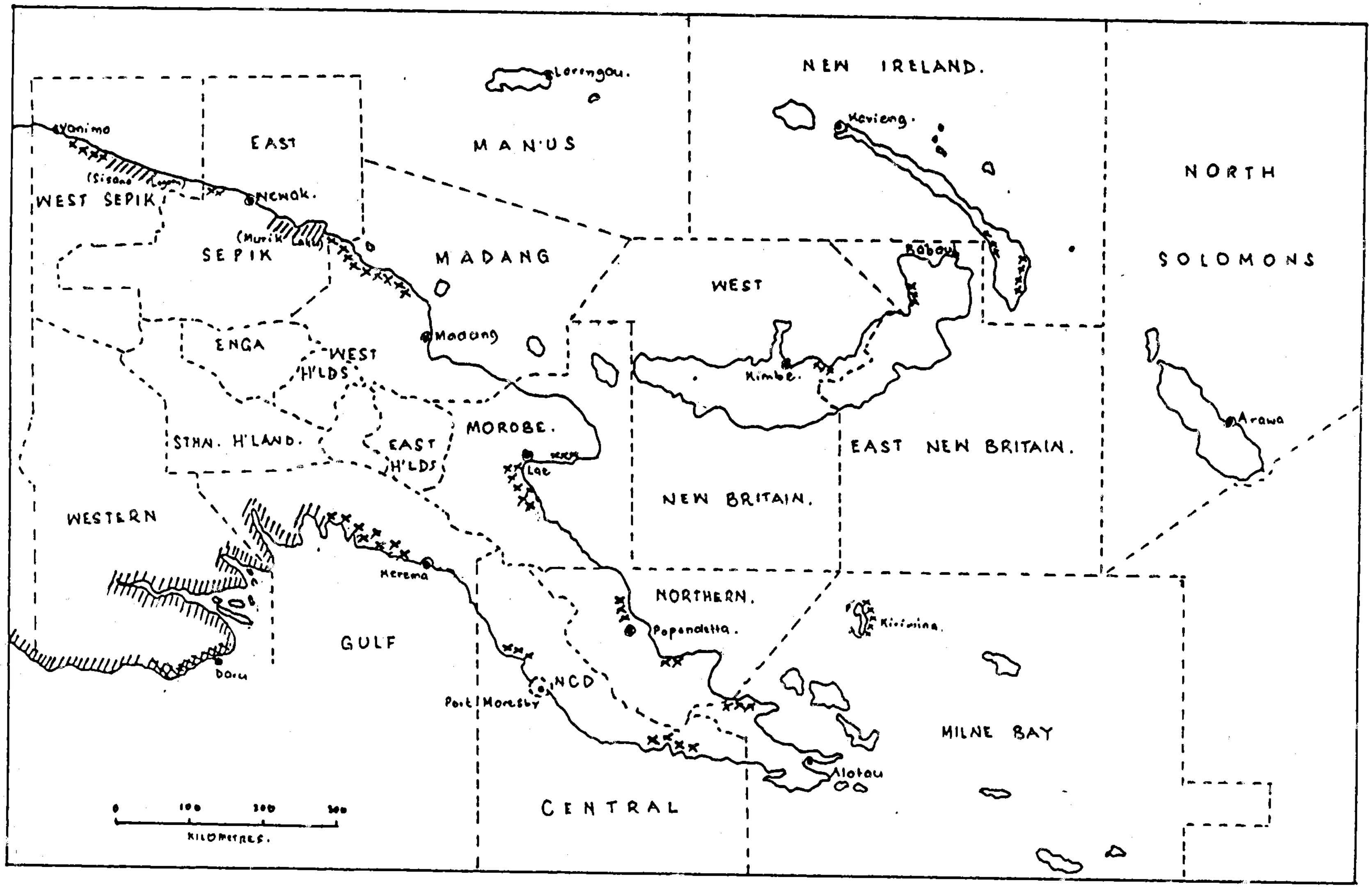


Figure 1. Predicted degree of inundation from anticipated sea level rise. Severe inudation; >500 m inland, and/or land areas > 1 km2. Moderate inundation; <500 m inland, and/or land areas < 1 km2. Negligible inundation; shoreline regression, < 20 m.

Table 1. Approximate composition of the Papua New Guinea coastline, as landform types.

| Papua New Guinea coastline | Deltaic floodplains and barrier-lagoon complexes | Islands and atolls |
|---|---|---|
| 17,100 kms | 4,250 kms | 4,180 kms |
| | (25 %) | (24 %) |

Coral atolls and cays at sea level

These will suffer virtual destruction from a sea level rise, unless coral growth can keep pace with the rising sea level. The effect on this landform type will be the loss of land and of the already limited supplies of fresh water for people dwelling on such islands. The effects of this, particularly the social implications of this total loss of land area are discussed by O'Collins (this volume).

Raised coral islands

The sample area chosen for this case study is Kiriwina Island, the largest island in the Trobriand Group (Löffler 1977; Ollier 1975; Ollier & Holdsworth, 1970). A 1 m rise in sea level will not only cause inundation of a major proportion of the low-lying and swampy land which makes up half of the island, but will cause salination of the island's fresh groundwater resource. This is discussed by Sullivan, this volume.

High islands

There are a variety of small high islands making up part of the total Papua New Guinean land area, and the islands chosen as joint case study examples are Lihir Island in New Ireland Province, and Misima Island in Milne Bay Province (see NSR 1987 and in prep.). On such islands the total land loss will be small, but the relative loss of economic resources and infrastructure will be high. This is discussed by Sullivan, this volume.

It was noted above that in the coastline mapping exercise an approximate assessment was made of the relative proportions of the Papua New Guinean coastline occupied by each landform type, and these are summarised in Table 1. It can be noted from this table that the distribution of landform types which will be affected varies markedly between Provinces. Deltaic floodplains and sand barrier and lagoon complexes occur mainly in West and East Sepik, Western and Gulf Provinces, while small high islands and coral islands or atolls occur in the main island Provinces of Madang, Morobe and Milne Bay, and in all the island Provinces.

OTHER EFFECTS OF SEA LEVEL RISE

The effects of sea level rise and consequent loss of coastal land in Papua New Guinea can be summarised under the following:

* loss of useful land;
* loss of fresh water and traditional economic resources;
* damage to roads and other infrastructure;
* damage to villages.

Loss of land

Together with land, itself a valuable resource for subsistence or cash cropping, for hunting and gathering, for pig husbandry or for security, other resources on it will be lost, primarily bushland resources, including food plants and building materials. There are likely to be land pressure problems in highly populated coastal areas of the country, such as the Sepik mouth, coral atolls and cays and some of the smaller high islands. In such areas, intensified use of the remaining land may lead to soil fertility depletion which in turn will lead to decreased crop yields.

Loss of fresh water and traditional economic resources

A 1 m rise in sea level will result in salt water incursion into the groundwater resources of many island and floodplain communities. Without additional field evidence it is not possible to predict the extent of this impact, but coastal villagers in many parts of Papua New Guinea are already faced with the problem of wells becoming brackish during dry periods, and groundwater salinity will rise as sea levels rise.

Those traditional resources which will be most directly affected by a rise in sea level are sago stands and mangrove forests. Sago is an important food source and building material in many coastal areas, particularly around the Gulf/Western and Sepik areas. Excessive salt water intrusion will deplete this important resource, by reducing the extent of brackish water zones, forcing sago stands into more restricted areas upslope. Mangrove forests, which provide in themselves valuable building timbers and firewood, also harbour other food sources such as various types of molluscs and crustaceans, as well as nursery sites for many marine organisms.

Coral reefs, rock platforms and other intertidal rocky shoreline features, provide niches for food sources such as various molluscs and fish. Many rocky shoreline features and coral reef complexes (until they re-adjust to higher sea levels) will be inundated, thus destroying littoral ecosystems. Living reefs may suffer from increased sedimentation and turbidity that will inhibit coral growth. Loss of important food resources from such areas is anticipated.

Damage to roads and other coastal infrastructure

Rugged terrain and limited construction funding in Papua New Guinea have resulted in relatively little road construction having been carried out in inland areas for any coastal locality where even a narrow coastal plain exists. Consequently coastal areas, particularly those fringed with depositional landforms are relatively well serviced with roads. Rising sea level will however be disastrous to such infrastructure, and money spent to safeguard roads threatened by rising seas will be money wasted.

Wharves and other coastal installations will also be directly affected by rising sealevels, and are likely to suffer from or to cause major sedimentation resulting from changed patterns of coastal erosion and deposition.

Damage to urban or village centres

Resettlement of villages elsewhere is foreseen due to inundation. There will be a particular problem for villages characteristic of the southern Papua New Guinean coastline, where rows of houses are commonly constructed supported on poles over the tidal zone. Social problems will arise directly in such instances, where particular clans may hold land rights only along the coast, in areas where total inundation is anticipated. Attempts to resettle people affected directly by loss of village land is likely to result in land disputes.

Urban centres situated on the coast are also likely to suffer tremendous infrastructural losses and consequent financial strain as a result of rising sea levels. Some relocation of urban centres is anticipated with consequent high compensation costs for new land acquisition likely.

## SUMMARY OF EFFECTS

It can be seen from the case studies that the effects of a rising sea level will be most profound for people living on depositional landforms on areas at and just above sea level, and which are not backed by rising land. It is also worth noting that these are generally favoured areas of occupation, since such localities provide good access to fishing zones as well as to gardening land.

The overall impacts can be evaluated also in economic and provincial/political terms. There is unequal distribution of resources in the country, and those Provinces which will be directly affected by the loss of coastal land will suffer to varying degrees. Highly populated areas which are generally not well off in terms of economic development (Murik Lakes, Milne Bay Islands) are likely to be most affected.

The relative effects of a sea level rise have been summarised for the 14 coastal Provinces of Papua New Guinea (Table 2). Provinces such as Gulf and Western Province which will lose proportionally higher areas of land than any others are also those with low incomes and little developed infrastructure to enable them to withstand major social and economic changes. Areas along the East/West Sepik Coastline will also be severely affected, and are similarly already financially disadvantaged.

Table 2. Coastal Provinces of Papua New Guinea showing the approximate percentage of their coastlines which will be affected by inundation (deltaic floodplains and lagoon and sandspit complexes), or will be affected to a varying extent (small high islands, reef islands and atolls), this extent unknown in the case of very small islands and atolls.

| PROVINCE | length of coastline (km) | % coastal length to be inundated | % coastal length affected to varying/ unknown extent |
|---|---|---|---|
| West Sepik | 440 | 50 | - |
| East Sepik | 490 | 40 | - |
| Madang | 1000 | 2 | 45 |
| Morobe | 1020 | 20 | 25 |
| Oro | 550 | 2 | - |
| Milne Bay | 3430 | - | 60 * |
| Central | 930 | 20 | - |
| Gulf | 1440 | 95 | - |
| Western | 1330 | 100 | - |
| Manus | 550 | 5 | 50 |
| New Ireland | 2400 | 30 | 45 |
| ENB | 1110 | - | 10 |
| WNB | 1420 | - | 10 |
| N.Solomons | 1000 | - | 10 * |

* Large numbers of atolls, proportion is an underestimate.

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# DELTAIC FLOODPLAINS: THE MANGROVES OF THE GULF OF PAPUA AND THE FLY RIVER, PAPUA NEW GUINEA

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## INTRODUCTION

The island of New Guinea is geologically young, being formed as a result of orogenic and tectonic activity at the northern extremity of the Australian landmass. The southern half of the island is formed from uplift of the Australian continental shelf which has collided with the island arcs running from Sulawesi out into the Pacific. Low-lying coastal plains are more extensive on the southern side of the island than in the north and consequently the impact of sea level changes will tend to be greater on this side of the island (Bualia & Sullivan, this volume).

Furthermore, the northern coast, is for much of its length currently undergoing uplift, whilst in contrast the southern side, particularly around the Gulf of Papua is sinking. Geomorphic changes will therefore tend to accentuate (over the long term) rather than diminish any impacts resulting from increased sea level on this side of the island.

The purpose of this case study is to examine potential impacts of sea level rise on two major coastal habitat types: mangroves and low-level swamp forest. Within Papua New Guinea, the mangroves fringing the Gulf of Papua (Figure 1) comprise some of the most extensive stands of largely unexploited mangrove forest anywhere in the world, whilst the floodplain of the Fly River forms an extensive system of low-lying habitats and ecotones which contrast with the majority of New Guinea which is covered in rain forest.

## THE MANGROVES FRINGING THE GULF OF PAPUA

### Recent geological history

The coastal area of the Gulf of Papua appears to have been a region of continuous shallow marine deposition throughout the Mesozoic and Tertiary eras. Limestones probably of reefal origin and formed in the Lower Miocene are common in the Purari Delta area indicating that at that time the present deltaic area was some distance from the present shoreline (Khan, 1974). Middle and Upper Miocene sediments are mainly marls and mudstones with some evidence of emergence and erosion. During the Quaternary period the southwestern section of the area was subsiding with volcanic eruptions occurring in the East.

Quaternary deposits include facies indicative of alluvial lakes, freshwater swamps, tidal flats and beach plains indicating oscillations between freshwater, estuarine and littoral environments (Ruxton, 1969). A bore hole sited WNW of Baimuru on the Era River revealed 1,700 m of Pliocene and Pleistocene sediments; the thickness of these sediments increase eastwards indicating marked subsidence in relatively recent times (APC, 1969). On the basis of such data Thom & Wright (1982) postulate that modern depositional environments are similar to those which have prevailed throughout the area over the last five million years. They quoted quoted Ruxton (1969) as follows:

'.... the coastal margin of the (Purari) delta area is subsiding in association with regional crustal downwarping but the coastline is actually advancing seawards because the deposition rate from the Purari drainage is so great.'

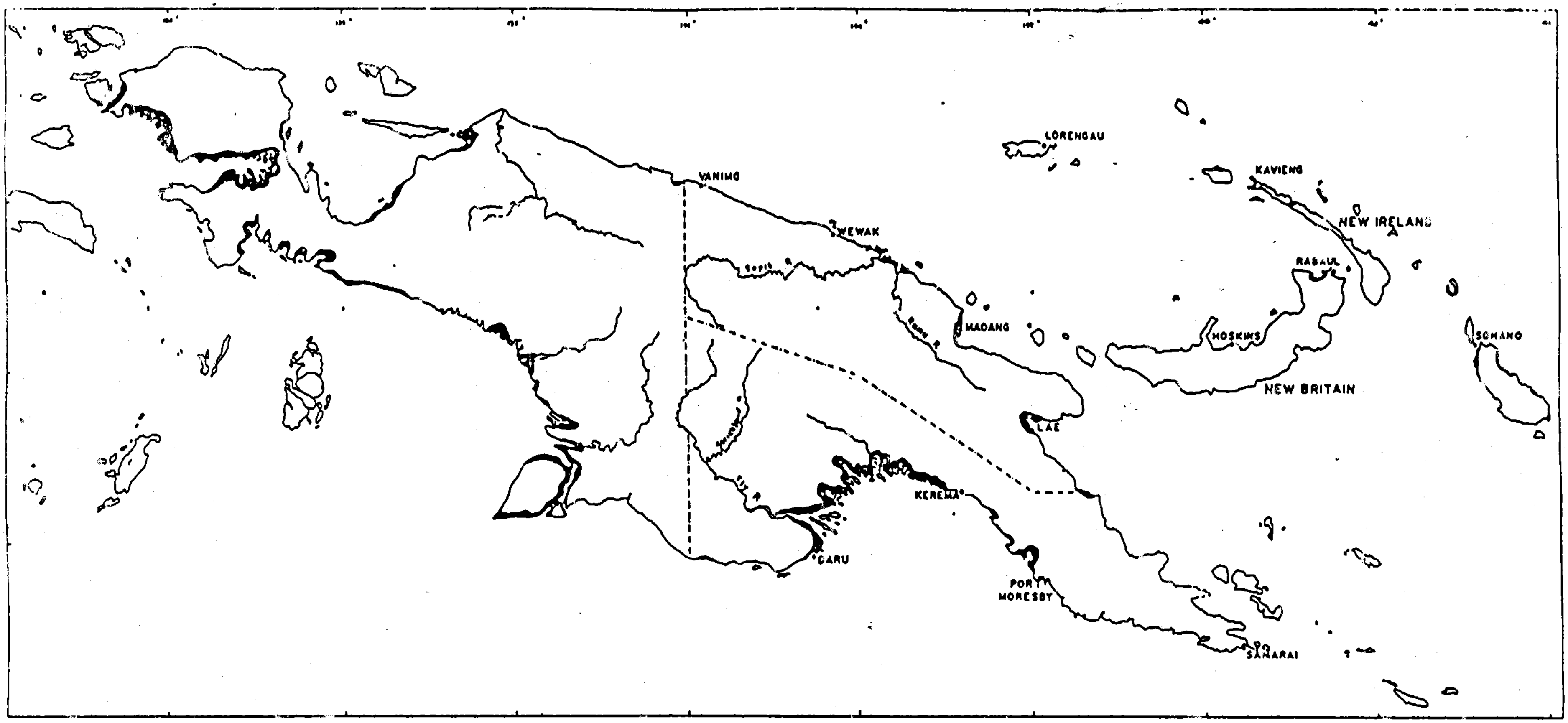


Figure 1. Shaded areas represent the main mangrove and Nypa swamps of New Guinea (after Percival and Womersley, 1975).

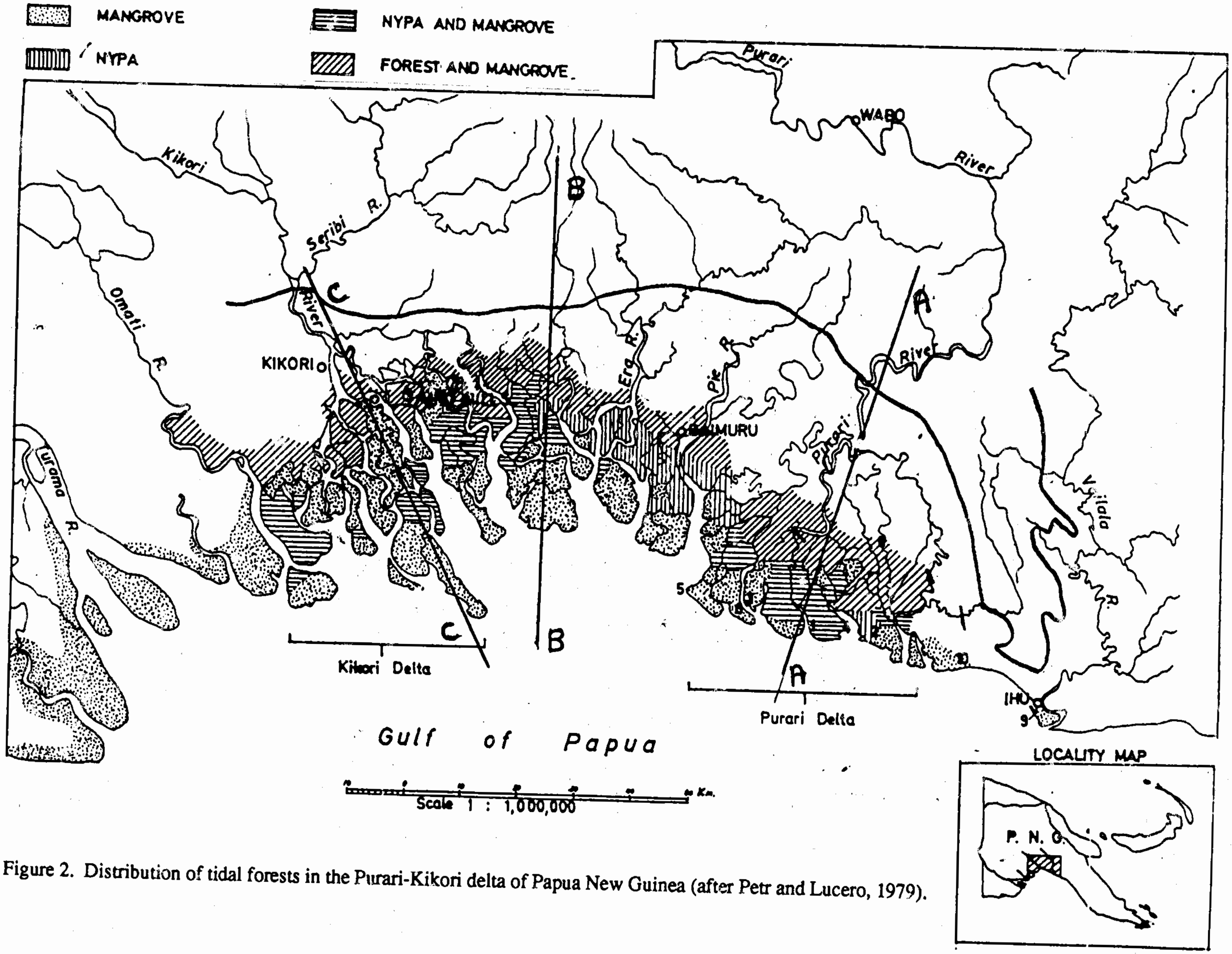


Figure 2. Distribution of tidal forests in the Purari-Kikori delta of Papua New Guinea (after Petr and Lucero, 1979).

Modern geomorphology

The area under consideration (Figures 2 and 3) covers a substantial sector of the central southern coast of Papua New Guinea and is traversed by several major rivers. To the east, the Purari has an extensive deltaic system of distributaries with three major river-dominated channels. Both the Pie and Era Rivers in the central section of the area have lower flows and tend to be more tidally influenced. The western end of the Gulf is dominated by the Kikori, Omati and Turama Rivers. This deltaic complex exhibits many of the environmental and morphological characteristics of the Ganges-Brahmaputra and Irrawaddy deltas (see Wright *et al.*, 1974). In terms of tidal range and wave regime all three complexes are similar whilst the discharges of the Purari and Irrawaddy rivers are comparable (Thom & Wright, 1982).

To the east of the region the shoreline is composed of a narrow plain (1-2 km wide) of beach ridges fronting freshwater swamps which merge into alluvial plains with locally accumulating peats in areas of poor drainage. Thom & Wright (1982) suggest some westwards reworking of medium to fine sands (Figure 3). The Purari deltaic plain has well-developed levees up to 2 m high along the main channels in its freshwater reaches. Aerial photographs reveal a mozaic of freshwater swamps, swamp forest and rain forest on the elevated areas.

The lower deltaic plain is characterised by brackish water conditions at least occasionally grading into the more saline conditions of the less active distributary channels. Petr & Lucero (1979) and Cragg (1983) have defined the limit between these two ecological units as coinciding with the lower limit for the distribution of the freshwater reed, *Phragmites karka* and the upper limit of *Sonneratia caseolaris* and *Pandanus* sp indet. The range of interstitial water salinities near the boundary of the lower deltaic plain is between 1 and 7.5 ppt (Petr & Lucero, 1979).

In distributary channels where river flow dominates the aquatic environment (*e.g.* the Ivo-Urika) the morphology of river mouths changes from year to year with consequent changes in the patterns of distribution of sand and smaller particles and dynamic changes to the balance of erosion and accretion. It is common therefore to encounter sections of coastline where mature mangrove forest is being steadily eroded due to local changes in patterns of sediment deposition.

The western section of this region is composed of an extensive complex of funnel-shaped estuaries and deltas dominated by tidal processes, with channels becoming moderately sinuous upstream (Wright *et al.*, 1974) and mud-laden waters being circulated by tides leading to vertical accretion of mangrove covered tidal flats. Linear tidal ridges extend offshore to a depth of 40 m. In tide-dominated estuaries flow rates are low, typically between 0.25-0.5 m $sec^{-1}$ also typically reversing with the tide (Thom & Wright, 1982). Generally such channels are deeper (10 m) than river dominated ones (3-4 m).

Figure 3 illustrates the distribution of substrata within the area; topographic detail is sparse with contour data based on 40 m intervals and a few spot height data scattered over the area. Any attempt to make detailed estimates of land loss which might occur due to a 20 cm or even a 1.5 m rise in sea level are doomed to failure given the present data. However it is possible on the basis of known distributions of vegetation types in relation to present salinity regimes to delimit zones of marine influence and given the general topography to obtain some estimate of the impact of future sea level rise.

Vegetation types

Percival & Womersley (1975) suggest that there are approximately 37 species of mangrove in Papua New Guinea. The high species diversity resulting from the presence of both Australian floral elements such as *Osbornia* and *Asian genera,* indeed the only Asian mangrove genus absent from the island of New Guinea is *Kandelia*. In addition to mangroves, *sensu strictu*, a wide variety of other plant genera are found in close association with mangroves, of these perhaps the most important from a subsistence economic viewpoint is the sago palm *Metroxylon sagu*.

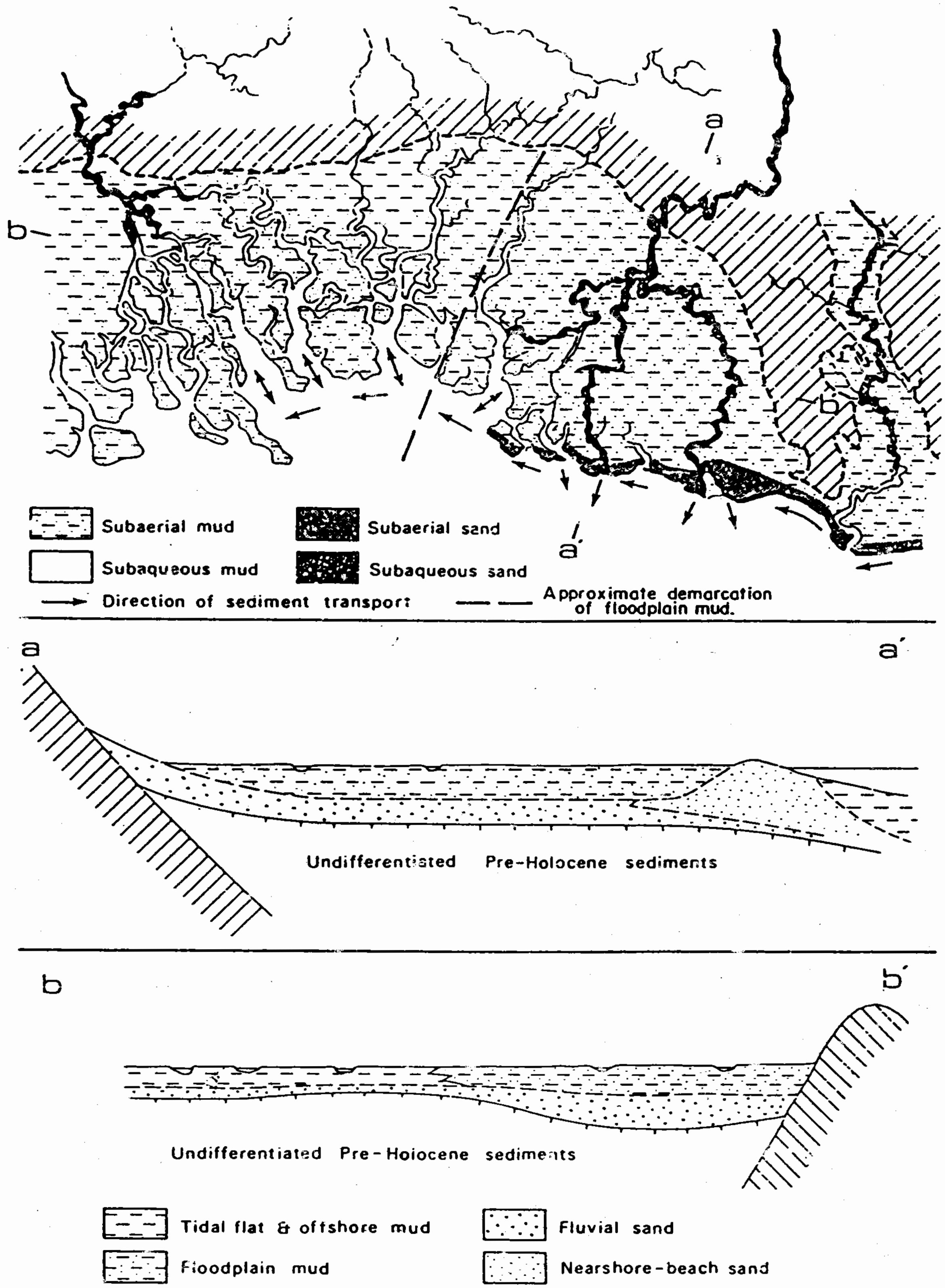


Figure 3. Suggested generalised depositional model of the Purari deltaic complex showing sediment types, stratigraphic units and directions of sediment transport (after Thom and Wright, 1982).

Estimates of the extent of mangrove forest in the Gulf Province vary. Hillis (1976) estimated that there are approximately 121,500 ha of Rhizophoraceae forest, 26,730 ha of pure *Nypa* palm. Paijmans (1969) on the basis of Forestry Map No. 1373 estimated 134,400 ha of mangrove swamp; 119,800 ha of mixed mangrove swamp forest; 67,400 ha of mixed mangrove *Nypa* swamps; 48,500 ha of *Nypa* swamp and 156,600 ha of freshwater swamp forest. Paijmans recognised 5 major associations including scrub dominated by ***Avicennia***; woodland dominated by ***Bruguiera*** interspersed with ***Rhizophora*** and a wide variety of other species; *Nypa* association; low forest predominantly of ***Sonneratia*** and ***Avicennia*** and a mid-height association predominantly composed of ***Rhizophora*** with some ***Bruguiera***.

The nature of the mangrove community differs from area to area depending upon a variety of factors. In general mangrove communities are characteristic of shorelines protected by off-shore barrier reefs; along shorelines running parallel to the prevailing winds; and in areas of active accretion. Percival & Womersley (1975) point out that 'a mangrove swamp on a stable shoreline will tend to be less extensive in width than one on an accretive shoreline' and the mangroves of the Purari delta are no exception. In the deltaic area of the Purari distributaries mangrove swamps extend some 35 km inland from the coast whilst further west in the area of the Turama River the extent is considerably less (Figure 1).

Mangrove succession and zonation

Zonation and succession are intimately related in mangrove ecosystems, and as Percival & Womersley (1975) note, mangroves do not cause shoreline accretion but may accelerate the process through increasing the rate of deposition of suspended materials. Hence pioneer mangrove species may alter the nature of the substratum and as a consequence are themselves replaced by other species in the process of succession. On stable shorelines where the rate of accretion is low the zonation characteristic of mangrove communities becomes compressed into a relatively narrow fringe between the marine and terrestrial communities. In actively accreting areas mangroves are more extensive and the zones individually wider. The mangrove systems fringing the Gulf Province fall into the latter category.

Areas subjected to differing degrees of salt water inundation may be divided into five major classes: areas inundated by all high tides; areas inundated by all medium high tides; areas inundated by all normal high tides; areas inundated by spring tides and areas inundated by exceptional high tides. No mangroves can withstand total inundation by salt water. The most resistant mangroves are those capable of withstanding inundation of their root systems by all medium high tides and include members of the genera ***Avicennia*** and ***Sonneratia***. Areas inundated by normal high tides are characterised by ***Rhizophora*** while ***Bruguiera*** is found only in those areas inundated by spring tides. In areas inundated only occasionally the mangrove community is dominated by ***Bruguiera gymnorrhiza*** and ***Rhizophora apiculata***.

