Guidance on using the Wetland Toolkit for Climate Change

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Purpose

This report provides guidance on how to use the Wetland Toolkit for Climate Change. More specifically, it guides the user in the application of tools developed to assess how climate change in the 2050s (2041-2070) might impact on wetland ecohydrology in England and Wales. The term ecohydrology is used because we have focused on the ecological and archaeological impacts of climate change through alteration of the freshwater hydrological cycle. For example, the tools do not cover any direct impacts of temperature or carbon dioxide changes on vegetation growth. The tools also exclude coastal wetlands that might be impacted through sea-level rise as a result of climate change; though such effects should be taken into account where relevant.

This guidance and the tools it supports are designed to be used by anyone concerned with the impacts of climate change on wetlands. It is anticipated that the main users will be site managers concerned with the eco-hydrological status of their wetlands. However, it will also be useful for broader scale river corridor analysis, river basin planning, local interests and academic studies.

This guidance and related documents from the study cover the following topics:

- In general terms, how wetlands might be affected by climate change, which is covered in a literature review (Acreman et al., 2011)

- Rapid assessment of the projected impacts of climate change in the 2050s on three broad types of wetland in England and Wales (referred to as the Tier 1 Wetland Tool for Climate Change) based on the medium emissions scenario of UKCP09 (see ukclimateprojections.defra.gov.uk and Murphy et al., 2009).

- Options for action if a wetland is assessed to be sensitive to change

- How to make a more detailed assessment of a wetland to confirm results of the rapid approach (using methods referred to as Tier 2 and Tier 3 tools) when a major management decision is needed

- Some examples of where different tiers of the toolkit have been applied to the same wetlands

- Details of methods behind the toolkit

We strongly recommend that you first read the introduction that follows on the next few pages which also helps you decide which part of the toolkit to use

1. Why produce a toolkit?

There is a broad consensus that our climate will be significantly different in the future with alterations in temperature and precipitation. This is likely to cause major changes to a range of ecosystems. Managers of wetlands sites are trying to assess likely future ecological character of their own sites and national NGOs and government agencies are looking strategically at the future for wetland sites across the UK. These organisations require tools to make these assessments in a consistent, scientific and justifiable manner. Some preliminary assessments have a tight time-scale and require rough estimates in a matter of hours, whist others need more certainty, particularly when major investment in wetland sites is being decided, in which case greater investment in time and funds is appropriate.

Three tools are described in this guidance. The tools are referred to as Tier 1, Tier 2 and Tier 3 because they provide a consistent hierarchical approach, with a sliding scale of complexity and detail (Table 1). The user can choose the best tool for the job depending on time and resources available. However, all three tools could be used in sequence as an investigation progresses from scoping through intermediate analysis to detailed assessment.

Table 1 Tool tiers

	Likely applications	Time needed	Skills needed	Data needed	Limitations
Tier 1	General rapid assessment, broad-level scoping	hours	No specific skills, just knowledge of the site and job	Broad location, water resource, interest feature	Results pre-defined for a few generic wetland types for 2050s medium emissions scenarios
Tier 2	Intermediate assessment for specific locations	weeks	Ability to handle large data sets and to set-up and run simple models	Specific location, water source, interest feature, soil type	Represents general wetland processes, not including site management, such as sluice gates
Tier 3	Detailed assessment to support major management decisions, such as site water level control	months - years	Ability to handle large data sets and to set-up and run complex models	Time series of hydrological data for the site including water levels	Data are time consuming and expensive, modelling needs high skill level

All three tiers include four key concepts in impact assessment.

1. the uncertainty in likely changes to the climate and hydrology of the wetland (*i.e*. the chance of any magnitude or direction of climate change occurring)
2. the importance of catchment water pathways and the differential impact of climate change on rain-fed, river-fed and groundwater-fed wetlands
3. the sensitivity of the wetland ecosystem to hydrological alteration (*i.e*. the magnitude of hydrological change required to cause an ecological impact)
4. the difference in response of different components of the ecosystem, such as birds and vegetation

The combination of these four concepts provides an assessment of impact.

2. Introduction

The Wetland Vision project (*http://www.wetlandvision.org.uk)* described how its partners would like England's wetland landscapes to be in 50-years time (2050). At the time the Vision was developed, only limited analysis of the impacts of climate change on English wetlands had been undertaken. In 2002, the UK Climate Impacts Programme (UKCIP) projected that future summers would be hotter and drier and winters warmer and wetter. Initial analysis of possible impacts on British wetland vegetation communities (Acreman *et al*., 2009) suggested that reduced summer rainfall and increased summer evaporation would put stress on wetland plant communities in late summer and autumn with greater impacts in the south and east. In addition, impacts on rain-fed wetlands would be greater than on those dominated by river inflows. Revised climate projections were provided by UKCIP in 2009 (see ukclimateprojections.defra.gov.uk and Murphy *et al*., 2009), which included information on the probability distribution of the projections (see Annex 1). The research underlying this project was supported by the Environment Agency and some of the Wetland Vision partners to develop tools to help assess climate change impacts and sensitivity for existing or proposed wetlands across England and Wales.

2.1 Assessment approach

Hydrology is the most important characteristic of wetlands; it is the periodic presence of saturated conditions or inundation that makes wetlands different from terrestrial and fully aquatic habitats (Acreman and Jose, 2000; Acreman and Mountford, 2009). Thus any changes in hydrology will have significant implications for wetlands. Our approach to developing tools for wetland assessment to climate change is therefore to quantify key aspects of wetland hydrology and to understand what will alter the hydrology and how this will impact on plants, animals and the historic environment of wetlands.

Our climate is defined by a range of meteorological variables, including precipitation, air temperature, wind speed and solar radiation. As greenhouse gases (such as carbon dioxide and methane) build up in the atmosphere, global and regional circulation will change and these meteorological variables will alter. Changes in temperature, wind speed and radiation will alter evaporation and together with changes in precipitation will have major consequences for the hydrological cycle and thus for wetlands.

Some wetlands are fed directly by precipitation and the major loss of water is through evaporation. The hydrology of such wetlands will be impacted directly by changes in climate. Other wetlands are fed by river water, thus modifications to their hydrology will depend on how climate change alters river flows, which will be conditioned by the movement of water from precipitation through catchment soils and along the river channel. Likewise, wetlands fed by groundwater will depend on how climate change will alter water levels in aquifers, mediated by recharge processes. For example, aquifers may be recharged by winter rainfall, thus climate change involving wetter winters may increase aquifer levels, which could provide more water to groundwater-dependent wetlands in the summer. In contrast, rain-fed wetlands may become drier in summer due to reductions in summer rainfall; much will depend on a more immediate balance of water supply and evaporation.

The perceived final impact of climate change on wetlands will depend on the feature or features of most interest. Some wetlands are important for their vegetation communities, whilst others support bird populations or conserve aspects of the historic environment, such as the pollen record or human remains. Each interest feature requires a particular hydrological regime to conserve it. For example, some birds over-winter on wetlands where surface inundation occurs, whilst saturated soils all-year may be required to conserve some archaeological remains. Some plants or animals will be very sensitive to small variations from this required hydrological regime and so might decline or disappear with minor alterations in hydrology; others may have broad requirements and may be highly tolerant, such that they may not be susceptible to even large hydrological modifications.

Our conceptual structure for development of the wetland assessment tools consists of four elements (Figure 1):

(1) Projected changes to the climate; (*e.g*. precipitation, temperature, wind speed) and its uncertainty
(2) Catchment response; how the water supply sources of wetlands (*e.g*. river flows, groundwater levels) respond to climate change
(3) Wetland plant community eco-hydrological response sensitivity
(4) Wetland ecosystem sensitivity; whether a small or large alteration in the wetland's hydrological regime is needed to cause change to the interest features

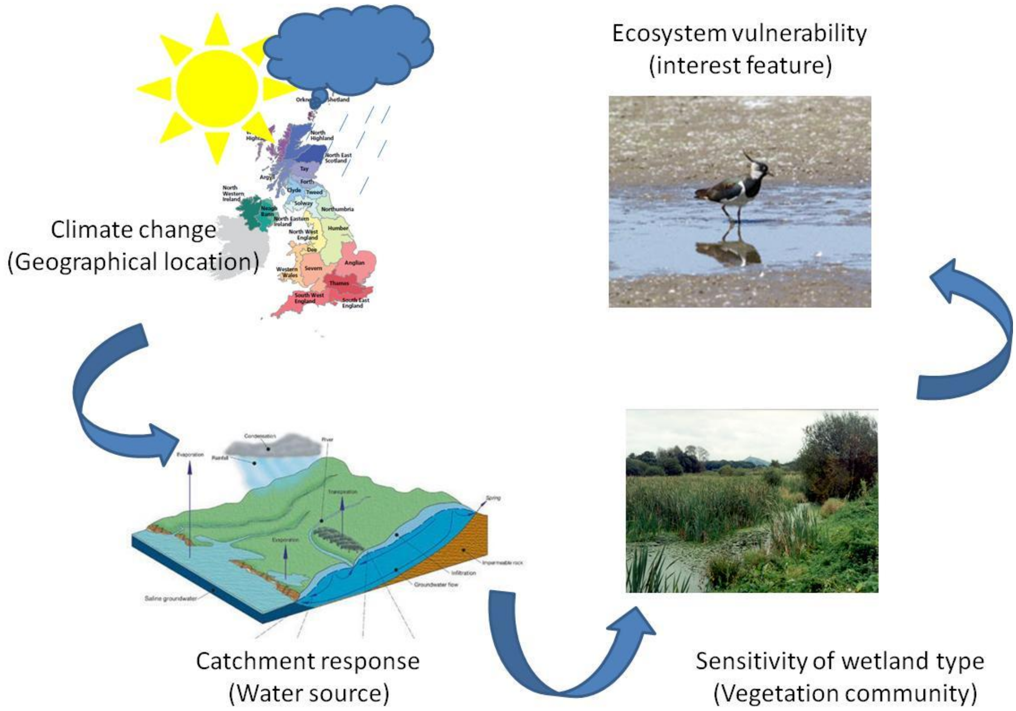


Figure 1 Conceptual diagram

Our approach to developing the assessment tools was to employ results of computer models that are able to simulate some key required characteristics of catchments and wetlands, which are responsive to changes in climate (*e.g*. rainfall and temperature) and are able to predict the impacts on interest features, such as vegetation. The models incorporate characteristics, such as the soil type, because, for example, permeable wetlands soils (*e.g.* sand) allow rapid movement of water into and out of the wetland, whereas impermeable soils (*e.g.* clay), restrict water movement. We have explored, developed and used various models to produce a set of tools that can be used to estimate the impacts of climate change of wetlands, linking climate change, catchment response and ecosystem sensitivity

2.2 Choosing the right assessment tool

There are many tools that can be used to link climate, catchment hydrology and wetlands; each is a simplification of reality. Some tools are based on the output of models, such as printed tables, whilst others involve running models. No model is right or wrong, but models have different characteristics that make them more or less suitable for different jobs. Some models are simple and represent only the key elements of a system; they often use analogies, such as considering the wetland like one large plant pot, focusing only on water entering and leaving the wetland by rainfall and evaporation. In contrast, there are complex models that include representation of site water management, such as sluice gates and penning boards. In broad terms, simple models tend to be relatively easy and inexpensive to setup and use, require limited data and give generalised results applicable to general wetland types, but not specific sites. Complex models produce results specific to the wetland site under study, but require more data and are more costly to set-up and run. As shown in Figure 2, choice of tool is a trade-off between how important it is to have accurate site-specific results and how much time and money can be invested in the analysis; *i.e*. the user should choose the tool that is fit for the purpose intended. In practice, models can be used in series, in which a simple model is used to give general results and more complex models are used later, if and when more specific results are required.

