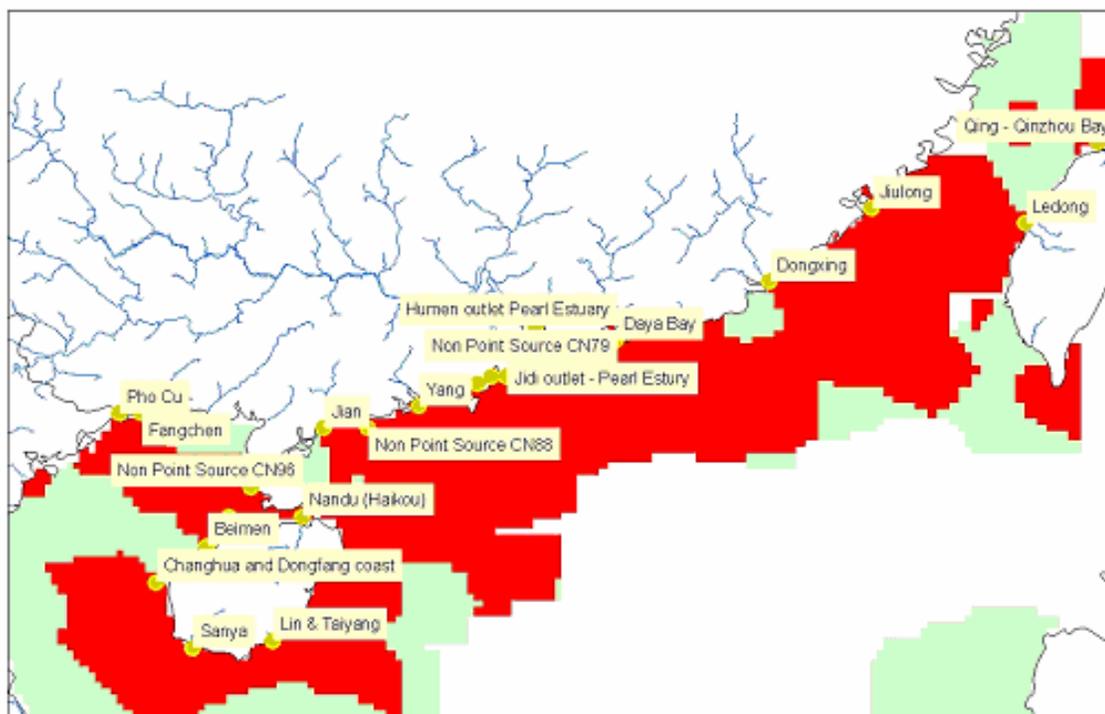




**Modelling the Carrying Capacity of the South China Sea Marine Basin with respect to Nutrient Loading from Land-Based Sources in the Context of the UNEP/GEF Project Entitled:**  
***“Reversing Environmental Degradation Trends in the South China Sea and Gulf of Thailand”***



10X Loading



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Cover Illustration: The Chinese coast showing areas that are more (red) and less sensitive (green) to nutrient input from land. Dr. Anond Snidvongs

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## MODELLING THE CARRYING CAPACITY OF THE SOUTH CHINA SEA MARINE BASIN WITH RESPECT TO NUTRIENT LOADING FROM LAND-BASED SOURCES

### INTRODUCTION

The UNEP/GEF South China Sea Project Document specifies that the Land-based Pollution Component should *evaluate carrying/assimilation capacity of sub-regions and sensitive ecosystems and transboundary movements of contaminants within the South China Sea*. Evaluation of the carrying capacity of an open ecosystem with respect to contaminants can be done in a variety of ways, perhaps the simplest of which is to estimate the 'assimilative capacity, that is the capacity of the ecosystem to internally absorb or convert some or all of the contaminant through some process, natural or manmade, into forms that have negligible impact on the biological processes of that system and are not exported into neighbouring ecosystems. The ecosystem is said to have a high assimilative capacity if all, or a large fraction, of the contaminant input is removed and the net export to the neighbouring ecosystems is either zero or only a small fraction of the input. The ecosystem is said to have a low or no 'assimilative' capacity if only a small fraction, or none, of the contaminant input is removed within the system and the export of the contaminant to neighbouring ecosystems is equal to, or almost equal to, the input. Some ecosystems may even have a negative 'assimilative' capacity if the export of a contaminant to the neighbouring ecosystems is greater than the total input to the system. Such a condition would indicate that there exist one or more internal sources of the contaminant within the system.

The fifth Meeting of the Regional Working Group on Land-based Pollution (UNEP, 2005) agreed to use the ambient concentrations of contaminants in coastal waters as indicators of the input of contaminants derived from riverine sources. Subsequently, the Regional Scientific and Technical Committee (RSTC) endorsed this approach and recommended that SEA START RC of Chulalongkorn University undertake a regional project to estimate the carrying capacity of the open shelf system based on its natural capacity to assimilate contaminants, in particular nutrient inputs from land. The RSTC recognised that the modelling of heavy metal inputs and impacts required more reliable data for heavy metal concentrations in coastal waters and loading in the South China Sea marine basin than are currently available.

### CONCEPTUAL FRAMEWORK

Contaminant inputs into a coastal system are naturally subjected to physical and biogeochemical processes that effect the concentration of the contaminant in the water column. A substance or property whose concentration depends solely on physical transport and dilution is said to be a 'conservative' substance. Salinity is an example of such a property. Most contaminants are non-conservative and therefore their distributions are subject to other processes in addition to physical transport including: biological uptake and release; adsorption and desorption from suspended and sedimentary particles; and interaction with the atmosphere. If the physical transport and mixing of a contaminant in a parcel of water can be estimated then the difference in concentration distribution of a non-conservative contaminant may be assumed to be due to additional processes

In an open shelf system, physical transport and mixing may be estimated using a variety of numerical models based on the conservation of mass and salinity. Such principles have been known and applied to numerous coastal systems such as those considered under the Land Ocean Interactions in the Coastal Zone (LOICZ) core project of the International Geosphere Biosphere Programme (IGBP). Over most of the South China Sea continental shelf, water depths of approximately 50-80 metres generally coincide with the thickness of the surface, mixed layer. This means that modelling may be carried out on a 2-dimensional basis making the assumption that the surface, mixed layer is vertically homogeneous. This assumption simplifies both the modelling and data requirements substantially.