Approaching a mangrove stand from the sea the first zone encountered is dominated by *Sonneratia alba* which may be inundated on a daily basis, however on most mangrove dominated coastlines the seaward zone is normally composed of *Avicennia marina* on the seaward edges, being replaced by *A. alba* along the mouths of tidal creeks, this zone in accreting areas may extend up to 750 m inland.

*Rhizophora* forests develop behind the pioneering species mentioned above with *R. mucronata* being more salt-water tolerant than *R. apiculata*. In this zone the substrata are inundated by normal high tides. Landward of this zone in the areas inundated by spring and exceptionally high tides the community is dominated by ***Bruguiera***, whilst in some areas *Ceriops* thickets form a landward fringe to the mangrove community.

In the fringing mangroves of the Gulf of Papua the *Nypa* association occurs in areas alongside tidal streams flooded by the highest spring tides. It is therefore an indicator of brackish water conditions. Mangrove succession for the Kikori River area has been described in detail by Floyd (1977) and for the Purari Delta by Cragg (1983).

Clearly any transect from the seaward edge to the landward side of the mangrove community, whilst it might conform to the general pattern described above is affected by local conditions of accretion, erosion, soils, freshwater inputs and tidal influences. No single transect profile would suffice therefore to describe the total area of the Gulf mangroves. Where the lower deltaic fraction of the Purari River estuary is dominated by massive freshwater inputs zonation differs from the central and western areas where the creeks and river mouths are more influenced by tides and salinity regimes.

Petr & Lucero (1979) have used the distribution of *Sonneratia caseolaris* to plot the limits of saline influence in the communities of the Gulf mangrove and swamp communities. The landward extension of this species corresponds with the lowest extension of the reed *Phragmites karka* and the landward extension of a particular estuarine *Pandanus* species. Thom & Wright (1982) accepted that this biological boundary corresponded to the geomorphological boundary between the upper and lower deltaic areas. It is possible therefore given a knowledge of the local geomorphology and the tidal range to make broad predictions concerning the changes in zonation which may occur following a rise in sea level of 1 m.

Along the southern coast the tidal range is around 2 m. In various areas of the Gulf coast tidal ranges are detected at considerable distances inland; thus 15 km from the confluence of the Wame and Pie rivers the river has a 150 cm tidal range, whilst the Pie River itself is tidal almost to the foothills. The Pie River is quite typical for the majority of the creeks and rivers of the western and central sections of the Gulf fringe.

Predicted changes to the mangrove community of the Gulf of Papua

Clearly saltwater intrusion will be extensive given the low-lying relatively flat nature of the coastal plain. The mangroves of this area are backed by freshwater swamps extending landwards to the foothills which rise abruptly (Figure 4). Whilst the mangrove and freshwater swamps show a mosaic distribution reflecting local variations in marine and freshwater influence and micro-topography, general patterns are discernable. In the eastern section of the area dominated by the freshwater inputs of the Purari River the influence of a 1 m sea level rise will clearly be less than the impacts in the central and western sections of the region under consideration.

*Sonneratia caseolaris* extends much further inland in the western and central regions than in the Purari delta area (Petr and Lucero, 1979) indeed in these regions it extends almost to the base of the foothills region. It seems highly probable therefore that extensive retreat of the mangrove community in this area can be expected, with a consequent compression of zones within the community itself. Zonal compression will not be equal but may be greatest in those zones furthest from the existing shoreline and saline influence, i.e. the transition between the mangrove and terrestrial communities will be more abrupt associated with the much greater slope encountered as one passes landwards in this area.

Figure 5 illustrates a simplistic model of possible changes across three profiles taken at points A, B and C in Figure 2. Thom & Wright (1982) provide a profile for the section at A (Figure 4) which is assumed to be typical for B and C. It is further assumed that the boundary between the coastal mangrove association of *Sonneratia, Avicennia* and *Rhizophora* and the more landward *Bruguiera* forest is located at around 105 cm tidal height, and that slope is uniform across the coastal plain to the immediate vicinity of the foothills. A rise of 1 m in sea level will therefore result in inundation of the coastal fringes and regression of the mangrove community back to the present boundary between the *Rhizophora*-dominated and *Bruguiera*-dominated associations.

For the profile at A, a sea level rise of more than 2 m is required before any compression of the zones will occur as a result of increased slope associated with the foothills. In the case of the profiles at B and C however a rise of 1 m will result in compression of the mangrove community. Three alternative scenarios are presented in each instance. The first assumes that each zone is merely moved further landwards and that the most landward zones disappear, an unlikely scenario. The second assumes that the reduced width of the coastal plain is divided amongst the various associations in proportion to their present extent at each site and the third scenario assumes that differential compression of the seaward zones occurs, in proportion to their present extent in the Purari Delta profile A. If shore-lines were to stabilise at 1 m above present the last scenario would be the most probable.

Profile C is of further interest in that it illustrates a section through a profile which is bisected by a wide seawater channel, hence the seaward mangrove zone is repeated twice. A 1 m rise in sea level will result in reduction in extent of the seaward (insular) mangrove area which may well become so small that it will be actually eroded completely. Given the mosaic nature the distribution of present-day vegetation it may be assumed that local variations in micro-topography exist. Clearly then saltwater intrusion may follow slightly lower-lying areas, resulting in the formation of smaller insular units within the newly formed seaward mangrove zones.

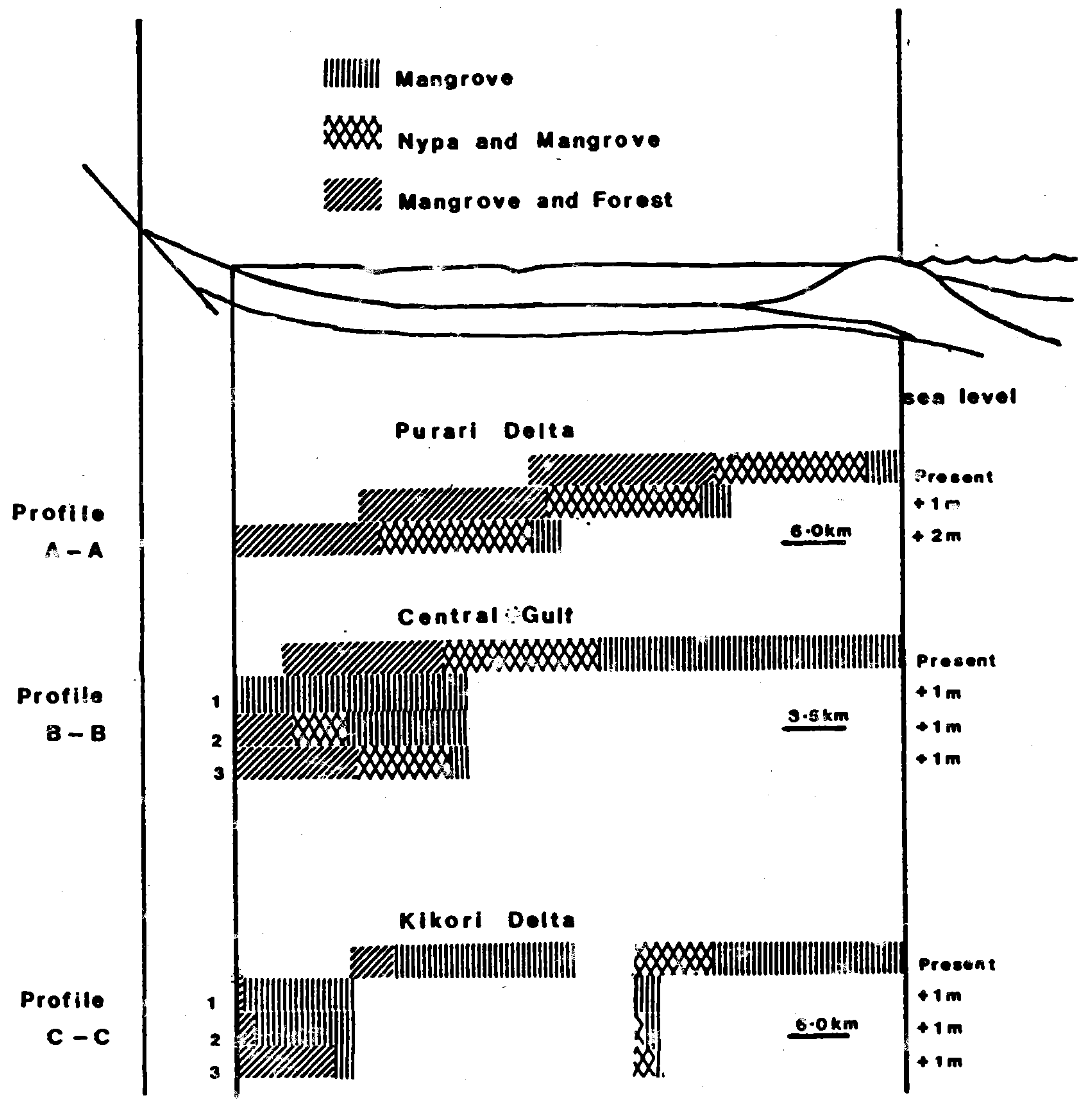


Figure 4. Hypothetical model of mangrove regression following sea level rise. Based on Gulf of Papua. (For location of profiles see figure 2).

Assumptions underlying the model

It should be pointed out that in the above model none of the dynamic factors presently operating in this system have been changed, thus it is assumed that sediment inputs will continue at much the same level and that crustal downwarping leading to sinking of the coast will continue at its present rate. It was noted above that sediment inputs are presently sufficiently large to compensate for crustal downwarping and indeed the coastline is advancing over at least part of its length around the Gulf. (It is also eroding elsewhere.)

McGregor (this volume) suggests that increased rainfall in the catchments will occur as a result of global warming, hence increased erosion may be expected to occur and sediment inputs will increase. Sinking of the coastline is also likely to increase due to the increased weight of water resulting from the increased sea level. Whether these two counter-acting forces will in fact balance is unknown. It would appear unlikely that increased sediment inputs will be sufficient to counter the increased rate of sinking. It is possible therefore that regression of the coastline in this area may indeed be more extensive than the present model suggests.

ASSOCIATED IMPACTS

The mangrove communities form a specialised habitat for a variety of organisms including several species of birds and fish which are confined to these habitats. Any reduction in habitat area in the Gulf Province mangroves will lead to reduction in species diversity and possible loss of some species totally.

The fish communities of mangroves in the Purari Delta are described in some detail by Haines (1979) who lists some 49 species from 24 families in the freshwater reaches of the river and delta. Liem & Haines (1977) list 143 species from 48 families from the estuarine area of the Purari-Kikori deltaic complex. Most riverine species are also found in the estuarine areas, whilst some congeneric replacement is seen when the estuarine and freshwater fish faunas are compared. Sixty three fish species are described as being estuarine, 59 as marine and 15 as riverine, any reduction in the extent of the mangrove habitats will significantly reduce fish species diversity in this area. Both individual density and species diversity of estuarine species are likely to decline with some species disappearing altogether.

In addition to providing important fish and wildlife resources for the people of the area (Liem & Haines, 1979; Haines & Stevens, 1983), some resources such as barramundi and the mud crab *Scylla serrata* are commercially exploited. The mud crab lives and breeds in the mangrove associations hence any reduction in habitat will result in a reduction in the size of the population which can be exploited. Barramundi, *Lates calcarifer* breeds in coastal waters and migrates whilst still juvenile to freshwater for growth to maturity. Again reduction in suitable coastal habitats could result in a reduction in the local populations of this species. Whilst the extent to which this mangrove system is utilised as a nursery area for marine fish species is not known; it is known that it forms an important nursery for penaeid prawns (Frusher, 1983; Gwyther, 1983) which are commercially trawled in the Gulf of Papua. The extent to which reduction in mangrove habitats will reduce nursery areas and hence reduce the carrying capacity of the environment for juvenile prawns is unknown, it may be presumed however that the offshore areas where prawns grow and mature will increase in area, whether the reduced mangrove habitats will provide sufficient area for increased breeding and hence increased population size overall is unknown. It would seem improbable and a decline in this resource might be expected.

The freshwater turtle, *Carrettochelys insculpta* is a large species which breeds extensively in tidal and other creeks and is found as far up river as Wabo on the Purari. Both the eggs and adults are extensively eaten throughout the area and up to 40,000 eggs may be sold during each breeding season at Kikori market. By far the greatest population densities of this species are found from the lower freshwater reaches of rivers through the estuarine areas fringing the Gulf. Breeding burrows are excavated on sand banks, hence the populations of the species are probably limited at the present time by the availability of suitable nesting sites. It would seem that by and large the area of available nest sites will be affected to some small degree, although reduction in the estuarine habitat will concentrate adult populations leading to higher mortalities of adults through increased capture in fishing nets. The species is of some conservation concern being found only along the southern coasts of New Guinea and in the Northern Territory of Australia and being the sole extant representative of its family.

The human population of this area, whilst not large is dependent on the mangrove and associated resources for a considerable proportion of their subsistence requirements. The staple carbohydrate source is *Metroxylon sagu*, the sago palm which is treated to obtain starch. Whilst sago will grow in brackish water habitats it is largely confined to the freshwater swamps behind the saline mangrove communities, any reduction in the extent of this zone will have profound effects on the distribution and abundance of this major human energy source.

Similarly *Nypa* palm provides thatching materials and mangroves provide timber for house construction. Whilst it is unlikely that the latter two resources will be reduced to the extent that alternative materials would have to be used, their local distribution may well be affected such that some clans or land-owning groups may find themselves without access to these resources on their own land. Peoples located in close proximity to the present shoreline and with only limited access or usufruct rights to areas in the current swamp forest habitats may find that the shift in zonation results in loss of the communities traditional sago sources. Social tensions are likely to be generated by differential loss of resources between communities.

A further problem which may well result in the necessity for moving current villages in coastal locations relate to freshwater access. Villages in this area rely either on freshwater runoff, rainwater (in small quantity) and wells for drinking and washing water. Most wells in the lower delta area are slightly brackish at the present time, hence any rise in sea level may result in increased difficulty for such communities to obtain potable water. A population shift landwards might therefore be anticipated to presage the actual inundation of coastally located village sites. Again the absence of ownership rights to suitable land areas inland may result in social tensions.

## THE FLY RIVER, ITS TRIBUTARIES, LAKES AND ASSOCIATED WETLANDS

The Fly Platform (Bain, 1973) is an extensive stable shelf comprising the vast plains and wetlands associated with the Fly and Strickland Rivers and the limestone plateaux to the northwest of the lowlands. The platform occupies nearly a third of the mainland of Papua New Guinea (Figure 5 and 6).

### General features

The Fly River is 1,120 km long with an average discharge of approximately 6,000 $m^3$/sec. Its drainage basin is only 76,000 $km^2$ and its high discharge results from heavy and persistent rainfall in the upper catchment. There are major climatic and ecological differences between the upper, middle and lower reaches of the Fly River. The most significant difference is between exceedingly high annual rainfall with little seasonality in the Upper Fly and lower, markedly seasonal rainfall in the Middle and Lower reaches of the river. Rainfall varies from 4.7 m at Kiunga to 11.9 m near Tabubil. The high rainfall in the catchment area is responsible for the average annual runoff through the Fly River exceeding that of even the Amazon River (Table 1). Downstream, rainfall diminishes with mean annual values of 2.6 m and 2.1 m at Bosset and Daru respectively.

The river is navigable as far as Kiunga, approximately 800 km from its mouth. The gradient in its lower course is extremely gentle as Kiunga is less than 20 m above sea level (Anon, 1965) (Figure 7). The river is tidal for 250 km upstream and typically river bed level in a straight reach at Kiunga is only 7.5 m above sea level. Rapid and significant water level changes (up to 15 m) may occur in the vicinity of Kiunga.

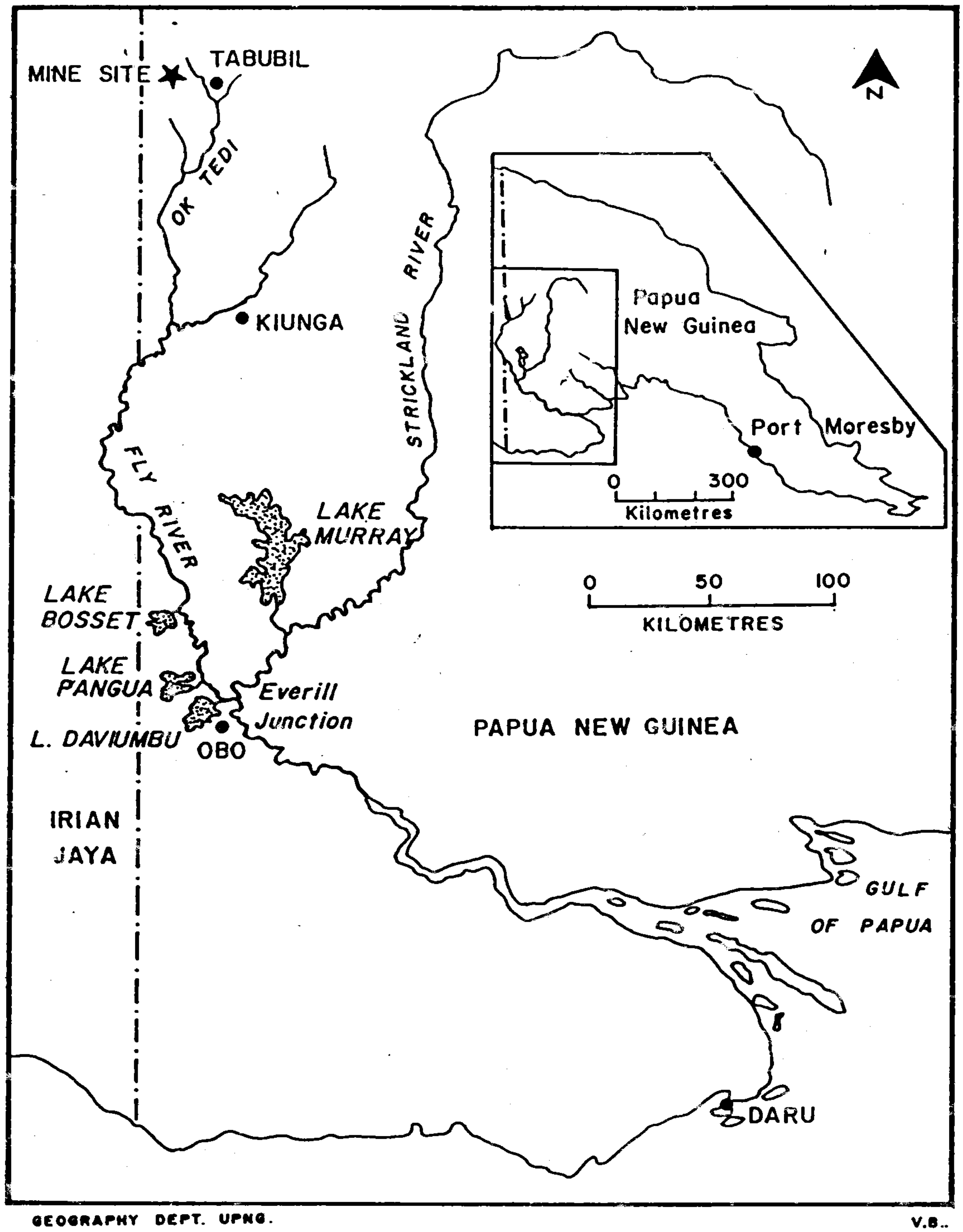


Figure 5 Map of Papua New Guinea sh^wing the two largest rivers in the country: the Fly and the Sepik and Lake Murray and the Stickland River.

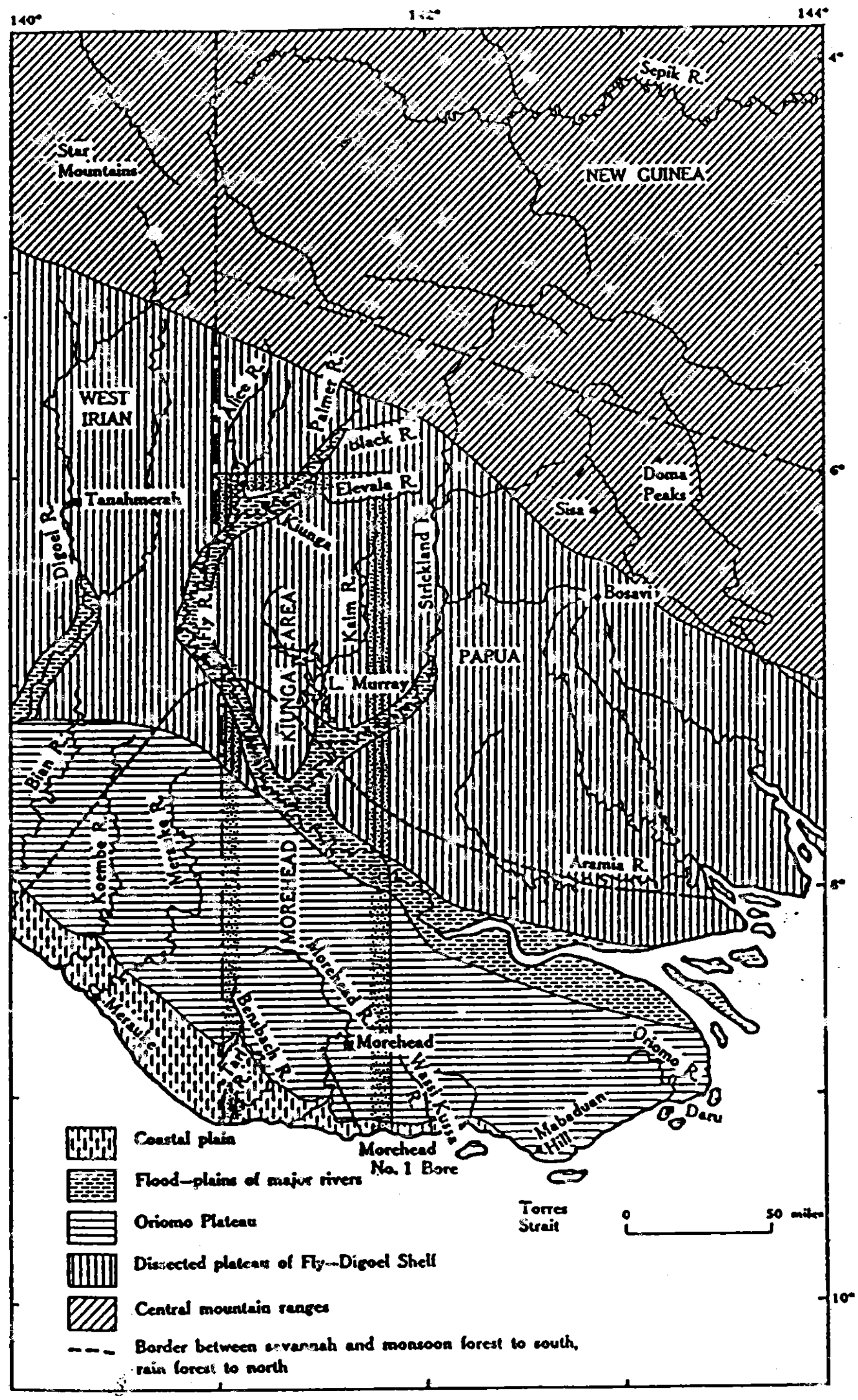


Figure 6 The Fly River floodplain and geographical features of the region (after Blake and Ollier, 1971).

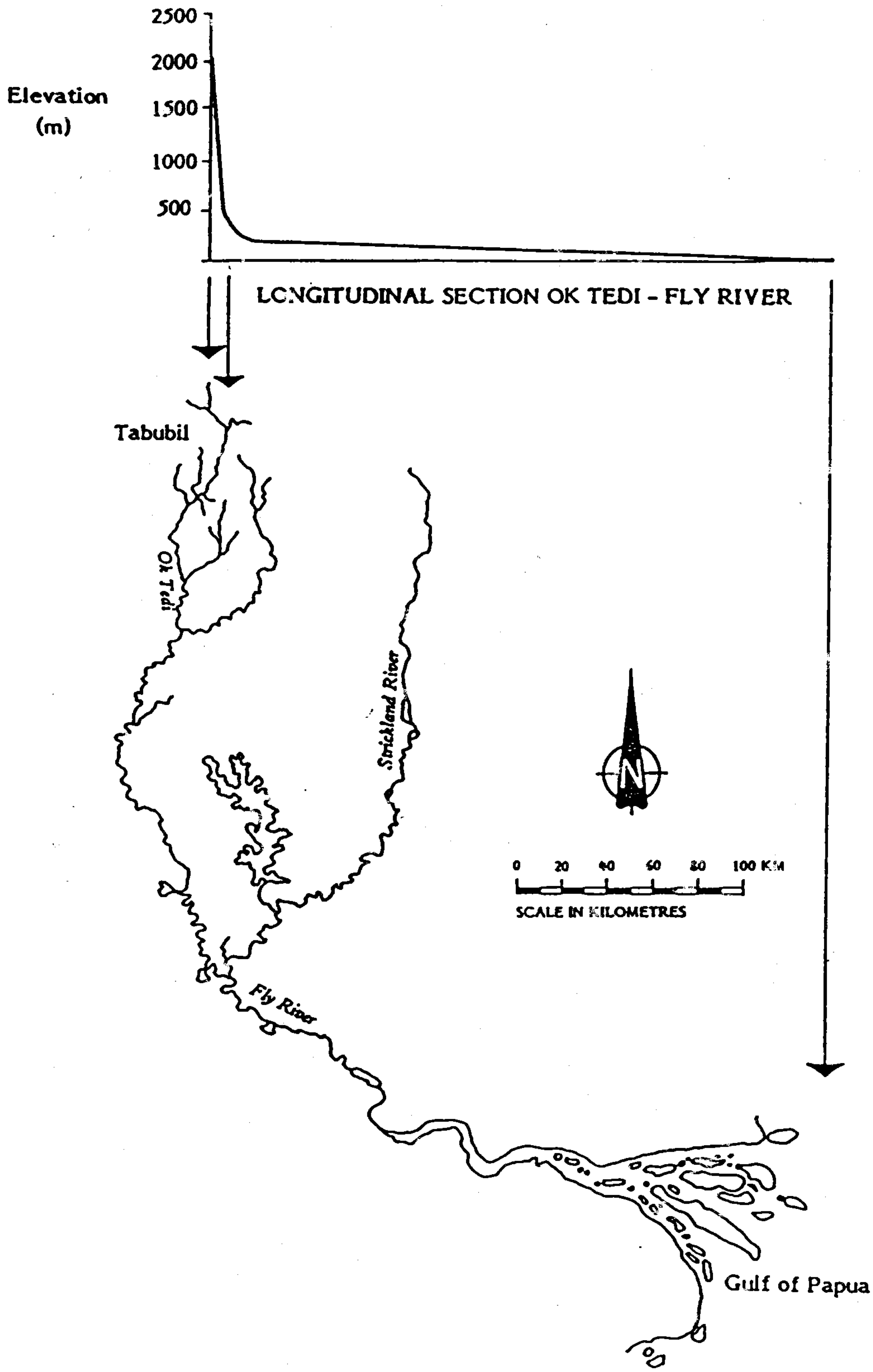


Figure 7 Longitudinal profile of the the Ok Tedi and Fly River showing the steep gradient in the upper reaches and very small gradient from Kiunga to the mouth of the Fly (Maunsell *et al.*, 1982).

Table 1. Comparison of the Fly River with other major world rivers.

| Name | Average annual discharge ($m^3 s^{-1}$) | Drainage area ($km^2$) x 1000 | Length (km) | Annual runoff (mm) |
|---|---|---|---|---|
| Amazon | 203,800 | 7,180 | 6,300 | 900 |
| Congo | 56,600 | 3,691 | 4,700 | 490 |
| Yangtze | 21,800 | 1,942 | 5,000 | 350 |
| Ganges | 20,000 | 2,054 | 2,900 | 310 |
| Mississippi-Missouri | 17,600 | 3,221 | 6,300 | 170 |
| Orinoco | 17,000 | 1,476 | 2,600 | 230 |
| Nile | 12,000 | 3,349 | 6,500 | 110 |
| Fly | 6,000 | 76 | 1,120 | 2,500 |
| Purari | 2,667 | 33 | 630 | 2,617 |

The low altitude and flat topography of the Middle Fly region, combined with mean annual rainfall of 3 m result in a predominantly swampy environment, with a mosaic of lakes, alluvial forest, swamp grassland, and swamp savanna. The active floodplain of the river is restricted to a relatively narrow belt between 10-16 km wide. The river flows on an alluvial ridge formed by deposition of material eroded from the upper catchment following an incision of the river into the plain estimated to have occurred as a result of sea level reduction about 27,000 years BP (Blake & Ollier, 1971). Deposition within the main river plain occurred more rapidly than in the tributaries which then became blocked, forming numerous tributary lakes.

The numerous lakes in the area fall into two categories: tributary lakes and ox-bow lakes. Tributary lakes are formed by the blocking of a tributary by a river and are usually shallow (e.g. Bosset Lagoon and Lake Daviumbu). Ox-bow lakes are of variable depth depending on age. Three lakes have been studied in some detail and descriptions of them are provided below.

Lake Daviumbu

Lake Daviumbu lies in a shallow depression connected to the Fly River by a narrow channel, 5 m wide. It was formed by a tributary stream being blocked through accretion by the Fly River. Water levels fluctuate seasonally being high (with depths of approximately 4 m) at the start of the year and declining between April and the end of the year. Occasionally the lake almost dries out completely (Maunsell & Partners, 1982).

The lake is surrounded by herbaceous swamp with *Phragmites karka* and *Sachharum* sp. dominant. The aquatic vegetation is very diverse and includes hydrophytic grasses such as *Hymenachne acutigluma, Ischaemum polystachyum, Oryza rufipogon* and *Sacciolepis myosuroides. Pistia stratiotes, Ceratophyllum demersum, Nymphaea macrosperma, Nymphaea violacea, Nelumbo nucifera* and *Utricularia* sp. are the dominant aquatics. Four species of *Blyxa*: *Blyxa japonica, B. novoguineensis, B. aubertii and B. octandra*) have been recorded from sites in the lower Fly River valley. *Limnophila aromatica* and *Limnophila indica* grow in shallow and newly exposed mud banks. Osborne *et al.* (in press) have shown that sediment from the Fly River is deposited in this lake (and presumably other lakes in the Middle Fly).

Bosset Lake

Bosset lagoon is also a tributary lake (catchment area 230 $km^2$) and like Lake Daviumbu it is connected to the Fly River by a narrow channel. Seasonal fluctuations in water level are similar to those described for Lake Daviumbu. Maunsell *et al.* (1982) recorded a general lake depth of 4.2 m. Local people at the time of their visit recalled water levels up to 2 m higher. This lake dries out on occasions and hence a possible water level range of over 6 m is indicated. Subsistence gardens can be established on the lake bed during periods of low water. The lake is surrounded by herbaceous swamp and the aquatic vegetation is similar to that found in Lake Daviumbu.

Lake Murray

The largest lake in Papua New Guinea, Lake Murray (surface area 647 $km^2$) lies in a shallow depression (maximum depth 7 m) in the Y formed by the Strickland and Fly Rivers. The lake is drained by the Herbert River, a tributary of the Strickland River. Lake Murray is subject to marked seasonal fluctuations in water level. Consequently plant development along the very long shoreline (over 2,000 km) is seasonal. During the period of low water (November-January) vast areas of barren mud are exposed. The water then is very turbid and the submerged and littoral vegetation is poorly developed.