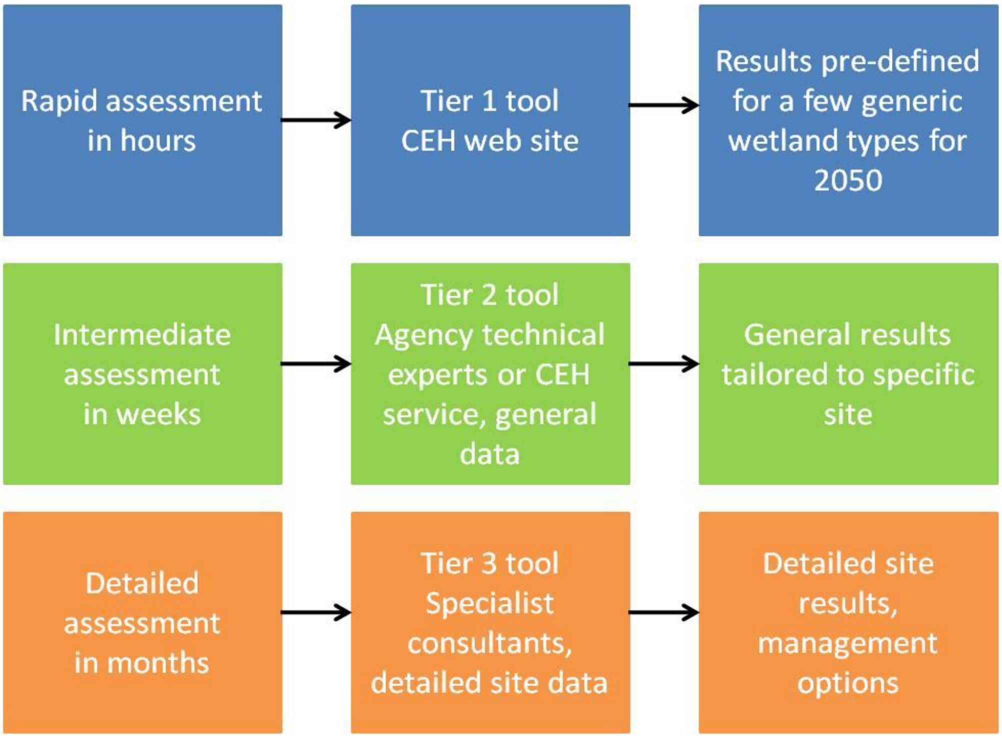


Figure 2 Flow chart for choosing between tools

Our tool-kit comprises of a three-tier approach to assessing climate change impacts and understanding climate sensitivity of wetlands (see Annex 2 for details of models).

***Tier 1 (Wetland Tool for Climate Change)*:**

This is a very simple tool to use, it is based on the results of models that have already been run and does not require the user to undertake modelling. The tool takes a few hours to assess the potential impacts of climate change on a wetland. The tool can be found on the CEH website; a step-by-step guide is provided below. The tool requires the following information about the wetlands:

- geographical location – the UKCP09 (Water Framework Directive, WFD) river basin region within which the wetland is located

- water source – whether rain-fed, river-fed (surface water dominated catchment), river-fed (groundwater dominated catchment) or groundwater-fed (according to bedrock aquifer type)
- wetland type – wet grassland, wet heath, raised mire etc.
- interest feature – the wetland feature(s) for which the investigation is being undertaken *e.g.* vegetation community, birds, historic environment (Box 1).

Box 1 Interest features

1. Site hydrology

Hydrology is the single most important feature of a wetland, periodic saturated conditions and/or surface water make wetlands different from terrestrial and fully aquatic habitats. The hydrological regime forms a generic interest feature that indicates general site conditions independently from individual species, communities or other elements.

2. Plant communities

Wetlands are characterised by specialist plants that can tolerate aeration stress. Plants tend to occur in assemblages or communities that have been described in the National Vegetation Classification (NVC) by Rodwell (2000). The communities are often associated with specific wetland water sources. In this study we include the following NVC types as distinct interest features.

Rain-fed wetland
7 NVC types (M16, M21, MG4 (Ecohydrological guidelines subtypes B and K), MG13 (Ecohydrological guidelines subtypes High and Low porosity), M24)

River-fed wetlands
7 NVC types (MG8, S4, MG4 (Ecohydrological guidelines subtypes B and K), MG13 (Ecohydrological guidelines subtypes High and Low porosity), S24)

Groundwater-fed wetlands
4 NVC types (M13, M21, M24, S24)

3. Historic environment

Wetlands are critically important for conserving aspects of the historic environment, such as the pollen record or human remains. The historic environment is a key interest feature considered in this study.

4. Birds

Wetlands support many different bird species. The two most important groups are over-wintering birds, especially waterfowl, during November to March, and breeding birds, especially waders during April to June. We include these two groups as interest features in this study.

Where the wetland is fed by more than one source, *e.g*. both rain and groundwater, the assessment must be run separately for each water source. A judgement is then required based on site knowledge of the relative importance of the two sources and therefore the contribution of changes. Likewise, at sites where more than one feature is of interest, the assessment can be repeated separately for each feature.

The tool has been built by using conceptually simple computer models within which the wetland has generalised characteristics and the climate input data are representative of the river basin region. The models have been run for pre-selected conditions, so that the users are provided with results and do not have run models themselves. Consequently, the results will not be specific to any wetland in terms of its local climate or its soil type or, for example, of the flows in the particular river feeding it. This type of tool is often used for 'risk screening', providing a general assessment of potential risks posed by a changing climate. It provides a single generalized result for a wetland and thus not spatial information with regard to differential impacts across the site.

Because of the inherent uncertainty in climate change predictions, results are provided in three categories, these are: (1) the chance that the wetland will not be significantly impacted; (2) the chance of moderate impact; (3) the chance of major impact. The definitions of no, minor and major impact are defined according to quantitative metrics (see Annex 3).

***Tier 2*:**

The Tier 2 tool is designed for application to specific wetland sites when a more precise and targeted assessment is required than can be achieved with Tier 1. The second tier approach involves application of the same computer models as used to generate the Tier 1 tool. However, rather than using the results of past model runs employed for Tier 1, the models are refined to represent better the conditions (such as the soil type) and are provided with climate data specifically for the wetland under analysis; the models are then run by the user. Application of the tool requires expertise in handling large data sets and preparing parameter and rainfall/flow/groundwater data input files to drive the command line wetland FORTRAN models.

The tool and its models can be made available. For a new user, collation and reformatting of suitable data, construction of the models and running is likely to take 2 to 3 weeks, particularly for the first application. The time required depends on the characteristics of the wetland. Analysis of rain-fed wetlands depends primarily on obtaining the climate change data from UKCIP and baseline data from the Met Office. However, analysis of river-fed and groundwater-fed wetlands requires the intermediate step of producing river flow or groundwater level data time series respectively adjacent to the wetland.

It is proposed that the Centre for Ecology and Hydrology establishes a service that can run the Tier 2 models for any location in England and Wales.

***Tier 3*:**

Tier 3 models are aimed at producing detailed assessments required to support major management decisions. This third tier involves application of complex models that consider more of the processes at work within the wetland. The models often required long series of hydrological data from the site and information, such as topography, physical soil properties and dimensions of channels and structure (*e.g.* penning boards and sluice gates). Examples of models which are commercially available include the MIKE-SHE/MIKE II coupled surface-groundwater model as employed to assess the impacts of climate change on the North Kent Marshes (Thompson *et al.,* 2004; Thompson, 2008) or the MODFLOW groundwater model, used to assess the impacts of abstraction on Habitats Directive wetlands in East Anglia (ENTEC, 2007). These models have the added advantage of predicting spatial patterns of changes within a wetland, thus providing areal extent of impacts. They require contracting specialist consultants or commissioned researchers and may take many months to setup and run. In contrast to simple Tier 1 and 2 models, it is generally impractical to run the complete set (10,000 realisations) of probabilistic climate change projections provided by UKCP09 for each timeslice and emissions scenario using complex Tier 3 models. In most cases 3 to 10 model runs have been undertaken.

The application of Tier 1, 2 and 3 models to three wetlands is described below.

3. Step by step guide to rapid assessment - Tier 1 Wetland Tool for Climate Change

The Tier 1 Wetland Tool for Climate Change does not require the running of models, but accesses the results of models run previously during the project. To locate the specific appropriate model results, choices need to be made in each of series of steps.

The model (Plate 1) can be found on the CEH web site at:
http://www.ceh.ac.uk/sci_programmes/Water/Wetlands/ClimateChangeAssessmentToolforWetlands.html

Users will be required to accept terms and conditions for using the tool.

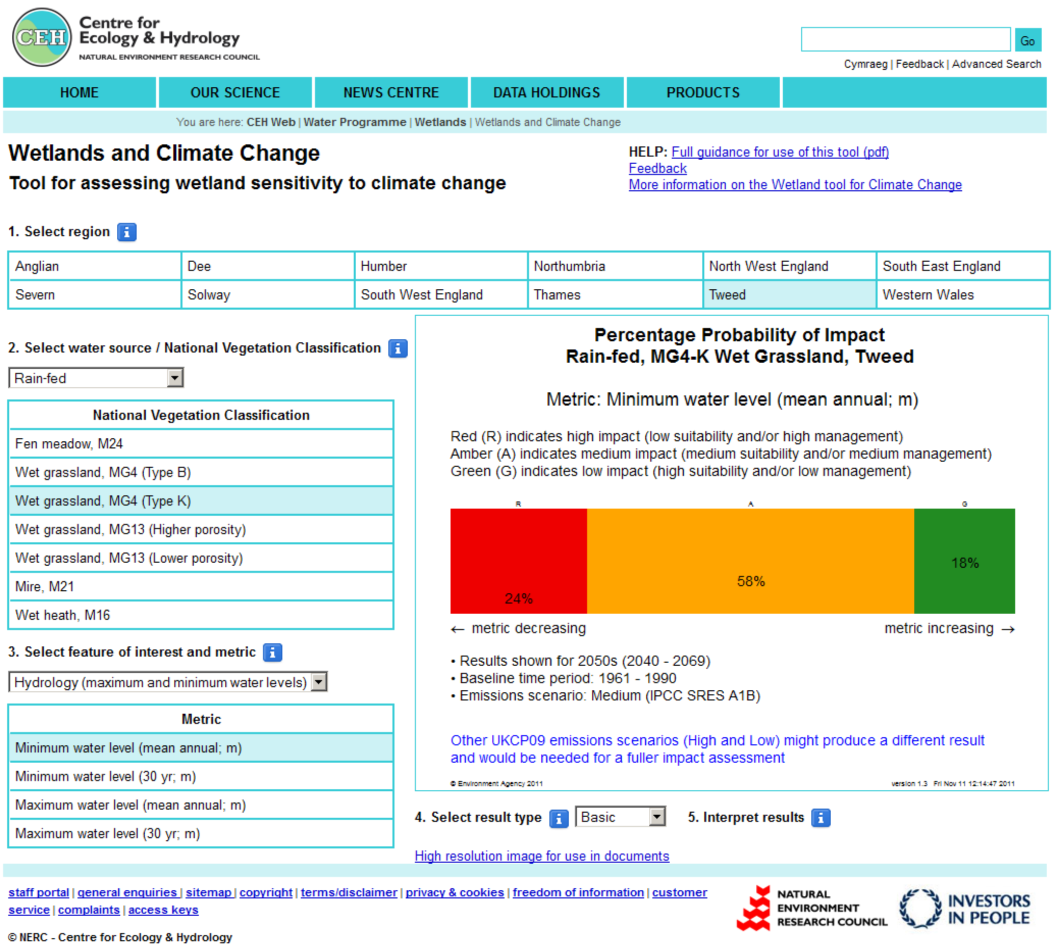


Plate 1 Opening screen of Tier 1 Wetland Tool for Climate Change

<u>Step 1 Identify geographical location</u>

Current and future climates vary across the UK, generally being wetter and cooler towards the northwest; warmer and drier towards the southeast. The UK is divided into river basin regions for the purposes of the EU Water Framework Directive; these regions have broadly consistent climate. The Tier 1 tool uses climate data assembled for each river basin region.