The mass balance of a non-conservative property of a two dimensional water mass can be estimated from the input and output of such a property along the two horizontal axes, physical advection and mixing terms and ambient concentration of the property. A transfer coefficient can be estimated for each water parcel. The conceptual framework for the modelling system is illustrated in Figure 1. Exchange of water and nutrients between the South China Sea and adjacent water bodies, such as the Western Pacific Ocean, East China Sea, Sulu Sea and Java Sea are all assumed to be zero due to the narrow widths and

shallow depths of most channels/straits connecting the South China Sea with these water bodies. The hydrographic properties of water masses on each side of the Bashi Channel, the largest channel that connects the South China Sea with the Pacific, are clearly distinct over distances of only a few hundreds kilometers (Zhang and Su 2006) suggesting limited exchange between the two seas.

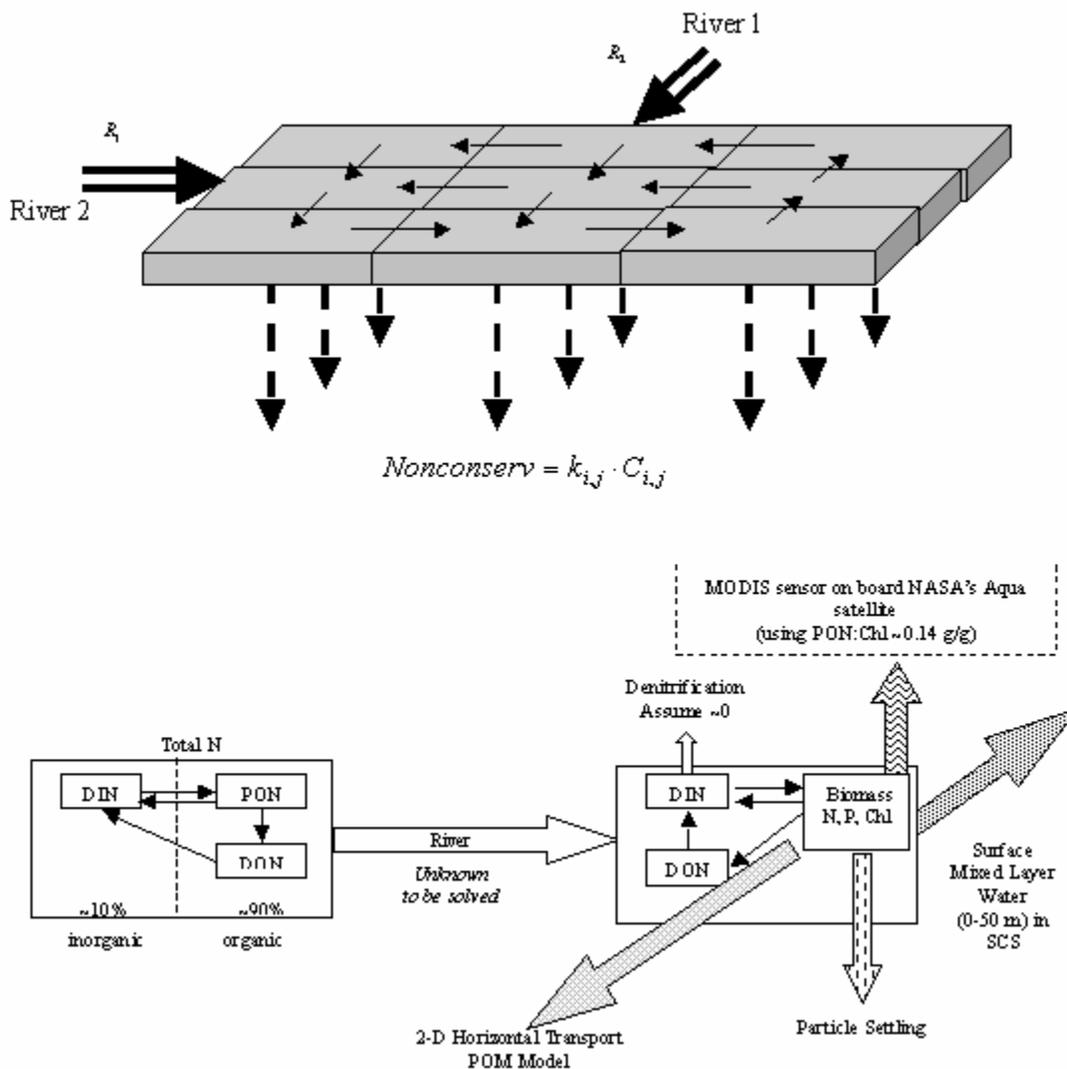


Figure 1 Conceptual framework for the modelling system and material transfer processes within the South China Sea marine basin.

Simulation of the ambient concentration of a property under different contaminant loads may be undertaken assuming the same physical transport terms and transfer coefficients. The ambient concentrations obtained from the model can be compared with water quality standards for the property, such as those agreed by ASEAN. The carrying capacity of an open shelf system can be said to have been exceeded when the ambient concentration exceeds the standard.

## APPROACH

Nutrient inputs from land via rivers into tropical seas are rapidly assimilated by phytoplankton such that they are generally not found in dissolved inorganic form but largely (>80%) in the form of organic particulates. The biomass of primary producers, particularly phytoplankton, in a tropical semi-enclosed coastal sea such as the South China Sea may be assumed to be directly related to the total loading of essential nutrients (N and P) derived from the nearby land mass. Consequently, nutrient elements carried

by rivers become part of the particulate organic pool in the surface water layer and may be assumed to be eventually removed into deep water layers or to sediments through organic particle settling.

At any given location and at any given time, the concentration of organic particulate matter is not only controlled by biological/ecosystem production and the vertical removal of particles but also depends on horizontal transport to and from adjacent water masses. The physical transport terms, including advection rates and various mixing processes, can be estimated using hydrodynamic principles but, in an open water system where the horizontal gradients of contaminant and particulate concentrations are usually small, mixing does not cause large net horizontal transport and only the advection term is significant. This can be practically estimated using an ocean circulation model driven by external forcing, such as wind stress, and internal forcing, such as density and pressure gradients.