Following the rains, the lake fills, becomes less turbid and a diverse aquatic vegetation develops. The aquatic plants then occur in two broad zones: an outer zone dominated by *Nymphoides indica* with some *Nymphaea nouchali*, *Ceratophyllum demersum*, *Pistia stratiotes* and, more rarely, *Blyxa novoguineensis*. The inner zone consists of hydrophytic grasses, such as *Echinochloa praestans* and *Leersia hexandra*, with some *Ipomoea aquatica*, *Azolla pinnata Ludwigia adscendens*, *Polygonum attenuatum* and *Utricularia* sp. *Limnophila indica* occurs on newly exposed mud and in shallow water. The seasonal fluctuation in water level also affects the water chemistry and primary production of the phytoplankton.

As the water level falls between April and December pH, alkalinity, conductivity, total hardness and the concentration of suspended solids increase. Similarly, the concentrations of calcium, magnesium, sodium and potassium increase during this period of falling water levels (for full details, see Osborne *et al.*, 1987).

With the onset of the rains, the lake fills rapidly. This filling process is due not only to inflow from the surrounding catchment and rainfall on the surface of the lake but also, more interestingly, to the reversed flow of the Herbert River. Current meter records from a station in the Herbert River show clearly periods of reversed flow (Natural Systems Research, 1987). These periods of reversed flow are accompanied by depressed water temperatures. The temperature of the Strickland River water is cooler than that in Lake Murray. This flow reversal clearly demonstrates the low-lying, flat nature of the landscape in this Trans-Fly area.

The Lower Fly River and Delta/Estuary

In the Lower Fly region, mangroves and sago swamps are the dominant vegetation zones in an estuary over 80 km wide, with some species extending up to 300 km up the Fly River. The soils on the islands in the estuary are subject to tidal inundation, are poorly drained, high in salt content and alkaline. The mouth of the Fly River is best described geologically as a tidal delta. It cannot be characterised as a true estuary, nor as a river delta because of its transiently polyhaline structure and strong current regime. The degree of marine penetration is severely limited for much of the year by high river discharge. This results in the almost total absence of a true marine (or estuarine) benthic community over much of the delta. Such organisms only occur near the seaward edge of the delta. The zone of saline influence moves seasonally, and many of the pelagic animals with it, depending on their salinity tolerance and habitat preferences.

Human resource use in the Middle Fly

Seventy-four thousand people (1980 census) live within the Fly drainage area. Those of the Middle Fly are Boazi and Zimakani peoples; those of the Delta area are Kiwai. The Boazi and Zimakani are hunter-gatherers operating in the wetlands and savanna of the Middle Fly. Habitable land is scarce, with only occasional small hills of firm ground rising above the floodplain swamps. Even so, most villages are subject to periodic flooding. Cultivation is difficult and sago is harvested from the surrounding swamp forests. The main factors limiting agricultural production are acid and infertile soils, poor drainage and flooding. Crocodile, wallaby, deer, fish and freshwater prawns provide an abundance of protein foods. Cash crops include rubber, crocodile skins and barramundi (*Lates calcarifer*). The relative abundance of nutritious food supports relatively large populations where high ground is available: Bosset (600 people), Kaviananga (Lake Daviumbu) (470 people).

At the mouth of the Fly River, the Kiwai people are also primarily hunter-gatherers living on fish, crocodiles and dugong. There is also some cultivation of banana, coconuts and taro.

The Fly River and its associated waterways are used extensively for transport, both at the subsistence level and to supply and export materials from the large Ok Tedi mine in the upper catchment.

## PREDICTED IMPACTS OF A RISE IN SEA LEVEL

### Hydrological considerations

Knowledge of the hydrology of the Fly River system is totally inadequate and specific predictions of the effects of a rise in sea level are extremely difficult to make and a detailed hydrographic and hydrologic survey of the Middle and Lower Fly River is urgently required. However, a number of general conclusions can be drawn. Undoubtedly an increase in sea level will result in a raised water table over much of this low-lying area. The people and organisms inhabiting this vast wetland are accustomed and adapted to marked fluctuations in water levels. The magnitude of these water level fluctuations is unlikely to change. However, the maximum, minimum and mean levels will all be recorded at higher water levels than at present. Given the scant information available it is impossible to even hazard a guess by how much these levels might increase. Consequently, lakes such Bosset, which dry out occasionally, will do so less frequently. Areas that are only flooded rarely will be flooded more frequently. Similarly, areas that are not flooded by high water levels at present, may well be in the future. These water level changes will result in a reduction of the area available for habitation and cultivation. This loss will be counter-balanced by an increase in the availability of aquatic food resources if only through the increased area of open water.

We know very little about the physico-chemical and biological effects of water level changes. Osborne *et al.* (1987) showed that, in Lake Murray, water chemistry and phytoplanktonic production varied markedly with seasonal changes in water depth. Aquatic plant distributions were also affected. Following a 1 m rise in sea level, it is likely that these water level fluctuations (and the related effects) will continue. However, with higher water levels, and given the very flat topography of the area, the magnitude of fluctuations may be reduced and greater stability in water levels may result.

Both the Strickland and the Fly Rivers carry large sediment loads. Furthermore, the construction and operation of large mines in the upper catchments of both rivers is likely to add significant amounts to the riverine suspended solids. Naturally-derived mercury in the Strickland-Lake Murray system occurs in sufficiently high concentrations in both carnivorous fish and humans as to cause concern. Similarly, other metals occur in high concentrations and these concentrations are likely to increase with the mining activity in the upper catchments of both rivers. Osborne *et al.* (in press) and Natural Systems Research (1987) have demonstrated that the suspended solids carried by these large rivers are deposited in the adjacent lakes. With regard to sea level rise an important question is whether higher river levels will result in increased sediment deposition in the middle Fly lakes and Lake Murray. Following a 1 m rise in sea level tidal effects will be extended further upstream. This will result in greater sediment deposition, through reduced flow rates, in the tidal reaches of the river.

The effects of sea level rise on the people living in the area are likely to be small. They are thoroughly accustomed to coping with dramatic fluctuations in water level, populations are low and food is abundant. Villages which are flooded now are likely to be flooded more frequently in the future. Given the paucity of high ground this may result in some compression of village sites. Local effects may include flooding of installations such as crocodile farms. Interpretation of SPOT imagery could assist in mapping low and high water levels, riverine inputs, land-use, vegetation and areas of sediment deposition.

SUMMARY

The mangrove habitats fringing the Gulf of Papua are likely to undergo substantial reduction in area, with compression of existing zones as a result of sea-level rise. Consequent upon this will be the loss of resources or loss of access to such resources on the part of some communities. Consequent social tensions may be envisaged. The reduction in nursery areas for penaeid prawns may have significant impacts on the size of this commercial resource and the fish community will both decrease in diversity and possibly also in abundance. Reduced access to potable water is likely to be a major problem for human communities located in close proximity to the present coast. The people living in the Middle and Lower Fly River areas are accustomed to marked fluctuations in water level and seasonal flooding. It is likely that following a rise in sea level flooding of the low-lying land along the Fly River will be more frequent and of longer duration. This will affect the availability of land (already in short supply) for habitation and cultivation. The loss of agricultural land may be compensated for by an increase in aquatic resources through the increase in flooded areas. Consideration should be given to a detailed study of how sediment deposition in Lake Murray and the lakes of the middle Fly region, particularly with regard to mercury and heavy metals, may change with higher river levels.

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# THE EFFECT OF SEA LEVEL RISE ON RAISED CORAL AND HIGH ISLANDS

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In the general overview of the Papua New Guinea coastline (Bualia & Sullivan, this volume), five landform types were identified as areas which would suffer particularly from a 1 m rise in sea level. These are:

* deltaic floodplains, with mangrove or swamp forest;
* lagoon and sandspit landform complexes;
* coral atolls and cays at sea level;
* raised coral islands;
* high islands.

In this preliminary study the effects of a 1 m rise in sea level are considered for two of these landform types, raised coral and high islands.

## RAISED CORAL ISLANDS

### Coral island forms

Coral based islands associated with reef provinces are of a variety of forms which reflect the conditions of coral growth and breakdown and tectonic processes. Constructional processes involve the upward and outward growth of coral reefs, into the zone of water turbulence. Reef platforms are thus developed near sea level, but may emerge from the water if they are raised tectonically, or if sea level falls. Raised or emerged reefs or islands may be uplifted during one or more tectonic phases, and thus may attain varying elevations.

As reef building proceeds at sea level, extensive sediments derived from reef erosion are banked up against the flanks of massive reefs (Bird, 1984:254) and great quantities of broken reef material accumulate against the reef flanks and on lagoon floors, from where they are available for redistribution throughout the reef zone, and for the building of emergent islands. Reef erosion to produce such debris occurs at both formational and emergent levels (Davies, 1972:71), and supplies sand, pebbles and boulders from which beaches and small islands or cays are constructed. Raised coral erodes severely to produce debris (Wiens, 1962:18), however as Bird noted (1984:271) although some of the debris which forms coral based islands is derived from emerged reefs, most is not, and the accumulation of sediment to form low islands and cays does not require tectonism or any relative shift in sea level.

Atolls and low islands or cays, which attain elevations of only a few metres above sea level and which are therefore particularly vulnerable to the effects of any rise in sea level, have been considered separately by Sullivan & Pernetta (this volume). In this study the effects of sea level rise on raised coral islands, landforms which are less directly affected by such changes, are considered.

### Raised coral islands

The sample area chosen for this case study is Kiriwina Island, the largest island in the Trobriand Group, Milne Bay Province (see Figure 1). The Trobriand Islands are located on the Woodlark Ridge, a well defined submarine ridge in the north of Milne Bay Province (Ollier, 1975:166; Löffler, 1977:123)

Like other islands in the Trobriand Group, Kiriwina is a raised coral island with no exposed bedrock of other material. It is part of the extensive barrier reef system which forms a wide semi-circular arc at the eastern end of the Papua New Guinea mainland, and which runs northwesterly through the D'Entrecasteaux Islands then northwards through the Trobriands (see Löffler, 1977:119ff). The barrier reef system consists largely of narrow elongated ribbon reefs in windward locations and irregular reefs and atolls in leeward locations. Most of the barrier reefs surround submerged islands or oceanic volcanic centres. Uplifted coral reefs are common in Papua New Guinea, and consist of simple reef platforms or sequences of terraces representing discontinuous or episodic uplifts.

The Trobriand Islands comprise both uplifted barrier reef islands, like Kiriwina, and atolls which are slightly to markedly uplifted, following the Woodlark Ridge, which rises to the east. The easternmost island in the group is Kitava, which is a well preserved atoll raised more than 100 m above sea level in a sequence of uplifts. The atoll structure is well preserved, and there are at least five coral terraces around the island (Ollier & Holdsworth, 1970). Most other islands in the Trobriand Group are predominantly low-lying, and do not show distinct terraces.

On Kiriwina Island two phases of uplift and regional tilting along the Woodlark Ridge has resulted in the formation of a generally low-lying island, with much of the land no more than 10 m above sea level. Along the eastern side of the island a ridge indicating the earlier phase of uplift rises to about 20 m above sea level tilted to a maximum elevation of 50 m near the northern end of the island.

The surface geomorphological features of the island include swamps which occupy the sites of old lagoons, mainly in the northwestern part of the island, ridges and terraces on the eastern side, marking phases of uplift, and cliffs along the coastline (see Ollier, 1975:169). Ollier noted that marine erosion of the coastal cliffs by solution is rapid. Karst features including several large caves formed by phreatic solution are common on the island.

Kiriwina Island, like other large coral islands, supports a sub-surface lens of fresh groundwater, recharged by infiltration from rainwater, and percolation through solution pipes (see Ollier, 1975:170). This lens of fresh water descends well below sea level near the centre of the island, converges towards the coastline, and extends right to the shoreline, which is truncated by submarine cliffs.. Submarine springs of fresh water are reported to enter the sea along this cliffed coastline (Ollier, 1975:170) and most of the island's fresh water sources are springs along eroding clifflines and ridges, and pools in caves.

The tidal range on Kiriwina Island is about 1 m, and Ollier also noted (1975:169) that at high tide many of these springs and cave pools become salty, indicating the very slight elevation of the general watertable above present sea level. Although phreatic pressure at the base of the lens of fresh water stored in the island's limestone is sufficient to maintain fresh submarine springs, any prolonged incursion of seawater into vadose cavities near the watertable surface, or into cave pools, would cause salination of this fresh groundwater store.

Should sea level rise as little as 1 m Kiriwina and similar barrier reef islands are likely to suffer severe impact in terms of proportional loss of land area, and disruption of communications. Insufficient exact spot height or mapped topographic data are available for Kiriwina to accurately project the coastline which would result from a 1 m rise in sea level. Nevertheless it is clear from the approximate projected new coastline shown in Figure 1 (which probably underestimates the extent of swampy ground which would be inundated), that Kiriwina Island will lose about half its present land area, and is likely to be broken into a chain of smaller islands. Most of the low-lying land which will be directly inundated is on the western side of the island, where a rising sea level will isolate a narrow ridge of limestone which forms the present low coastal cliffs, and intrude into the swampy land behind the cliffs.

Kiriwina, like most of the Trobriand Islands is densely populated (more than 80 people/km$^2$),but with little cash-based economic development (see CSIRO and DPI, 1987). The impact of a rise in sea level would be locally very severe, removing town or village locations, garden land, several kilometres of roads, and other communication links.

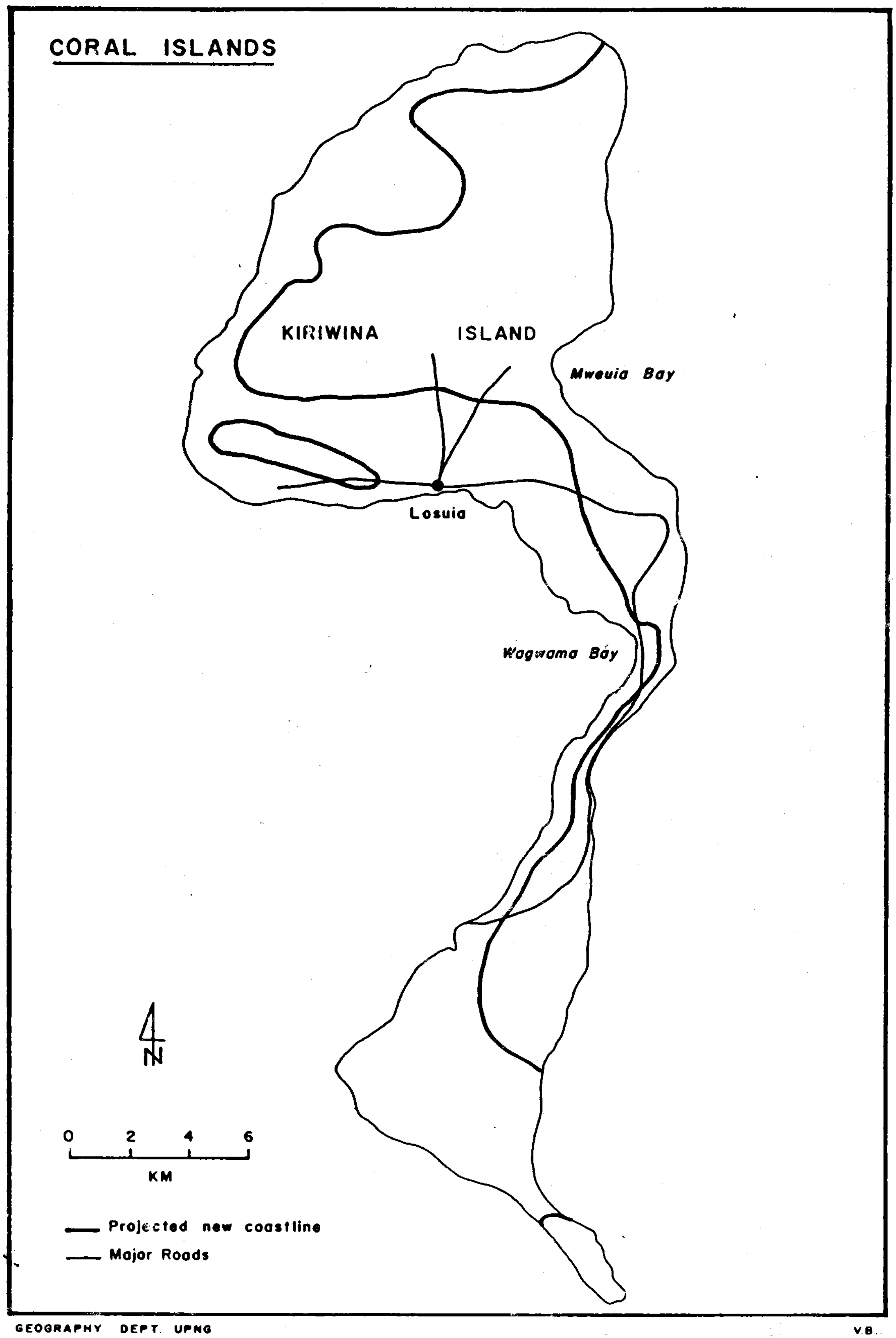


Figure 1. Kiriwina Island showing the present and projected new coastline should sea level rise by 1 metre.

In addition to this direct loss of land, a rising sea level will cause salination of the watertable in all but the highest land areas, rendering about half of the remaining land mass at best inconvienient to inhabit, since fresh water will need to be carried and stored.

A similar reduction in land area and disjunction of land is likely to occur on other islands in the Trobriand group, especially those south and west of Kiriwina, and in other parts of the barrier reef system.

A model of the effects of sea level rise on raised coral islands would include the following components:

(i) rising saline water table, and consequent compression or contamination of fresh water lenses;

(ii) sea water intrusion into low lying and swampy land, with consequent disturbance of infrastructure, especially coastal roads;

(iii) major loss of land at low elevations, and fragmentation of island landmasses.

HIGH ISLANDS

There are a variety of small high islands in Papua New Guinea, and the islands chosen for examination are Lihir Island in New Ireland Province, and Misima Island in Milne Bay Province (see Figure 2).

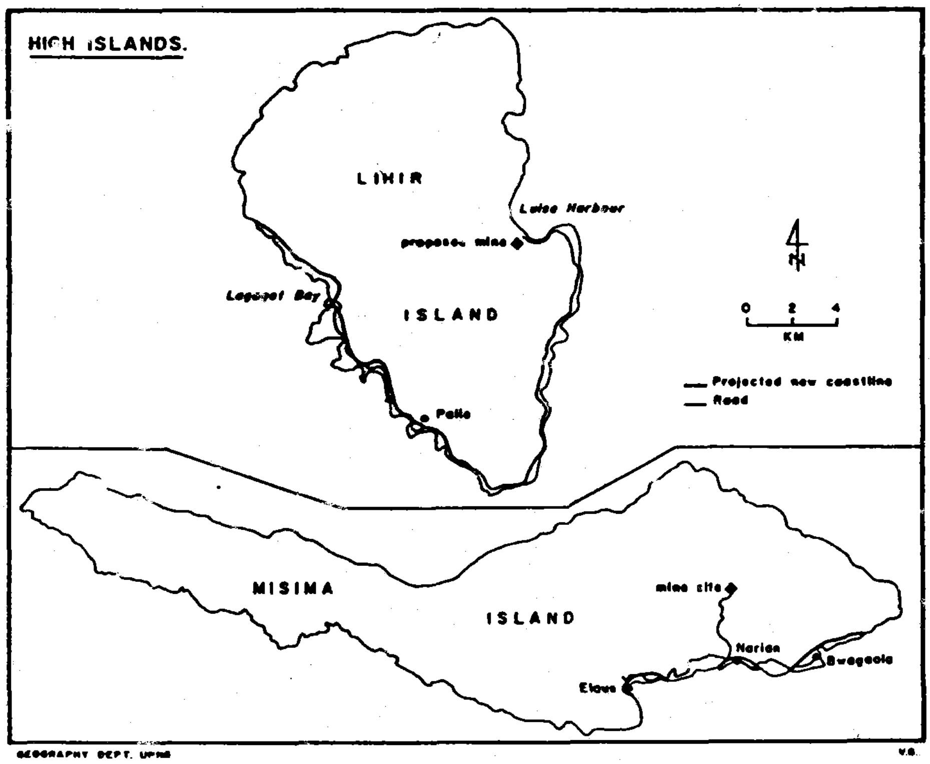


Figure 2. Small high islands, Lihir and Misima, showing the likely effects of a 1 metre rise in sea level

These islands were chosen because they exemplify the variation in small high islands in Papua New Guinea. Misima Island is relatively stable, with a central core developed on metamorphic rocks, and a terraced coastal fringe on uplifted coralline limestone (NSR, 1987). Lihir Island, which is a volcanic island, is typical of many islands on the Pacific Island Arc in that it is undergoing gradual uplift from the east, a process which is tilting the island, and causing slow inundation of its western side (NSR in prep.).

Most of Misima Island's coastline comprises low cliffs on uplifted coralline limestone. A sea level rise of 1 m would make little difference to this cliffed coastline. Sections of the island's shoreline however comprise sandy or gravelly beach and beachridge complexes, and the roads which exist on the Island have, wherever possible, been constructed on the crests of beachridges, rather than on the broken limestone surfaces above the low cliffs.

Although the absolute effect of a rise in sea level is the same on high islands as on the rocky shoreline sectors of the mainland or large islands, the relative effect of the removal of part of the coastal zone of such small islands is considerable.

On Misima Island this effect will involve the removal of part of the island's limited infrastructure. The major town on Misima Island is Bwagoia, at its eastern end, a port town close to sea level, and this town is linked by road to villages along the southern coastline at the eastern end of the island. Like many such roads the southern coast road on Misima Island is built on the lowest coral terraces and at the back of gravelly beaches, much of it on land which will be partially inundated should sea level rise by 1 m. In fact, the site of the recent major economic development on Misima Island, a goldmine, is linked to Bwagoia by this coastal road, through the coastal village of Narian. The road will be reconstructed and upgraded as part of the mining project, and will be left as a major link in the island's transport network when mining ceases, in 10 to 15 years. Narian, Bwagoia and the road are all likely to be partially inundated by a sea level rise, with consequent disruption to economic activity on the island.

It is worth noting that infrastructure now being planned for the proposed mining and town development would be wisely concentrated on the coral terraces, not on the beachridges behind stretches of depositional coastline, like that near Narian.

On Lihir Island the coastal area most likely to suffer inundation due to a rise in sea level is the subsiding western side of the island. This is the part of the island furthest from the proposed gold mine which is likely to be established on the island, and thus furthest from proposed economic activity. It is however that part of the island which currently provides the major part of the island's sago - a plant of considerable traditional economic importance, since it is used for roofing for virtually all the island's buildings, and for the shutters which cover the window openings in the walls of houses, as well as being an occasional food source. Small sago swamps occur in the coastal reaches of virtually all the streams on the western side of the island.

In the Environmental Plan for the proposed Lihir Gold Project (NSR in prep.), attention was drawn to the importance of sago swamps to the Lihir economy, and the impact of the proposed mine on sago swamps was assessed. As most of the sago swamps are on the western side of the island, the proposed mine will in fact have little effect on sago resources. A 1 m rise in sea level however will have the effect of destroying both the present sago swamps on the western side of the island, and the road which allows access to this resource, and between villages. Undoubtedly the presence of sago swamps on the western side of the island is largely due to the fact that that side of the island is submerging. A rising sea level will re-inforce this effect, and will, initially at least, facilitate the extension inland of some sago swamps. This will affect access however, and will necessitate reconsideration of ownership of sago stands. More importantly, the area of sago will diminish if the rise in sea level combined with the continued gradual tectonic tilting of the island forces the coastline up against the steep hillslopes which rise to the island's drainage divide.

As on Misima, the absolute effect of a 1 m rise in sea level will be small in terms of land lost, but in relative terms the economic effects on Lihir will be greater than on the mainland or the large islands of Papua New Guinea.

SUMMARY OF EFFECTS

It can be seen from the examples of Kiriwina, Misima and Lihir Islands that the effects of a 1 m rise in sea level would have severe economic, if not land pressure effects on raised coral and small high islands in Papua New Guinea. Detailed assessment of land losses require fieldwork, as does a definitive assessment of the effect on fresh groundwater sources. It is clear however from this preliminary study that although prior warning and the consequent careful planning of the siting roads and other infrastructure may alleviate some of the direct costs of a rise in sea level, the inevitable proportional loss of land and specific resources will be severe on these small islands.

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# THE IMPACTS OF SEA LEVEL RISE ON A LOW-LYING COASTAL LANDSCAPE IN PAPUA NEW GUINEA: A CASE STUDY FROM THE GULF OF PAPUA

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## INTRODUCTION

In the first report by the ASPEI task team a number of major impacts expected to result from any rise in sea level were identified, including: coastal inundation, coastal flooding, changes to coastal geomorphology, saline intrusion, water table elevation, and compression of the marine/terrestrial transition. Such impacts are expected to be particularly severe in areas where the coastline profile is flat or gently sloping. Some land types would be more severely affected than others, including deltaic floodplains and sand barrier and lagoon landform complexes.

In Papua New Guinea the Gulf of Papua is one area where these conditions apply extensively and where the impact of sea level rise is expected to be particularly severe (see for example Bualia & Sullivan, this volume; Pernetta & Osborne, this volume). This case study presents the findings of an investigation of the likely impacts of sea level rise on a 70 km long, low-lying stretch of coastline in Gulf Province extending from Kerema in the east to near the mouth of the Purari River in the west (Figure 1).

Data concerning the biophysical, social and economic setting of the study area were taken primarily from the PNG Resource Information System (PNGRIS) prepared by CSIRO/DPI (1987) and the earlier CSIRO Land Systems Report for the Kerema-Vailala area (Ruxton *et al.*, 1969). The study area is covered by several CSIRO/DPI Resource Mapping units (RMUs), and five of these (RMUs 91, 135, 138, 139 and 267), which were representative of the range of biophysical, social and economic settings (Figure 2), were chosen for more detailed investigation (Bualia, 1989).

Six days were spent in the field in the study area, during which time observations were made of a wide range of landform types and their associated settlement and land use patterns. Villagers were interviewed about their resource use activities, and any changes which have occurred in the position of the shoreline in the recent historical past. In a number of places profiles across beach ridges were surveyed, from the low water mark to the back swamps inland.

Back in Port Moresby the probable position of the new shoreline following a 1 m rise in sea level was plotted on the 1:100,000 topographic sheets and the amounts of land that would be lost by inundation were estimated. The likely biophysical, social and economic impacts of such a rise in sea level were also considered.

## ENVIRONMENTAL SETTING

### Biophysical environment

Figure 2 summarises some of the physical features of the study area that are discussed briefly below. The main features shown are landform, vegetation, soils and present/potential landuse. This cross-section is for the coastal plain environment.

#### Geomorphology

The study area is part of the vast plain found in this part of the country. It is difficult to determine precise altitudes above sea level from the 1:100 000 topographic maps because the contour interval is 40 m. There are, however, several spot heights within the study area, none of which exceeds 10 m.

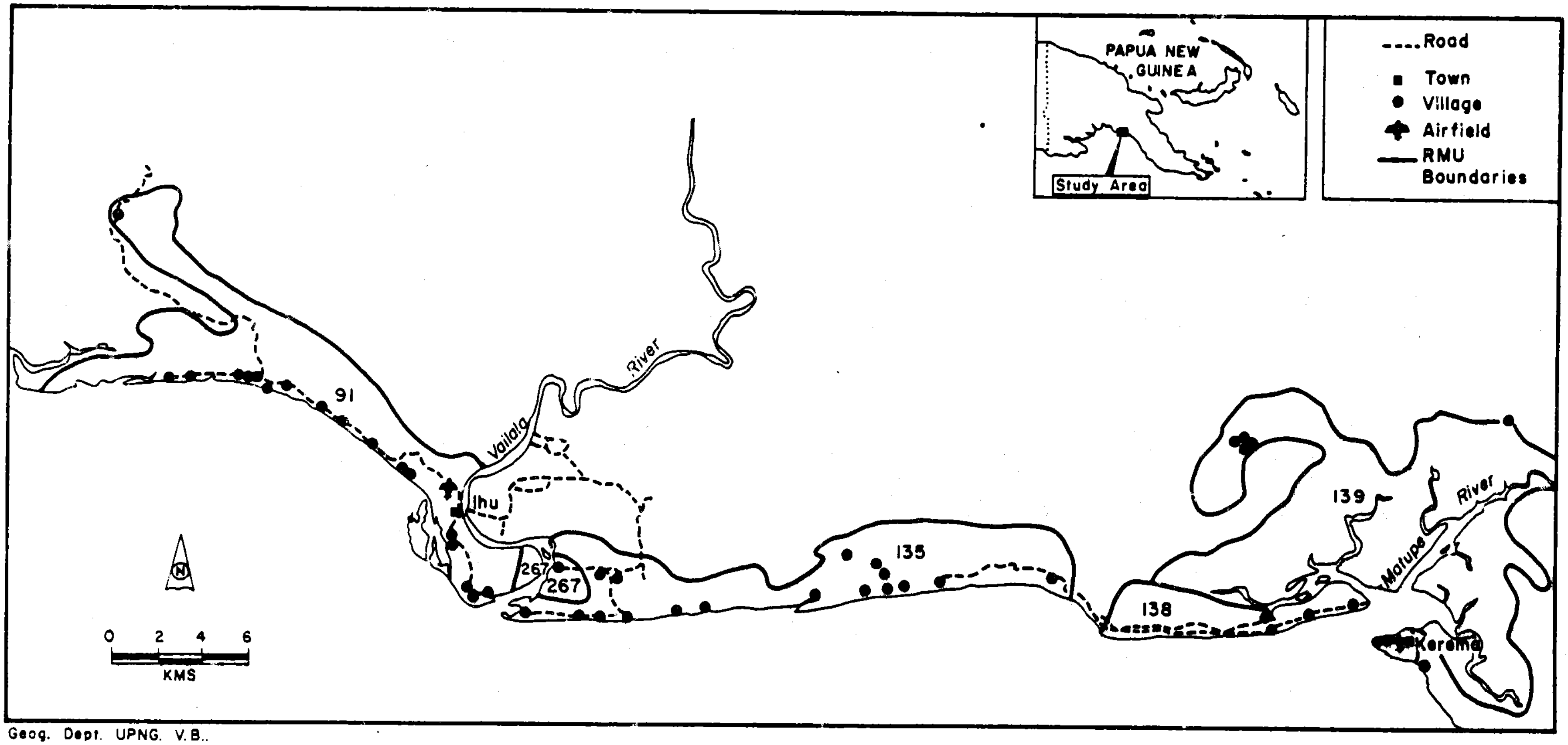
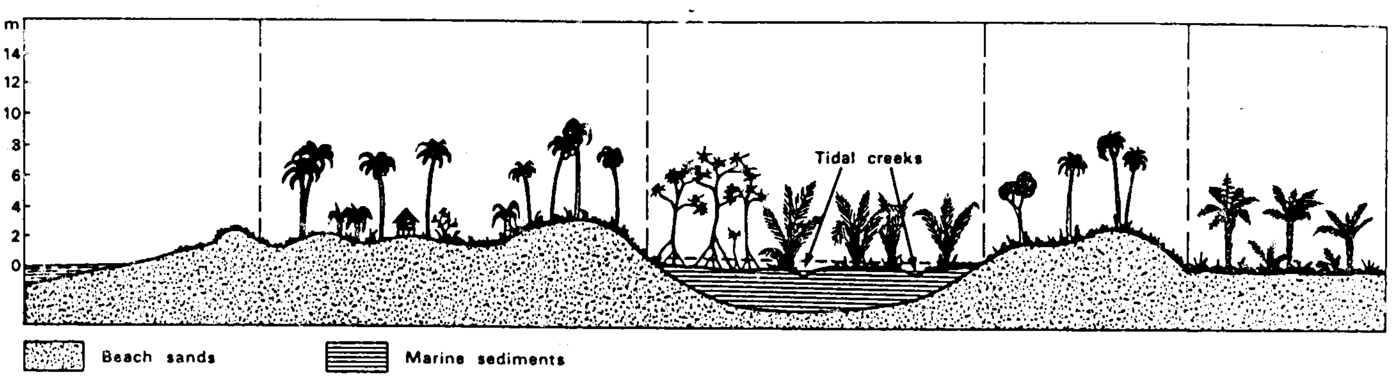



Figure 1. The study area showing the location of the RMUs and villages

| | | | | | |
|---|---|---|---|---|---|
| Landform | Present beach & active beach ridge | Present stable beach ridge | Tidal flat | Inland beach ridge | Swale |
| Vegetation | Bare & colonising vegetation | Coconut groves & gardens | Nypa palms; near coast mangroves | Coconut groves | Sedge, grassland & sago |




| | | | | | |
|---|---|---|---|---|---|
| Soils | Well-drained sandy soils formed by wave & wind action. On beach ridges have weakly developed A1 horizons; alkaline to weakly acid | | Swampy soils, often with interbedded thin peat layers. Strongly gleyed | As for stable beach ridges | Very poorly drained to swampy sandy soils |
| Land use | Unsuited for agriculture | Mainly suited for coconuts. Low fertility somewhat limits arable cropping. Used for gardening & coconut groves | Unsuited for agriculture Used for gathering resources & timber sources | As for stable beach ridges | Unsuited for agriculture. Used for sago processing |

Figure 2. Schematic cross-section through a coastal plain, Gulf Province (after Bleeker 1983: Fig. 3.2)

All CSIRO/DPI RMUs are described as having a relief of less than 10 m, and none of the area is more than about 10 m, and most of it is less than 2 m above sea level.