Table 2 Linking river basin regions and hydrometric areas

WFD River basin region	Hydrometric areas
Solway	76
North west England	68-75
Dee	67
Western Wales	58-66
Severn	53, 54 (plus Land Yeo and Congesbury Yeo in 52)
South West England	43-52 (excluding Land Yeo and Congesbury Yeo in 52)
South East England	40-42 (excluding Medway and Darent in 40)
Thames	38-39 (plus Medway and Darent in 40; Roding, Beam, Mar Dyke in 37)
Anglian	29-37 (excluding Roding, Beam, Mar Dyke in 37; Rase, Waithe Beck and Lud in 29)
Humber	26-28 (plus Rase, Waithe Beck and Lud in 29)
Northumbria	22-25
Tweed	21

The location of the wetland under assessment needs to be identified on the river basin region map (Figure 3). The river basins are consistent with hydrometric areas used by the Environment Agency (Table 2). For further detail, see UK hydrometric register (CEH/BGS). http://www.ceh.ac.uk/products/publications/UKHydrometricRegister.html

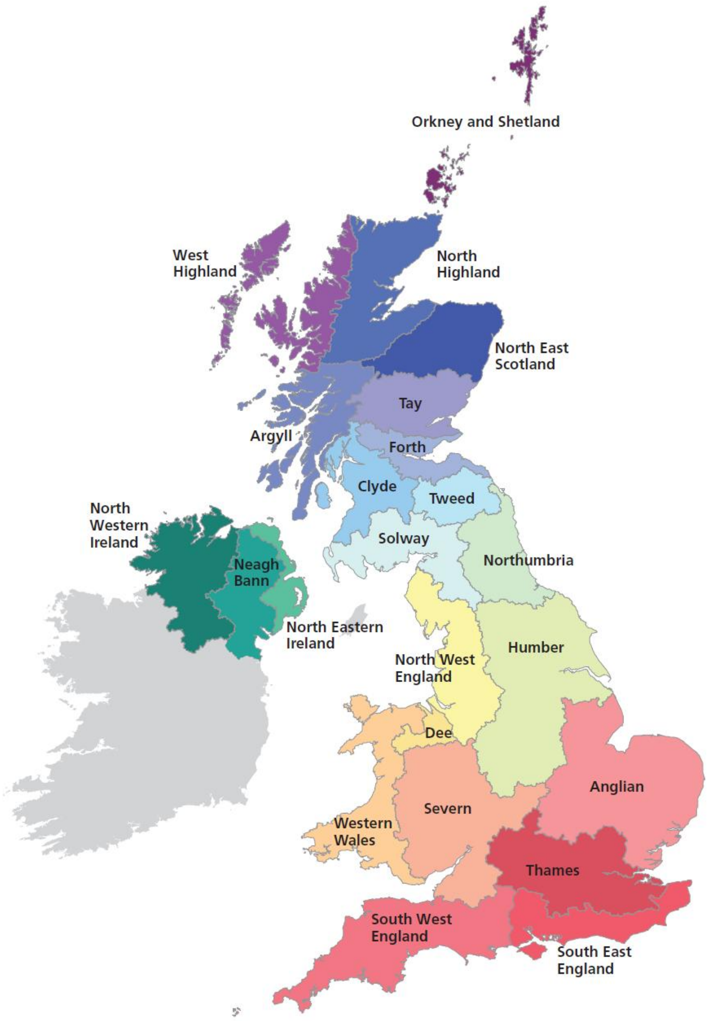


Figure 3 Map of WFD river basin regions (source: UKCP09)

Location within river basin regions can be defined using the UKCP09 location selector; this requires a login id.
http://ukclimateprojections-ui.defra.gov.uk/ui/req_bldr/loc_start.php

River basin region static maps can be found at:
http://ukclimateprojections.defra.gov.uk/content/view/602/690/

ACTIONS FOR STEP 1 Select river basin region in which wetland is located (Plate 2) by clicking the appropriate cell.

1. Select region

Anglian	Dee	Humber	Northumbria	North West England	South East England
Severn	Solway	South West England	Thames	Tweed	Western Wales

Plate 2 Selecting a region

Step 2a Define water source

There are various water sources that can provide water to wetlands; these can be divided into three broad types and the user selects the appropriate water supply mechanism.

1. **Rain-fed**. Some wetlands are fed primarily or exclusively by precipitation that includes rain, snow, dew and other types of precipitation. However, since rainfall is the principal mechanism in England and Wales, we use the term rain-fed wetlands.

2. **River-fed**. Many wetlands exchange water with surface water bodies, including rivers and lakes, either through lateral water movement through soils or overbank flow as a resulting of flooding. In this tool we cover flowing surface water, *i.e.* rivers.

   The flow regimes of rivers in some regions are very varied, so we have sub-divided rivers into (a) impermeable catchments with 'surface water'-fed rivers (for which the flow regime is flashy and responds quickly to rainfall) and (b) permeable catchments with groundwater-fed rivers (for which the flow regime is damped and responds slowly to rainfall). The base flow index (BFI, which ranges between 0.0 and 1.0) records the proportion of water in a river that comes from groundwater (as opposed to surface water); figures near 1.0 are groundwater dominated, whereas figures near 0.0 are surface water dominated. Base flow index has been calculated for all primary river flow gauging stations in the UK. See:

   http://www.ceh.ac.uk/products/publications/UKHydrometricRegister.html

   The type of river can be defined by reference to the BFI at a nearby gauging station; rivers with BFI 0.7 or below can be considered as surface water-fed, whilst those with BFI greater than 0.7 can be considered to be groundwater-fed.

3. **Groundwater-fed**. Wetlands can exchange water with aquifers, by various mechanisms, including spring flow, seepage and vertical discharge/recharge. The current tool covers wetlands with direct vertical discharge-recharge and/or lateral seepage relationship(s) with the aquifer.

In many cases the water supply mechanism is clear. Hilltop blanket peat and raised mires are normally fed exclusively by rainfall, fens directly overlying Chalk outcrop are fed predominantly by groundwater and floodplain margins are fed by river water. However, interaction between groundwater and wetlands can vary significantly between individual wetlands, even ones that are close to one another. For example, three wetlands in Eastern England are visually similar and geographically close to each other, but they are hydrologically different (Acreman and José, 2000). Langmere is in direct hydrological contact with the underlying Chalk aquifer and its water regime is controlled by groundwater fluctuations. Ringmere is partially separated from the same aquifer by a low hydraulic conductivity lining of organic matter (an aquitard) and controlled partly by groundwater. In contrast, Fenmere is isolated from the Chalk aquifer by a clay layer (very low hydraulic conductivity; an aquiclude) and its water levels are controlled exclusively by rainfall and evaporation.

It is vital to understand that models used to produce the Tier 1 tool simulate rain, river or groundwater sources separately, but not any combination, i.e. it does not permit explicit integrated assessment of wetlands with dual water sources. Many wetlands will have more than one source. For example, Figure 4 shows a cross-section through a hypothetical floodplain. In zone 1, the river margin, water table levels are predominantly controlled by lateral exchange with the river (L = lateral inflow, D = drainage) and over-bank inundation (OB = overbank flow, OF = outflow). Further away from the river, in zone 2, water table levels are predominantly controlled by exchange with groundwater (GD = groundwater discharge, GR = groundwater recharge). In zone 3, water table levels are predominantly controlled by precipitation (P) and evaporation (E). In such cases, the assessment of climate change impacts should be undertaken by applying the river-fed results to zone 1, the groundwater-fed results to zone 2 and the rain-fed results to zone 3. Classification of wetlands according to water supply mechanism was studied as part of the Environment Agency 2004 project 'Impact assessment of wetlands: focus on hydrological and hydrogeological issues' (Acreman, 2004; Acreman and Miller, 2007). Local hydrological and hydrogeological knowledge is the most important source of information supported by geological and topographical maps. The vegetation communities present (NVC type) and WETMEC (Wheeler *et al*., 2009) class in the wetland may also provide clues to the water source; see Annex 4.

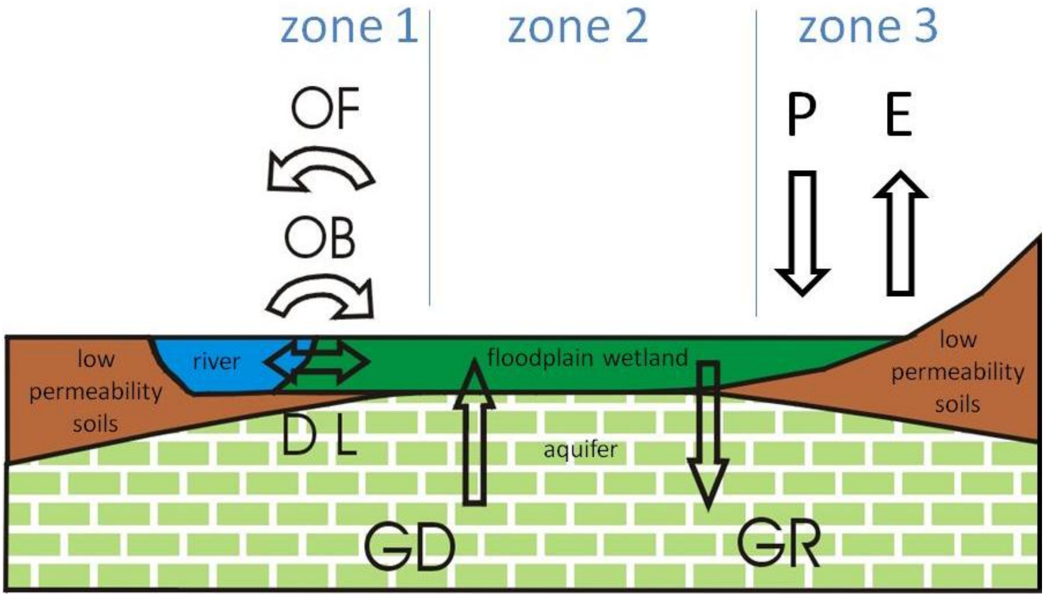


Figure 4 Zoning a floodplain according to water supply mechanisms (after Acreman, 2004)

The guide to monitoring water levels and flows at wetland sites published by the Environment Agency (2003) in collaboration with English Nature, Wildlife Trusts and RSPB outlines how surface water and groundwater may interact at wetlands and how information on water levels and flows can be used to gain a better understanding of the dominant processes at work in a wetland.