Organic particles that settle from the euphotic surface, mixed layer into deeper water layers continue to oxidise and deplete dissolved oxygen in the bottom water masses. The capacity of the system to maintain above zero concentrations of dissolved oxygen depends on the replenishment of oxygen through vertical exchange across the thermocline from the surface, mixed layer (which is assumed to be saturated with oxygen) and through the horizontal transport of dissolved oxygen from adjacent deep waters that can also be modelled. Figures 2 and 3 illustrate the observed surface chlorophyll concentrations and deep water oxygen concentrations derived from MODIS satellite data in February and May.

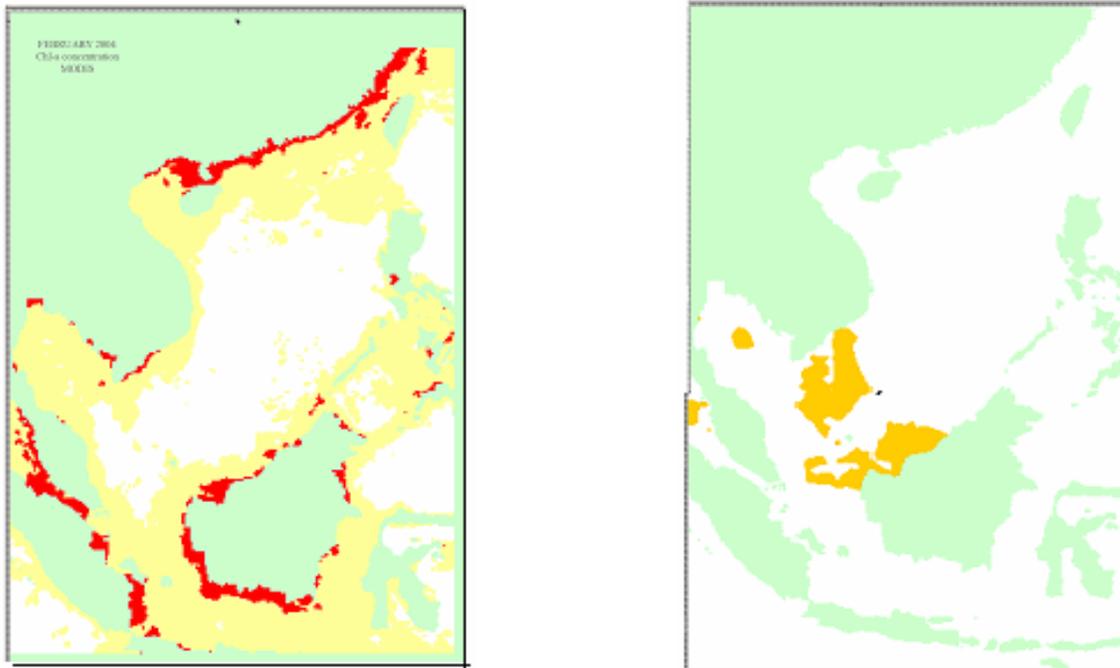


Figure 2 MODIS satellite observations of surface chlorophyll (left) and oxygen concentration (right) in the deep layer beneath the surface, mixed layer for the month of February. Red and yellow indicate areas where concentration of surface chlorophyll are  $0.2-2 \text{ mg/m}^3$ , and  $>2 \text{ mg/m}^3$ , respectively. Orange indicates areas where dissolved oxygen concentration is less than  $3.5 \text{ mg/l}$ .

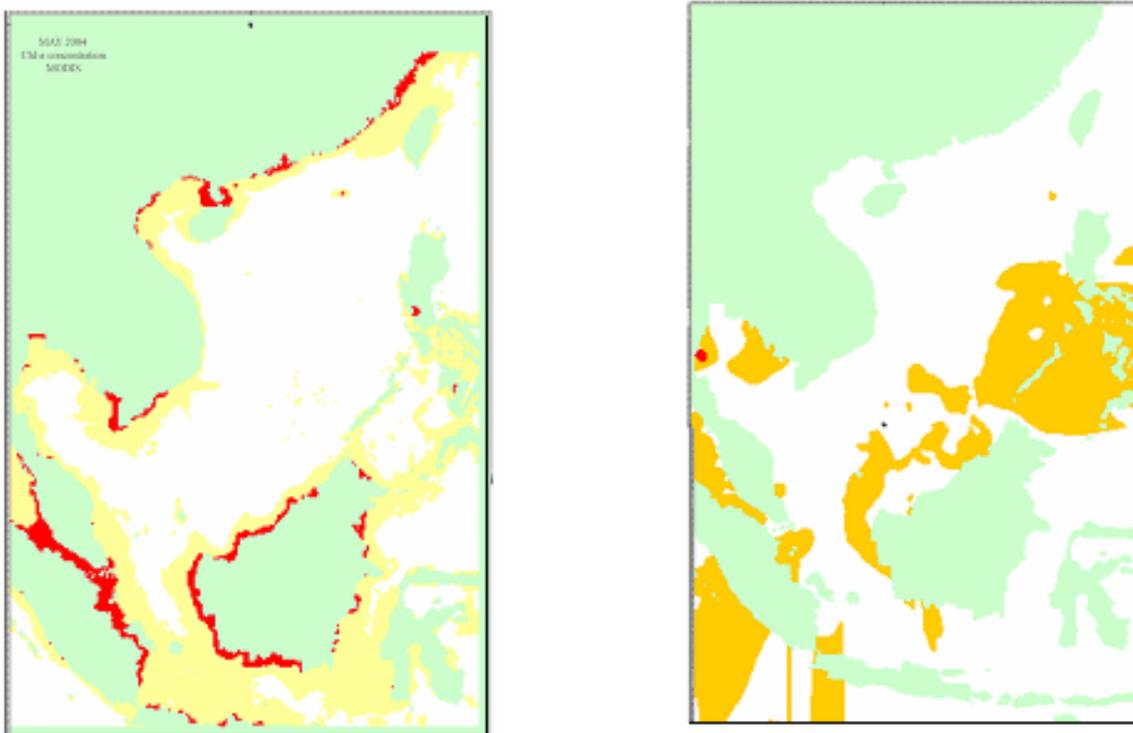


Figure 3 MODIS satellite observations of surface chlorophyll (left) and oxygen concentration (right) in the deep layer beneath the surface, mixed layer for the month of May. Red and yellow indicate areas where concentration of surface chlorophyll are  $0.2-2 \text{ mg/m}^3$ , and  $>2 \text{ mg/m}^3$ , respectively. Orange indicates area where dissolved oxygen concentration is less than  $3.5 \text{ mg/l}$ .