The major landform types in the study area are beach ridge complexes and beach plains, mangrove swamps and associated tidal flats, and freshwater, non-tidal swamps. Table 1, which was derived from Ruxton's (1969) geomorphological map for the Kerema-Vailala area, shows the landform composition type, and area of each, by each RMU.

Table 1. Landform composition, and areas of each type (km2), by RMU.

| RMU No. | Area of RMU (sq.km.) | Landform composition. (type & area [sq.km]) | | | |
|---|---|---|---|---|---|
| | | Beach ridge & beach plains | Brackish & salt water tidal flats | Fresh water tidal swamps | Fresh water non-tidal swamps |
| 139 | 103 | 3 | 70 | -- | 30 |
| 91 | 56 | 53 | -- | 3 | -- |
| 138 | 13 | 7.5 | -- | 5 | 0.5 |
| 267 | 6 | -- | -- | 6 | -- |
| 135 | 44 | 42 | -- | 2 | 1 |
| Total | 222 | 105.5 | 70 | 15 | 31.5 |

The beach ridge complexes are long, parallel sand ridges (both active and stable under current conditions) and swales, with local relief of up to 2 m high, but gradually decreasing inland to form a level or gently undulating plain. Most of the sand here is marine in origin. The swales are generally swamps, with tidal creeks and standing water. The level to gently undulating beach plain has extremely low relief, and slopes are of less than one degree.

The mangrove swamps and associated tidal flats occur mainly at the river mouths, especially those of the Matupe River (RMU 139) and the Vailala River (RMU 267). The tidal flats are subject to daily salt and brackish water inundation. The fresh water swamps have formed on former tidal flats, built up of estuarine deposits which comprise lagoonal mud, silt and local peat.

The beaches are prograding slightly, especially at the western end of the study area, as a direct result of the supply of sediments from rivers entering the Gulf of Papua and transported by longshore drift. The absence of high energy wave impact on the coast has also enhanced the prograding of the beach. One important factor which is perhaps important in determining the wave environment in the area is the presence of rather shallow waters. This means that the point at which waves break is a fair distance offshore and thus there is little direct impact of breaking waves on the coastline.

Climate

The area experiences high rainfall in the period between the months of May-August. The mean annual rainfall is about 3,500-4,000 mm. Soil moisture storage is rarely depleted below two thirds of the maximum capacity and the annual water surplus stands between 1,000 and 3,000 mm per year. The level of monthly rainfall is heavy (wet) and all months have more than 200 mm. The maximum and minimum temperatures experienced in the study area are 32-30°C and 23-19°C respectively.

Vegetation

The vegetation on the coast reflects to a large extent the present inundation status of the area, which is defined as the extent of the area subject to inundation within the RMU, expressed as a percentage of the total area of the RMU.

In the study area current information extracted from the PNGRIS (1987) shows that, as expected, more than 80% of the area designated as mangrove swamp is affected by tidal flooding. For beach ridge complexes and beach plains, less than 20% of the area is affected by long-term inundation. Such inundation may last for periods of up to 4 to 6 months, but water levels are generally shallow (less than 0.25 m) and the area is subject to drying out for short periods. Inundation is usually restricted to the wet season, but areas with high dry season rainfall may also be affected at that time.

Three dominant vegetation types are found in the study area: terrestrial forest, swamp vegetation and mangrove forest. The first type is medium crowned forest on plains and fans, and where there are well to imperfectly drained, deep soils that are either not flooded or flooded infrequently or for short periods only. The water table remains well below the surface most of the year, and pools of water may form during heavy rains and remain for several days. Littoral forest is confined to the coastal sandy beach ridges and more or less permanently swampy swales. Generally these forests are well-drained but parts are inundated in the wet season due to lack of surface runoff. The permanent swampy swales have floating and submerged water plants in their deepest parts, and swamp grasses, reeds, sago palm, pandans and swamp woodland in progressively shallower water. Mangrove forest, the third vegetation type, is restricted to river mouths where large quantities of fine sediment are deposited and the areas are subject to tidal flooding.

Soils

The PNGRIS has provided detailed information of the types of soils found in the area. Basically, most of the soils are either poorly drained or permanently saturated. They are also undifferentiated in profile. Fine textured soils are restricted to tidal estuaries and swamps, while the sandy textured soils are predominant in the coastal beach ridges and beach plains.

Socio-economic environment

Settlement pattern

Field observations in this study of the settlement pattern, confirm that reported by McAlpine (1969). Two distinct types of settlements are found in the study area, both of which are directly related to land-use and landform associations. On the littoral and alluvial plains settlement is nucleated, particularly on the coastal beach ridges where villages are by PNG standards, relatively large. Villages are usually situated on the first stable beach ridge near the sea (Figures 1 & 2).

Where villages are situated in the riverine alluvial areas they are built on levees; where they are situated in the deltaic alluvial areas, they are raised on stilts along the tidal channels. Village settlements in the alluvial environment are considerably more scattered than those of the coastal beach ridges. Where the beach ridge environment extends furthest inland village clustering increases, and this is probably a direct result of a greater area of suitable land being available for subsistence cropping. Conversely, where the beach environment is narrowest villages tend to be of equal size, of smaller than average population size, and evenly distributed along the coast rather than clustered.

Population, land and resource use

In 1980 the total population of the five RMUs in the study area was about 7,413, occupying an area of some 222 $km^2$ The distribution of this population is such that RMU 91 has the highest (3,235) followed by RMU 135 (2,432), RMU 138 (886), RMU 139 (738) and RMU 267 (122).

Land use in the two most populated areas is such that RMU 91, 39 $km^2$ has low to very low land use intensity. In RMU 135, 5 $km^2$ of the area is subject to very high land use intensity with tree crops, particularly coconut plantations, while 13 $km^2$ has very low landuse intensity and 26 $km^2$ remained unused. On the whole there seems to be a generally low intensity land use in the area. It is worth noting that of the 222 $km^2$ of land in the study area,as a whole 68% or 152 $km^2$ is virtually unused land. This is due to poor drainage of the soil as evident when we look at the inundation extent which is more than 80% in RMUs 139 and 267. In the other three RMUs, less than 20% of the land is subject to permanent or frequent inundation by flood waters.

A proportionately high percentage (72%) of the population in the five RMUs is engaged in food crop production, both for their own consumption and for selling locally if there is a surplus. They grow a great variety of food crops such as banana, taro, yam, pawpaw, cassava, sugarcane, corn and greens such aibika. Other tree crops planted or husbanded are sago which is the staple food, and breadfruit. They also grow a lot of betelnut. Gardening is done on a shifting cultivation basis, the fallow period ranging from 1-2 years. The villagers rarely garden close to where they stay. Informants interviewed in the coastal villages of Petoi, Mei 1 & 2, and Uaripi, 3-5 km west of Kerema (Figure 1) all said they lay claim to garden land (and therefore their customary land as well) up in the head waters of the Matupe River. The Siviri and Karaeta villages, close to Kerema town, also have land in this area. People travel up the river to garden and may on occasions stay for a couple of days in their gardens before returning to their villages.

Fishing

This is almost a daily activity, weather permitting. A large proportion of the population (71%) is engaged in it. Fishing is carried out also in the lagoon. The villagers fish particularly for their own consumption and only sell when there is a surplus. Crabs and fish in the tidal flats also provide an important food source.

Sago

This is the staple food for the villagers, and the palm is grown both in the beach ridge complexes and swales and also in the swamps. Not only does sago palm provide an important food source, but the people also use the leaves and the trunk for building houses. Mangrove is another important building material.

Water

Rain water is the major source of fresh water for the villagers. Some of the villagers have roof runoff tanks. During the dry season, they get it from streams. At Araimiri Vocational School (15 km west of Kerema) and Siviri village, ground water extraction by hand pumps was noted. The water table in the area, and in fact the whole deltaic floodplain in the Gulf and Western Provinces, is high - probably less than 2 m below the surface. This source of water is brackish and thus unfit for drinking.

Other economic activities

The following is a summary of other economic activities carried out by the villagers. The main cash crop in the area is coconut. Figures from the PNGRIS indicate that 72% of the population are engaged in copra production. About 22% rear pigs, 21% grow spices, 6% grow coffee, 2.4% are into cattle business, 2.1% grow rubber and 0.12% grow cocoa.

## THE IMPACTS OF SEA LEVEL RISE

The possible physical consequences, and thus environmental impacts resulting from a rise in sea level, can be considered, according to Titus *et al.* (1984), under three categories; shoreline retreat, temporary flooding and salt intrusion. Perhaps the most serious environmental consequence in the Gulf Province would be the inundation, and in places erosion, of thousands of square kilometres of swamps and other wetlands.

Sea level rise causes shorelines to retreat both because land lying below future sea level will be permanently inundated and because erosion of the nearby land will increase. According to Titus *et al.* (1984), the particular method appropriate for estimating shoreline retreat at given points on the coastline depends upon topography, beach composition, wave climate, sediment supply and available historical data.

Modelling the effects of sea level rise

With respect to retreating or eroding shorelines, there are several different shoreline response concepts that can be used to model the resulting shoreline configuration as a function of sea level rise (Kana *et al.*, 1984). The simplest to quantify is the inundation concept, whereby pre-existing contours above shorelines are used to project new shorelines. Here, slope is the controlling factor, such that shorelines with steep slopes will experience little horizontal displacement of the shore. Gently sloping shorelines will experience much broader area of inundation. The inundation concept, in fact, is the preferred methodology to apply for immobile substrat or rocky or armoured shorelines, or where the shoreline is exposed to active wave action or strong currents.

According to Kana *et al.* (1984), the analysis becomes more complicated when dealing with mobile sediments such as sand-sized material along beaches. In such situations, Kana *et al.* (1984) used the Bruun's (1962) model to predict shoreline profile adjustment to a change in water elevation. The model hypothesised that a typical concave-upward profile in the nearshore zone will maintain its configuration, but the profile will be translated landward and upward as sediments erode near the old water level and settle in deeper water offshore as the shoreline encroaches landward.

From my knowledge of the study area, I have been able to present here some first approximations of the manner in which shoreline will retreat and also impacts that are likely to be experienced some kilometres inland from the coast.

Permanent inundation

As far as shoreline retreat is concerned, permanent inundation of land resulting from sea level rise is perhaps the easiest to quantify according to Kana *et al.* (1984). This is because the approach employed here utilises the known contour lines on the map to project the the extent of inundation. It can also be taken as a first approximation of the likely 'new' coastline. This is without consideration of the contribution of coastline erosion which is very important in shoreline retreat.

On the basis of the interpolated 1 m contour line (Figure 3) re-drawn from the 1:100 000 topographic base map of Papua New Guinea, the land areas that are likely to be lost due to permanent inundation when sea level rise by 1 m, have been calculated for the relevant RMUs are as follows: RMU 91, 8 $km^2$; RMU 135, 8 $km^2$; RMU 138, 3 $km^2$

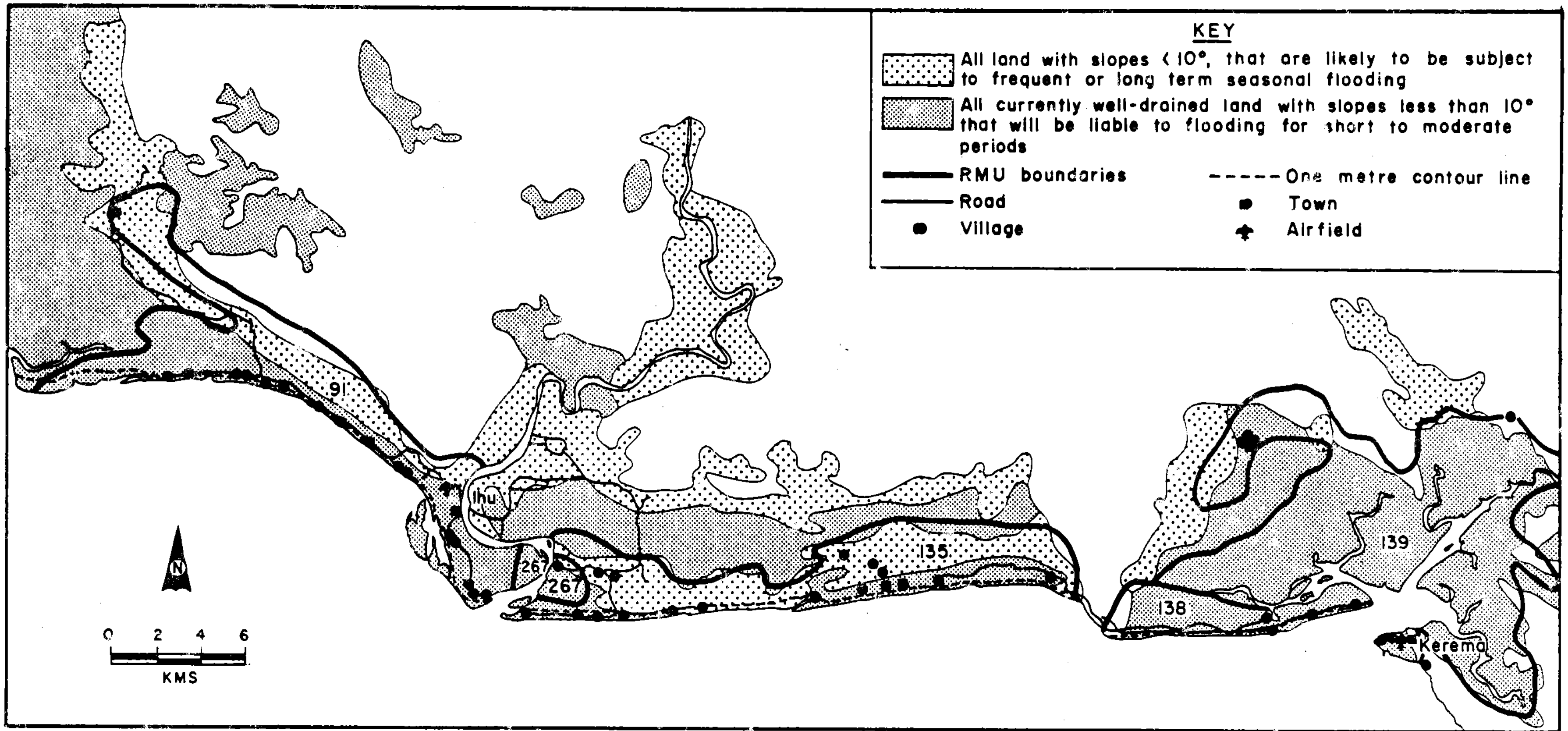
In these circumstances, a total of 27 villages might have to be partially or totally relocated, as these are within the area designated as that expected to be inundated by a 1 m rise in sea level. Most of the settlements are on the first vegetated stable beach ridge adjacent to the sea

Coastal erosion

Increased coastal erosion will come about as the elevated sea level will continue to erode back the coastline to maintain the beach profile. Theoretically, aftera new equilibrium is achieved, erosion may slow down to its normal rate. To make sensible estimates of the magnitude of this problem, knowledge of the physical controlling factors mentioned above are again vital.

The most important element to consider here is the beach profile. This consideration is needed to see how the elevated sea level will affect the beach both in plan and form, as sediments are eroded, transported and deposited at rates that were perhaps never experienced before on the coast. The results from the beach profile survey at several locations along the coast showed that there is great consistency in slope angles. This is such that from the high water mark (HWM) to the low water mark (LWM), the slope was 4 degrees, and from the high water mark to the back of the present active beach ridge, the slope was 2 degrees. From the data obtained, a general beach profile for the study area was drawn (Figure 4).

What is expected to happen to the beach profile is that, after a sea level rise, the beach profile that existed prior to the rise will be restored (but its location will be further inland) through wave action eroding away the upper part of the beach and depositing the material at the bottom of offshore waters. These effects could be counter-balanced if there is increased sediment supply to the coast (especially




Geog. Dept. UPNG. V.B.

Figure 3. The likely increase in extent of flooding following sea level rise in the study area

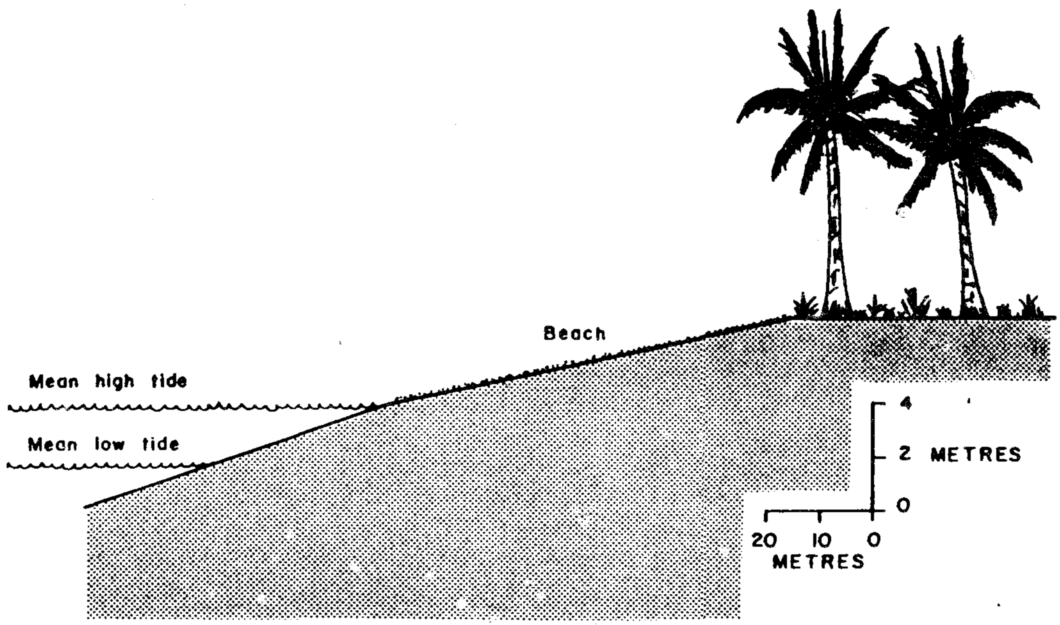



Figure 4. A generalised beach profile for the study area.

from the Purari River). However this is unlikely to occur and any such effects are likely to influence only the western end of the study area.

Incidence of floods

Flooding, other than that associated with tides, is a common problem in the area especially during the wet season when rivers overflow their banks. Wet season flood levels may reach up to 0.8 m above the ground level as shown in Figure 5. This results in the inundation of vast areas of the fresh water environment, including the margins of the hilly terrain.

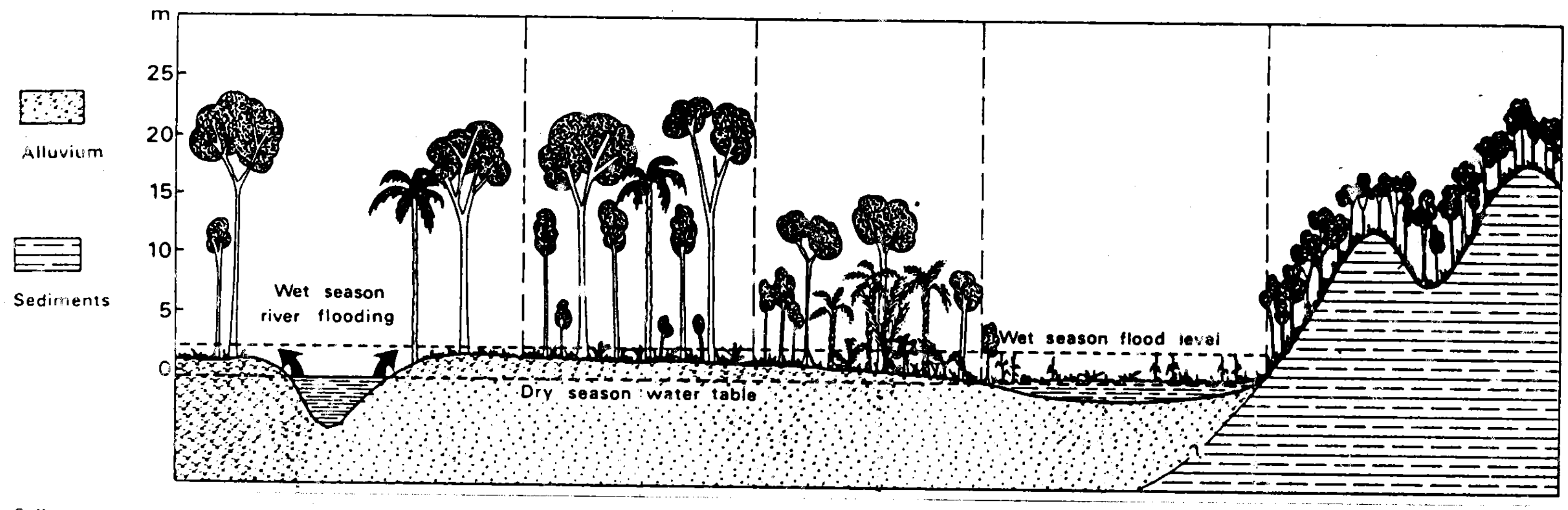
Tidal flooding is a problem that is frequently being experienced by the villagers. This problem is likely to exacerbated in the event of sea level rise. The tidal range in the study area, like all coastal areas in the Gulf/Western Provinces, is around 2 m. This particularly high tidal range has always been a problem to the coastal villages and infrastructural developments, e.g. the maintenance of the only unsealed road going through the study area. The adaptation of villagers to this problem in as far as housing is concerned is the use of stilts to raise the house floors above the upper tidal limit.

A 1 m rise in sea level will raise the already rather high local water table and is likely to then increase the area impacted by floods. The predicted increase in rainfall will also play a major role in the severity and duration of floods. Overbank flooding is also likely to increase in the initial stages as channels adjust their banks and beds to cope with increases in the volume of water.

The impact here will be the extension of the flood-prone areas which will in turn have adverse effects on the resource base for the local population, e.g. further reduction in the areas currently used for gardening due to poor drainage of the soil.

Figure 3 shows the magnitude of this problem. This map was re-drawn from Paijmans (1969, map entitled Access Category) the original map shows the inundation and flood regime of the different land systems. It is envisaged that after the sea level rise, the areas recognised by Paijmans (1969) as prone to long-term flooding will extend to include those that experience temporary flooding. The currently well-drained areas are expected then to be prone to temporary flooding.

| | Levee & river | Floodplain | Backplain | Back swamp | Hills (on hard rock) |
|---|---|---|---|---|---|
| Landform | Levee & river | Floodplain | Backplain | Back swamp | Hills (on hard rock) |
| Vegetation | Tall, rather open alluvial forest | | Poor alluvial forest, sago & rattan common, dense undergrowth | Herbaceous or phragmites swamps | Lowland hill forest |




| | Levee & river / Floodplain | Backplain | Back swamp | Hills (on hard rock) |
|---|---|---|---|---|
| Soils | Well to imperfectly drained alluvial soils. Textures mainly silty to fine sandy. Weakly acid to neutral. Commonly thin, weakly developed A1 horizon. Occasional wet season flooding for short periods | Poorly to very poorly drained alluvial soils, weakly acid to neutral. | Swampy alluvial or peat soils, usually waterlogged. Fine textured with interbedded peats. | Well drained slightly to moderately weathered soils. |
| Land use | Well suited for arable cropping where subject to short flooding only. Also tree crops. At present occasionally used for gardening, hunting & fishing. | Used mainly for sago processing, hunting & gathering | No present land use | Generally suitable for tree crops and some arable crops. Now used for occasional gardening, hunting & gathering. |

Figure 5. Schematic cross-section through freshwater environment to hilly terrain (after Bleeker 1983: Fig. 3.4)

Table 2 below shows firstly the current situation in terms of the areas (sq.km) that experience flooding of various durations, and secondly what the likely situation will be after sea level rise, which will extend the respective flood-prone areas. The increase in the areas prone to floods of varying duration extends beyond the boundaries of the RMUs as can be seen from Figure 3. The likely impacts are envisaged to be widespread.

Table 2. Present and projected flooding conditions (areas in $km^2$)

| | Present conditions | | | Projected conditions | |
|---|---|---|---|---|---|
| RMU No. | Long-term flooding | Short to moderate term flooding | Well-drained | Long-term flooding | Short to moderate term flooding |
| 139 | 98 | 5 | 3 | 103 | 3 |
| 138 | 7.5 | 5.5 | -- | 13 | -- |
| 267 | 6 | -- | -- | 6 | -- |
| 91 | 23 | 25 | 8 | 48 | 8 |
| 135 | 15 | 9 | 24 | 24 | 24 |
| Total | 149 | 44.5 | 35 | 184 | 35 |

Salt water intrusion

Salt water intrusion resulting from sea level rise will affect water resources both on the surface and in aquifers (Titus *et al.*, 1984). In this study area the problem is likely to manifest itself in the manner described below. In the brackish and salt water tidal flats, particularly RMU 91, extension of this environment type is likely to occur as salt water intrudes surface channels and underground reservoirs. My own estimate, based on Table 1, is that this brackish environment, which currently covers 70 $km^2$, may increase in area, thus including parts or all of the adjoining 30 $km^2$ of fresh water, non-tidal swamp environment.

In the beach ridge complexes and beach plains of the other RMUs, the intrusion of salt water into aquifers will result in the water source becoming brackish. This will affect particularly people that rely to some extent on ground water for fresh water supplies..

## ENVIRONMENTAL IMPACTS: A SUMMARY

The environmental impacts which are likely to result from the anticipated sea level rise, are related to the physical consequences of shoreline retreat, increased flooding, and salt water intrusion discussed above. The sorts of anticipated impacts that will be felt by the local population are summarised below.

Water resources

Salt water intrusion will severely affect the water resources of the local people, especially their surface water supplies. A lot of the local people get their water supply from streams and also from rainfall, which is stored in drums.

Ground water is an under-utilised resource and field observation showed only two cases, both on beach ridge landform, where ground water was actually used; at Araimiri Vocational School and at Siviri Village close to town. The water extracted here is usually brackish and is used therefore only for washing.

Any problems with the water resources in the area are likely to be mitigated to some extent by the predicted increase in rainfall for the area.

Loss of land

The loss of land is perhaps the most important environmental impact that will be faced by the people. This will result from coastal erosion and retreating shoreline, increased flooding and the intrusion of saltwater, changing the salinity and alkalinity of the soil and thus rendering land now used for growing food and cash crops unsuitable for cultivation. The problem will manifest itself in the manner described below.

Settlement

On the basis of the interpolated 1 m contour line, (Figure 3), the first arbitrary mark of any likely future coastline, a total of 17 villages with a total population of 3,240 are within the boundaries of the area which will be subject to partial or total inundation from a 1 m rise in sea level.

Taking into consideration frequent and long-term flooding, together with the problem of coastal erosion that will to a greater or lesser extent dictate the new coastline, another 26 villages with a total population of 3,312 people will be affected.

Given the above situation, we are looking at a population of about 6,500 people, many of whom will have to vacate their current settlement areas and establish themselves else where, particularly on higher ground which is a fair distance inland. In RMUs 91 and 135, people may still be able to settle in the areas designated as subject to moderate and short-term flooding, building their houses on stilts to raise the house floors above the upper tidal limit. From the limited available information regarding customary land ownership in the RMUs, it is highly likely that relatively few of the local people will still actually be residing on their own land after the sea level rise.

Agricultural land

Productive land totals just about 70 $km^2$ in the five RMUs, or 32% of the entire area. The rest of the RMUs are marginal in that they are poorly drained and are subject to occasional flooding. This makes it difficult for the local population to put the land into productive use.

Gardening is a major everyday activity and is mainly done on the present stable beach ridges and also on inland beach ridges. In the event of a sea level rise, total inundation, increase flooding and salt water intrusion are likely to reduce the available agricultural land. People may still be able to garden in the areas designated as short-moderate term flooding areas, particularly in RMUs 91 and 135. But there will of course be the problem again of conflicting land-use, i.e., that between settlement and gardening.

People will also face the problem of shortage of suitable land to grow other cash crops, eg., coffee, tea, rubber, cocoa, spices and coconut. Most small holder coconut plantations are within the area highly vulnerable to the impacts of sea level rise. A considerable loss in monetary terms is anticipated for this economic activity which is very important to the villagers.

Infrastructure

There is not much in the way of infrastructural developments in the study area that will be likely to be impacted. The only unsealed road which runs through the study area, will almost certainly be rendered unusable as a result of total inundation at several points, and also from coastline erosion and long-term flooding as can be seen from Figures 1 & 3. Relocating the road some distance inland will still pose problems with impacts resulting from short-moderate term floods.

Kerema town is mainly on a series of hard rock ridges about 20 m above sea level. The airport however, which is built on the coastal plain at an elevation of about 1.5 m above sea level, is likely to be subject to more frequent and long-term flooding, which will make it less serviceable. Coastal erosion during the rainy periods and rough seas between the months of May-August is already causing damage to the airport, particularly at the Ipisi Point.

Food resources

The anticipated sea level rise will have implications on both the land and marine based food resources.