ACTIONS FOR STEP 2A Select water source type from 4 choices: rain-fed, river-fed surface water river (low BFI), river-fed groundwater river (high BFI), groundwater-fed (according to bedrock aquifer type) from the drop-down menu (Plate 3).

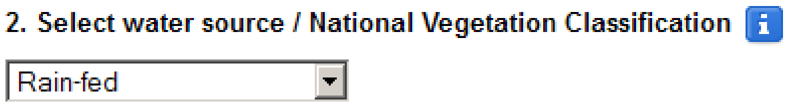


Plate 3 Selecting a water source

<u>Step 2b Wetland type</u>

There are many interrelated characteristics that control the internal hydrological regime of wetlands. For example, soil type controls the movement of water laterally and vertically through the wetland substrate. Also, the rooting depth of the wetland plants controls the water table depth at which transpiration ceases. Wetland NVC type can be used to provide standard variables for these controlling factors. The models used to develop the rain-fed Tier 1 tool are based on 7 types.

M24 *Molinia – Cirsium* Fen meadow
M24 communities can be found in fens and wet grasslands. Examples of M24 have commonly been included with *Molinia* Meadows on Calcareous, peaty or clayey-sil-laden soils and Chalk-fen dominated by Saw Sedge. Characteristic species are *Molinia caerulea* and *Cirsium dissectum* with a wide range of associated species, including rushes, sedges and tall-growing herbs. M24 primarily occurs in the warmer parts of Britain. It is widespread in Eastern England, but occurs at scattered and infrequent locations across Wales and in central and southern England, with some examples in Yorkshire. The majority of stands in eastern England are associated with valley head wetlands where they occupy a zone between wetter fen communities and drier grasslands and heath. M24 also occurs on un-drained floodplains often in a narrow marginal zones alongside main stands of fen.

MG4 *Alopecurus pratensis–Sanguisorba officinalis* Lowland hay meadows.
The MG4 community is species rich, containing up to 18 different grasses plus a few sedges and rushes. The most notable feature of the community is the abundance of broad-leaved herbs, which dominate in mid-summer. Characteristic species are: *Briza media, Lotus corniculatus, Centaurea nigra, Sanguisorba officinalis, Silaum silaus and Filipendula ulmaria*. The current extend of MG4 grassland centres on the floodplains of large English rivers with deep alluvial soils and/or gravels, e.g. Thames, Severn, Great Ouse and Trent. There are two sub-types: B and K. Sub-type B relates to MG4 in areas over river terrace deposits which can be derived from local maps of drift geology. A further difference is that type B is associated with high potential soil moisture deficit in July (> 80 mm) whereas sub-type K relates to areas with lower (< 80 mm) soil moisture deficit. Median SMD in July is provided in MAFF Technical Bulletin 34 (1976) Climate and Drainage. It maps England and Wales (approx by county) and gives the median July figure for each area assuming a mean rainfall scenario.

MG13 *Agrostis stolonifera – Alopecurus geniculatus* Grassland

The MG13 community is an important habitat for over-wintering waterfowl. The community is dominated by sprawling grasses with a few mainly low growing broadleaved herbs. Characteristic species are *Alopecurus geniculatus, Agrostis stolonifera, Ranunculus flammula, Oenanthe fistulosa, Persicaria amphibian and Rumex crispus.* MG13 often occurs on both poorly-structured alluvial soils with low permeability and on more permeable substrates including peat. MG13 is widely distributed throughout lowland England with large expanses on washlands alongside large rivers Eastern England e.g. Nene and, Great Ouse

M21 *Narthecium ossifragum-Sphagnum papillosum* valley mire

Relative to many other bog-types, the M21 community is quite species-rich comprising carpets of bog-moss (*Sphagnum*) within which *Eriophorum angustifolium* and especially *Narthecium* are frequent together with an open growth of heathers (*Calluna* and *Erica tetralix*). Typically the community grows in valley mires within heathland complexes where the water-table constantly at or close to the oligotrophic peat surface and the pH 3.5-4.5. Peat depth is only 20-150 cm and M21 often occurs in the transition between soligenous poor-fen along the axis of the valley mire and *Erica tetralix* wet heath where the peat is shallower. Such vegetation is best developed in warmer parts of Britain below 200m altitude, and especially from the New Forest westward in England and in south Wales, where the rainfall is <1200mmm/year. As well as the constant species (*Calluna vulgaris, Drosera rotundifolia, Erica tetralix, Eriophorum angustifolium, Molinia coerulea, Narthecium ossifragum* and *Sphagnum papillosum*), this vegetation can support scarce plants such as *Erica ciliaris* and *Hammarbya paludosa*.

M16 *Erica – Sphagnum* Wet heath

M16 is characteristic of drier climates in the south and east, and is usually dominated by mixtures of *E. tetralix*, *Calluna* and *Molinia*. The bog-moss *Sphagnum compactum* is typically abundant. In the south, species with a mainly southern distribution in Britain, such as marsh gentian *Gentiana pneumonanthe*, brown beak-sedge *Rhynchospora fusca* and meadow thistle *Cirsium dissectum*, enrich wet heaths. At high altitude in northern Scotland forms of the community rich in northern and montane species occur and often also have an abundance of *Cladonia* lichens

Details of these ecohydrological types can be found in texts such as Wheeler *et al*. 2009.

NVC type is partly determined by water source. When the water source is selected from the drop-down menu the NVC types associated with that source are given as a list (Plate 4).

ACTIONS FOR STEP 2B Select wetland NVC type by clicking the appropriate cell (Plate 4).

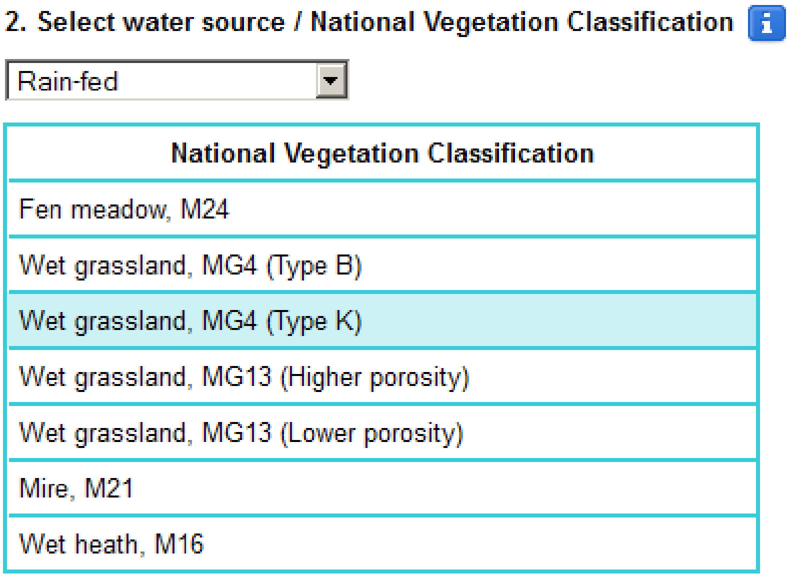


Plate 4 NVC types associated with rain-fed wetlands

Step 3a Interest feature

Wetlands are of interest for many different reasons, including their visual landscape impact, their vegetation communities, the birds they support or the historic environment preserved in their soils. In addition, some managers may be interested in the general health of their wetlands indexed by the presence of inundation or soil saturation for specific periods. Consequently a series of measures of the impacts of climate change is required to suit various users of the assessment tools. Between these ecological and hydrological end-members we have some predominantly hydrological measures but which have an ecological importance. In this work, we use the term interest feature to denote different elements of the wetland ecosystem that users wish to assess impacts.

We provide results for six interest features as follows:

Interest feature	Wetland metric
Hydrology	Reflecting general wetland water levels
Hydrology (eco-related)	Reflecting water levels at ecologically important times of the year
Hydrology (water balance)	Reflecting the overall availability or lack of water
Plant communities	Reflecting the specific water table requirements of a range of NVC plant communities
Historic environment	Reflecting conditions in the wetland that conserved archaeological remains or environmental history, such as pollen sequences
Birds	Reflecting hydrological conditions required by birds for over-wintering and breeding in wetlands

ACTIONS FOR STEP 3A Select an interest feature from the drop-down menu (Plate 5).

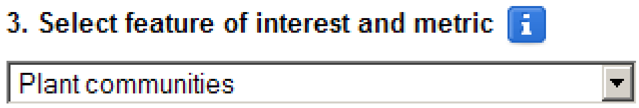


Plate 5 List of interest features

Step 3b Metrics

The relationship between the hydrological regime and interest features is complex, such that it is not possible to define a single hydrological index that is uniquely critical to conserve the feature. Thus in this study, we defined a set of metrics for each interest feature, the form of which was constrained by nature of the models we employed (for example, the models simulate water table level and not soil moisture, so soil moisture could not be a metric). In addition, the hydrological regime of wetlands is often complex, varying from day to day, month to month and year to year. We need to select some specific measures of hydrological regime. Below we define the metric under each interest feature.

Hydrology
There is a multitude of possible metrics to describe the hydrological regime of a wetland. We used 8 that were considered most significant.

- Minimum water table level (mean of 30 annual minima)
- Minimum water table level (minimum of 30 year record)
- Maximum water table level (mean of 30 annual maxima)
- Maximum water table level (maximum of 30 year record)

- Number of months per year with positive or neutral water balance (mean of 30 years)
- Number of months per year with positive or neutral water balance (minimum of 30 years)
- Gross annual water balance: rainfall - evaporation (mean of 30 annual balances)
- Gross annual water balance: rainfall - evaporation (minimum of 30 year record)

Historic environment
Historical features may be at different levels in the soil profile. Therefore we have defined four metrics for this interest feature in two sets, to cover artefacts at 35 cm and 70 cm below the soil surface.

- Number of months per year with water table level at 35 cm depth (mean of 30 years)
- Number of months per year with water table level at 35 cm depth (minimum of 30 years)
- Number of months per year with water table level at 70 cm depth (mean of 30 years)
- Number of months per year with water table level at 70 cm depth (minimum of 30 years)

Plant communities
Water requirements of wetland plant communities have been defined by Wheeler et al. 2004. These define, for each community, zones of desired water table level, zones of tolerable water table for short periods and zones of unacceptable water table level. These diagrams (Figure 5) were used to quantify the botanical relevance of water table levels. We defined 2 metrics that were applied to each of the NVC interest features (Box 1).