Blooms of phytoplankton in coastal waters induced by land-derived nutrient loading were cited in the Transboundary Diagnosis Analysis (Talaue-McManus, 2000) as one of the top priority impacts of land-based activities in the South China Sea. This report recognises that different coastal areas could have different capacities to assimilate nutrients and, therefore, not all nutrients delivered from nearby land masses end up in planktonic biomass in the area. Dispersion as well as particle settling, were suggested as important processes that remove nutrients from the surface water system that could also induce anoxia in bottom water masses. These removal processes operating in the surface, photic layer of the sea can be estimated and the potential assimilative capacity and hence “carrying capacity”, of each sub-region of the South China Sea can be determined.

## METHODOLOGY

The mass balance model for phytoplankton biomass and dissolved oxygen as functions of total nutrient loading were calibrated and verified using contemporary baseline ambient concentrations and loading. Once the model was satisfactorily calibrated, it was used to simulate such variables in both surface and deep layers of the South China Sea. This model couples ocean circulation with the biogeochemical mass balance to simulate the geographic distribution of phytoplankton biomass and bottom anoxia under different scenarios of nutrient loading from rivers into the South China Sea. Such a model is an objective approach to quantifying the net capacity of the natural systems within the South China Sea to maintain the concentration of dissolved oxygen at a level sufficient for organisms to survive and ecosystem function and services to be maintained. The model was run to achieve steady state over a time step of 1 month and has been developed based on the following assumptions:

- Chlorophyll and oxygen concentration in the surface layer are the state variables of the water column that functionally respond to land-based nutrient loading;

- The upper/surface water is defined as the layer between the sea surface and a depth of 50 m or the sea bottom, whichever is less;
- The water in the surface layer is vertically well mixed and can only move horizontally due to wind forcing calculated using the Princeton Ocean Model (POM);
- Suspended particulate biomass in the upper layer is removed by particle fallout that follows a first-order kinetics; and
- Organic particles respire in the lower layer and consume oxygen.

### Ocean Circulation and Transport Modelling

Physical oceanographic data, comprising monthly wind, temperature, salinity, surface current and bathymetry, were compiled from regional and global sources such as NOGAPS, NOAA, JODC and SEAFDEC. A common bathymetry and grided modelling domain was created for the South China Sea using spatial grid of  $0.1^\circ$  in both horizontal dimensions. The Princeton Ocean Model (POM) was run for the defined domain using wind and density as the primary forcing functions. The model was run both in barotropic and baroclinic modes so that both depth-integrated transport and velocities in each layer were obtained. The monthly aggregated surface velocity from the baroclinic output of the POM and the resulting u and v components of the vectors are interpolated to obtain the surface current streamline that was verified against the observed surface current from JODC ship-drift data as shown in Figure 4.

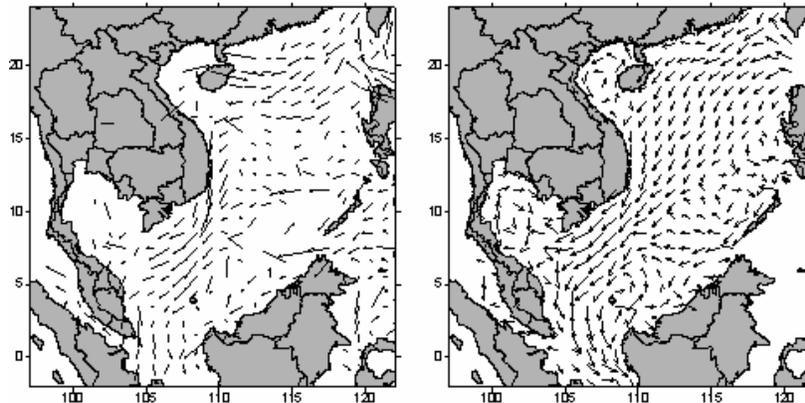


Figure 4 A comparison between JODC current implied from ship drift data (left) and POM output in this study. Data were aggregated to 1-degree.

The net horizontal transport among grids in the domain was calculated from the barotropic output of the POM and the monthly output was manually checked to ensure that quasi-steady state was maintained in all grids.

### Compilation of Ambient Concentration Data

The depth integrated phytoplankton biomass expressed as chlorophyll in the surface, mixed layer and dissolved oxygen in deep water layer were compiled from oceanographic profiling station data from global and regional sources, such as NOAA (WDC-A), JODC, WESTPAC-GoT and SEAFDEC. To maximise the aerial coverage from the limited available data, data from the same month but for different years between 1970 and 2004 were combined.

A preliminary review of profile data from major global and regional sources indicated that data from these sources could contribute up to about 20% of the monthly mixed layer biomass (chlorophyll) and about 70% of the monthly deep layer dissolved oxygen contours for the South China Sea. To fill in the remaining gaps in space and time, additional data from national sources were compiled. It is not absolutely necessary that chlorophyll and oxygen data are completed for all 12 months to make good contour maps of these variables. Missing data in space and time can always be interpolated using a mathematical function.