Land-based

Sago is the staple food, providing about 75% of the dietary carbohydrate of the local villages. The palm also provides provides building material for houses. The extension of the brackish and tidal swamps to include parts or all of the fresh water swamps (Figures 2 & 5) will mean the loss of huge stands of sago, particularly in RMU 139. There is likely to be a compression of the low salinity environment for growing sago to against the hilly terrains.

For land-based food resources, the reduction in agricultural land will simply mean a reduction in food production. Increased intensity of land use is likely to exacerbate this problem as land is degraded to a stage that the soil fertility declines. Other problems that may be expected to result from this will be a drop in the nutritional status of the local population.

Marine-based

Marine resources are anticipated to be enhanced as well as adversely affected.

Fishing, like gardening, is an everyday activity, weather permitting. Without proper knowledge of the marine resources found in the offshore waters, I can only make a general statement here regarding this activity. Fishing is done both in the lagoon and out in the open sea. In the event of a sea level rise, coastal erosion and subsequent deposition of sediments at the bottom of the rather shallow off-shore waters is expected. This is likely to have some implications on the marine resources, especially fish, in the zone (within 2 km offshore) where most of the fishing is carried out.

Molluscs and crabs which thrive in the tidal flats may actually be enhanced with the extension of the brackish and salt water tidal areas. With this, the mangrove environment, particularly at RMU 139 is likely to extend inland, the extent to which this may occur is not certain, but a decrease in the extent of this habitat may adversely affect prawn resources in the Gulf of Papua.

## SUMMARY

It can be seen from the case study that the effects of a rising sea level will be most profound for those villagers who are now occupying the depositional landforms just above sea level and not backed by rising land. It is worth noting that these are generally favoured areas of occupation, since such localities provide good access to the fishing zones as well as to gardening land.

The overall impacts of sea level can also be evaluated in economic and provincial/political terms. This already disadvantaged province, in terms of economic development and the provision of essential services to the people, may be placed in an even worse situation.

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# THE EFFECTS OF SEA LEVEL CHANGE ON PORT MORESBY AND LAE URBAN AREAS, PAPUA NEW GUINEA

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## BACKGROUND

In terms of social and direct infrastructural costs the effects of a sea level rise will be relatively greater in highly populated and developed urban areas than in rural areas. An assessment has been made of the likely impacts of projected sea level rises on the two major cities in Papua New Guinea, Port Moresby, the capital city, on an erosional section of the south coast, and Lae, near the mouth of the Markham River on the north coast.

## STUDY METHOD

Draft copies of topographic maps of both Port Moresby and Lae city areas are available at a scale of 1:2,000. These maps are drawn with a surveyed contour interval of 2 m, but with some irregularly interpolated contour lines at closer intervals where such data are available. Buildings and roads which existed in Port Moresby in 1977 are included on the maps of that city, and for Lae these details are up to date to 1984.

These maps were used as the basis for the estimation of the likely impact of various projected sea level rises. Contour lines at 0.5, 1.0, 1.5 and 2.0 m were drawn onto the 1:2,000 sheets, and new coastlines produced for a sea level rise of those magnitudes. These are presented in Figures 1 and 2.

The areas of urban land which would be inundated or rendered useless, the lengths of made roads, and numbers of the buildings which would be affected by each projected sea level rise were noted. These results are summarised below.

Since 1977 there has been considerable urban growth in the foreshore zone of Port Moresby. A comparison of 1987 airphotos of sample areas near Hanuabada, Ela Beach and Koki Village with the 1977 maps indicate that the number of both formal and informal buildings in the study area had increased by about 10%. Accordingly the numbers obtained from counting all buildings on the 1977 map were increased by 10%. In the case of Lae the 1984 data are used as the increase in the number of buildings in the intervening period is likely to have been small.

The population estimates for both cities are based on an average of seven occupants for a formal dwelling, and 10 occupants for an informal dwelling (King & Devi, 1986). It should be stressed that these population figures are crudely determined and thus are rough approximations.

In addition to the direct physical impacts of inundation and erosion on buildings, roads and other infrastructure items such as wharves, sea walls, water supply and sewerage systems and storm water drains, there will be an increase in indirect impacts such as a progressive rise in water tables and the increasing inability of storm water drains and sewerage systems to cope with loads at high tides.

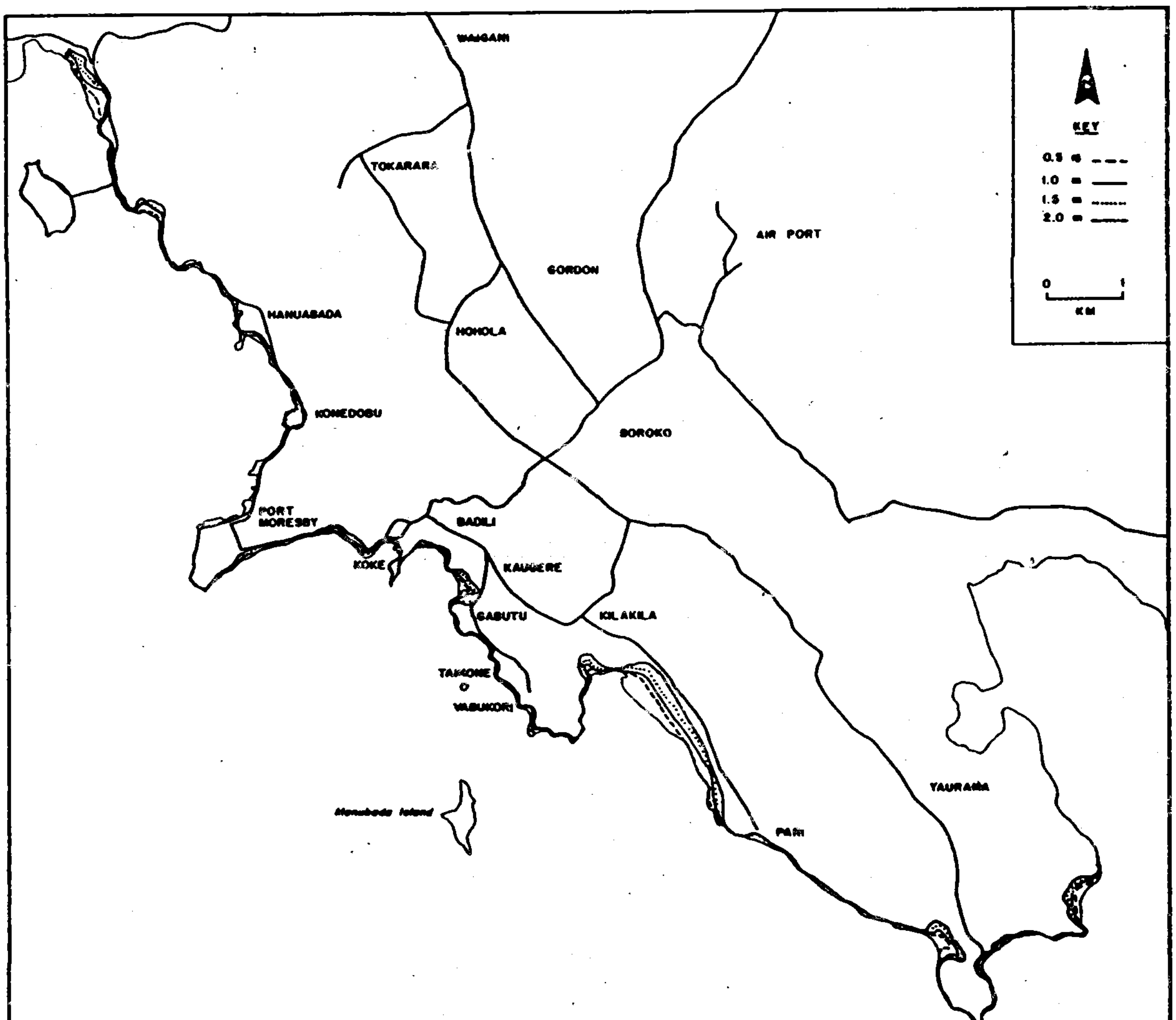


Figure 1: Port Moresby coastline showing likely zones of inundation.

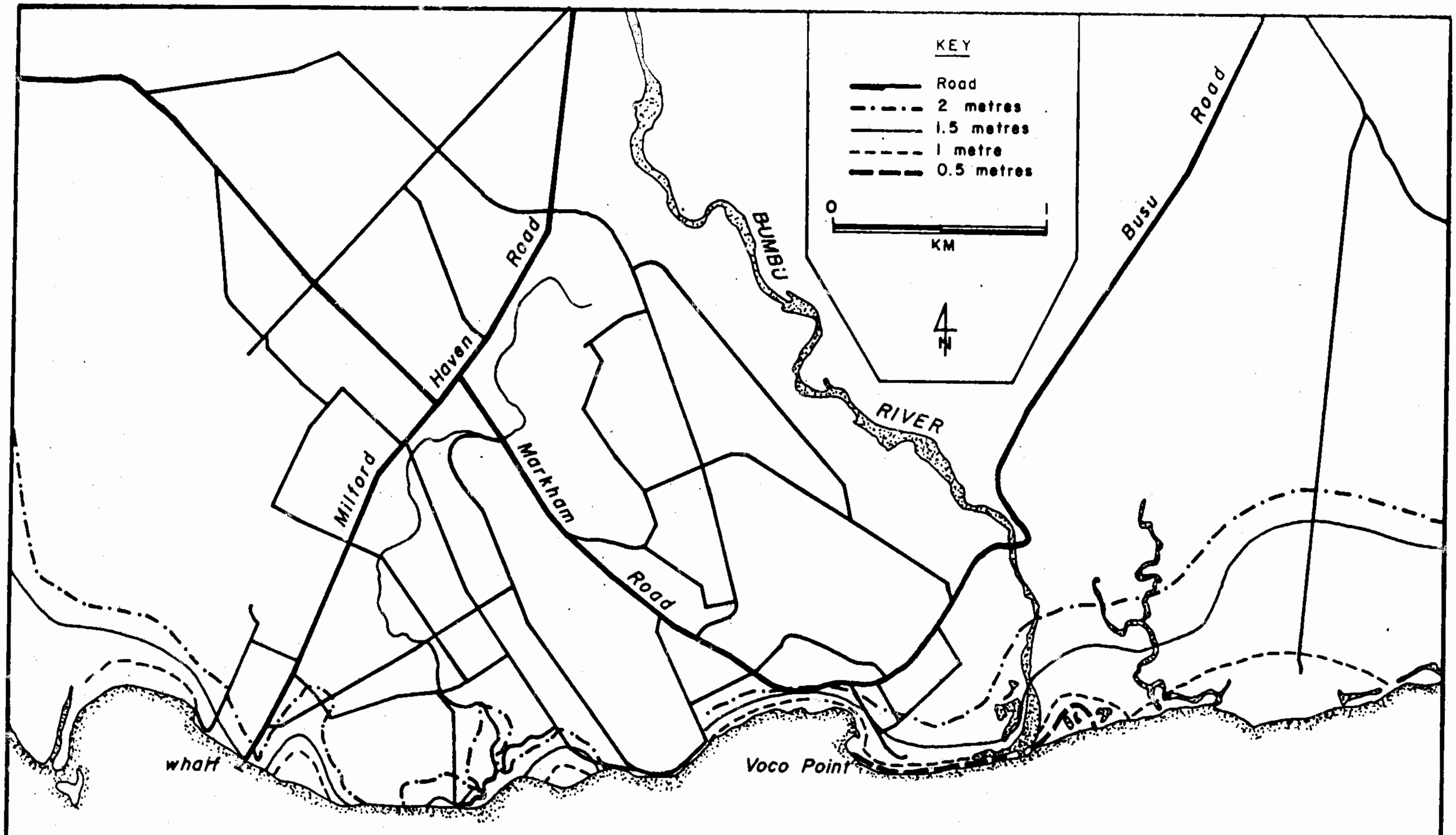


Figure 2 : Lae coastline showing likely zones of inundation.

## RESULTS

The results of this analysis are presented in Tables 1 to 3. In both cities the loss of land will be relatively small, but it will affect a large number of people living in informal housing structures - in Port Moresby about 11,000 people, many in villages built on elevated platforms over tidal flats or on the adjacent beaches, and in Lae about 2,700 people in urban squatter settlements.

Table 1. Areas of land which would be inundated by a sea level rise of 0.5, 1.0, 1.5 and 2.0 m

| Projected rise (m) | Area Inundated (ha) | Total area inundated (ha) |
|---|---|---|
| **Port Moresby** | | |
| 0.5 | 36 | 36 |
| 1.0 | 30 | 66 |
| 1.5 | 10 | 76 |
| 2.0 | 11 | 87 |
| **Lae** | | |
| 0.5 | 10 | 10 |
| 1.0 | 25 | 35 |
| 1.5 | 250 | 285 |
| 2.0 | 15 | 300 |

Table 2. Number of buildings, mainly dwellings, which would be lost at each projected level of inundation. Formal structures are those built of higher-cost commercial materials, and which have services connected such as electricity, water and sewerage. Informal structures are built of a wide variety of generally lower-cost materials, and most do not have electricity, water or sewerage connections.

| Projected rise (m) | Buildings lost (sumulative total) | | Population affected (approx. cumulative total) |
|---|---|---|---|
| | Formal | Informal | |
| **Port Moresby** | | | |
| 0.5 | 50 | 960 | 9,500 |
| 1.0 | 100 | 1,030 | 10,100 |
| 1.5 | 110 | 1,065 | 10,800 |
| 2.0 | 165 | 1,105 | 12,000 |
| **Lae** | | | |
| 0.5 | 0 | 16 | 160 |
| 1.0 | *10 | 86 | 860 |
| 1.5 | *28 | 158 | 1,580 |
| 2.0 | 72 | 270 | 3,200 |

* Mainly commercial buildings, no resident population.

Table 3. Length of formally constructed roads, both sealed and unsealed, which will be lost at each projected level of inundation.

| Projected rise () | Length of made road lost (km, cumulative total) |
|---|---|
| **Port Moresby** | |
| 0.5 | 5 (plus wharf facilities) |
| 1.0 | 10 |
| 1.5 | 15 |
| 2.0 | 20 |
| **Lae** | |
| 0.5 | 0.5 (plus wharf facilities) |
| 1.0 | 1 |
| 1.5 | 3 |
| 2.0 | 5 |

The effects would initially be less severe for people living in dwellings built out over the water, but even these would eventually be affected as the sea rose progressively higher.

No estimate has been made of the cost of the losses, but in both cities several kilometres of roads, wharf infrastructure, fuel storage tanks and about 30 commercial buildings, mainly in Lae, would be affected by these projected sea level rises.

It can be seen from these results that should sea level rise more than 1 m, the effects in both Port Moresby and Lae would have profound economic implications.

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## ACKNOWLEDGEMENTS

Much of the mapping, measuring and counting for this exercise was carried out by Geography students: Ralph Kimbu, Ricky Kaisek Kumung and Michael Wau.

# MURIK LAKES AND THE MOUTH OF THE SEPIK RIVER

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## INTRODUCTION

At the mouth of the Sepik River, the longest river in Papua New Guinea (see table in Pernetta & Osborne), there is a complex of deltaic floodplain and mangrove swamps covering about 1,160 $km^2$ (Figure 1). This area is constricted along its inland margin, about 40 km from the coast, by bedrock ranges. The study area presently supports a population of about 2,800 people.

The following brief account of the biophysical, social and economic setting is taken from CSIRO/DPI (1987). The prediction of likely impact are based on an assumed 1 m rise in sea level. The base map for Figure 1 was drawn from the 1:100,000 topographic sheets. It is impossible to determine precise altitudes above sea level from the topographic sheets as the contour interval used is 40 m. There are however several spot heights marked within the study area, and none of these exceeds 9 m. All of the CSIRO/DPI Resources Mapping Units (RMUs) are described as having a relief of <10 m. On the basis of the topographic evidence and the RMU descriptions presented below it is concluded that none of this area is more than about 10 m, and most of it is less than 2 m, above sea level.

The coastline is formed by a narrow zone of beach and beach ridge terrain backed by mangrove swamps, estuarine plains and beach ridge plains which extend inland for about 20 km. The near-coastal zone is dominated by extensive mangrove swamps which cover about 25% of the study area yet support about 70% of its resident population (especially Kaup Lagoon [RMU 374] and Murik Lagoon [RMU 280]). About 80% of this area is subject to tidal inundation and areas suitable for settlement are very limited.

Immediately behind the coastal zone is a sparsely settled plain (RMU 81), 80% of which is permanently or frequently inundated by floodwaters from the Sepik River. At the eastern end of the study area the coastline is backed by moderately well-drained beach ridges and beach plain (RMU 82) which comprises about 4% of the study area and supports about 10% of its population. Further inland again, along the Sepik River, are freshwater backswamps and alluvial plains (RMU 279) which support about 16% of the population.

The major subsistence and commercial activity is fishing in the coastal lagoons, rivers and the sea. Subsistence gardens and pig-raising provide up to 50% of the food requirements of people other than those living in the mangrove swamps. Sago, grown in freshwater swamps, is a major source of food. Copra, coffee, cocoa and rubber provide small but important sources of cash income.

## BIOPHYSICAL, SOCIAL & ECONOMIC SETTING

The following descriptions of the RMUs are taken from CSIRO/DPI (1987), Province 14, East Sepik (Tables 1 and 2). The population data are based on the 1980 census. The total population at that time was 2,345 and the average population density was 2 people/$km^2$. Assuming a rate of increase of 2.5% per annum, the national average, and that there has been no net migration, the present population of the study area is about 2,800. Economic activity refers to production for cash sale, not subsistence use.

Table 1. Physical and demographic characteristics

| RMU: | 279 | 280 | 281 | 81 | 82 | 279 |
|---|---|---|---|---|---|---|
| Area (km2): | 20 | 172 | 99 | 503 | 42 | 323 |
| Landform: | CP | MS | MS | EP | BP | BS |
| Lithology: | A | E | E | E | MS | A |
| Inundation type: | T/F | T | T/F | F | PI | PI |
| Inundation extent (%): | >80 | >80 | >80 | >80 | <20 | >80 |
| Population: | 624 | 981 | 51 | 100 | 213 | 376 |
| Pop.density (no./km2) | 31 | 5.7 | 1.9 | 0.2 | 5.1 | 1.2 |
| No. of villages: | 2 | 6 | 1 | 1 | 2 | 2 |
| No. of households: | 149 | 432 | 12 | 23 | 56 | 86 |

CP=coastal plain MS=mangrove coast EP=estuarine plain BP=beach plain BS=back swamps

A=alluvium E=estuarine deposits MS=marine sand

T=tidal flooding F=freshwater inundation PI=permanent freshwater inundation

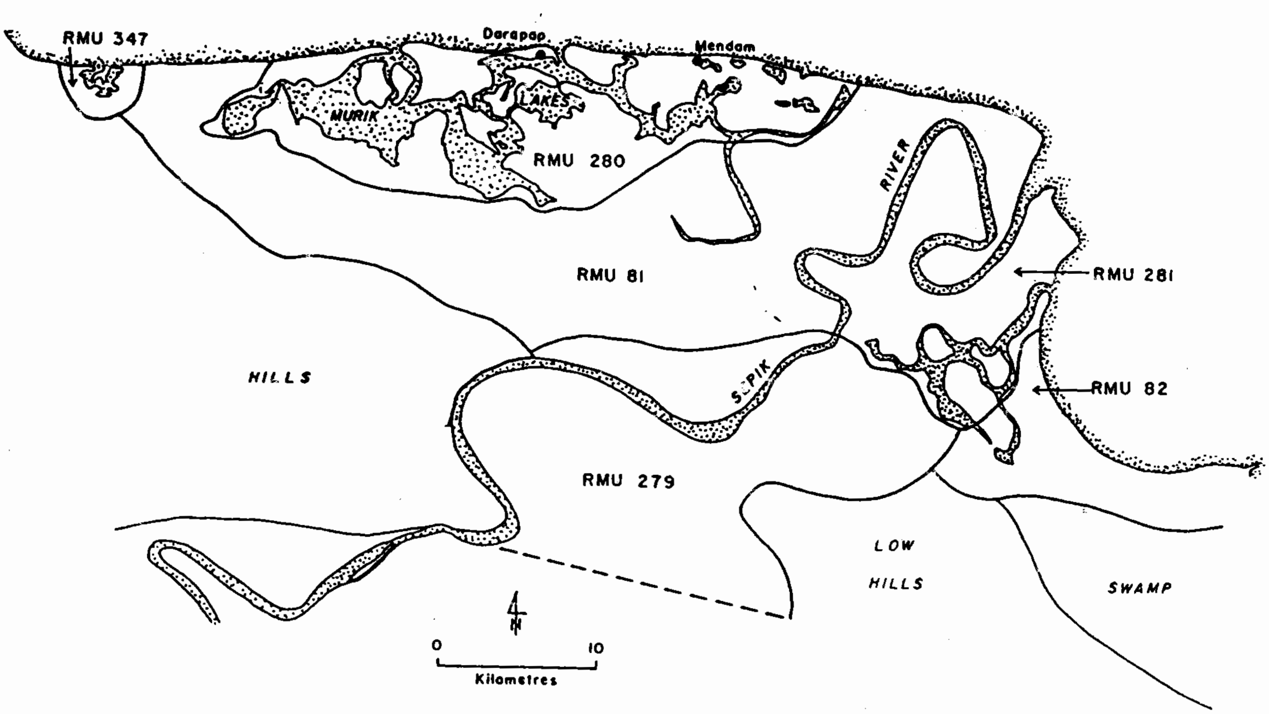


Figure 1. Murik Lakes and the mouth of the Sepik River.

Table 2. Vegetation, land use and economic activity

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**RMU 279** (Kaup Lagoon)
**Vegetation:** Swamp woodland with mangrove
**Land use & small holder economic activity:**
About 50% of the land is used at a low level of intensity. About 90% of households engage in some economic activity, especially cocoa (81%), food crops (79%), fishing, (75%) coconuts (75%), pigs (50%), spices (29%) and coffee (21%).

**RMU 280** (Murik Lagoon)
**Vegetation:** Mangrove forest
**Land use & small holder economic activity:**
Most of the land is virtually unused. The only economically significant activity is fishing, by about 48% of households.

**RMU 281** (Watam Lagoon)
**Vegetation:** Mangrove with swamp woodland.
**Land use & small holder economic activity:**
5% of the land is used for sago production and the rest is virtually unused. All households engage in fishing and 10 out of 12 in food crop production.

**RMU 81**
**Vegetation:** Swamp woodland with herbaceous swamp vegetation & swamp grassland.
**Land use & small holder economic activity:**
14% of the land is used for sago production and the rest is virtually unused. Almost all households engage in some economic activity, especially fishing (96%), coconuts (83%), pigs (74%) and food crops (48%).

**RMU 82** (Broken Water Bay)
**Vegetation:** Woodland with grassland and littoral forest.
**Land use & small holder economic activity:**
About 43% of the land is used at a low to extremely low level of intensity. About 80% of households engage in some economic activity, especially fishing (80%), coconuts (59%) food crops (57%), pigs (45%), rubber (18%) and coffee (14%).

**RMU 279**
**Vegetation:** Swamp woodland with herbaceous swamp vegetation and swamp forest.
**Land use & small holder economic activity:**
About 64% of the land is used for sago production and the rest is virtually unused. About 85% of households engage in some economic activity, especially food crops (81%), fishing (50%), coconut (17%) and pigs (14%).

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IMPACTS OF RISING SEA LEVEL

The areas of productive land which are not or are only slightly affected by inundation are very small, probably less than 20% of the total area. Hence a 1 m rise in sea level would have a severe and possibly catastrophic impact on the subsistence and commercial economy, and the settlement patterns of the area. This impact would come about through an inland extension of the area subject to tidal inundation and increased flooding of inland areas due to rising water tables and overbank flooding. The effects of flooding would be especially severe if the sea were to rise at more tham 0.3 m/100 years (see Chappell, this volume).

Rising sea levels will cause erosion of the shoreline, putting coastal settlements at risk. Especially vulnerable will be villages on sand beach ridges directly fronting the ocean. Examples of such villages are Darapan (population about 260) and Mendan (population about 140) which are located on the low, narrow sand barrier which encloses Murik Lakes (Figure 1).

Groundwater on sand barriers and around estuaries will become tainted with brackish water and alternative water supplies will have to be found.

All of these impacts combined will make the study area virtually uninhabitable and most of the population will have to be re-located on adjacent areas of higher ground or further afield.

REFERENCE

CSIRO/DPI 1987. Papua New Guinea Inventory of Natural Resources, Population Distribution and Land Use. Code Files, 7 Volumes, Canberra & Port Moresby.

# CARTERET ISLANDERS AT THE ATOLLS RESETTLEMENT SCHEME: A RESPONSE TO LAND LOSS AND POPULATION GROWTH

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> Growing cash crops and making gardens are the plans we have in mind. This we believe will cause a change in our lifestyle. Instead of spending most times out in the sea fishing we will spend time gardening or doing necessary things to keep us occupied (Views given at a meeting on 29 April 1982, at Han Island, in the Carteret Group to discuss resettlement).

## INTRODUCTION

Estimates as to the extent of sea level rise over the next 20 years vary from only 20 cm to several metres. Nevertheless, many island nations in the south Pacific are already aware of the far-reaching social and economic impact, particularly on coastal villages and low-lying islands, of even small changes in sea levels. Within the next 10 to 20 years, lines of coconuts and other food or cash crops may disappear into the sea; schools and other facilities close to the shore may have to be relocated; roads, wharves and airstrips may be damaged or even totally destroyed.

An even more dramatic and far-reaching impact has been a growing awareness among 'temporary' migrants from villages located at sea level that they may not be able to return home as the piece of land which they had called 'home' may no longer exist.

Among the most vulnerable of populations in the south Pacific are those living on small low-lying atolls, where land available for food or cash crops is already diminishing at a time when population growth is increasing pressure on land for both subsistence and economic production. In the past out-migration has provided one solution to land shortage but usually even long-term migrants still look forward to possible return or retirement to their home island. What will happen, however, if island land loss is so severe that a more massive and more permanent relocation must be considered?

This study of the Atolls Resettlement Scheme in the North Solomons Province of Papua New Guinea illustrates the decisions confronting, both the small groups of atoll dwellers and also local and national government policy-makers and planners. The latter must begin to plan for populations which are in danger of losing their land because of sea level rise and for whom a new homeland must be found. For some island people the extent of the impact is less severe as they have areas of land well above sea level but in many of the smaller atolls in the western Pacific, to the north of Bougainville and Buka islands (see Figures 1 and 2), increasing erosion of the shoreline and damage to fringing reefs over the past 20 to 30 years has lent urgency to proposals for resettlement.

In the case of the Carteret or Kilinailau group, land loss and population growth have led to periodic food shortages and this was a major factor in persuading both the North Solomons Provincial Government and island leaders that immediate steps should be taken to begin the process of resettlement on mainland Bougainville Island.

Sources of information for this study include patrol reports by Australian administrative officers over the period 1950 to 1975; North Solomons Government reports and minutes of meetings; interviews with island leaders, settlers, government and non-government officials; field reports from agriculture and social work students; and other information which was obtained during several visits by the author to the Atolls Resettlement Scheme.

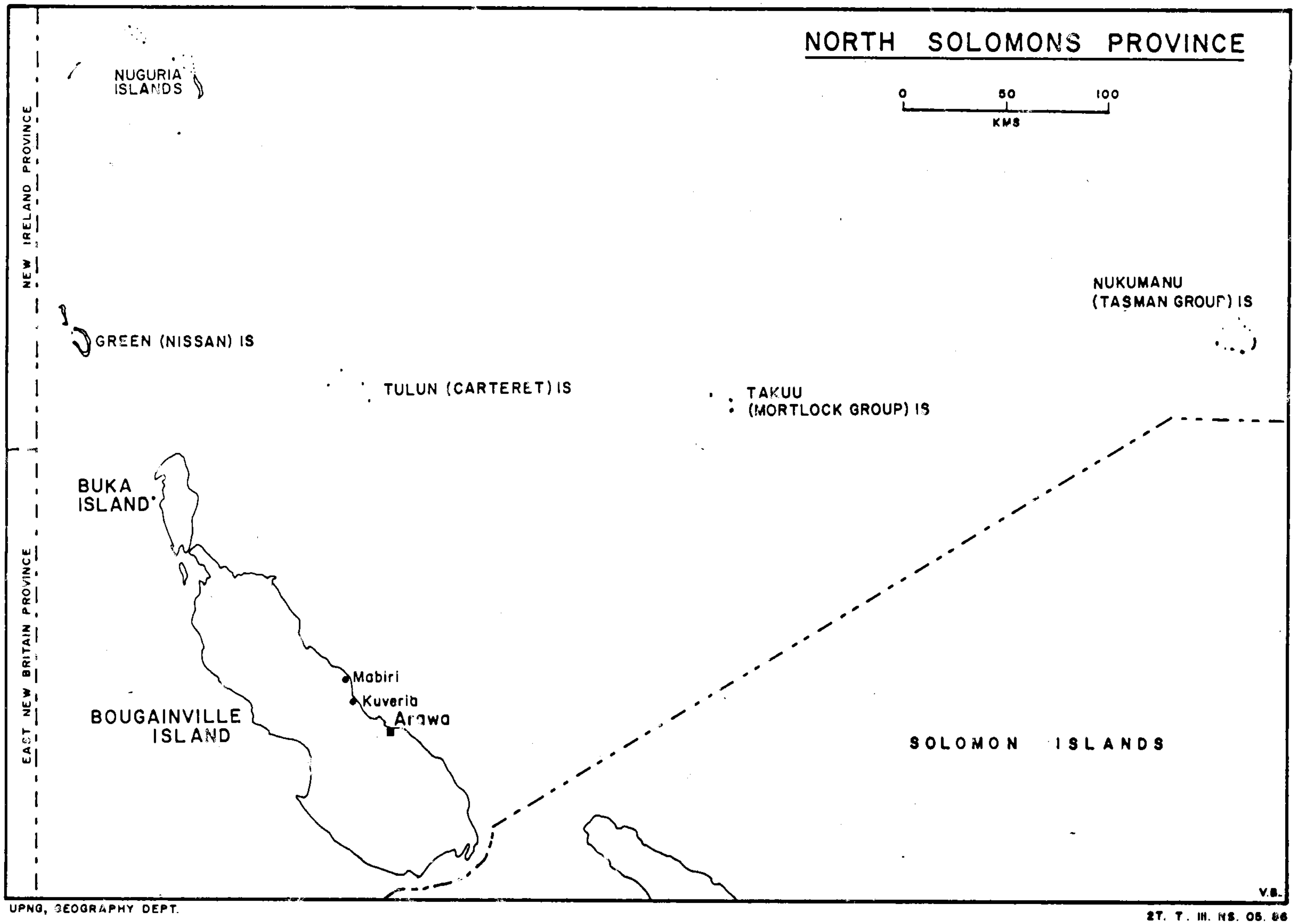



Figure 1. North Solomons Province, showing the location of atolls.