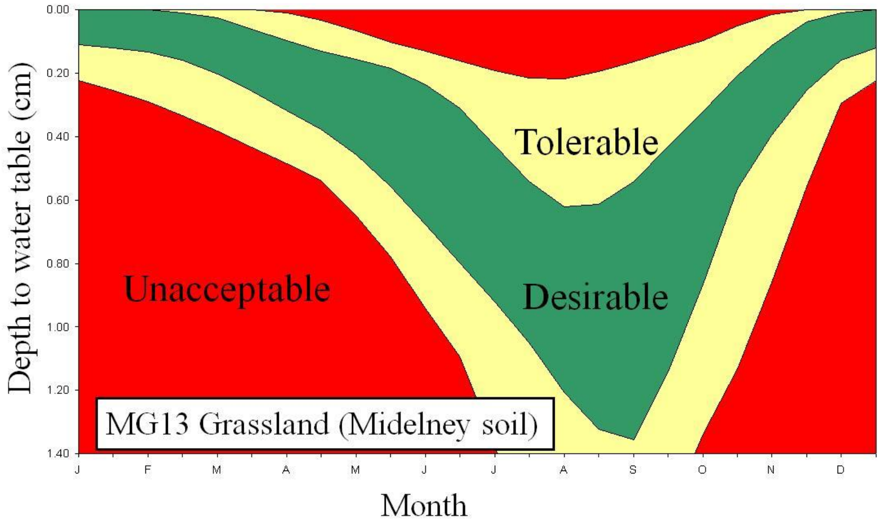


Figure 5 Water requirements for MG13 wetland plant community

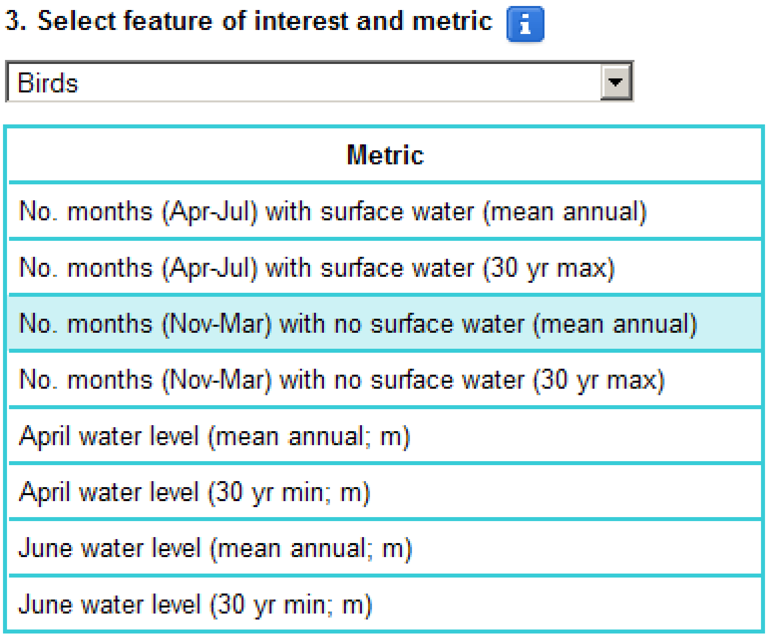
- Departure from water level requirements regime: sum of 1.0 × number of 'unacceptable' months + 0.5 × number of 'tolerable for short periods' months (mean of 30 years)
- Departure from water level requirements regime: sum of 1.0 × number of 'unacceptable' months + 0.5 × number of 'tolerable for short periods' months (maximum of 30 years).

Birds
Two periods of the year were considered to be critical for birds: November to March for over-wintering birds, especially waterfowl, and April to June for breeding birds, especially waders. Over-wintering wetland birds require surface inundation, whereas breeding birds need water at or near the surface. We have defined one pairs of metrics for wintering birds and 3 pairs for breeding birds.

- Number of months, November to March, without surface water (mean of 30 years)
- Number of months, November to March, without surface water (maximum of 30 years)
- Number of months, April to July, with surface water (mean of 30 years)
- Number of months, April to July, with surface water (maximum of 30 years)
- April water table level (mean of 30 years)
- April water table level (minimum of 30 years)
- June water table level (mean of 30 years)
- June water table level (minimum of 30 years)

Since metrics are related explicitly to interest features, the list of metrics associated with a given interest feature are listed once the interest feature is selected.

ACTIONS FOR STEP 3B Select metric by clicking the appropriate cell (Plate 6).


3. Select feature of interest and metric

Birds

Metric
No. months (Apr-Jul) with surface water (mean annual)
No. months (Apr-Jul) with surface water (30 yr max)
No. months (Nov-Mar) with no surface water (mean annual)
No. months (Nov-Mar) with no surface water (30 yr max)
April water level (mean annual; m)
April water level (30 yr min; m)
June water level (mean annual; m)
June water level (30 yr min; m)

Plate 6 List of metrics for bird interest feature

<u>Step 4 Results</u>

Users will wish to know whether changes in any of the metrics described in Step 3b are significant or not a cause for concern. To achieve this, thresholds were defined for each metric to give a three-stage ‘traffic-light’ indicator of impact. These are:

Green – minor change in metric, low impact

Amber – intermediate change in metric, medium impact

Red – major change in metric, high impact

The precise thresholds adopted for each of the metrics are given in Annex 3. It is important to recognise that although a high impact may indicate a low degree of suitability of the projected hydrological regime to the current interest feature, it could alternatively indicate a need for a high degree of management of the wetland to adapt to climate change.

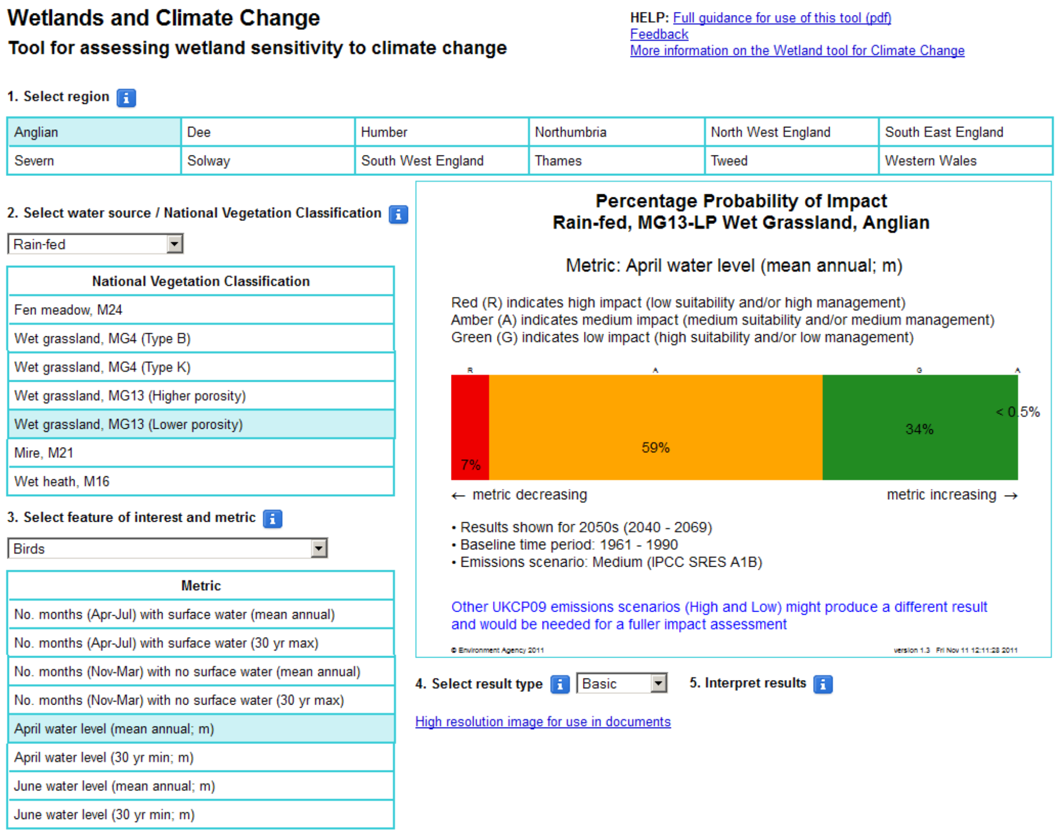


Plate 7 Basic results. For birds - change in mean April water level by 2050 for a rain-fed MG13 (lower porosity) wet grassland in Anglian region of England

Because of the uncertainty in climate change projections and the different results obtained from using different climate models, UKCP09 provides 10,000 different realisations of future climate for each future time-slice and emissions scenario, each of which is equally likely (or unlikely). So for each chosen location, water source, vegetation community and interest feature (metric) there are 10,000 results. To summarise the 10,000 results, the primary Tier 1 tool outputs are coloured blocks with percentage values defining the proportion of the 10,000 results that are green, amber and red, i.e. low, medium and high impact (Plate 7). The user can then both recognise the uncertainty of the climate change projections and visualise the likely degree of impact (the size of the red, amber and green regions is proportional to the probability of each impact level).

Some users familiar with statistical analysis may prefer to see the 10,000 results presented as a histogram, showing the location of the baseline and metric impact boundaries. This is produced by selecting the alternative results view (Plate 8, 9). These users also could manually overlay their own metric thresholds onto the output histogram if they have detailed knowledge of thresholds for a particular wetland site. However it should be noted that the plots are static and cannot be re-coloured automatically according to user-defined thresholds.

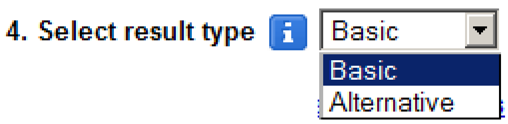


Plate 8 Selecting basic or alternative results.

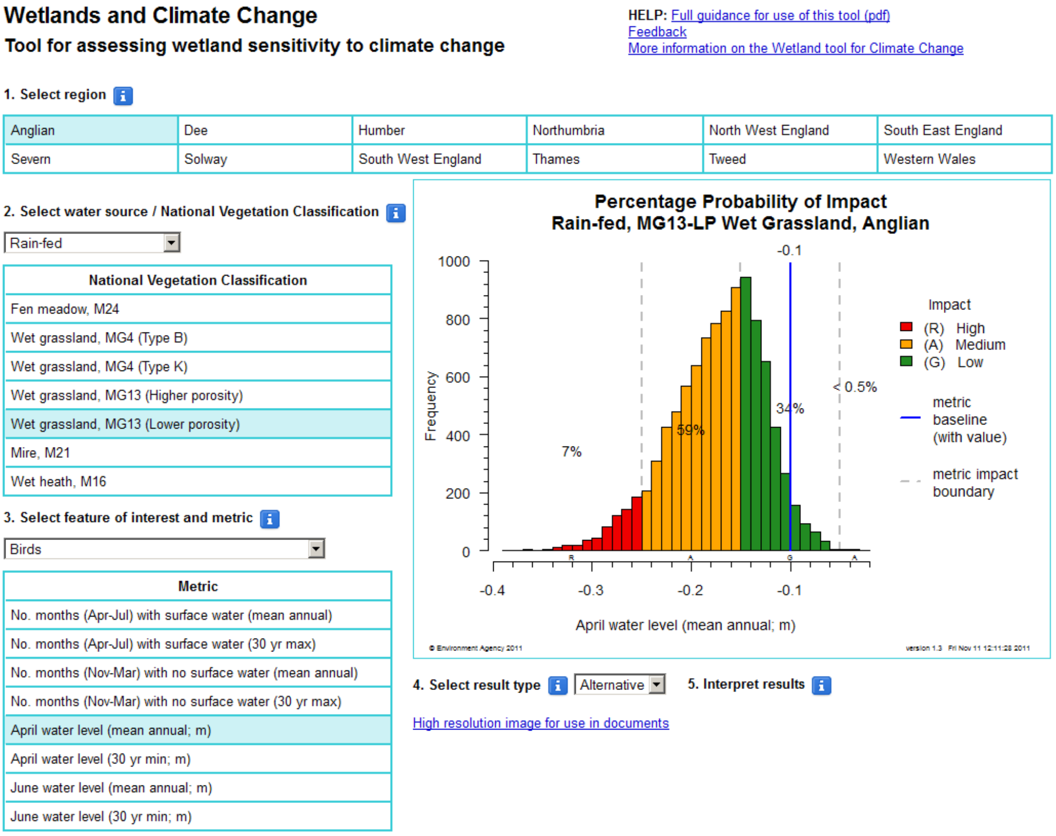


Plate 9 Alternative results. For birds - change in mean April water level by 2050 for a rain-fed MG13 (low porosity) wet grassland in Anglian region

A link is also provided on the interface to allow high resolution versions of the plots to be exported (in .png format) for later use.