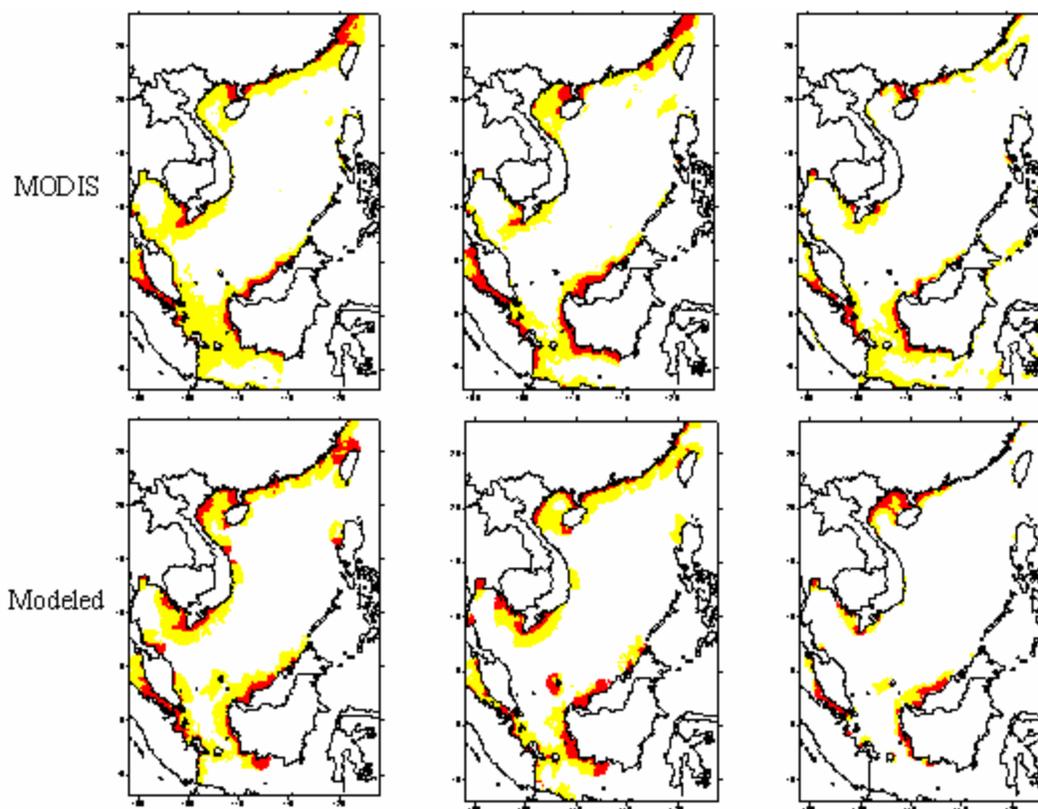


Figure 5 A comparison of MODIS observations and modelled chlorophyll concentration

### Biogeochemical Mass Balance Modelling

A tool for the estimation of the phytoplankton biomass and dissolved oxygen concentration in the South China Sea was developed and the model was based on the principle that the South China Sea is a closed system and that the concentration at any location, in time and space, depends only on internal physical transport and non-conservative removal, namely particle settling in the case of phytoplankton and chlorophyll, and biological consumption of oxygen in the deep layer.

A computer program was written to reiteratively calculate the mass balance of chlorophyll and oxygen in each grid cell for a monthly time interval taking into consideration both conservative transport and non-conservative production and removal terms. The program was designed such that it could be linked to some standard visualisation tools in order to display the outputs in terms of horizontal contours of chlorophyll and dissolved oxygen. The model was calibrated by forcing with the current loading of nutrients from major rivers and parameterised such that the model outputs best match the observed contours of mixed layer chlorophyll and deep layer DO for the same month.

### OUTCOMES

#### Modelling Principles, Domain and Constraints

The modelling system was based on a series of box models of biogeochemical mass balance, comparable to those used in LOICZ Project but with the individual boxes connected into a horizontal 2-dimensional array that covered the entire South China Sea marine basin (Figure 1).

Organic particles that leave the surface layer were originally assumed to be respired and to consume oxygen in the lower layer. This assumption was proven to be unrealistic as no correlation was found between observed surface chlorophyll biomass and the oxygen concentration in the water layer immediately beneath the surface, mixed layer in the South China Sea (Figures 2 and 3). The deep water in many parts of the South China Sea appeared to be better oxygenated than predicted by the model, which might be due to ventilation of the water mass through physical process in the deep water layer.

Modelling of the bottom oxygen distribution was discontinued until a better modelling concept could be developed and applied (Snidvongs 2005).

The modelling domain was between 10°S – 30°N and 99°E – 124°E and segmented into 100,651 grids of dimension 0.1° x 0.1° each. Of this total number, 58,618 grids were ‘sea’ grids. Bottom topography from U.S. National Geophysical Data Center ETOPO5 (<http://www.ngdc.noaa.gov/mgg/global/etopo5.html>) was used and the surface layer was defined as the upper 50 m layer of the sea.

**Surface Circulation**

Circulation of water in the surface layer was estimated using the Princeton Ocean Model (POM) driven by reanalysis of daily wind data for 2004 from U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS—<https://www.fnmoc.navy.mil>). The modelled outputs were verified with observed ship-drift data Japan Oceanographic Data Center (JODC) archive (<http://jodc.go.jp>).

**Mass Balance Equation and Numerical Solution**

The mass balance equation at a quasi steady state for phytoplankton biomass (as indicated by chlorophyll concentration) in any grid *i, j* ( $C_{ij}$ ) can be described as a function of transport in *x* and *y* directions ( $u_{ij}$  and  $v_{ij}$ ), intrinsic removal ( $k_{ij}$ ), and river input ( $R_{ij}$ ) as:

$$u_{i-1,j} \cdot C_{i-1,j} - u_{i,j} \cdot C_{i,j} + v_{i,j-1} \cdot C_{i,j-1} - v_{i,j} \cdot C_{i,j} - k_{i,j} \cdot C_{i,j} + R_{i,j} = 0$$

The total sum of the square of errors (SSE) between calculated and MODIS chlorophyll concentration ([http://oceancolor.gsfc.nasa.gov/PRODUCTS/L3\\_chlo.html](http://oceancolor.gsfc.nasa.gov/PRODUCTS/L3_chlo.html)) for each grid was:

$$SSE = \sum_{i=0}^{250} \sum_{j=0}^{400} (u_{i-1,j} \cdot C_{i-1,j} - u_{i,j} \cdot C_{i,j} + v_{i,j-1} \cdot C_{i,j-1} - v_{i,j} \cdot C_{i,j} - k_{i,j} \cdot C_{i,j} + R_{i,j})^2$$

Monthly input of nutrient by each river ( $R_{ij}$ ) was obtained by optimizing the above inverse problem, that is, optimizing such that SSE is a minimum. Monthly loading of nutrients estimated by the modelling system, developed in this project could be verified for only 19 of the total of 200 rivers around the South China Sea (Figure 6). Nutrient budgets for these 18 rivers were calculated during the LOICZ Project (<http://data.ecology.su.se/mnode/>).