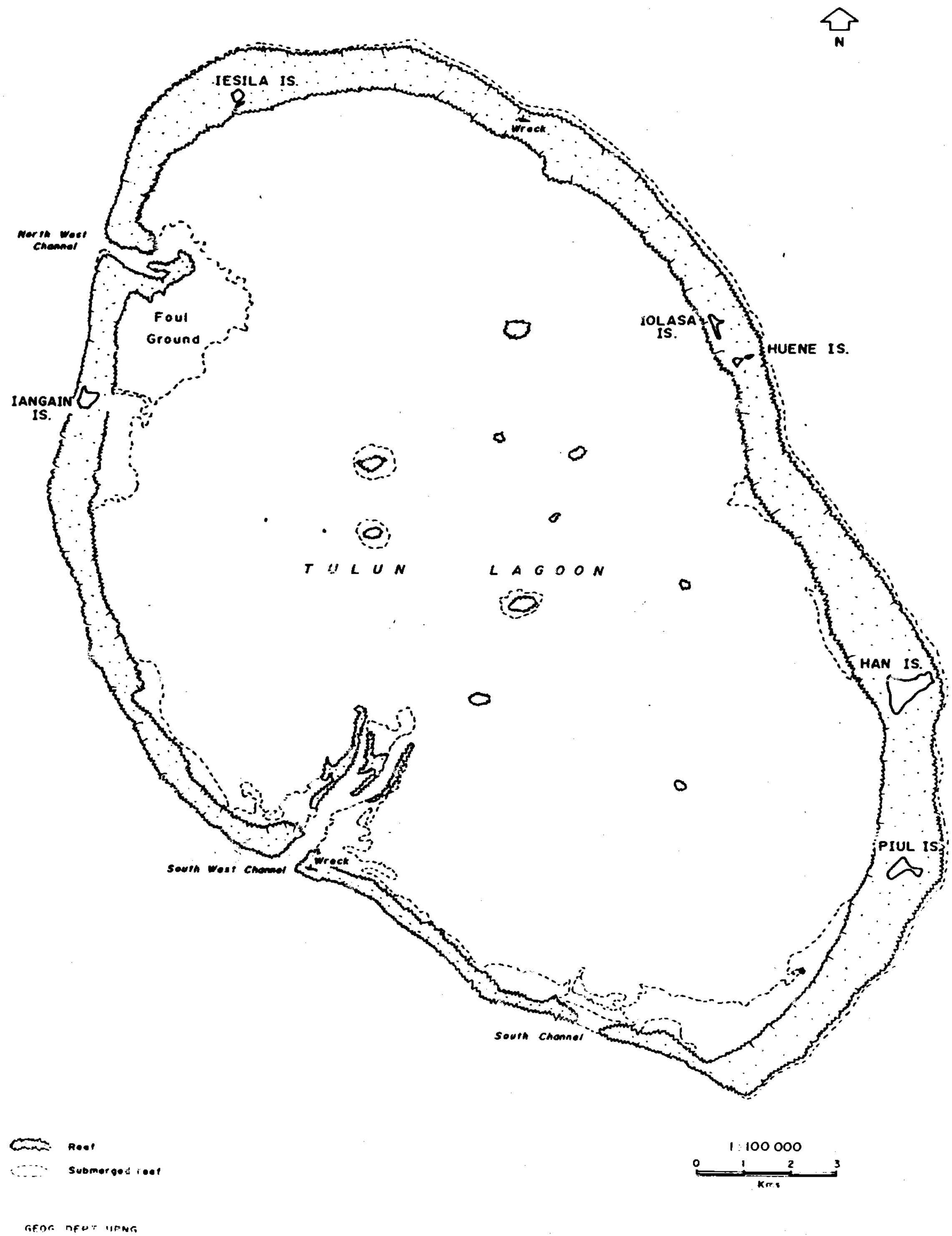



Figure 2. The Carteret Island group.

## THE CARTERET ISLANDS: BACKGROUND TO PLANNED RESETTLEMENT

### The outer islands of North Solomons Province

The Carteret Islands are part of the Islands Census Division of Buka District in the North Solomons Province of Papua New Guinea (Figure 1). This Census Division includes, to the east of Buka Island, the outlying Tasman and Mortlock groups, with the Carterets to the northeast, Nuguria or Fead islands to the north, and Nissan and Malum islands to the northwest. The total land area of these islands is about 49 $km^2$ with a resident population density of about 100 persons/$km^2$ (this compares with 11/$km^2$ for North Solomons Province as a whole). In 1980 the resident population of the Outer Islands was 4,887 citizens, 2,412 males and 2,475 females (National Statistical Office, 1982a:2). Many adults, especially males, have left the islands to work in other parts of the North Solomons Province or elsewhere in Papua New Guinea. In 1980 about 35.6% of all adult males were absent and more than half (53.4%) of the resident population was under 18 years of age (National Statistical Office 1982b:13).

The islands are all a considerable distance (100 to 500 km) away from the mainland of Bougainville and aidposts, community schools and ports of call are sparsely scattered throughout the island groups. Economically these atolls are less developed with very scant resources and no steady cash income as sales of copra, shells, beche-de-mer and other fish products depend on regular sea transport to Kieta on Bougainville Island. While improvements in communication have occurred in recent years, with the installation of radio links and monthly visits to each island by the vessel Atolls Enterprise they have remained as isolated Polynesian and Melanesian outliers far off in the ocean.

Their small population and lack of economic potential has meant that many of the remoter islands were rarely visited by government administrators except when attention was drawn to them by reports of severe food shortages; destruction caused by storms, epidemics (whooping cough, influenza or measles); or plagues of rats and other pests which often followed a ship's visit.

The islands were briefly under German Administration prior to World War 1 and later came under Australian Trusteeship until this was interrupted by the occupation of some of the major islands by the Japanese during World War 2.

Following World War 2 when the Australian Administration re-established patrols in the late 1940s, some enthusiastic patrol officers were struck by the happy and tranquil existence apparently enjoyed in many of the atolls. Others noted the growing problems of land shortage and population growth and the possibility of resettlement to ease population pressures began to be seriously considered. However, as one patrol officer reported (Sebire, 2nd June 1960) the Mortlock islanders were firmly opposed to any move to another area and this view was also expressed by other island leaders who feared a loss of cultural identity and that they would be swallowed up on the mainland. At the same time the idea remained that one day, in the distant future this might have to be considered.

The Carteret Islanders were the one striking exception to this general rejection of administration sponsored proposals for relocation. By the late 1960s they were reported to have a unanimous desire for resettlement as 'heavy seas have devastated garden land and there is an obvious shortage of food crops'(Letter from K.J. Hanrahan, Assistant District Commissioner to the District Commissioner at Sohano, Buka Island on 11th January 1968).

### The Carteret Islands: population, social structure, climate

The Carteret Islands (also known as the Kilinailau or Tulun Islands) are located approximately 115 kms northeast of Buka Island in the North Solomons Province. They consist of a group of six small islands formed from a raised coral reef which encircles an oval shaped lagoon 20 km long and 15 km wide (Figures 2 and 3). Five of these islands are inhabited (Han, Piul, Iangain, Iolassa and Iesila) with a total land mass of less than 200 acres (80 ha), only 55% of which is suitable for agricultural or tree crop production (Figure 3). The 1982 National Population Census recorded a resident population of 672 out of a total population of 1,058.

Many of the 376 absentees (36% of the total population) are adult males working on Bougainville Island or in other parts of Papua New Guinea. There is little employment as such on the islands and residents rely heavily on remittances from working relatives to supplement their meagre cash incomes. They also rely on the monthly visits of the *Atolls Enterprise* carrying goods to stock the island trade stores. During December and January there is an influx of returning residents bringing large quantities of food and other items to share with their families back at home.

Lying close to the Equator with temperatures generally around 30°-35°C the main climatic variations relate to the northwest trade winds which prevail between November and April and it is during this period that storms and accompanying heavy rainfall are likely to occur. This adds to the problems of regular marketing of sea or agricultural produce as well as regular visits to the island by health, commerce or other government extension officers.

Historical background

One of the earliest recorded descriptions of this group of atolls was in 1767 when Captain Philip Carteret recorded having sighted a group of nine islands and having observed some of the men from the islands who came near to his ship in one of their boats. In Carteret's *Voyage Round the World 1766-1769* (edited by Helen Wallis, 1965:177-178), a footnote refers to the inhabitants as 'descendants of refugees who fled many years ago from Buka'. A survey of the islands carried out in 1964 by government officers (Redmond *et al.*, 1965:1-2) included the following history of the group.

The Carteret Islands, also known as the Kilinailau group, consist of six islands of which five are inhabited. They are located approximately 110 km (70 miles) northeast of Buka Island at a latitude of 4° 45'S and longitude 155° 20'E.

The islands are actually an atoll group, being formed from a raised coral reef and are arranged almost in a circle with a diameter of 20 km (twelve miles). They are low lying with swamp areas and during the northwest season sections are flooded by heavy seas.

The islands are populated by descendants of invaders from Buka Island (mainly from the Hanahan area, northeastern sector of Buka), and the spoken language *Halia* is the same as that spoken by the Hanahan people. The physical stature, colour of skin, habits and customs of the Carterets people is closely akin to that of the Buka people.

Legend has it that long before the advent of the European, the islands were inhabited by people of Polynesian stock. The Buka people knowing that the islands existed, conducted three invasions of them. The first two were repulsed, but the third, made by overwhelming numbers, was successful. The indigenous men were slaughtered and their women taken by the conquerors who then proceeded to settle on the islands. The oral traditions of the Carteret Islanders are that in the past the people who lived on their islands were Polynesians like the Mortlock and Tasman Islanders, and that the invasions referred to above occurred three to four hundred years ago. Trade and other interchanges between the Carterets and Buka have continued since that time and, although the Carteret version of Halia is slightly different, the local language pre-school on the Carterets uses Halia language teaching materials.

Carteret society is a matrilineal clan based system, with two distinct matriclans and a number of lineage groupings within these. Members of a clan come together to prepare for larger marriage or funeral ceremonies but daily tasks and activities are mainly carried out on a family/household basis. Traditional lineage leaders were appointed as village officials by the Australian Administration as they were influential and respected men, who were often skilled fishermen and canoe builders.

The 1964 survey report described the traditional type of housing as being built directly on the sand with an arch combining roof and walls of sago palm leaves. This practice has continued although those with readier access to cash have imported timber to build raised houses. Wood has always been in short supply and much use is made of driftwood, material from wrecked ships or other debris washed up on the reef.

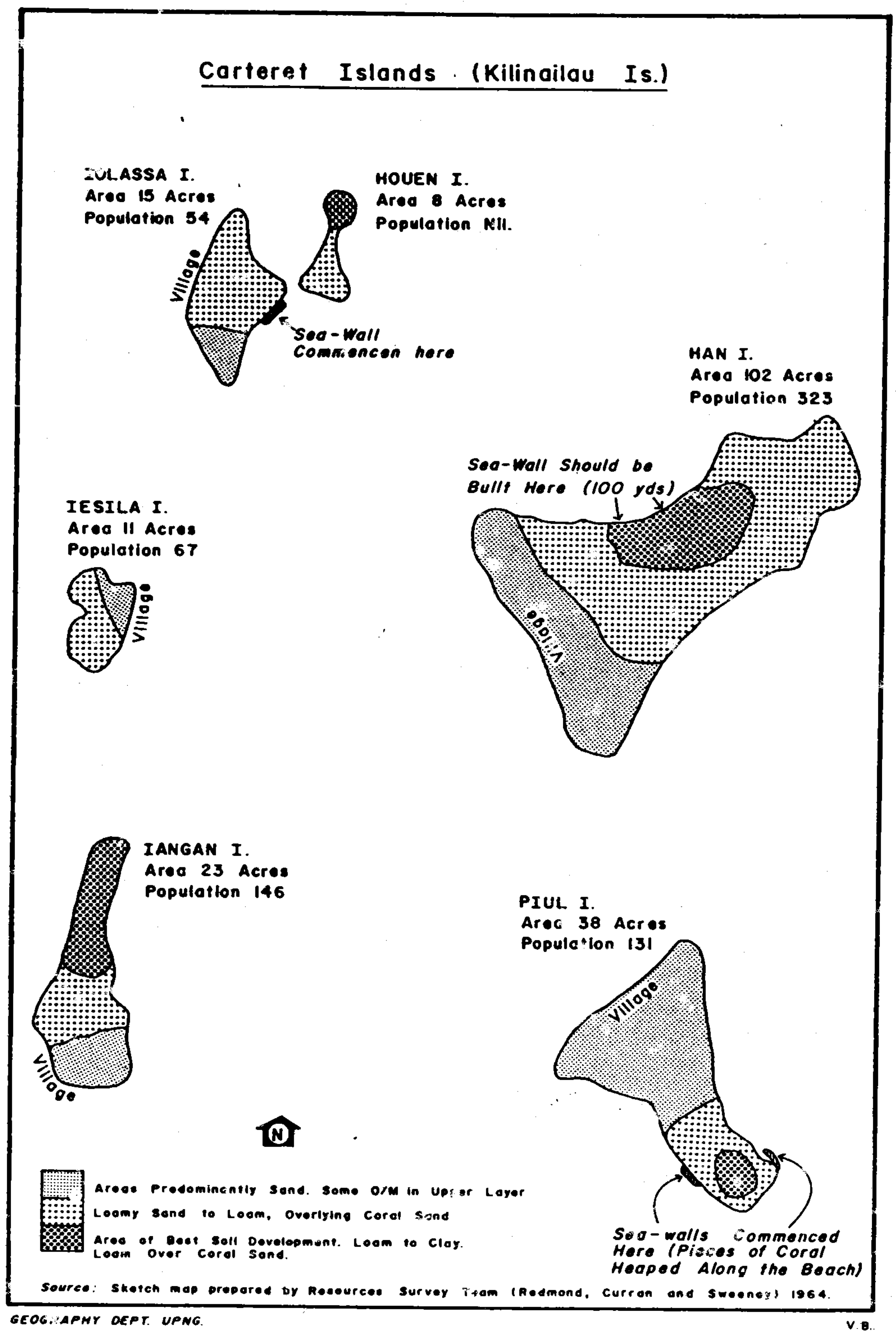



Figure 3. Individual islands of the Carterets, showing population, soils, size and seawall construction.

Fish, coconuts and some green vegetables and fruits have continued to be the basic diet subsidised, (as the survey team noted) by purchases of meat, rice and flour. By 1960, all available agricultural land was being intensively cultivated and patrol reports throughout the 1960s described how many small pockets of land would be cultivated by one family in an attempt to produce adequate food supplies.

Despite these efforts, reports continued of periodic food shortages and the 1964 resources survey was partly in response to a letter from Reverend W.P. Fingleton to the District Commissioner (21st September 1963) that there was 'an acute food shortage among the people due to coconut failure'. Problems of land shortages and inadequacy of food produced to meet the dietary needs of the population of 721 were identified by the 1964 survey team who recorded that, out of 110 acres (45 ha) considered suitable for cultivation, about 70% were in constant use and that the fallow period was too short for any sort of recovery to take place.

> Almost all of the land on the islands is planted with coconuts and where the ground is suitable, food crops such as bananas, taro, and cassava are planted amongst the coconut palms. There is no attempt at marking-out when the crops are planted, but [they] are scattered haphazardly. There are few previous reports to refer to, but most of the ground appears used year after year for subsistence crops. There is no knowledge of composting, crop rotation, or utilisation of legumes.
>
> The people have been instructed previously to thin out their coconut groves but considering the significance of the coconut in the lives of the people, this should be done with caution. Erosion is a constant menace in these islands, and destruction of palms could be a further factor (Redmond *et al.*, 1965:13).

Land loss and population growth

During the 1960s efforts were made to alleviate or prevent the effects of sea erosion and the consequent loss of tree crops and arable land. The Piul Islanders requested a quantity of old oil drums and began building a seawall using these and coral heaped along the shoreline. Han, the largest of the six islands was also affected and it was suggested that a seawall should also be built there to try to protect the island from the devastation which occurred during storms and high tides (see Figure 3).

None of the suggested measures proved effective and the people began to accept the inevitability of land loss. A report by Assistant District Officer Marks, after he visited the Carterets in December 1967, noted that -

> Since the 1964 resources survey, hundreds of mature coconut palms have been destroyed by erosion - particularly on Han and Piul. Over the past three years severe northwesterlies and southeasterlies expose the islands to ruinous erosion ... (and attempts to build a seawall were abandoned) as ... the venture proved fruitless against the first heavy seas.

Reports of food, firewood and water shortages continued, and population growth exacerbated the pressure on available land. In 1964, the survey team had recorded a population of 721, noting that this represented an average annual growth rate of 2.4% since the 1954 census figure of 581. They warned that, by 1984 the population would be well over 1,000 (Figure 4). As noted earlier, this prediction proved correct but increasingly out-migration has been a factor reducing the rate of resident population growth.

By 1967 the Assistant District Officer reported the population had risen to 821 and economic opportunities were diminishing as fish and coconuts, the staple diet of the people, were often only sufficient for subsistence use. He had discussed resettlement with the leaders, concluded that 'the communities on the Carteret Islands want resettlement' and recommended that all available prospects for locating suitable land be investigated (Marks, 16 December 1967). In February 1968, the Director of Native Affairs (T.W. Ellis) wrote in support of the Bougainville District Commissioner's recommendation that land be acquired for the resettlement of the islanders.

PLANNING FOR RESETTLEMENT

Moves to acquire suitable land failed and no action took place for another 10 years, although the question was periodically raised following patrol reports recording food shortages and requests by the Carteret Islanders themselves for government assistance to resettle on the mainland. During the early 1970s, as moves to establish a provincial government gathered momentum, various communities throughout the atolls region complained that they were forgotten or neglected by mainland Bougainvillians. Following the establishment of the North Solomons Provincial Government, the problem of land shortages on many of the island groups was debated. Finally, on 9 April 1979, the member for Outer Islands, Albert Hannett, obtained the assent of members to the motion -

> That in view of the critical shortages of land in the Outer Islands, due to the increasing population and the steady erosion of land by sea waters, that as a matter of top priority, this Government allocate suitable government land on mainland North Solomons where such people can come and settle for their livelihood.

At a special meeting on 4 June 1979, the Provincial Land Policy Committee resolved to carry out a survey to identify the numbers of people who wished to settle on the mainland and the amount of land needed for each family and to identify all alienated land which might be available for resettlement purposes (letter from Deputy Provincial Commissioner M.F. Bell to the North Solomons Administrative Secretary 8 June 1979).

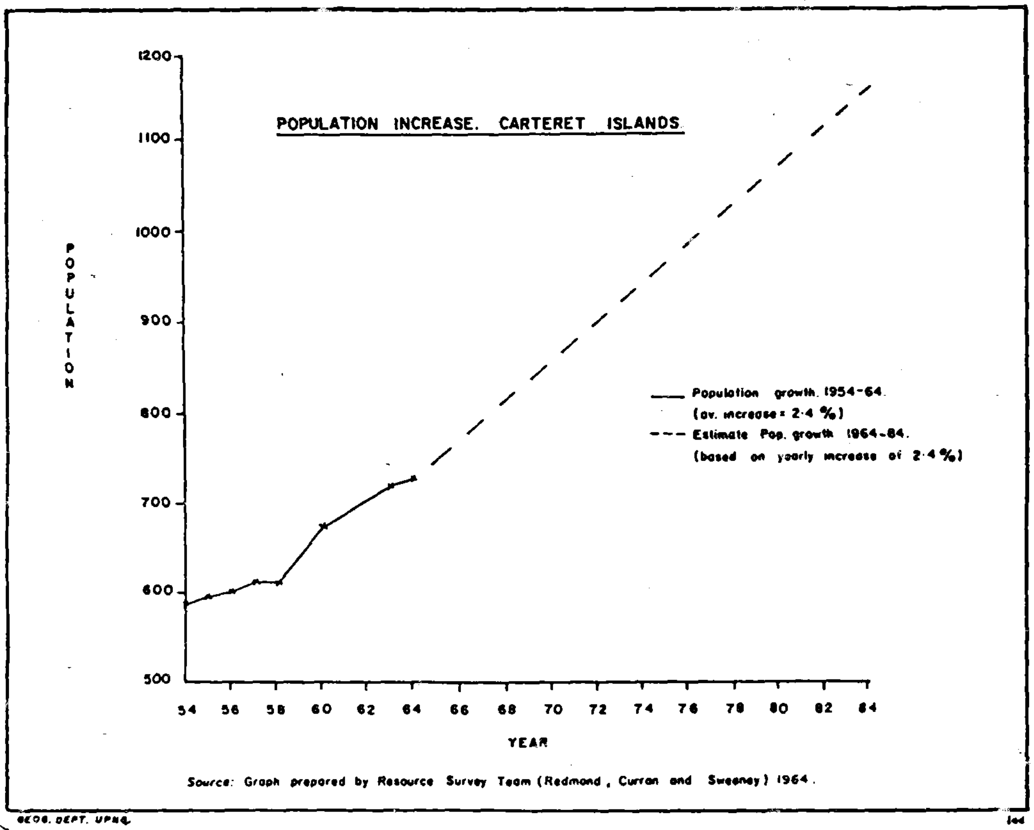



Figure 4. Population projection for the Carteret Islands.

The Atolls Resettlement Project: 1982 - 1985

In April 1982, the Atolls Resettlement Committee (ARC) held its first meeting, attended by representatives from the Department of Lands, Provincial Administration and Primary Industry. The ARC was later expanded to include a Carteret Islands representative, and government officers from health, education, commerce and community development.

During 1982, attempts to locate suitable land failed and finally it was decided to make use of alienated land at Kuveria (adjacent to the provincial corrective institution) which was no longer needed by the Department of Primary Industry. While the land transaction was being finalised, the Kieta District Manager was authorised to 'carry out a survey on the number of people from Carterets intended to be settled, the size of the family and the number of people to be settled in the first year and following years' (Minutes of ARC meeting 8 April 1982).

Minutes of the ARC meeting on 30 March 1983 recorded discussion of the type of title to the land which would be needed and what sort of occupancy guarantee should be given to the settlers. This was not decided upon although it was agreed that a certificate of occupancy be given immediately to the North Solomons Provincial Government. [Despite this recommendation a Certificate of Occupancy for 70 ha of Lot 338 Kuveria Milinch Kieta (File 44-2 Folio 129) was actually not issued until 20 February 1986, some three years later. Letter from Mr Peter Tsiamalili, Administrative Secretary, 29 September 1986.]

An initial settlement site close to the sea proved to be too swampy for the building of transit houses and the planting of communal gardens so a new location close to the main highway and the Corrective Institution was selected (Figure 5). This was clearly not an ideal location for the incoming islands settlers but the project was planned to commence in March 1983 and no other suitable land was immediately available.

A report prepared for the committee on garden size and land utilisation suggested that for an 'average' family of five (man, wife and three children), the amount of land for subsistence gardens might range from a minimum of 0.14 ha to a maximum of 0.38 ha. If the traditional cycle of cropping followed by fallow periods were continued, clearly each family would need a larger area of land over time. The report suggested that desirable average size would also be affected by the quality of the garden land and the degree of dependence by settlers on this land. These factors could increase the average garden size to a maximum of 0.57 ha. By comparison it was noted that the land area available for food or other crops on the Carteret Islands was estimated as an average of 0.66 ha/five person family although this did not take account of the poor quality of the soil (Report by I.Davey to the Atolls Resettlement Committee June 1983).

As the Carteret Islands were suffering the most immediate and serious land shortage problems, it was agreed that 40 families from the Carterets, 20 from the Mortlocks, 10 from Fead (Nuguria) and 10 from the Tasmans would be resettled. The ARC Minutes for a special meeting on 21 July 1983 recorded that the committee 'passed the motion that 120 families over 15 years is acceptable'. It was later decided that families from Nissan would also be included in the Scheme (see Figure 6 for the final design of the Atolls Resettlement Project).

The programme was designed to allow for 10 families to be resettled at a time. Subsistence food gardens would be prepared for harvesting by the settlers when they arrived and they would initially be accommodated in transit houses for a period of three months after arrival to enable them to build homes on the communal sites allocated to different atoll groups. An initial meeting had been held with leaders from villages surrounding the project site and questions such as access to the beach and fishing rights were discussed. The general attitude of nearby villages was that fishing should be limited to minor fishing for household consumption only. Although the then project co-ordinator considered that the overall attitude of nearby villagers was 'quite good' he cautioned that access to fishing grounds and fishing rights generally would be a major problem 'as the settlers have been brought up fishermen' (theconcern of local village elders that rights to fishing grounds should be protected was again voiced at a meeting held in June 1984 at the project site).

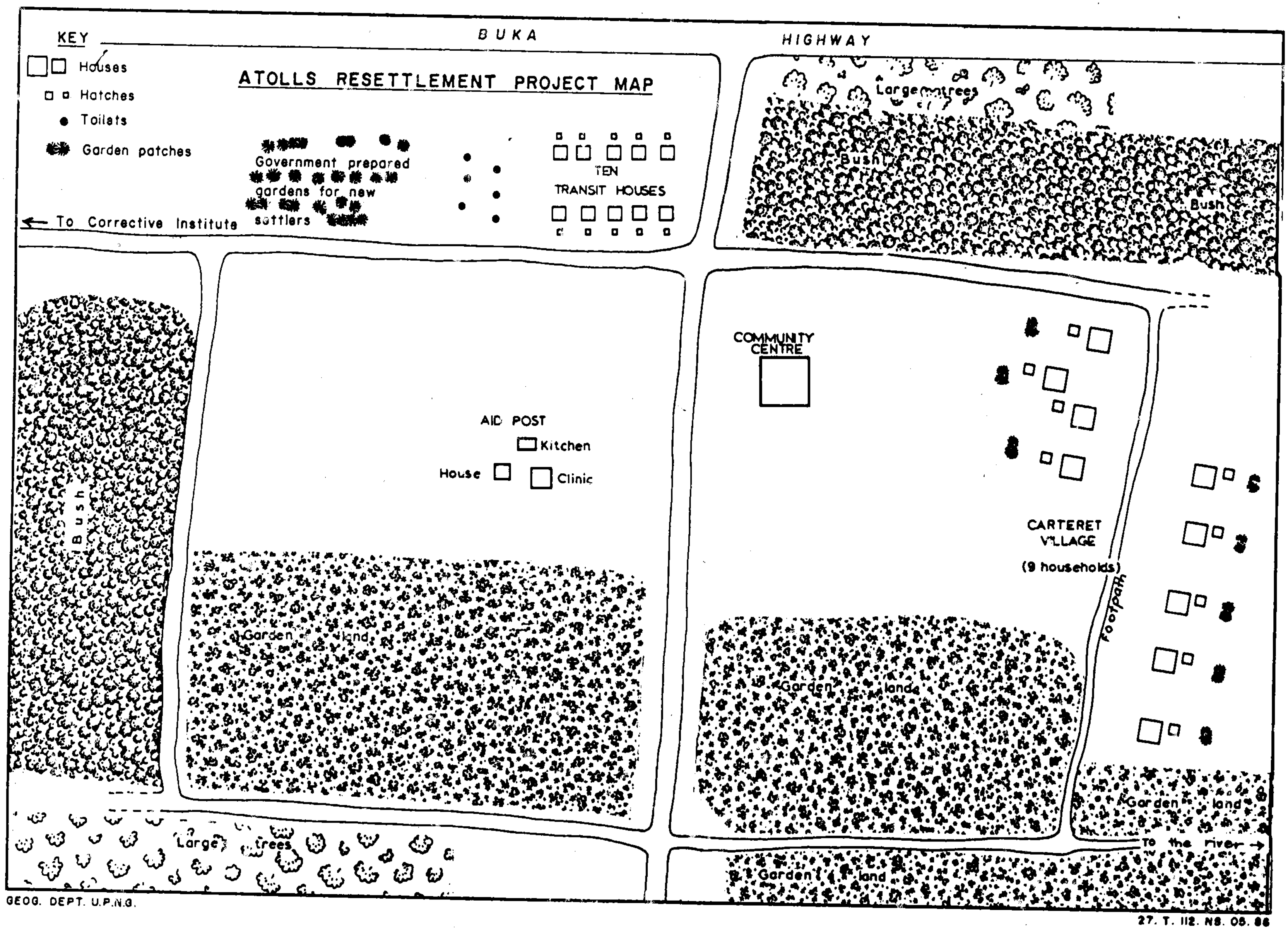



Figure 5. Sketch map of the Atolls Resettlement Scheme.

On 10 November 1983, a White Paper outlining the policy of the North Solomons Provincial Government on the resettlement of atolls peoples on the mainland was endorsed. A project co-ordinator was appointed and, despite administrative, budgetary and general management problems, the project gradually took shape. Facilities and initial infrastructure were designed and implemented under the supervision of the project co-ordinator and the ARC. These included roads, communal food gardens, an aid post and residence, and 10 transit houses. A community centre, wells and a communal water supply were planned for the next phase of the project.

Arrangements were made for school age children to attend the Catholic Mission school at Manetai. An aid post orderly was appointed and it was agreed that the aid post would also be available for use by local villagers.

Visits by the Kieta District Manager to the Outer Islands provided more detailed information as to the willingness of non-Carteret Islands to resettle. Recent storms and increasing land erosion and food shortages had influenced Carteret families to make the decision to move but others found the idea of permanent relocation impossible to accept. Concern was expressed by Mortlock and Tasman Islanders over the absence of fishing rights and over possible problems of security if they resettled at Kuveria. They finally decided that they wanted to retain the right to participate but not at this stage.

At the ARC meeting held on 24 August 1983, it was agreed that Nissan Islanders, especially from the Tanaheran area, would also be included in the scheme. As the problems experienced by the Carterets were the most pressing it was decided that the initial group would consist of 10 Carteret families.

Discussions as to the assistance to be given by various government extension services took place and it was noted that health, education, primary industry, commerce and community development would all be involved, particularly after the initial settling in period.