ACTIONS FOR STEP 4 Produce results

<u>Step 5 Interpretation</u>

When interpreting the results, it is very important to ensure that you understand the precise form of the metric very clearly. These are given in Annex 2. We provide below a set of example results to guide interpretation. Furthermore, detailed notes explaining the shapes of particular groundwater-fed wetland metric histograms can be found in Annex 7. It is also useful to be aware of the limitations of the Tier 1 Wetland Tool for Climate Change (see Box 2)

Example results

The results in Plate 10 show the projected impact on birds as measured by changes in June water level by 2050 for a rain-fed MG4 wet grassland in south-east England. It can be seen that under the current baseline conditions, mean June water table level is 0.703 m below the surface. There is a 12% chance that under climate change by 2050, the mean June water level will only experience a minor change (green); where minor is no more than 0.05 m below this baseline (-0.753 m). However, there is a 51% chance that June water level will fall by more than -0.753 m, but remain above -0.853 m, i.e. within the zone that we consider to be an intermediate impact (amber). Additionally there is a 37% of a major impact on mean June water level with reduction below -0.853 m (red).

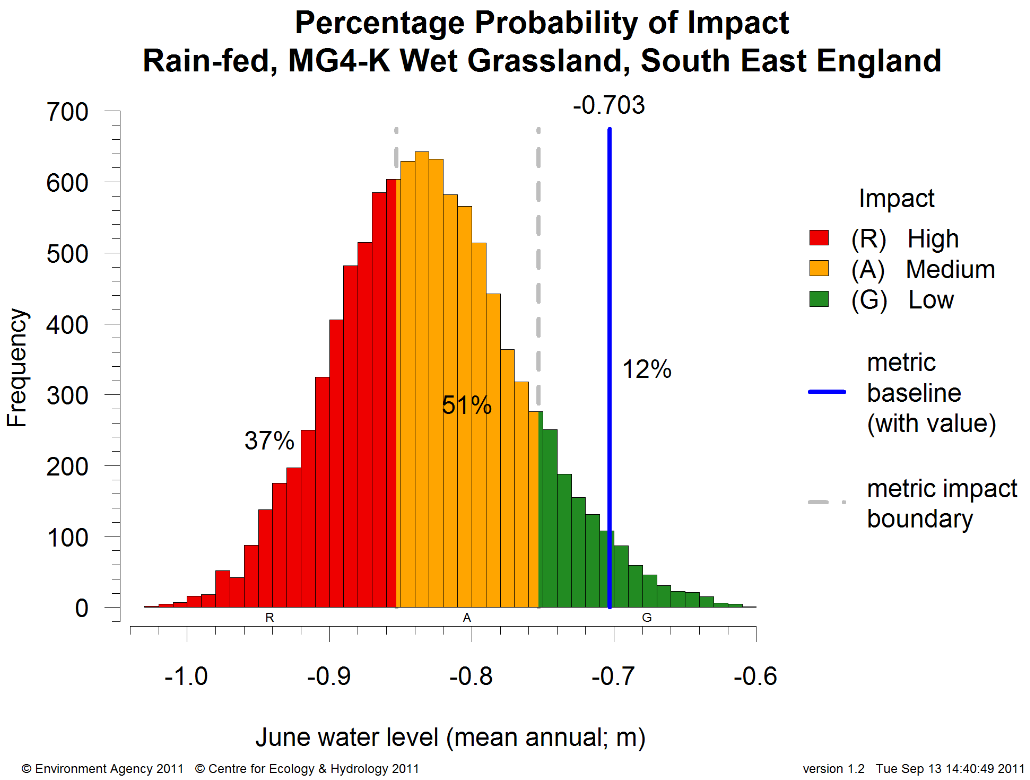


Plate 10 Histogram output. For birds - change in mean June water level by 2050 for a rain-fed MG4 (type K) wet grassland in south-east England

The results in Plate 11 show the projected impact on gross water balance as measured by changes in mean annual rainfall minus evaporation for an M16 wet heath in East Anglia. It can be seen that under baseline conditions, mean annual rainfall exceeds actual evaporation by 116.4 mm. There is a 33% chance that under climate change by 2050, the water balance will only experience a minor change (green); where minor is within plus or minus 10% of this baseline (in the range 105.8 – 128.0 mm). However, there is a 42% chance (35+7) that the water balance will experience an intermediate impact (amber). This could be the result of slightly drier or slightly wetter conditions. Specifically, there is a 35% chance that conditions will be slightly drier with the water balance less that 105.8 mm, but remain above 116.4-25% mm, or slightly wetter, with the water balance greater than 128 mm but less than 116.4+25%. Additionally there is a 25% (23+2) chance of a major impact, consisting of a 23% chance of significantly drier conditions and a 2% of significantly wetter conditions.

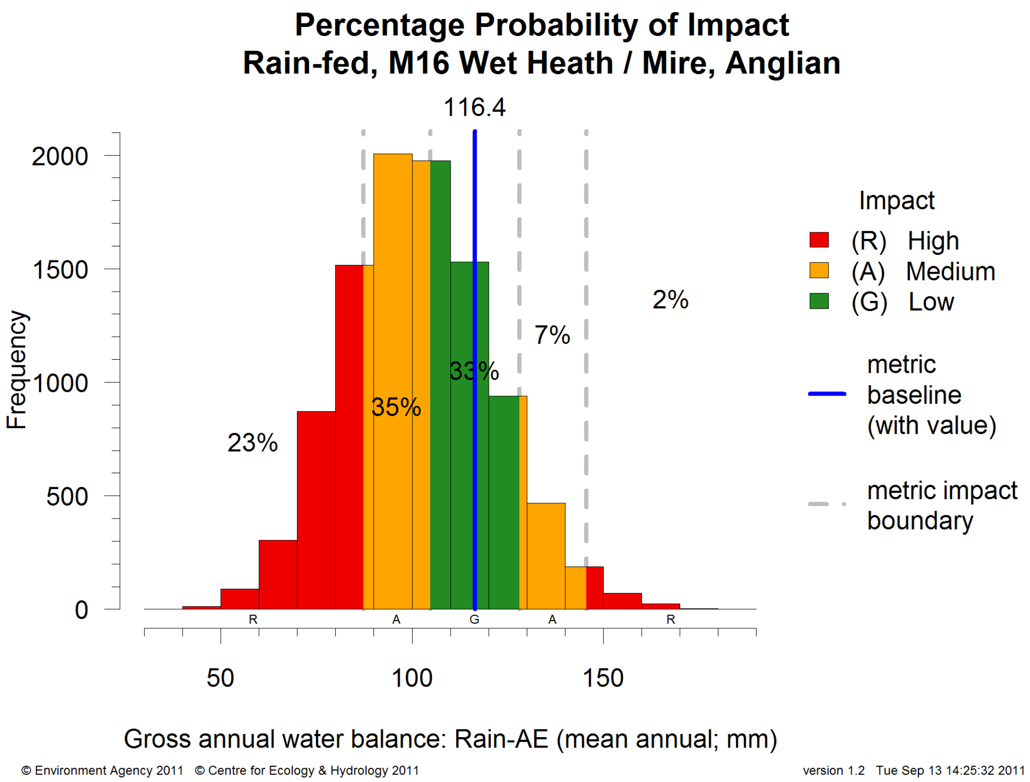


Plate 11 Output for hydrology – gross mean water balance (rain-AE) for rain-fed M16 wet heath in East Anglia

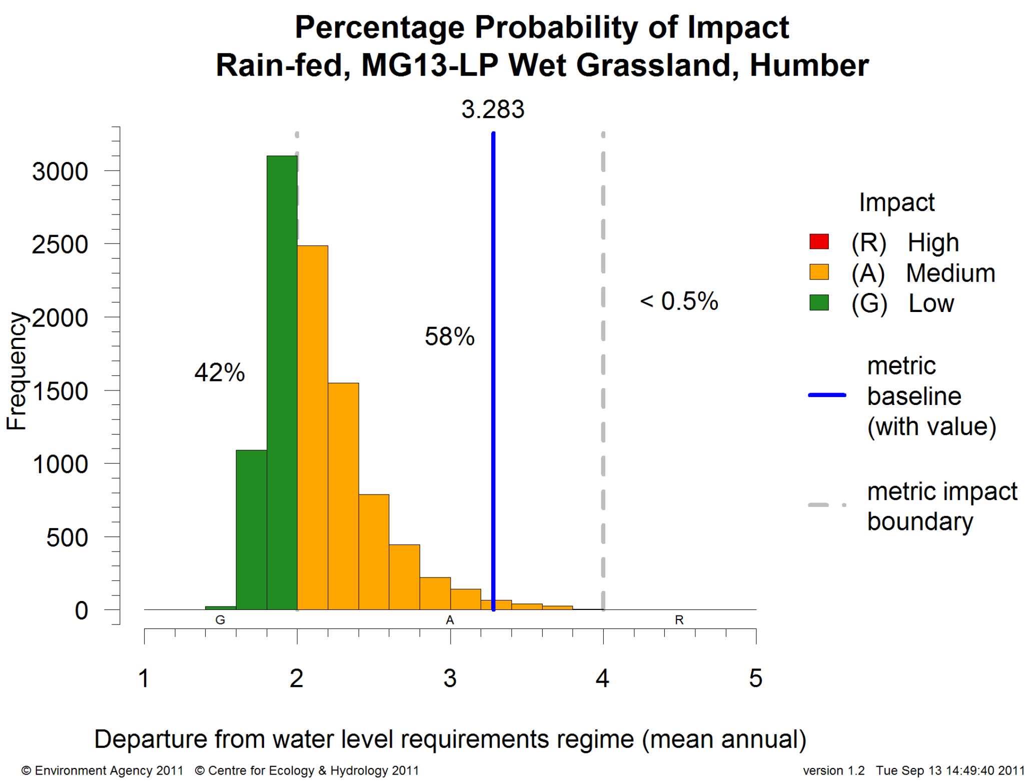


Plate 12 Output for vegetation – departure from required water regime for rain-fed MG13 (lower porosity) wet grassland in Humber region

The results in Plate 12 show the projected impact on MG13 grassland vegetation as measured by departures from the required water regime for the Humber region. It can be seen that the baseline conditions are in the amber, suggesting that the current water level regime is moderately unsuitable for this vegetation community. The current metric value for departure from the required water level regime is 3.283 calculated from

Σ (1.0 × number ‘unacceptable’ months, 0.5 × number ‘tolerable for short periods’ months)

Because it lies in the range 2 to 4, it is consider moderately unsuitable. However, there is a 42% chance that under climate change by 2050, the water table regime will change to be suitable for this MG13 community because the metric will reduced to less than 2. There is a very small chance that will conditions will worsen, with greater departure from desired water table level conditions.