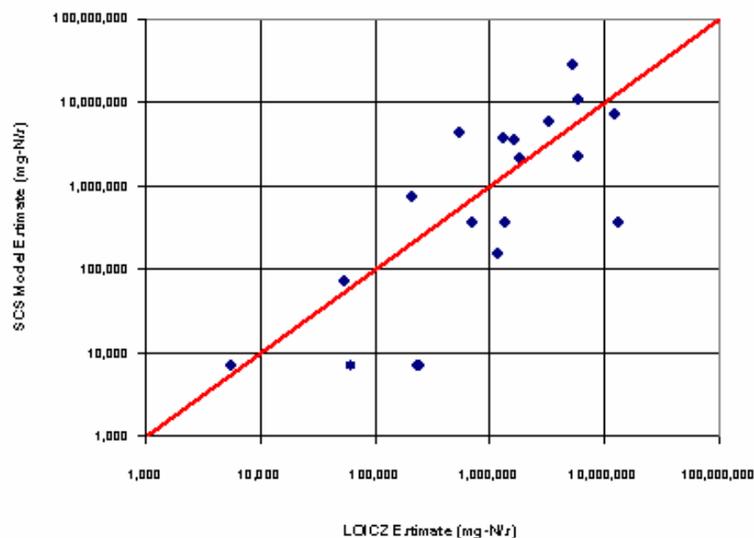


Figure 6 A comparison between modelled loading of total nitrogen and values estimated by LOICZ for 18 catchments in the South China Sea, including Daya Bay, Qing River-Qinzhou Bay, Pearl Estuary, Modao outlet-Pearl River Estuary, Jidi outlet-Pearl River Estuary, Jiulong (China); Terengganu (Malaysia); Agno, Pampanga (Philippines); Pak Phanang, Bangpakong, Tapi, Mae Klong, Prasae, Tha Chin, Chao Phraya (Thailand); Thu Bon, Hau Giang, Phan Thiet Bay (Viet Nam).

### Sensitivity Assessment and Assimilating Capacity

The calibrated model was analysed for its sensitivity to an increase in nutrient loading by rivers. River loadings were increased by ten and one hundred times using the model, and the resultant distribution of surface chlorophyll was calculated (Figure 7). Because there have been no standards for marine chlorophyll concentration adopted in the South China Sea countries, this study assumed that marine waters with concentrations above  $2 \text{ mg m}^{-3}$  would be 'eutrophic'. This arbitrary indicator is well within the range used elsewhere, e.g., from  $1 \text{ mg m}^{-3}$  for the Great Barrier Reef lagoon (Steven *et al.* 1998) to  $10 \text{ mg m}^{-3}$  for the North Sea region (Allen *et al.* 2002).

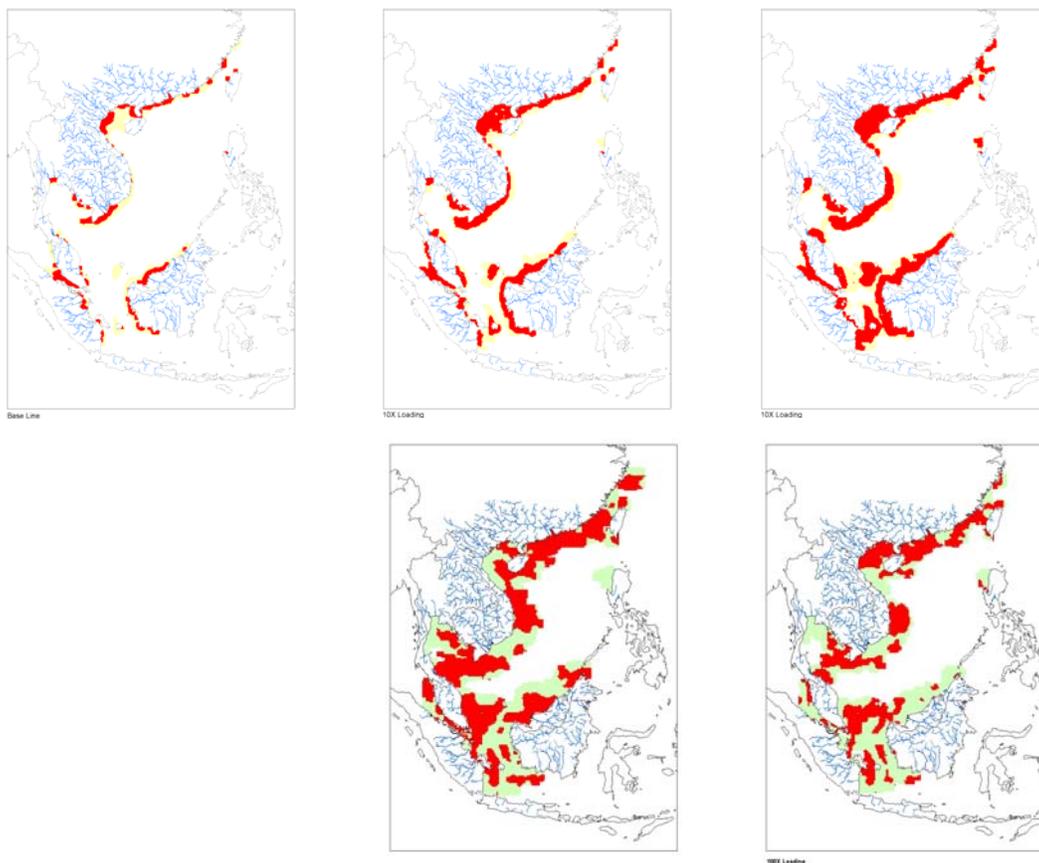


Figure 7 Sensitivity analysis of the responses of chlorophyll concentration to increases in nutrient loading. (10x and 100x) Upper row: Modelled surface chlorophyll concentrations for current baseline nutrient loading (left), for 10 times current nutrient loading (middle), and for 100 times current nutrient loading (right). White  $< 0.2$ , yellow  $0.2\text{--}2$ , and red  $> 2 \text{ mg/m}^3$ , respectively. Lower row: Sensitivity analysis of the responses of chlorophyll concentration to increases in nutrient loading. Legend: red = high sensitivity (response is proportionally higher than loading increase), low sensitivity response is proportionally lower than loading increase), white = chlorophyll concentration not response to land-based nutrient loading.

An area was said to be sensitive to land-based nutrient loading and had a higher risk of becoming eutrophic, that is, it potentially has a low assimilative capacity, when the chlorophyll concentration increased disproportionately.