<u>The reality of resettlement</u>

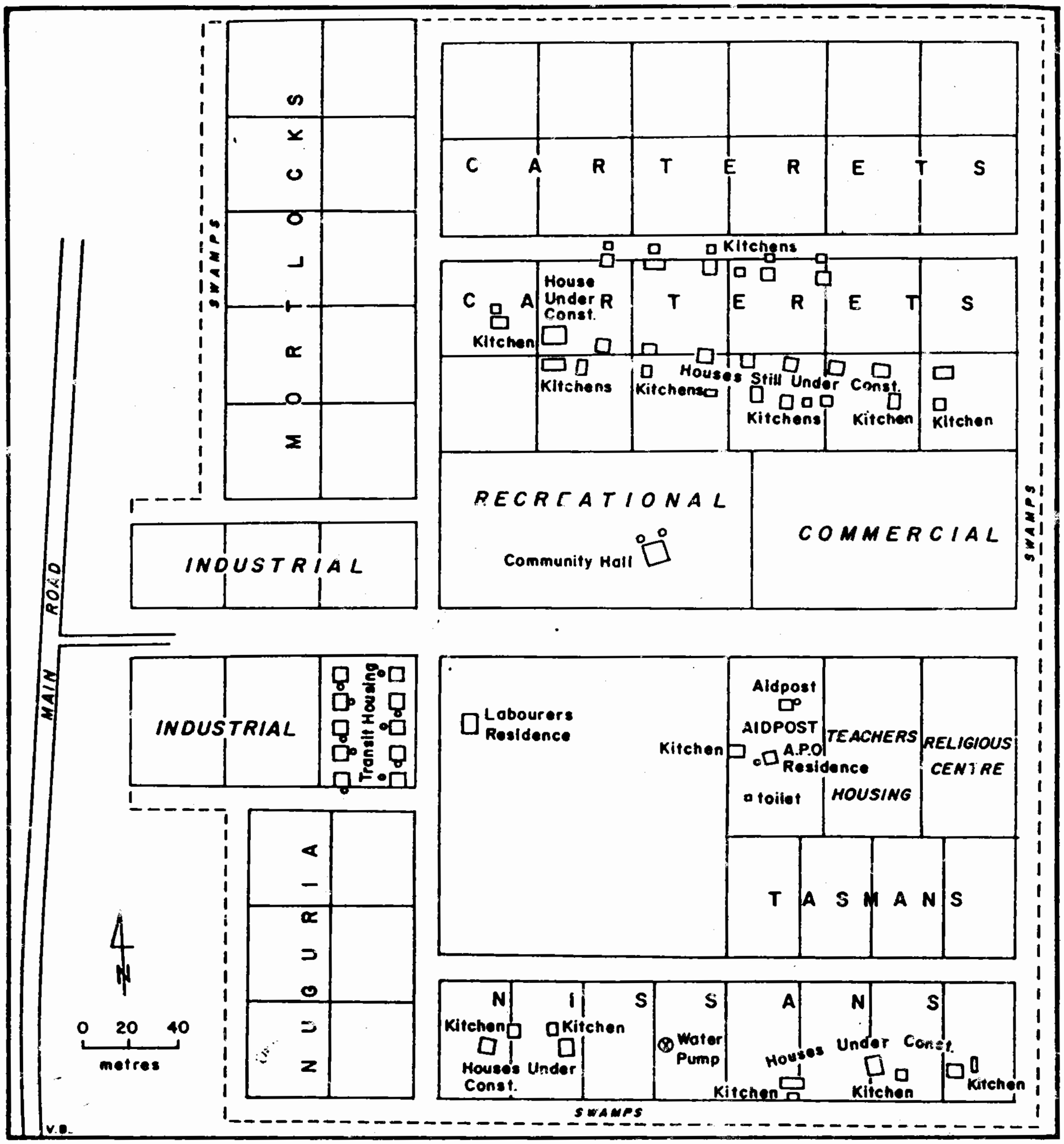
In August 1984, the first group of settlers from the Carteret Islands arrived at the Atolls Resettlement Scheme. The departure of these families from their home islands and their arrival and welcome by officials and local villagers at Kuveria was a significant event both for the atolls peoples, and for those responsible for the planning and implementation of the project.

It had been recognised by members of the ARC and others involved in the project that the settlers might experience some cultural dislocation, especially those who had left their island homes for the first time. However, the full extent of the impact on individuals and families of this relocation to a completely new environment was not anticipated.

The families, and particularly those members engaged in clearing and establishing food gardens and in building houses, had to become used to many new food crops, new building materials and different techniques. Upon arrival the families had to accustom themselves to living under an iron roof, out of sight of the sea and surrounded by unfamiliar and rather frightening thick bush. The presence of the Corrective Institution added to the desire to keep close together and increased dependence on the project co-ordinator and relatives for advice and guidance.

Children had to walk 6 km to school and this was a great distance for those who had had no opportunity to walk any distance on their small atolls. Road traffic hazards, for those who had no experience of roads or vehicular traffic; fear of snakes for those who had no experience of walking on paths through thick bush; and the experience of being surrounded by tall trees, all required individual and community adjustment.

In many ways, Carteret women had the most difficult adjustment to make. Although theirs is a matrilineal society, men make all the public decisions and are more likely to speak at any public meetings. Many women, particularly older women and those who have not been away from the islands,do not speak either *Tok Pisin* or English and so were less able to fully understand the decisions being made on behalf of the family by the male heads of household.




Source: Survey by Lands Department Arawa, N.S.P. April 1986. GEOGRAPHY DEPT. UPNG.

Figure 6. Lands Department plan of the resettlement scheme area.

The problems of adapting to a new environment for which most members of the family had little or no preparation meant that the timetable for building a new Carteret Village, establishing food gardens and moving from the transit houses had to be considerably extended. Many women sat for long periods of time thinking about their island homes. On Sundays they would often risk the 20 minute walk through terrifying tall trees and bush to reach the seashore and gaze for hours out to sea towards the atolls.

The settlers found the diet of sweet potato and the unavailability of coconuts and fish another difficult adjustment but they were pleased with the ease with which food could be grown. Older family members told me that the main reason they had been determined to take this opportunity to resettle was their concern for their children and grandchildren. Most of the settlers adapted remarkably quickly to the many unfamiliar and challenging tasks which they faced in this new environment and only one family returned home at that time.

In August 1985, when a group of five third-year agriculture students carried out a study of food gardens and the social impact of resettlement, the settlers had been living in their new village for several months. Flowers and fruit trees obtained from nearby villages had been planted between the houses and throughout the area. Extensive food gardens had been planted; gardens which provided not only for nine households but also enabled quantities of vegetables to be sent back to the Carteret Islands at regular intervals on the *Atolls Enterprise*. The settlers had chosen three representatives to work with the co-ordinator and other extension officers in the general management and further development of the scheme and a number of social and management problems had been discussed and resolved.

During the field survey, information was gathered from community members, government and non-government officials and other informants. Crops grown in food gardens and around the village site were recorded and the food gardens were mapped. Discussions with heads of households and their families helped members of the team to understand the factors which influenced the decision to leave the Carteret Islands for Kuveria, the challenges which faced the settlers during their first year at the Scheme, and their hopes of future social and economic benefits for their children and grandchildren.

The description of the Atolls Resettlement Scheme which follows is extracted from the team report (Kukang *et al.*, 1987).

## THE ATOLLS RESETTLEMENT SCHEME 1985

(T. Kukang, J. Selwyn, A. Siau, E. Tade and M. Wairiu)

The Atolls Resettlement Scheme is located 30 km from Arawa, along the Kieta-Buka Highway adjacent to the Kuveria Corrective Institution.

### Landforms, climate and vegetation

The resettlement scheme is located on a relict alluvial plain of volcanic origin, with a steep gradient and up to 1 km wide. Relief is generally low, up to 10 m locally. The plain is generally well drained, with minor swampy areas, and is backed by hills rising to 40 m. This area falls within the larger Siwai land system of elongated plateaus with incised parallel valleys (Scott *et al.*, 1967:28).

The annual rainfall at Kuveria ranges from 2,500 to 3,000 mm, the wet months being May to September while the dry months are from November to March. The annual relative humidity ranges from 70 to 80%. The maximum temperature range is between 27° and 34°C, while the minimum is between 23° and 24°C annually (McAlpine, 1967:62-70).

The native vegetation on the site was tall forest. Since rainfall never falls below 130 mm each month, the forest is not subjected to water stress and has attained climax commonly dominated by *Vitex* and *Pometia* trees with tall grasses (*Saccharum robustum*) growing along the river banks.

Stripe chlorosis in maize plants and chlorotic spot on peanuts were observed in some gardens, suggesting low potassium and/or magnesium levels. Samples of garden soils have been tested by the Fresh Foods Section of the Division of Primary Industry and reports given to the Atolls Resettlement Committee (Niamis, 1985).

The land is suitable for all crops as the settlers are the first to clear the primary forest and, unlike other nearby land, it has not been severely disturbed by human activity. Much of the land next to the settlement has been converted into cocoa and coconut plantations. However, the Provincial Government wants the settlers to grow food crops only and not cash crops as it is proposed that the settlers will grow cash crops on another site of 1,000 ha located at Mabiri.

Many of the crops grown are tuber crops, with banana, sugar cane and some maize. Initial garden preparation involves slash and burn methods although, where weeds have invaded previously cleared land burning is rarely practiced prior to planting. The settlers do not practice mulching or composting and it was observed that the same piece of land is used again after harvesting of the previous food crop. This practice reflects the settler's gardening practices on their home islands.

Nitrogen, phosphorus, calcium, manganese and magnesium levels are sufficient to support favourable plant yields but soil tests by the Analytical Service of Bougainville Copper Ltd. indicated a low potassium availability in the soil. This is a problem as this type of sandy loam soil requires an N/K ratio of 0:2 to 1:2 for adequate sweet potato yield. Cassava requires a similar N/K ratio to produce a high number of well formed tubers. The potassium content is moderate to good for the growth of bananas. Other nutrients are sufficient but their availability varies from field to field (see also the 'Second Report on Soils' to the Atolls Resettlement Committee by A. Niamis, Fresh Foods Officer, Division of Primary Industry, 7 May 1985).

Considering all these factors, mulching and composting should be practiced and the burning of grasses and application of ashes should be encouraged. This would help to maintain the soil structure while reducing leaching of nutrients; retard weed growth and conserve water and moisture, by reducing free drainage of water. Seagrass or sea weed are rich in potassium and could be applied as well, although the results should be monitored carefully as there may then be a problem with high sodium (Na) levels.

If the above agricultural practices are not carried out, the use of crop rotation and fallow systems should be emphasised as tuber crops remove large quantities of nutrients from the soil. If the present system of cultivation used by the settlers is not modified the result will be a rapid decline in the nutrient content of the soil. The intensive land utilisation which will be required as the numbers of settlers increase should also be taken into account.

Physical setting and infrastructure

Ten transit houses have been provided to house newly arrived settlers while their own houses are being constructed. These houses are of modern materials with iron roofing, prefabricated walls and timber floors. Each house has a separate bush material kitchen and water tanks beside the transit houses collect rainwater which the Carteret settlers and newly arrived Nissan families depend on for drinking and cooking food. Six toilets have also been built at the back of the transit area. An aid post and accommodation for the aid post orderly and his family is provided, a community centre has just been completed and a well has recently been dug. Nine houses, made of timber and local materials have been built as the first stage of the new Carteret 'village' (Figure 5).

Prior to the arrival of the first group of settlers an area of ground near the transit houses was cleared and food gardens were prepared for use by the settlers during the first few months.

A lateral road has been constructed from the Buka highway through the Scheme, past the transit houses to the Carteret village. Other roads provide access to the aid post and the orderly's house; the community centre; the garden areas; the site for the Nissan Island settlement; the boundary of the Kuveria Corrective Institution, and the river. At the moment there is no road linking the settlement to the beach which is about twenty minutes walk along a track through forest and other vegetation.

The nearest community school is at Manetai, 6 km away and trade stores are located in nearby villages, along the highway, and at the Corrective Institution.

Although the original estimate was that the settler families would have an average family size of ·e children, the average number of children per family is much higher, being closer to six. In addition, settlers follow the normal Melanesian custom of accommodating other relatives so the average household size is more than nine members. Married sons and daughters and their children, also live with some of the settler families. As the numbers of school-age children increase there will be a need to provide a community school at the scheme, particularly if the planned 120 families are settled.

Leadership and social structure at the scheme

The settlers have established a committee at the Atolls Resettlement scheme which is responsible for village affairs and the well-being of the atoll settlers. There are three representatives from the Carteret islanders and others will be added from the recently arrived Nissan group.

The village committee usually meets with the project co-ordinator to bring up proposals and problems faced by the settlers. The project co-ordinator also meets with the church leaders and clan leaders to discuss the progress of the settlers. The clan leader is a member of the village committee and is the spokesman for the villagers in meetings. Any proposal brought forward by the settlers is taken by the project co-ordinator to the provincial Atolls Resettlement Committee for consideration and possible implementation.

Education

The children from the nine Carteret families who enrolled at the Manetai Catholic community school had to become used to walking along the main highway six km to and from the school. The children were not familiar with the experience of taking part in large classes and group sports and recreational activities. The older women were unfamiliar with the idea of adult education and since their arrival, a DPI nutritionist has begun visiting the settlement to teach the mothers and young women about food and nutrition.

Housing

Living in the transit houses which had corrugated iron roofs and other introduced building materials was a strange experience for most families and, as some settlers pointed out, they were very frightened the first time they heard heavy rain beating on the roof.

In their new village, building houses on posts and making use of timber for walls and flooring was an unfamiliar task for most male settlers as wood was scarce on the atolls. The village houses are made of local materials, with sago leaves used for roofing and walls, and timber for the flooring. Six toilets were provided at the transit houses but once the settlers moved to their own houses on the permanent site, they were expected to build their own toilets. At the time of our visit, this had not yet been done, although some settlers had dug holes in preparation for the construction of toilets.

Health

A major change has been in the health of the children. When the families arrived, many of the children showed signs of malnutrition. The aid post records and the comments of the settlers indicate that the children are now much healthier. One settler stated that -

> We are now really happy because the health of our children has improved greatly and this is another reason why we are not going back to the Carteret Islands. This is our new home.

Living away from the sea

An important change in the lives of the settlers has been that they have settled in an area which is some distance from the sea. Instead of fishing they are now spending most of their time gardening and improving their village. Some men have plans to build canoes and begin fishing but this will depend on whether nearby villages give them fishing rights. At the moment they do not fish very often so there are no immediate problems relating to access.

Economic activities

The Carteret settlers do not have any cash crops as yet: cocoa, poultry, pig and vegetable production will be the settler's source of income, as planned by the North Solomons Provincial Government.

At the time of our visit, there were no shops or other economic activities within the Atoll Resettlement Scheme. Most of the settlers interviewed stressed that they would like to have a source of income as soon as possible. Some stated that the North Solomons Provincial Government was planning to provide the settlers with blocks of land at Mabiri so that they could grow cocoa.

A trade store business had been proposed by the Carteret Island group but had been delayed due to the lack of business knowledge and skills to manage the store. Most of the settlers are unfamiliar with any type of business operation so if this project is started without adequate help from business development officers, it seems likely to fail.

Other social changes

The payment of bride price is unfamiliar in the tradition of the Carteret people and some tension recently occurred when a male member of a Carteret family married a girl from a nearby village and her family demanded bride price.

The Community Centre (which was near completion) will be important as it will provide a focal point and meeting place where provincial government, DPI extension, health and other government officers can meet with the settlers regardless of the weather. It is also to be used for church, youth and women's activities and settlement meetings.

Family food gardens

The total area under food garden cultivation at the settlement is about 3.5 ha and this has been developed by the nine households in less than a year, while they were also settling in to their new environment and building their homes. The tools used in cultivating the food gardens are forks, spades, bush knives, shovels and axes.

The food crops grown in these gardens are mainly for consumption and not for sale. In cultivating these gardens the families have faced tasks which were not familiar to them. Most families had never used tools such as spades, forks, and hoes. Some unfamiliar crops such as sweet potato, cassava, new varieties of taro, banana and new types of green vegetables, were unfamiliar to the settlers.

In addition, the mounding and holing methods of planting were unfamiliar to the settlers. It was their first experience of making sweet potato mounds using a hoe and using a fork to harvest sweet potato tubers from the soil. Garden size or areas are much larger than those on the Carteret Islands. Moreover, they have had to clear the bush and fell big trees using axes. One Carteret settler told us that -

> Back in the Carteret islands we don't have big trees like these ones at the settlement. Now we have to clear the bush and cut down the tropical rainforest which is a very difficult task and for some of us it is our first time to do this job.

The roles of family members in gardening have also been changed, men now carry out some garden preparation tasks which used to be done by women. The small undergrowth within the clear land is cleared by the husband, wife and older children of the family. This is followed by males, usually the husband and older sons, clearing the forest trees which is a heavy job. The females help by cutting small branches off the fallen forest trees using bush knives. After clearing the land, mounds are made for sweet potato and cassava, holes for taro, chinese taro, banana suckers, coconut and sago. These tasks are carried out by both men and women with the females planting the food crops. Garden maintenance such as weeding and 'earthing up' of exposed tubers or corms is done by both sexes and both males and females harvest the food crops.

It is not customary for the settler families to help each other in garden work and house building; work is usually carried out as a household unit (this reflects the social structure described for the Carteret society in 1964).

Increased diversity in food crop production

It was interesting to observe that the varieties of food crops grown in the resettlement area are much more diverse than to those grown on the atolls. This is shown in Table 1.

While some of the 'new' crops had occasionally been grown on the Carterets, many were totally unknown. It was clear that the settlers (and particularly the women) were happy to try out new food crops. Fruit trees and flowers were also planted outside the garden plots, in and around the houses. Settlers commented that many root crops and fruits were much larger than those grown on the islands.

Number of garden plots and overall area cultivated

Each household selected their own garden sites and decided on the number of garden plots to be cultivated. There was great variation in the number of plots cultivated and the total area per household (Table 2). In addition, small patches of taro and fruit trees were planted near and around the houses. The number of garden plots per household ranged from one to five and the total area cultivated per household from approximately 1,330 to 7,070 m2. Most gardens contained several food crops although some small mono-crop plots were observed (Figures 7 and 8).

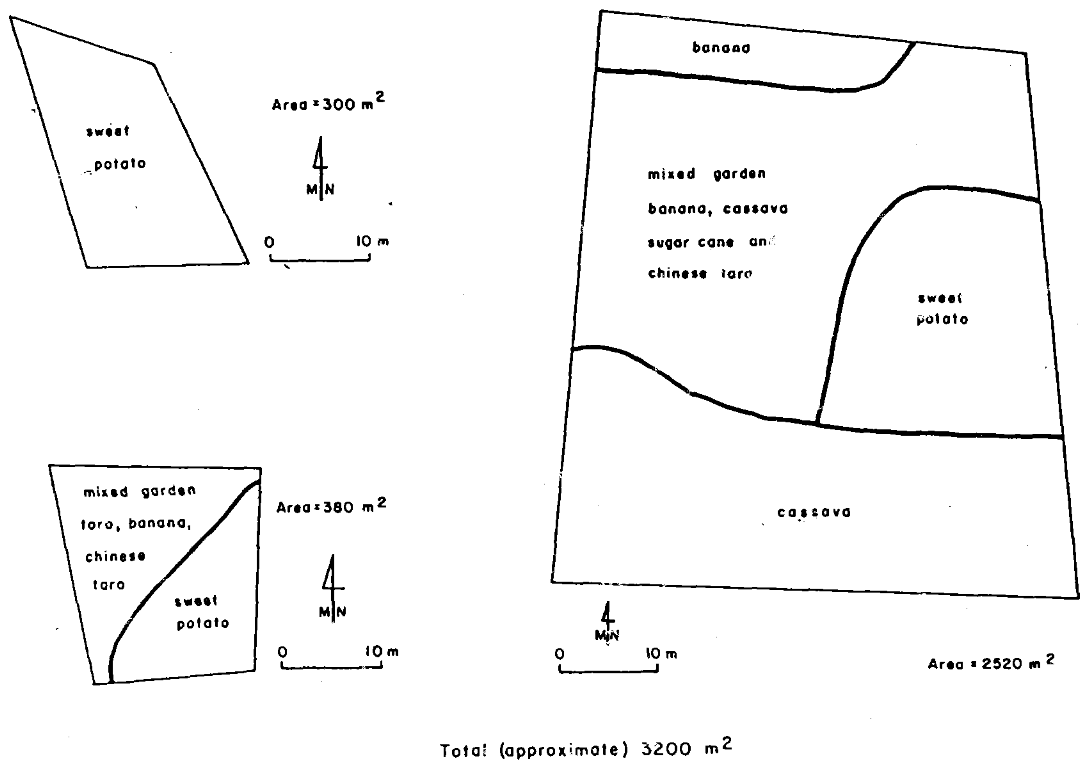



Figure 7. Household D, gardens showing crop distribution.

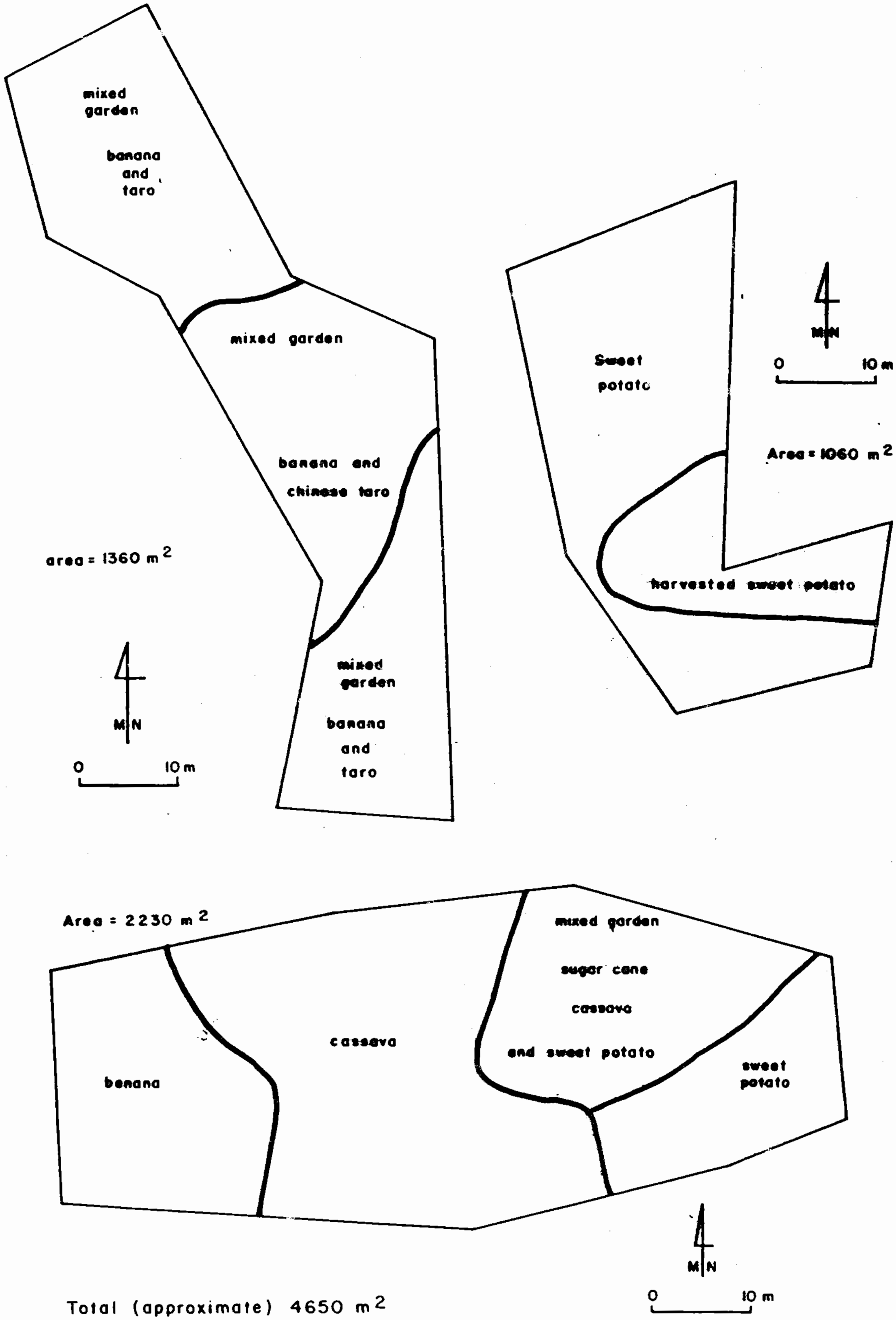



Figure 8. Household G, gardens showing crop distribution.

Table 1. Comparison of crops grown on the Carteret Islands 24 and at the Atolls Resettlement Scheme

| Carteret Islands | Atoll Resettlement Scheme |
|---|---|
| Banana | Banana |
| Breadfruit | Breadfruit |
| Cassava (occasionally) | Cassava |
| Chinese taro | Chinese taro |
| Coconut | Coconut |
| Green vegetables(limited) | Green vegetables |
| Pawpaw | Pawpaw |
| Taro | Taro |
| Less familiar crops now grown by settlers include: | |
| | Amaranthus |
| | Chinese taro |
| | Ginger |
| | Maize |
| | Peanut |
| | Pineapple |
| | Sugar cane |
| | Sweet potato |
| | Tomato |
| | Yam |

(In addition to many new varieties of leafy vegetables, tobacco, bamboo and betelnut palms are also planted by the Carteret settlers.)

The amount of time and energy expended by settler households on developing food gardens varied greatly. Some clearly followed the patterns established at home of developing a number of smaller gardens while others seized the opportunity to garden a much larger area than would have been possible on the atolls. The gardens of households D and G are illustrated to show the variation in garden plots (Figures 7 and 8).

Future needs and possible problems

Most of the problems raised by the settlers concern long term needs. They want a school to be built at the settlement; a road to the beach; fishing rights; and involvement in cash crop production so as to earn some cash income, rather then relying so much on 'wantoks'. They are concerned about the need for a clean water supply but the well which was under construction at the time of our visit and the planned communal water tank should cater for future needs in this regard.

Although many parents were happy about the marked improvement in their children's health and nutritional status, it seemed that the diet was based largely on quantity rather than quality. The settlers were obviously getting enough (or even excess) starchy foods and some greens from their food gardens, but inadequate amounts of protein were the main problem. Some of the older men we interviewed expressed concern about the lack of protein and a few families were beginning to raise chickens (free-range). If the proposed poultry and piggery projects eventuate, these will be very important sources of protein as well as a possible cash income. In addition the settlers come from a community heavily dependent on marine resources (fish) for food. Fish would supplement their protein diet if they were guaranteed fishing rights at their new settlement.

Table 2. Number and size of settler gardens

| Household | Size (m2) | Number of plots | Total area (m2) | |
|---|---|---|---|---|
| A | 570 | | | |
| | 760 | 2 | 1,330 | |
| B | 1,900 | 1 | 1,900 | |
| C | 2,850 | 1 | 2,850 | |
| D | 300 | 3 | | |
| | 380 | | | |
| | 2,530 | | 3,210 | |
| E | 620 | | | |
| | 1,070 | | | |
| | 1,780 | 3 | 3,470 | |
| F | 3,650 | 1 | 3,650 | |
| G | 1,060 | | | |
| | 1,360 | | | |
| | 2,230 | 3 | 4,650 | |
| H | 2,800 | | | |
| | 3,750 | 2 | 6,550 | |
| I | 180 | | | |
| | 220 | | | |
| | 1,570 | | | |
| | 1,900 | | | |
| | 3,200 | 5 | 7,070 | |
| Total | | 21 | 34,680 | (3.47 ha) |

Vegetables (especially aibika and cabbages) were affected by giant African Snails and no control measures seem to have been taken so this may become a serious problem in the future. Problems with pests, as well as problems of decline in soil fertility discussed earlier, in our report, need to be considered at this time before the number of settlers increases and the problem worsens.

From our observations and interviews it was clear that the settlers have worked hard and their gardens are much larger than the gardens they cultivated back in the Carteret Islands. They are continuing to clear the tropical rain forest towards the beach to grow more crops and the average garden size for each household is likely to increase over the next few years.

Opportunities to generate income will become increasingly important in order to pay for items such as school fees and to improve the general welfare of the settlers. At this stage, school fees are often met by 'wantoks' and working relatives. Small projects such as trade stores, and pig, chicken and vegetable production have been proposed as well as the future development of the 1,000 ha block of land allocated for cash cropping at Mabiri. This land is however 30 km from the settlement, so relocation of some of the settlers or a regular form of transportation will have to be considered if they are to make full use of the land for economic purposes.

Most settlers want to be involved in the cash economy and do appreciate help from extension officers but, from their point of view, this aspect is not being emphasised by the provincial government.

The settlers say that at present they do not face any problems with nearby villages. Future relations are hard to predict, population increases and involvement in the cash economy may affect the relationship of settlers with surrounding villages. In addition conflict may arise between different atoll groups, particularly if population increases put pressure on available gardening land.

Overall, we noted that the nine families in the small Carteret village were very happy. They have built houses, planted flowers and fruit trees around the village and established large food gardens. The families that we interviewed told us that they felt it was their new home and that they are much better off than when they lived back on the Carterets. They have plenty to eat and their children are healthier than before so they are determined to make a permanent home on the scheme, despite their longing for the familiar environment and their relatives on the atolls.

After a long period of struggle with the problem of food shortage and the pressures of their new environment the families are now pleased with what they produce. They are full of hope and determination and this is evident from the increasing size of food gardens that they are cultivating.

One must not be too optimistic at this time as it is proposed that families from Nissan, Tasman and Mortlock Islands will settle at the same site and in future there may be problems, due to land shortage for food gardens. As the population increases, the consequent danger of a decline in soil fertility is likely to become important. It will be some time before these problems occur so, for the moment, the settlers are convinced that they have made the right decision to leave the Carteret Islands and make a new home at the Atolls Resettlement Scheme.

## THE CARTERET EXPERIENCE: MOVING INTO THE CASH ECONOMY

The general lack of defined economic opportunities and or any government action regarding the acquisition of additional land for cocoa and copra production continued throughout 1986. Two social work students stayed on the project site in August 1986 and reported that although most settlers were still pleased that they could grow garden produce they were becoming more aware of the limited nature of these activities and of their continuing dependency on the project co-ordinator for advice and on relatives working in Arawa and elsewhere for financial assistance.

The settlers expressed their concern about the delay of planned, community economic activities which are to include a fishing project to be operated by Nissan Island settlers; a trade store project which is to be operated by the Carteret Island settlers, and the Mabiri cocoa and copra project. The settlers mentioned that from the time they settled in they were told they would be involved in these projects but since that time they have not been informed of any progress (August & Kalamoroh, field report, 1986).

Women at the Scheme were now much more interested in commencing some sort of club and in organising both social and economic activities. They felt in need however, of assistance from adult education and women's activities officers and lacked the confidence to take the initiative themselves. The view was expressed again and again that without more contact from extension workers they felt lost and it was clear that on the Provincial Government side the initial enthusiasm to assist the settlers to adapt to a new environment had lost momentum.

When I last visited the project in September 1987, two of the original settler families had returned 'home' to the Carteret Islands because they were frustrated with the long delays in finalising land for cocoa and copra production at Mabiri. One settler told me that people were afraid they would lose their rights to the little land that was available on the islands and ultimately be left without land rights at all. While he could see that eventually they would have to leave the islands and that it was better to put pressure on the Provincial Government to take immediate action to secure agricultural land for cash crop development, others had become tired of waiting. Waiting in a sense, just as they had waited back on the Carterets for the *Atolls Enterprise* to come bringing supplies.

The project co-ordinator who had worked with the original Atolls Resettlement Committee to start the Scheme had also lost his initial enthusiasm and one could sense a general feeling of irritation that the settlers seemed to be still very dependent on outside assistance. The reality that adaptation to a new environment is neither a smooth nor a rapid process seemed to have been forgotten and that the settlers had accomplished all the initial tasks of establishing gardens and building new houses with relative ease.

By September 1987 however, it had been agreed that more decisive action was needed on the allocation of agricultural blocks to the settlers and that a new project co-ordinator would be entrusted with the task of linking the settlers with government and other extension officers. At a general meeting some alternative small scale projects were discussed with the settlers and plans for a community school and youth and women's activities were considered.

A tour of the Atolls by the North Solomons Administrative Secretary and other senior government officials had shown that land loss was continuing on the Carterets. The community school had had to be relocated and those who were familiar with the islands reported that there had been further loss of coconut trees and arable land. So, whether in the immediate future or in the longer term, substantial resettlement of most of the population is inevitable.

## FINAL COMMENTS: LESSONS FOR OTHER LOW-LYING ISLAND GROUPS

Patrol reports from the 1950s described the Carteret Islanders as enterprising independent people who were seen as showing a 'much greater degree of independence of thought and action than mainland people' yet still living 'dangerously and close to marginal subsistence' (A.K. Jackson, 27/7/50). By 1961, a report by Patrol Officer Rochfort, who visited the Carterets in December of that year, showed that planning for the islanders had begun as, despite all their efforts to limit the inroads of the sea, it was considered that -

> What appears to be necessary is for a decisive step to be made to move the people for their own good, for like anybody unwilling to leave their home, they will probably never agree to such a step being made.