Ambiguous type selection

In some cases there will be ambiguity in the selections made in various steps. For example, it may be uncertain as to whether the wetland is groundwater-fed or river-fed or it may be known that groundwater and the river water provide equal contributions. Furthermore, it may be that a floodplain margin is fed by river water, whereas distant from the river the wetland could be rain-fed (see STEP 2A above). The current version of the tool does not permit explicit assessment of dual water sources. It such cases, we recommend undertaking an assessment separately for each water source. Results might then be weighted according to the relative importance of the sources. The assessment can help to project whether the relative contributions may change. For example, if a rain-fed wetland is projected to dry-out and a groundwater-fed project to get wetter, it is likely that groundwater will become more dominant. Specific guidance cannot be given on how to combine the results, it is a matter of judgement based on knowledge of the site.

Water quality

The models used in developing the tool do not explicitly simulate water quality. However, it is the combination of hydrological regime and water quality that determines the ecological character of many wetlands. At North Meadow, on the upper Thames floodplain, annual inundation from the river is important not only because it saturates the wetland, but also because it bring nutrients to the soil. Water quantity and quality are often linked so that the implications for quality can be assessed as a secondary issue. For example, if in a fen wetland, chalk groundwater increases in dominance relative to rainfall, the wetland may become less acidic. Again it is not possible to give specific guidance as assessment will depend on knowledge of the site.

ACTIONS FOR STEP 5 Interpret results

Box 2 Limitations of the Tier 1 Wetland Tool for Climate Change

- The Tier 1 tool does not provide a detailed prediction for a particular wetland. It provides a generalised regional indication of the potential likelihood and magnitude of climate change impacts on wetlands suitable for risk screening and investigating uncertainty.
- Only the ‘medium’ emissions scenario and 2050s timeslice from UKCP09 are considered. Other emissions scenarios (‘high’ and ‘low’) might produce a different result and would be needed for a fuller impact assessment, although climate change is predicted to be relatively insensitive to emissions scenario until about 2040 (Murphy et al., 2009, p.42). Other timeslices (2020s and 2080s) are also available.
- Metric impact thresholds have been defined according to current literature and expert consensus. Users should consider whether these thresholds are appropriate for the particular wetland being assessed.
- The Tier 1 tool only considers hydrologically-driven impacts of climate change. Other non-hydrological factors influencing interest feature sustainability, such as changing migratory patterns for bird species, are not considered.
- Existing site management has not been considered for the baseline period nor projected into the climate change future timeslice. For example winter water storage or management of ditch water levels to retain water could make an existing wetland more sustainable under baseline conditions and mitigate future climate change impacts.
- Direct effects of, for example, temperature and carbon dioxide changes on plant physiology, as projected for the climate change scenario and timeslice, have not been considered.
- Multiple water sources to the wetland have not been explicitly considered. As discussed below, multiple water sources should be assessed separately and the results should then be considered in combination using site understanding.
- Water quality/nutrients have not been explicitly considered. As discussed below, it may be possible to use site understanding to infer impacts under climate change. For example, if the water balance metrics show increasing groundwater supply from a Chalk aquifer, the wetland base-richness may well increase.

4. Responding to projected climate change impacts

4.1 Do nothing option

For many assessments of the impact of climate change on wetlands, there will be a high probability of no significant impact. In such cases, the decision may be that no action is required.

4.2 Assessing trajectories

The results of the assessment may be that there will be significant impact on the current interest feature(s). This will be particularly problematic for sites designated for interest feature at risk, such as in the specification of an SSSI or Habitats Directive where conservation of the feature is of upmost importance.

In other cases, it may be that the current interest feature(s) will be replaced by others of equal interest. For example, drying of a site currently supporting MG13 wet grassland may stimulate its replacement by MG8 or MG4 wet grasslands (Figure 6). Development of the *Ecohydrological guidelines* (Wheeler *et al*, 2004) included definition of trajectory diagrams that suggest the possible succession of one plant community to another as conditions, including wetness and nutrient status change. The speed at which succession will occur depends on many other factors including the local availability of seeds and propogules of the new communities. Succession may be assisted by trans-planting or seeding.

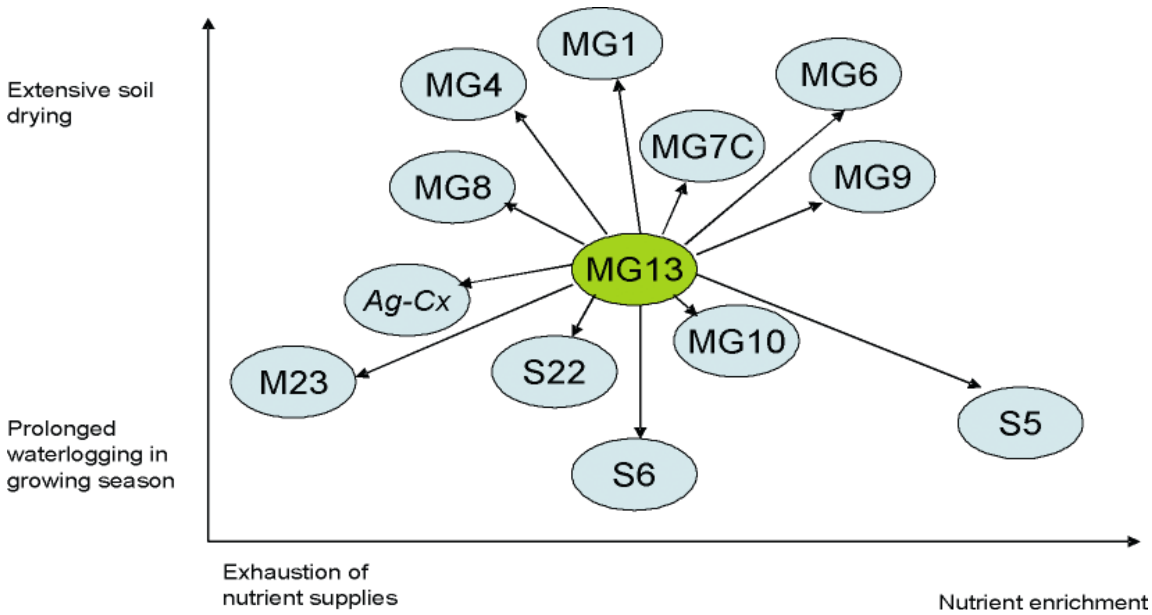


Figure 6 MG13 wetland plant community trajectories in response to changes in nutrient and wetness (after Wheeler et al., 2004)

4.3 Undertaking more detailed analysis

It important to remember that the results of the Tier 1 Wetland Tool for Climate Change are intended to be general and should not be used as the basis of major decisions about the management of specific sites. If the Tier 1 assessment suggests that any particular wetland will be significantly impacted, and hence major action should be taken, it would be advisable to undertake a more detailed analysis with a Tier 2 (Chapter 6) or Tier 3 (chapter 7) approach to produce results with more certainty. Tier 2 models can also be used to run other climate change scenarios such as high emissions or for other periods e.g. the 2020s or 2080s.

4.4 Monitoring

As stressed above, the assessment tools provided produce general results. Greater confidence in future changes at a site will be achieved by monitoring and analysis of results. At many sites regular monitoring takes place, including hydrological recording of water table levels in dip-wells, bird numbers and plant community surveys. Focus should be on indicator species or those that are most sensitive to hydrological change such that they will be the first to be impacted and their disappearance may signal future impacts on the community as a whole. Likewise appearance of new species, such as those better able to compete in drier conditions, may signal alterations in conditions. Although all such data are subject to inter and intra-annual fluctuations, trends in the status of interest features can be detected and the direction and speed of change recorded.

A guide to monitoring water levels and flows at wetland sites was published by the Environment Agency (2003) in collaboration with English Nature, Wildlife Trusts and RSPB. The booklet suggests a number of methods to collect accurate and meaningful measurements of groundwater levels and surface water levels and flows; it also outlines how surface water and groundwater may interact at wetlands and how information on water levels and flows can be used to gain a better understanding of wetland processes.

4.5 Site management

The hydrological regime of many wetlands is managed to optimise certain objectives, such as conserving plant communities or attracting wintering or breeding birds. Water management may be achieved by various types of infrastructure including penning boards and sluice gates to maintain target water levels in ditches and pumps (often wind powered) to distribute water around the site. Morphological features including shallow surface channels (grips or grypes) and scrapes can help feed water from ditches to in-field areas or retain open water habitats. Larger scrapes and depressions can act as reservoirs to hold water from wet periods for use during dry periods, which may become more necessary in future, if wetter winters and drier summers transpire.

The design and operation of water storage areas and other infrastructure depends very much on the characteristics of the site. A notable example is the Great Fen Project in East Anglia which is restoring up to 30 km^2 of wetland between Peterborough and Huntingdon. Currently, large volumes of water are pumped out of the area to prevent flooding of agricultural land. Plans are being considered to build water storage within the fen to hold 3.5 million m^3 of predominantly winter rainfall, which will be made available to support the wetlands in summer. Climate change projections (for the four UKCIP02 emissions scenarios) suggest that the storage would need to be expanded sufficiently to offset a potential 6 to 8 million m^3 average wetland water deficit by the 2050s (Blake and Acreman, 2009).

Various references are available to assist with site management such as the *Wet grassland guide* (Benstead *et al*., 1997) and the *Waterways & Wetlands: A Practical Handbook* (Brooks and Agate, 2007) and *The Fen Management Handbook* (McBride et al., 2011).

4.6 Catchment management

Wetlands are intimately linked to their surrounding catchments. Abstraction from upstream water courses or underlying aquifers, impoundments or off-takes may impact on wetland hydrology. Concerns about potential change in wetlands need to be raised through the catchment planning process or CAMS.

It is not always possible to mitigate loss of one water source for another. Shirley Pool in Cheshire is a peat bog on the Sherwood sandstone, which contains important archaeological wood remnants of Bronze Age settlements. The site has become drier and English Nature made an application to take water from a Magnesium Limestone aquifer to keep the site wet. However, it was felt that the pH of this water could be too high to conserve the wooden remains. The same problem applied to restoration of Holme Fen, a raised mire near Huntingdon. Raised mires are acidic as their primary water source is rainfall. Compensatory water could not be pumped from surrounding ditches due to high pH plus fertilizers and pesticides from adjacent farmland.

Although we tend to think of insufficient water during summer as the most likely major impact of climate change on wetlands, increased winter rainfall may make some wetlands too wet at that time of year. Otmoor in Oxfordshire is bowl-shaped clay-based floodplain wetland which suffers from frequent and major inundation during the winter. The site owners (RSPB) often have difficulty removing water from the site as receiving ditches are often full during the winter and additional water would cause flooding of downstream farmland.

Pawlett Hams in Somerset is a reclaimed salt-marsh on the floodplain of the River Parrett estuary. It has a very small natural catchment and estuary water is to saline. To support the wetland grasslands, water is pumped through a pipe under the Parrett from a stream that drains to the opposite bank. Water supply is a major limitation to current management and this is likely to worsen under climate change. Trials of solar-powered pumps have been undertaken in search of a cheaper more sustainable water management option.

4.7 Managing historic environments

Wetlands contain four, usually overlapping, categories of remains that are of a particular value to the historic environment, and these determine the most appropriate management options when considering the impacts of climate change.

- Wetlands are frequently themselves ancient landscapes that have been shaped by the activity of previous generations, and are valued for their idiosyncratic manifestation. This includes landscapes that were drained and cultivated, or where peat was used for fuel. Management options for this type of historic wetland environment should focus on the minimization of surface-altering activities and vegetation.