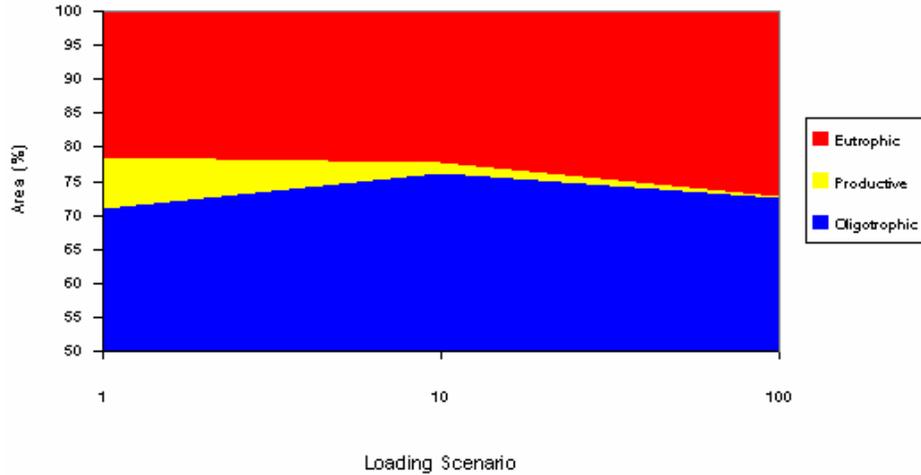


Figure 8 Proportion of the area classified as eutrophic, mesotrophic and oligotrophic under nutrient loading scenarios of 1x present load, 10 and 100 times present load.

**High-Risk Marine Areas and Hotspot Rivers/Catchments**

Increased nutrient loadings, even as much as 100 times above present, could only cause eutrophication in nearshore waters of the South China Sea, mostly in shallow areas within 150 km of the coast. Marine water along the Philippine coast from Luzon to the Palawan Islands has the highest assimilative capacity and this part of the South China Sea should never become eutrophic. However, this would not apply to the potential eutrophication of bays and estuaries that were not the foci of the modelling system. Another area that has relatively high assimilative capacity is the Gulf of Thailand where the response of chlorophyll biomass in marine waters was comparatively less sensitive to the loading from nearby rivers.

Examples of areas with low and high carrying capacity, as well as rivers that are potential hotspots for nutrient loading into coastal waters, are shown in Figures 9 to 12.

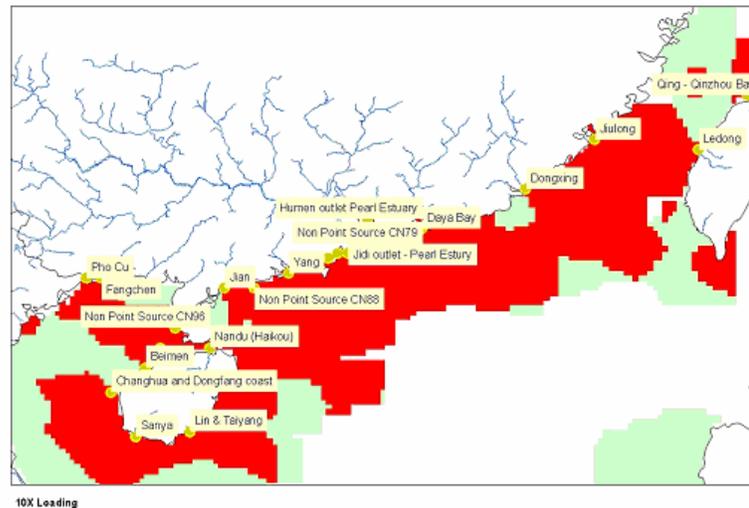


Figure 9 The Chinese coast showing areas that are more (red) and less (green) sensitive to nutrient input from land.

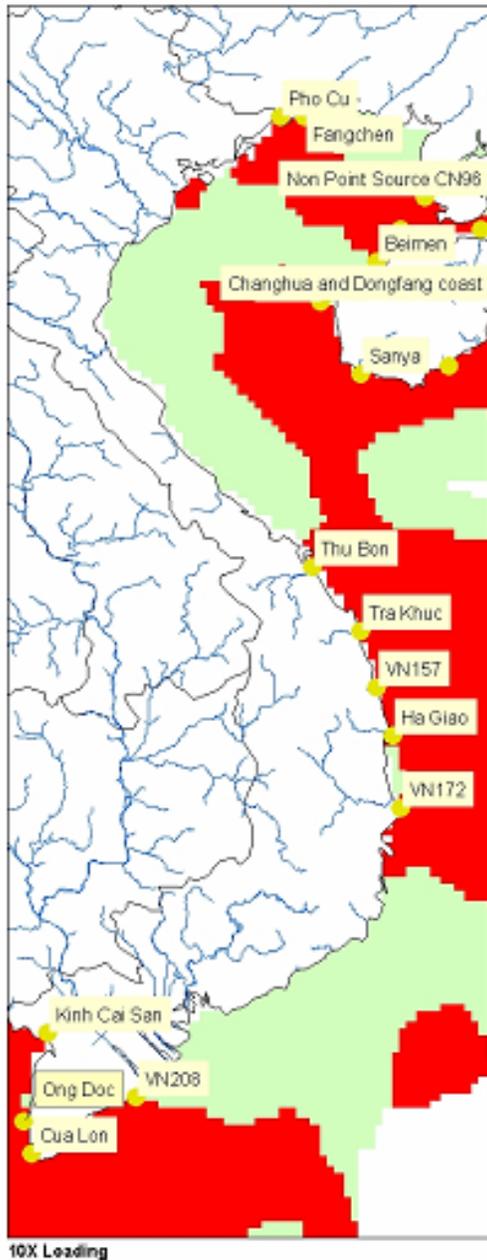


Figure 10 The Vietnamese coast of the South China Sea showing areas that are more (red) and less (green) sensitive to nutrient input from land.