Some 25 years later, the reality of resettlement has provided a new and more severe challenge to the self-sufficiency and independence of these atoll dwellers. What is needed by policy-makers, planners and project managers is an understanding of the ambivalence they feel when confronted with the prospect of leaving their island homes and an imaginative Plan of Action to enable them to remain a self-reliant people with the confidence and resources to manage their new environment.

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# CLIMATIC CHANGE AND AGRICULTURAL PRODUCTION IN THE HIGHLANDS OF PAPUA NEW GUINEA

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## INTRODUCTION

About 1.2 million people, one third of the population of Papua New Guinea, live in the highlands above 1,400 m asl in a series of large intermontane basins and valleys, and on plateaux and hillslopes above them (Figure 1). The following account of population and land use is drawn from Brookfield (1964), Brookfield with Hart (1971), Brown (1978) and Golson (1977).

These populous highland communities live in extensive anthropogenic grasslands whose beginnings date back 9,000 years (Golson 1977, Golson & Hughes 1980). They subsist largely on cultivated crops, the most important of which is the sweet potato (*Ipomoea batatas*). There is considerable variation in agricultural practices throughout this large area, however the separation of sweet potato from the mixed plantings of other crops such as sugar cane, taro, yam, beans and green, leafy vegetable is normal practice (Golson 1977:602). Preparation of the grassland soils through tillage is widespread and the staple, sweet potato, is commonly grown in mounds or in flat-bed plots formed within a grid of garden ditches.

Population densities are commonly in the order of 40 persons/km2 and locally may rise to 120 and even 200.

Although the sweet potato and some recently introduced crops are grown by communities living up to 2,770 m, the most productive areas are in a vertically and laterally restricted zone below this. Four-fifths of the population lives in a series of intermontane valleys between 1,400 m and 2,000 m (Golson 1977:607). The most important of these highly productive areas are, from east to west, Goroka-Asaro, Chimbu, the Wahgi Valley, Wabag and Tari (Figure 1).

Temperature declines with altitude and above about 2,000 m there is a noticable decrease in agricultural productivity, the nature of which is described in greater detail below. Just as the zone of close settlement and most productive cultivation is sharply delimited above, so it is equally sharply delimited below, over an altitudinal range of about 1,225-1,525 m (Golson 1977:607). The reasons for this have less to do with temperature than with other local and regional factors. The intermontane valley bottoms do not go below this altitudinal range and communities living below this range do so on the outward-facing sides of the mountain ranges which delimit these valleys. Other factors include characteristically steep and rugged terrain, persistent cloudiness, proneness to drought and high incidence of malaria (Brookfield 1964:31-4).

## CLIMATE, SETTLEMENT AND AGRICULTURE

The present climate of the highlands varies systematically along a gradient from east to west, and these variations are reflected in the settlement patterns and agricultural systems. The highlands between 1,400 and 3,000 m have a mean annual maximum temperature of about 24°C and mean annual minima of about 13°C (McAlpine *et al.*, 1983:160-161). Seasonal variation in both temperature and humidity regimes is not marked. Ground frosts are likely to occur above about 1,500 m, their incidence and severity increasing with elevation. Frosts are more likely to occur during prolonged dry periods and in physiographic locations conducive to their development such as upland valleys subject to cold air drainage and ridges leading to montane areas.

McAlpine *et al.* (1983:160-161) divide the highlands climatic regime into two main classes: lower montane subhumid (Type 8) and lower montane humid (Type 9).

Lower montane subhumid. The area in the eastern highlands around Goroka and Henganofi experiences relatively low annual rainfall (1,500-2,000 mm) with moderately high seasonality. Mean annual water surpluses are not large, but soil moisture is only very rarely depleted to drought levels.

Lower montane humid. This climate class spreads over most of the rest of the highlands area shown in Figure 1. Rainfall in these areas is between 2,000 and 3,500 mm annually, with slight to moderate seasonality. Mean annual water surpluses are high and there are no occurrences of drought.

For the purposes of this study the highlands is divided into three rather than two zones: eastern, central and western.

In the eastern zone, which extends from east of Kainantu to east of Goroka (Figure 1), the valley bottoms are generally at a lower altitude, 1,200-1,500 m, than elsewhere in the highlands. This zone has the lowest rainfall, less than 2,000 mm, and a distinct dry season from May until November. There are frequent periods of soil moisture stress during the dry season and short periods of drought are common. The eastern zone is characterised by small areas of densely populated valley bottom land, especially along the major rivers, surrounded by extensive areas of sparsely populated grassland. Moisture stress is a moderately severe limiting factor on agricultural use of these grasslands, even for moisture-stress tolerant crops such as sweet potato and tapioca or cassava. In prehistoric times extensive areas of land were terraced to retain soil moisture in the garden beds (Sullivan *et al.*, 1986).

The central zone, from Goroka in the west to Mendi in the east, is characterised by higher rainfall, averaging about 2,500 mm, and the dry season is very much less pronounced. Soil moisture stress is very much less a problem and droughts are infrequent. The valley floors and slopes below 2,000 m in this zone are the most productive in the region and they support the highest population densities. Examples of highly productive and heavily populated areas include the Goroka-Asaro Valley, Chimbu, the Wahgi Valley between Kudjip and Mt Hagen and the Lai Valley near Wabag.

Further west again the rainfall is even higher at 3,000-3,500 mm, there is very little seasonal variability in its distribution and soil moisture stress is uncommon. However, the higher rainfall results in increased cloudiness which to some degree inhibits plant growth, including that of crops. More importantly, much of the western zone is above 2,000 m, i.e. above the agriculturally most productive altitude range (Figure 1). For these reasons the population densities are generally lower than those in the central zone. The exception is the heavily populated Tari Basin which is environmentally more like the central zone than it is like the rest of the western zone.

The highlands area shown in Figure 1 as having a cover of grassland and other anthropogenic types of vegetation totals about 7,700 km$^2$. Of this, about 5,700 km$^2$ or 74% of the total is below 2,000 m. West of Mount Hagen there are several large tracts of land which are almost entirely above 2,000 m and which together total about 1,350 km$^2$. These include the Laiagam-Kandep area which has a moderately high population density and the Ialibu area where the population density is low. In the rest of the study area all but the highest valley side slopes are below 2,000 m.

## THE RELATIONSHIPS BETWEEN ALTITUDE AND AGRICULTURAL PRODUCTION

### Subsistence crops

Temperature declines with altitude, and because of this there is a progressive decrease upwards both in the number of food crops that can be grown and in their yields. As an example of these trends we have used data collected from garden surveys in the Porgera Valley carried out as part of the Porgera gold project environmental planning study (Hughes & Sullivan 1987). The altitudinal zone covered by our study, 1,900 to 2,450 m, is precisely that which we argue below will be most dramatically affected by any temperature rise. Our Porgera investigations used as their starting point the detailed study of subsistence

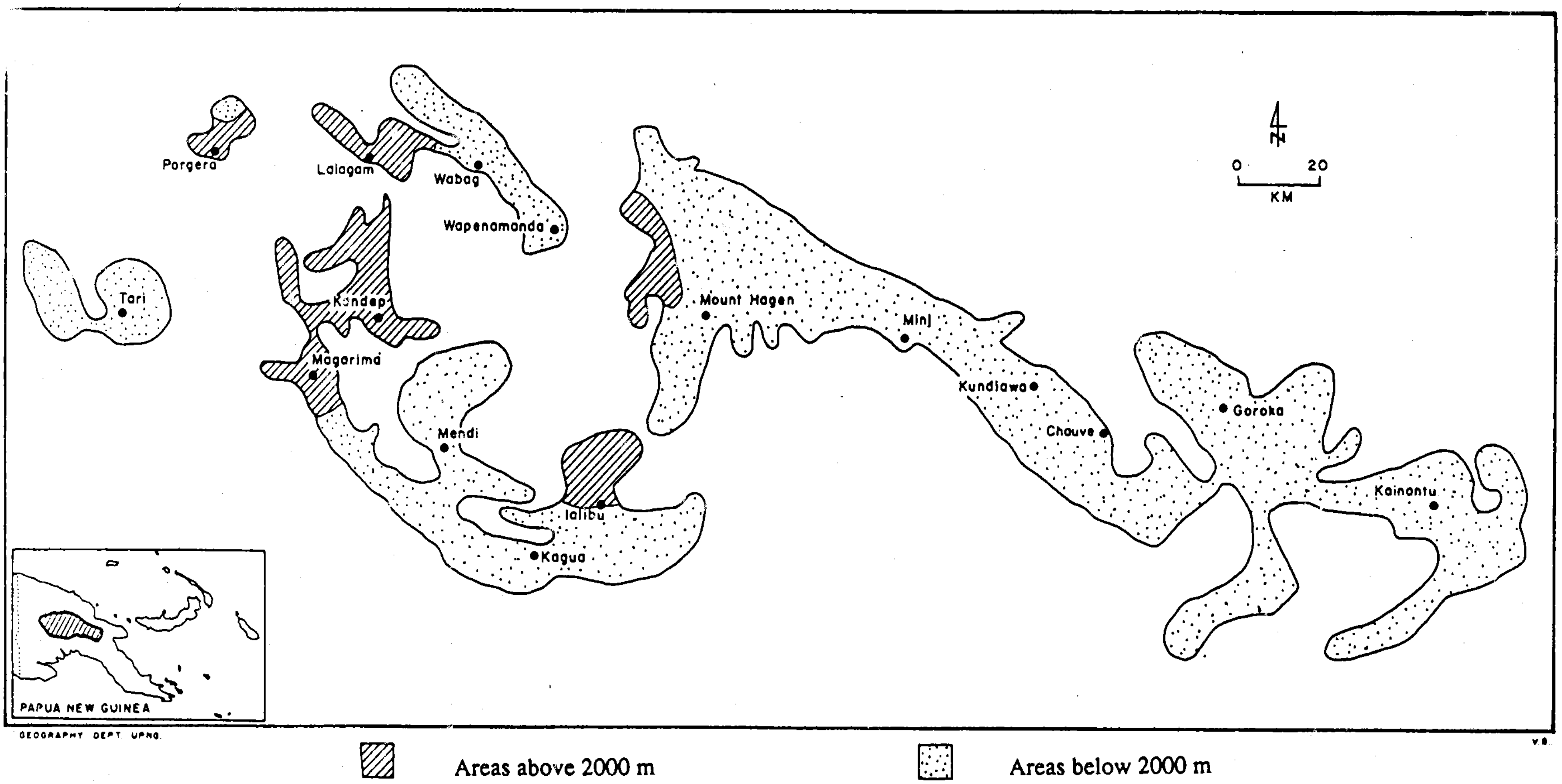


Figure 1. Highlands areas with predominantly anthropogenic vegetation.

horticulture in Enga Province undertaken by Bourke & Lea (1982), including their assessment of the altitudinal limits of crops (Table 1).

The usual lower altitudinal limit for virtually all of the crops shown in Table 1 is below 1,500 m. The exceptions are the cultivated 'karuka' (1,850 m), radish (2,100 m), banana passion fruit (2,300 m), pyrethrum (2,400 m) and wild 'karuka' (2,550 m).

At a number of localities in the Porgera Valley garden surveys to identify land use practices were carried out in conjunction with villagers. The primary aims of these investigations were to examine the altitudinal variation in crop types, maturation periods and yields, and the intensity of land use. Four localities were studied in some detail: Waruwari Ridge (GS1) at 2,450 m, Alipis (GS2) and Payam (GS3) at 2,300 m and Tibinini (GS4) at 1,900 m (Figure 2).

The register of crops grown at each locality was essentially the same as that described by Bourke & Lea (1982) and summarised in Table 1. There was a distinct decrease with increasing altitude in the number of crops that could be grown. For example at the highest locality (GS1) bananas, corn, and pumpkin could not be grown successfully whereas all three were commonly observed growing at GS2, which is only 150 m lower in altitude.

There was also an increase with increasing altitude in the time needed for crops to reach maturity. At the highest locality, GS1, sweet potato takes 12 months, and taro 15 months, to mature. At GS2 and GS3, 150 m lower, the maturation periods are 10-12 months and 12-15 months respectively. Villagers at Alipis (GS2) had a clear perception that both the range of crops and their yield declined with increasing altitude while the maturation period increased. They were adamant, for example, that gardens around the Yuyan Mission down-valley at an altitude of 1,800-2,000 m were much more productive on all three counts. At Yuyan sweet potato matures in about eight months and taro in less than 12 months.

At Tibinini (GS4), which at 1,900 m is at about the altitude of Yuyan Mission, a predictably wider range of crops was grown than at GS2 or GS3. Maturation periods were however unexpectedly long with sweet potato maturing in 12 months and taro in 18 months. Yields were perceived by the Tibinini villagers as being low compared with those of their neighbours. This suggests that factors other than altitude influence the productivity of gardens, at least in this area. Variations in microclimate, soils and aspect might account for these differences. Whatever the cause, clearly care must be taken in extrapolating findings (and predictions) from one locality to another.

Cash crops

Cash cropping is an increasingly important component of the highlands economy. Coffee (*Coffea arabica)* is the main cash crop and is grown both on a large scale, in commerical plantations, and on a small scale in village gardens. Other important crops are cardamon, tea and vegetables.

Coffee is the most important agricultural export for Papua New Guinea and over the five years 1980-1984 coffee receipts average K95 million a year (Shaw *et al.*, 1986). In 1982/83 more than 190,000 households in the highlands were growing Arabica coffee and household and plantation production combined accounted for more than 90% of the total coffee produced in Papua New Guinea.

Arabica coffee can be grown throughout the highlands at altitudes between 2,200 and 1,000 m (Shaw *et al.*, 1986, Figure 7). It thrives most successfully in the central highland zone (Figure 3) where rainfall and cloudiness are not too great. In recent years large areas of grassland in drier areas in the eastern zone have also been converted to coffee production.

## EFFECTS OF A RISE IN TEMPERATURE

In the scenario followed in this study, it is predicted that a doubling of carbon dioxide levels would result in a 2°C rise in temperature in the highlands (Liss & Crane 1983:74). In Papua New Guinea there is a regular rate of decline in temperature with altitude (i.e. the lapse rate) between 500 and 3,000 m asl (McAlpine *et al.*, 1983:92-95). Lapse rates ranges from -0.710°C/100 m for maximum temperature to -0.532°C/100 m for minimum temperature and averages -0.621°C/100 m.

## TABLE 1

**ALTITUDINAL LIMITS OF SOME CROPS AT PORGERA**
(metres above sea level)
Based on Bourke and Lea (1984: Table 6.4)

| Common Name | Scientific Name | Usual Maximum | Extreme Maximum |
|---|---|---|---|
| **A. Below 2000 m** | | | |
| 'Aibika' | *Abelmoschus manihot* | 1900 | 1950 |
| Bean, hyacinth | *Lablab purpureus* | 1900 | 2100 |
| Bean, lima | *Phaseolus lunatus* | 1950 | 2250 |
| Bean, winged | *Psophocarpus tetragonolobus* | 1850 | 1920 |
| Cassava | *Manihot esculenta* | 1900 | 1980 |
| Cucumber | *Cucumis sativus* | 1950 | 2020 |
| Ginger | *Zingiber officinale* | 1950 | 2020 |
| Marita | *Pandanus conoideus* | 1750 | 1780 |
| 'Pitpit', lowland | *Saccharum edule* | 1850 | - |
| Rungia | *Rungia klossii* | 1950 | 2510 |
| Taro, Chinese | *Zanthosoma sagittifolium* | 1950 | 2000 |
| Yam, greater | *Dioscorea alata* | 1900 | 1920 |
| **B. 2000-2400 m** | | | |
| Amaranthus | *Amaranthus* spp | 2050 | 2360 |
| Bananas | *Musa* cvs | 2200 | 2350 |
| Bean, common | *Phaseolus vulgaris* | 2400 | 2680 |
| Celery | *Apium gravedens* | 2350 | 2680 |
| Choko | *Sechium edule* | 2350 | 2680 |
| Corn | *Zea mays* | 2450 | 2680 |
| Lettuce | *Lactuca sativa* | 2250 | 2630 |
| Passionfruit, purple | *Passiflora edulis* | 2300 | 2380 |
| Pumpkin | *Curcurbita* spp | 2300 | 2680 |
| Raspberry, black | *Rubus lasiocarpus* | 2300 | 2670 |
| Tomato | *Lycopersicon esculentum* | 2300 | 2630 |
| **C. Above 2400 m** | | | |
| Bean, broad | *Vicia faba* | 2600 | 2630 |
| Cabbage, round | *Brassica oleracea* var *capitata* | 2700 | 2850 |
| Highland 'kapiak' | *Ficus dammaropsis* | 2700 | 2820 |
| 'Karuka' cultivated | *Pandanus jiulianetti* | 2500 | 2730 |
| Leek | *Allium ampeloprasum* | 2650 | 2680 |
| Oenanthe | *Oenanthe javanica* | 2700 | 3000 |
| Passionfruit, banana | *Passiflora mollissima* | 2800 | - |
| Pea | *Pisum sativum* | 2700 | 2740 |
| 'Pitpit', highland | *Setaria palmifolia* | 2700 | - |

| Common Name | Scientific Name | Usual Maximum | Extreme Maximum |
|---|---|---|---|
| Potato | *Solanum tuberosum* | 2700 | 2850 |
| * Pyrethrum | *Chrysanthemum cinerariaefolium* | 2700 | 2850 |
| Radish | *Rorippa islandica* | 2700 | 2850 |
| Raspberry, red | *Rubus rosifolius* | 2800 | 2900 |
| * Reeds, dressmaking | *Eleocharis dulcis* | 2700 | 2820 |
| Shallot | *Allium cepa* | 2650 | 2680 |
| Spring onion | *Allium cepa* | 2700 | 2850 |
| Sugarcane | *Saccharum officinarum* | 2700 | 2730 |
| Sweet potato | *Ipomoea batatas* | 2700 | 2850 |
| 'Tanget' | *Cordyline fruticosa* | 2700 | 2850 |
| Turnip | *Brassica rapa* | 2650 | 2790 |
| Water cress | *Nasturtium officinale* | ? | 2960 |
| * 'Yar' | *Casuarina oligodon* | 2700 | 2820 |

* non-food crops.

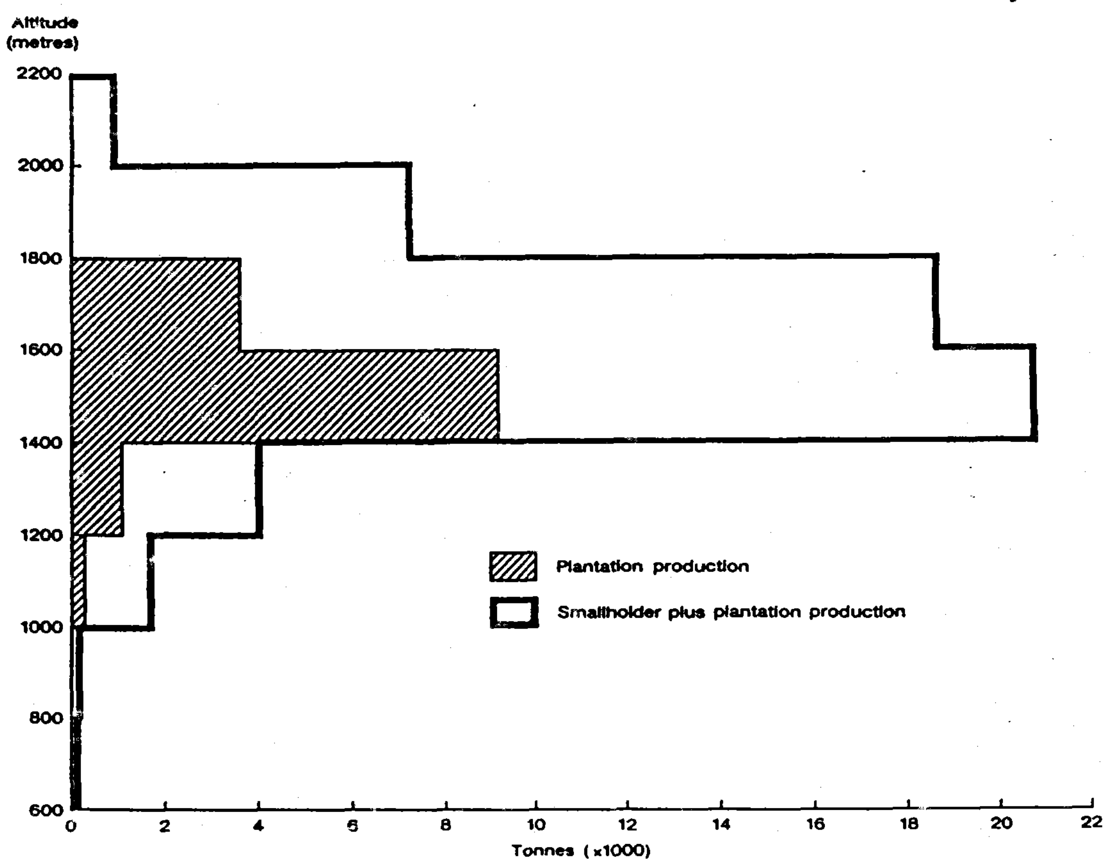


Figure 3. Altitudinal distribution of Arabica coffee production in Papua New Guinea (source: Shaw *et al.* 1986).

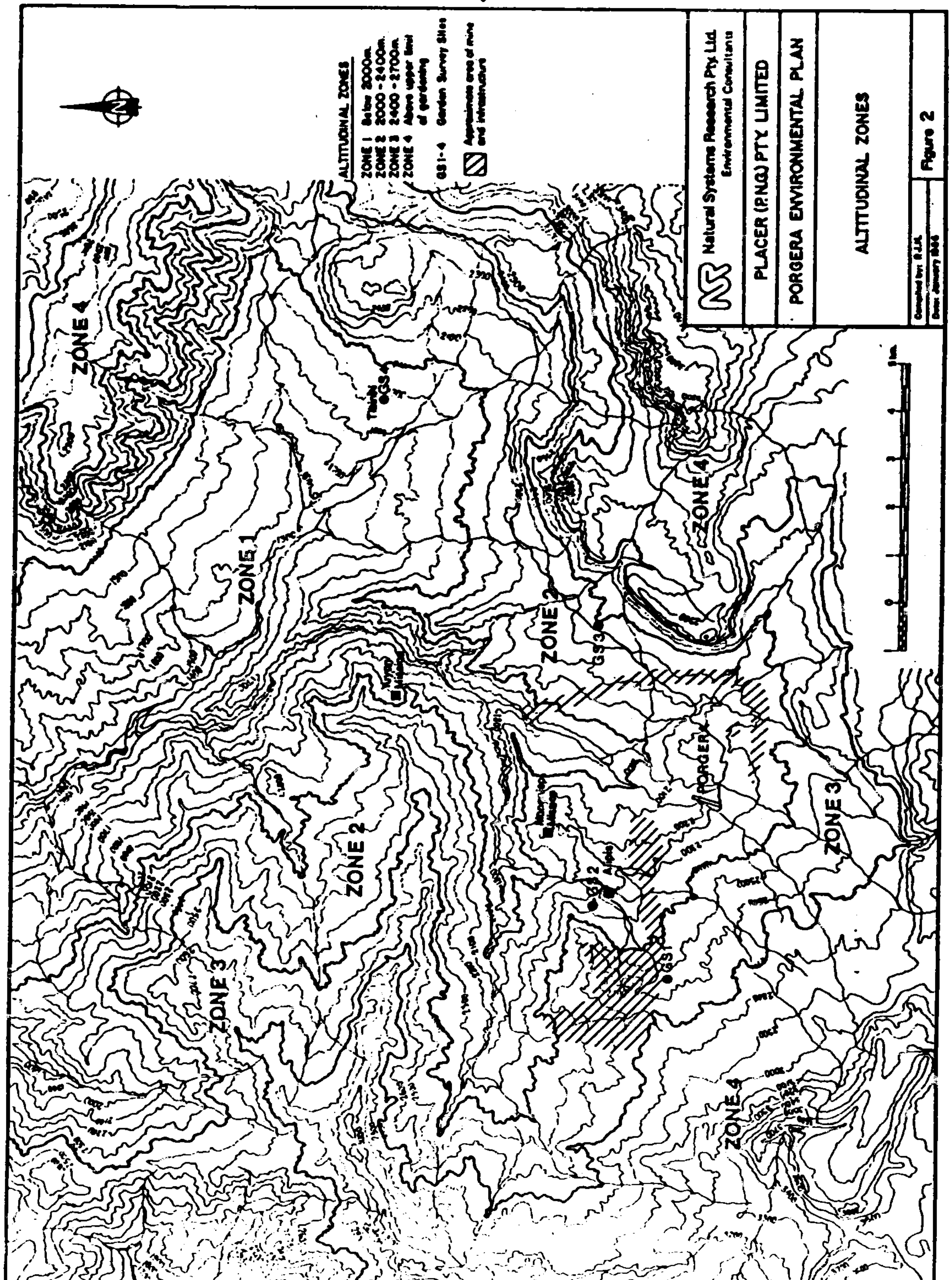


Figure 2. Porgera area altitudinal zones (source: Hughes and Sullivan 1987).

With a rise of 2°C in air temperature there would be a corresponding altitudinal increase of 320 m in present-day temperature regimes. Put simply, the average annual temperature at any given place would rise by 2°C and in the highlands people could move upslope through a vertical distance of about 300 m and still maintain their present temperature regime.

Implications for subsistence and cash cropping

Taking into account only the impact of temperature change, it is likely that presently highly productive areas below 2,000 m would undergo little change, except for low altitude areas in the east which may become even less productive due to hotter conditions. The upper limit of the most highly productive zone would rise to about 2,300 m and this would open up either previously less productively used or new areas of forested land for intensive, productive use. In the eastern and central zones most such land would be on comparatively steeply sloping mountainous terrain above the major intermontane basins and factors such as steepness, thin and unstable soil cover and cloudiness will make such lands less productive for both subsistence and cash (e.g. coffee) cropping than might otherwise be expected. In these circumstances we would expect the expansion in area under coffee to be mainly in the form of small-holder plots rather than commerical plantations. Our estimate from the topographic maps and personal observations throughout the highlands is that there would be an increase of about 10% in the area of more highly productive land.

The most dramatic likely effect would be in the western zone where large areas of valley bottom land presently of marginal or low productivity, simply because it is above 2,000 m, could come into intensive use, for both subsistence gardening and possibly coffee. In perhaps as much as 50% of the higher altitude area marked on Figure 1 the only major constraint to much greater productivity is altitude/low temperature.

Just as the upper limit of highly productive cultivation would rise by 300 m, the upper limit to which the staple crop, sweet potato, could be grown would rise from about 2,700-2,800 m to more than 3,000 m. This would result in an estimated increase of 10-20% in the area of land that could be brought gradually into agricultural production for the first time ever.

The overall effect of a rise in temperature therefore would be to increase both the total area of land that could be used for agriculture (by about 10-20%) and the area that could be used highly productively for both subsistence and coffee gardening (by about 30%).

The example of Porgera

The agriculturally most productive part of the Porgera Valley today is the uppermost part of Zone 1 (below 2,000 m) shown on Figure 2. Productivity as measured by the range of crops, yields and length of maturation periods is much higher at Yuan Mission than, for example, at Alipis. A 2°C rise in temperature and the concomitant 300 m rise in the upper limit of the most highly productive zone would mean that most of Zone 2 would become much more highly productive than it is now. The present upper limit to which agriculture is currently practiced is about 2,400 m (the upper limit of Zone 2), and it would be possible to extend this to about 2,700 m without changing present agronomic practices. Such an extention would encompass Zone 3 as marked on Figure 2.

Very little coffee is grown in the Porgera Valley at present. Carrad (1982:150) estimated that in the early 1980s only 5% of households in the Valley grew coffee. All of this would have come from plantings in Zone 1 below 2,000 m. With a rise in temperature it would be possible to grow coffee in much of Zone 2.

Thus even in a relatively small valley such as Porgera a rise in temperature and consequent change in the altitudinal limits and productivity of crops would have a major impact.

Implications for social and demographic change

There is little doubt that these changes would be beneficial for the highlands regions as a whole, especially if the potential 'profits' from increased production of both subsistence and cash crops were channelled into activities aimed at improving the social and economic conditions of their communities. Provided the rate of population increase did not outstrip the rate at which the newly-created 'productivity' could be harnessed, the present trend towards increased land pressure and associated social strife could be eased or in places even halted. Presently disadvantaged people living on marginally-productive lands at higher altitudes would benefit most from improved production.

If the temperature rises as projected, the population of the highlands will probably increase at a greater rate than it would have had the temperature not changed appreciably. Inevitably there will be a degree of demographic redistribution and social disruption, however the prehistoric and post-European contact evidence suggests strongly that highlands people are not only capable of adapting to changes but indeed that they thrive on change.

OTHER EFFECTS

Because conditions would be warmer, there is a very real possibility that diseases such as malaria would move upslope and that, for example, many of the valleys which currently have a low incidence of malaria would become highly malarial. Such a possibility would be enhanced if the postulated increased productivity was accompanied by increased population densities. Gorecki (1979), for example, argued that periods of abandonment of the normally highly populated Wahgi Valley floor and other highland valleys in the recent prehistoric past (i.e. the last 250 years) was the result of the spread of epidemics, possibly malaria.

Throughout this study we have argued that changes will occur caused solely by an increase in temperature. Temperature changes would also be accompanied by changes in other parameters such as humidity, rainfall and consequently soil moisture. An increase in temperature would result in increased potential evapotranspiration and without increased rainfall there would be a decrease in soil moisture availability. It is unlikely that rainfall and soil moisture will decline to a point of inhibiting plant growth anywhere but in the eastern highlands. If, as Glenn McGregor argues for elsewhere in Papua New Guinea, increased temperature is accompanied by decreased rainfall in already seasonal areas, this might have a major deleterious effect on agricultural productivity, especially at the eastern end of the highlands.

IMPACT ON NATURAL ENVIRONMENT

Any climatic warming would result in gradual upslope movement in the montane forest vegetation and sub-alpine grass and shrubland zones. Such natural changes would be very slow and might not become evident for decades. The upper limit of the lower montane forest, which extends up to about 1,500-2,000 m (Johns 1977), would rise to about 1,800-2,300 m. This would however be matched by the even more rapid rise in the upper limit of the intensively used and most highly productive agricultural zone. Thus it is unlikely that there would be any extention of the area of this forest type, which has suffered the brunt of human impact through clearance over the last 9,000 years. Indeed it is likely that the rate of destruction of this already endangered ecological zone would accelerate.

The upper limit of the mid montane forest zone would gradually rise from 2,700-3,000 m to 3,000-3,300 m. This would be matched by the concurrent and probably even more rapid rise in the practicable upper limit of agriculture and this forest type would certainly not expand in area and would probably be removed at an even greater rate than under present environmental conditions.

The upper montane forest would remain relatively unaffected by human impact. Its present altitudinal range is relatively narrow, from 2,700-3,000 m up to about 3,200 m. There are only very small areas of mountain tops higher than this and an upwards change of 300 m in its altitudinal range would result in a very dramatic decrease in its total area and geographic distribution.

There would be an even more dramatic decrease in the total area and geographic distribution of the sub alpine and alpine grasslands and shrublands. They would disappear from most of Papua New Guinea and would be well represented only around the summits of Mt Wilhelm and Mt Giluwe.

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