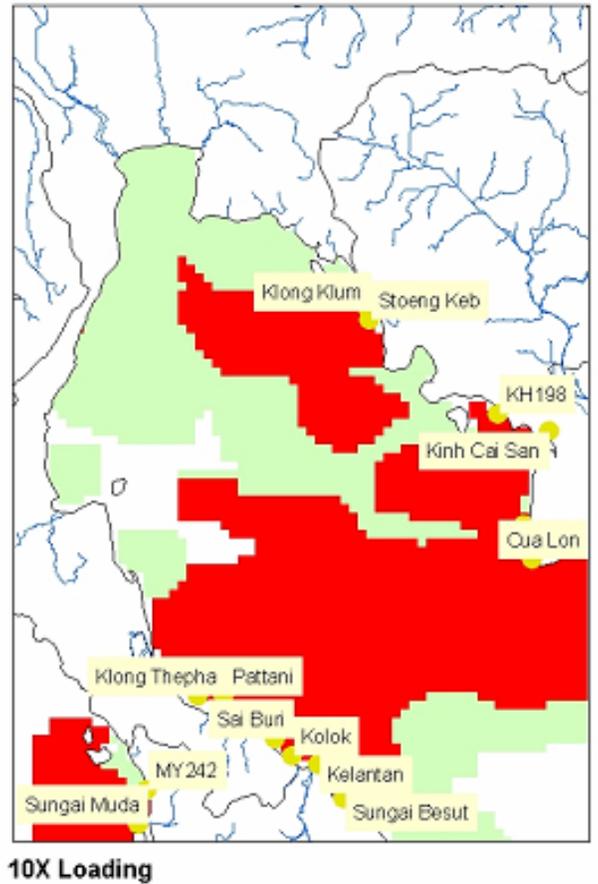


Figure 11 The Gulf of Thailand showing areas that are more (red) and less (green) sensitive to nutrient input from land.

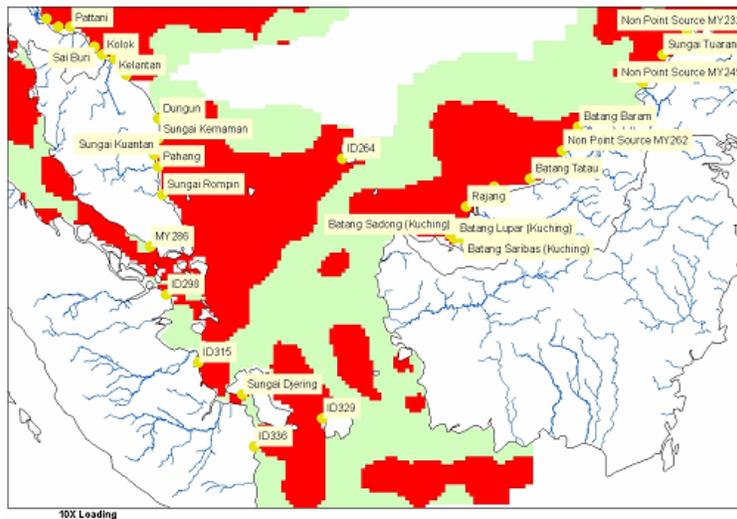


Figure 12 The Malaysian and Indonesian coasts bordering the South China Sea showing areas that are more (red) and less (green) sensitive to nutrient input from land.

### Modelling Workshop

A modelling workshop was held at Chulalongkorn University, Bangkok, 2-5 July 2005, and attended by 23 participants from South China Sea Project countries. Participants were trained in the use of the modelling system developed in this project that is executed on a Microsoft Excel platform. The modelling system was also distributed to all participants to continue modelling tasks at their home institutions. Using only MODIS satellite chlorophyll data, participants in the workshop were able to estimate the baseline monthly nutrient loading from catchments around the South China Sea to be within the right order of magnitude, usually within less than 0.5 times on the logarithmic scale. These estimates, however, need to be verified against some direct estimation of total nutrient loading by rivers.

During the workshop, participants also simulated the distribution of chlorophyll under different nutrient loading scenarios. It was apparent that different areas of the South China Sea have different capacities to assimilate nutrient input. The model seems to show that nutrient loading from the small but numerous rivers and streams and from non-point sources along the coast could be even more important in controlling phytoplankton biomass and eutrophication at the South China Sea regional scale. More thorough modelling for the whole South China Sea over an annual cycle is needed. Rivers and catchments where loading of nutrients into the adjacent coastal area could easily trigger the proliferation of chlorophyll biomass need to be carefully assessed and higher priority given to actions to control or curb generation and/or disposal of nutrients.

### DISCUSSION AND CONCLUSIONS

A modelling system was developed and enabled the estimation of land-based nutrient loading via rivers despite the limited chemical and hydrological data for these rivers. Nutrient loading from particular rivers, stretches of coastline, or catchments may be varied and the distribution of surface chlorophyll in the South China Sea or a sub-region or sub-basin therein can be simulated for each month of the year. The results, in terms of concentration and horizontal distribution patterns, may be evaluated and the response of the phytoplankton biomass to nutrient input from land can be varied in time and space. The model developed is freely available to anyone; uses US Navy NOGAPS global wind reanalysis to force the POM circulation model; uses the JODC ship drift data to verify surface circulation/current outputs; uses MODIS satellite-based chlorophyll concentration as the frame to calibrate the present monthly nutrient loading from 190+ rivers; and uses national data to verify such loads for some rivers. The modelling system is run entirely in Microsoft Excel and can be accessed by visiting [http://www.unepscs/nutrient\\_model/](http://www.unepscs/nutrient_model/).

The region now has a tool and human resources in each country to perform such modelling. The model can be run to estimate the monthly 'effective' loading of total nutrient from any catchment, as point or non-point loading, in chlorophyll equivalent units that can be converted to nutrient elements, such as N, using a Chl:nutrient ratio; can simulate the monthly responses of the chlorophyll biomass in any area of the South China Sea (at a resolution  $0.1^{\circ} \times 0.1^{\circ}$ ) to different loading scenarios; and can be used to estimate the maximum monthly load of nutrient from any selected catchment to ensure that the chlorophyll-defined biomass remains under a pre-defined limit.

The regional modelling effort should be continued and linked with other regional programmes such as COBSEA and GPA/LBA; and with development of regional criteria for chlorophyll concentrations in marine waters of the South China Sea. Model improvements, including the linkage between loading and social/economic development in a catchment, will lead to better estimates of loading scenarios for each river, improved treatment of mixing and internal removal kinetics, and use the ambient chlorophyll data or scenario more comprehensively to calculate directly inputs from individual rivers.

Anond Snidvongs & John Pernetta,  
Bangkok, September 21<sup>st</sup> 2007

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