- Wetlands which have been formed through peat-growth or sediment accretion contain frequently buried ancient landscapes, which include the remnants of field systems, settlements, and burial sites. These landscapes are especially valued because of the outstanding preservation of the historic environment that may be encountered here because of the exclusion of more recent impacts. Management options for this type of historic wetland environment should focus on the protection of the over-lying wetland deposits that will ensure the continued preservation of the buried historic landscape.

- Wetlands frequently preserve, through waterlogging, organic remains that are rarely discovered in ‘dryland’ contexts, and this includes bog bodies, ancient trackways and settlements, and wooden artefacts such as bows, axe-handles, and logboats.

Management options for this type of historic wetland environment should focus on maintaining groundwater levels at minimum heights, and where soils are exposed to oxygen for more than three months a year, the desiccation of these remains is inevitable. However, input of water with a different chemistry from the groundwater should be avoided, as this will have long-lasting adverse effects on the buried environment. A range of monitoring techniques are now available for determining groundwater levels and chemistry, and these can play a key role in establishing the likelihood of future preservation potential. Where groundwater levels and chemistry cannot be maintained, the archaeological excavation of the organic remains will be the most appropriate management option.

- Wetlands are archives of environmental and climate change, sometimes going back in time in excess of 10,000 years, in the form of the accumulated sediments and peats containing pollen, insects and plant macro-fossils, phytoliths, testate amoeba, and other types of remains; these sediments and indicators can be dated through radiocarbon essay, providing chronological accuracy in the reconstruction of the environmental development of wetlands and their hinterlands. Management options for this type of historic wetland environment are the same as for those that have preserved organic archaeological remains, and should focus on maintaining groundwater levels at minimum heights, and avoiding input of water with a different chemistry from the resident groundwater, as this will have long-lasting adverse effects on the buried environment and the environmental remains. These wetlands can be sampled (e.g. through coring and sampling) and studied with causing only very limited damage to the wetland environment.

5. A closer look – the Tier 2 tool

As described above the Tier 1 tool was derived by running a set of simple wetland models in each river basin region of England and Wales. In each case the models were set up to simulate a representative wetland (e.g. average soil characteristics) driven by average climate data for the region from UKCP09. A simple improvement in precision using the same available models can be achieved by using locally appropriate variables.

5.1 Rain-fed wetlands

Key variables in modelling rain-fed wetlands are rainfall amounts and wetland soil characteristic 'specific yield' – which is the amount of water that can be drained from a unit volume of saturated soil. Local rainfall projections for all 25 km squares of the UK have been defined by UPCP09; these are available from
http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/download/gridMaps/25kmMapSearch.html
These data will provide more locally appropriate rainfall inputs for specific wetlands. Future rainfall and temperature data would need to be downloaded from the UKCP09 web site along with baseline climate data from the Met Office.

Specific yield can be derived by laboratory analysis of soil samples from the wetland. Alternatively, it can be estimated from published tables using expert knowledge of the wetland soil (Table 3).

Table 3 Hydraulic characteristics of peat soils related to their state of decomposition (after Boelter, 1975)

Peat type		Sample depth (m)	Specific yield cc/cc	Hydraulic conductivity (m/day)
Sphagnum moss peat	Live, un-decomposed	0-0.1	0.86	
	Un-decomposed	0.15-0.25	0.6	32.9
	Un-decomposed	0.45-0.55	0.48	0.9
	Moderately decomposed (woody)	0.35-0.45	0.23	0.12
Woody peat	Moderately decomposed	0.35-0.45	0.27	4.3
	Moderately well decomposed	0.6-0.7	0.19	0.48
Herbaceous peat	Slightly decomposed	0.25-0.35	0.57	11.1
	Moderately decomposed	0.7-0.8	0.13	0.006
Decomposed peat	Well decomposed	0.5-0.6	0.08	0.004

5.2 River-fed wetlands

The main driving data for assessment of these wetlands are river flow time series. In the Tier 1 tool, data from a 'typical' river in the river basin region were used. Baseline data were obtained from the National River Flow Archive http://www.ceh.ac.uk/data/nrfa/. Projections of future flows in 2050 under climate change were generated from a database of 108 flow stations established for a Defra funded project (Crooks *et al.,* 2009).

Application of the Tier 2 tool involves using river flow time series for the wetland site under assessment. Where there is a river flow gauging station nearby with data in the Defra archive, these can be used directly. A list of stations is provided in Annex 5. If there is a nearby gauging station not included in this archive, a rainfall–runoff model would need to set-up and calibrated using data for the station from the Environment Agency or the National River Flow Archive. Where no gauging station exists a flow generation method, such as CERF (Environment Agency, 2008; Young et al., 2008) would need to be employed. In either case, rainfall and temperature data would need to be downloaded from the UKCP09 web site along with baseline climate data from the Met Office. Ideally, site specific values of levee height, bankfull discharge and rating equation terms are also required.

5.3 Groundwater-fed wetlands

The main driving data for assessment of these wetlands are groundwater level time series. In the Tier 1 tool, data from 'typical' boreholes for each aquifer in the river basin region were used. Baseline data were obtained from the National Groundwater Level Archive http://www.ceh.ac.uk/data/nrfa/data/ngla.html. Projections of future groundwater levels in 2050 under climate change were selected from 24 observation boreholes modelled as part of 'Future Flows and Groundwater Levels', an Environment Agency funded project (http://www.ceh.ac.uk/sci_programmes/Water/FutureFlowsandGroundWaterLevels.html).

Application of the Tier 2 tool involves using groundwater level time series for the wetland site under assessment. Where there is a groundwater observation borehole nearby, which has been included in the Future Flows and Groundwater Levels project, this can be used directly. A list of boreholes is provided in Annex 6. If there is a nearby observation borehole not included in this dataset, a point scale model as applied for the Future Flow and Groundwater Leves project (e.g. Jackson, 2012) or a local and possibly regional groundwater model would need to be set-up and calibrated using data for the particular location. Where no observation data exists it may be possible to interpolate groundwater levels from other nearby observation boreholes and river/surface water levels, although there would be a significant increase in uncertainty. In either case, future rainfall and temperature data would need to be downloaded from the UKCP09 web site along with baseline climate data from the Met Office. Ideally, wetland surface elevation with reference to Ordnance datum is also required.

The rain-fed, river-fed and groundwater-fed wetland models can be made available by CEH as executable files.

Applying the Tier 2 tool requires the ability to handle large data sets and to set-up and run simple command line models. As it can take several weeks to apply the Tier 2 tool plus any initial familiarisation, it is recommended that the work is undertaken by CEH (in collaboration with BGS for groundwater modelling).

6. Detailed assessment – the Tier 3 tool

In the face of climate change projects, some major decisions may need to be made for some wetlands, such as excavating channels to distribute water, managing level water or provision of water storage reservoirs. Implementing these options can be very expensive.

Tier 3 models are aimed at producing detailed assessments required to support major management decisions. This third tier involves application of complex models that consider more of the processes at work within the wetland and often describe spatial patterns of hydrology, ecology or the historic environment, not simulated by the Tier 2 models. Such models often required long series of hydrological data from the site and information, such as topography, physical soil properties and dimensions of channels and structure (*e.g.* penning boards and sluice gates). Examples of models are commercially available MIKE-SHE/MIKE II coupled surface-groundwater model employed to assess impacts of climate change on the North Kent Marshes (Thompson *et al.,* 2004; Thompson, 2008) or MODFLOW groundwater model (Bradford & Acreman, 2003), used to assess impacts of abstraction on Habitats Directive wetlands in East Anglia (Whiteman et al., 2004). These models have the added advantage of predicting spatial patterns of changes within a wetland, thus providing areal extent of impacts. However, in contrast to simple Tier 1 and 2 models, it is generally impractical to run the complete set of 10,000 probabilistic climate change projections provided by UKCP09 using complex Tier 3 models. They require contracting specialist consultants or commissioned researchers and may take many months to setup and run.

Typical models of this type require time series (1-2 years) of water table level data, soil hydraulic properties (such as hydraulic conductivity and specific yield), details of underlying geological strata (nature of aquifers and superficial deposits), local rainfall, river flow and evaporation data. The modelling activities may take several weeks, including development of conceptual understanding of the site, configuration and calibration. In addition, rainfall and temperature data for future scenarios would need to be downloaded from the UKCP09 web site. The case studies below provide more information on the application of Tier 3 models.

7. Case studies

Each of the 3 tier tools was applied to a set of case studies. Several criteria were used to select the sites.

- covering rain-fed, river-fed and groundwater-fed wetlands
- availability of pre-constructed and calibrated Tier 3 models
- distribution across England, but focusing on areas where climate change was like to have an impact
- a range of interest features

7.1 North Kent Marshes, Kent

The North Kent marshes are an archetypal example of UK coastal lowland wet grassland and the largest remaining area of this habitat in south-east England. They cover 8.7 km^2 on the south side of the Isle of Sheppey and have a mean elevation of approximately 1.90 m aOD. The marshes are surrounded by embankments and drainage to the sea is facilitated by gravity tidal sluices. Elmley Marshes Reserve lies in the south-west corner of the marshes. The reserve consists of 3,300 acres of rough, damp grazing pasture intersected by meandering 'fleets' and ditches and bordered by the saltmarsh and tidal mudflats of the Swale Estuary as well as some arable farmland. In winter, the marshes provide habitat for thousands of wildfowl and waders from the Swale use the reserve as a safe roost. In summer, redshanks, lapwings and avocets breed. Marsh harriers breed here, peregrines can be seen year round and, in winter, there are hen harriers, merlins and short-eared owls.

A study was undertaken to understand the major processes within the land phase of the hydrological cycle including overland, unsaturated and saturated subsurface flows, interception and evapotranspiration. This employed a Tier 3 model of the Elmley Marshes developed using the coupled MIKE SHE (hydrological) / MIKE 11 (hydraulic) modelling system. A detailed account of the development, calibration, validation and results of the Elmley model is provided by Thompson *et al.* (2004). A relatively fine spatial scale (30 m × 30 m) is employed and the model was parameterised using a range of primary and secondary data. Robust calibration and validation was based on comparisons of observed and simulated water table depths and ditch water levels with original meteorological data being available for a 36 month period (25/06/1997–29/06/2000).

To project the potential impacts of climate change on the Elmley Marshes climate data from three Regional Climate Model (RCM) runs (HadRM3-PPE; medium emissions scenario): AFGCX, AFIXA and AFIXQ were employed (see http://badc.nerc.ac.uk/data/hadrm3-ppe-uk/ensemble_members.html). For each, a 30 year baseline period (1961-1990) and a 30 year future period (2040-2069) were defined. Daily simulated precipitation and potential evapotranspiration (PET) were provided for each scenario / period. In this study direct application of daily RCM precipitation and PET for 30 year simulations was used. For each of the three scenarios two 30 year simulations were specified in which the daily precipitation and PET for the baseline and future periods were directly specified as model inputs. The impact of climate change upon wetland water tables associated with each scenario can be visualised by comparing 30 year baseline water tables with 30 year future water tables. This permits the derivation of monthly delta factors for water table for each scenario which can be applied to observed water tables or those simulated by the calibrated model.

MG11 is a key wet grassland vegetation community at North Kent Marshes, as simulated in the Tier 3 modelling. Since MG11 is not currently one of the wet grassland variants represented in the Tier 1 modelling, it was approximated as MG13 (lower porosity variant).

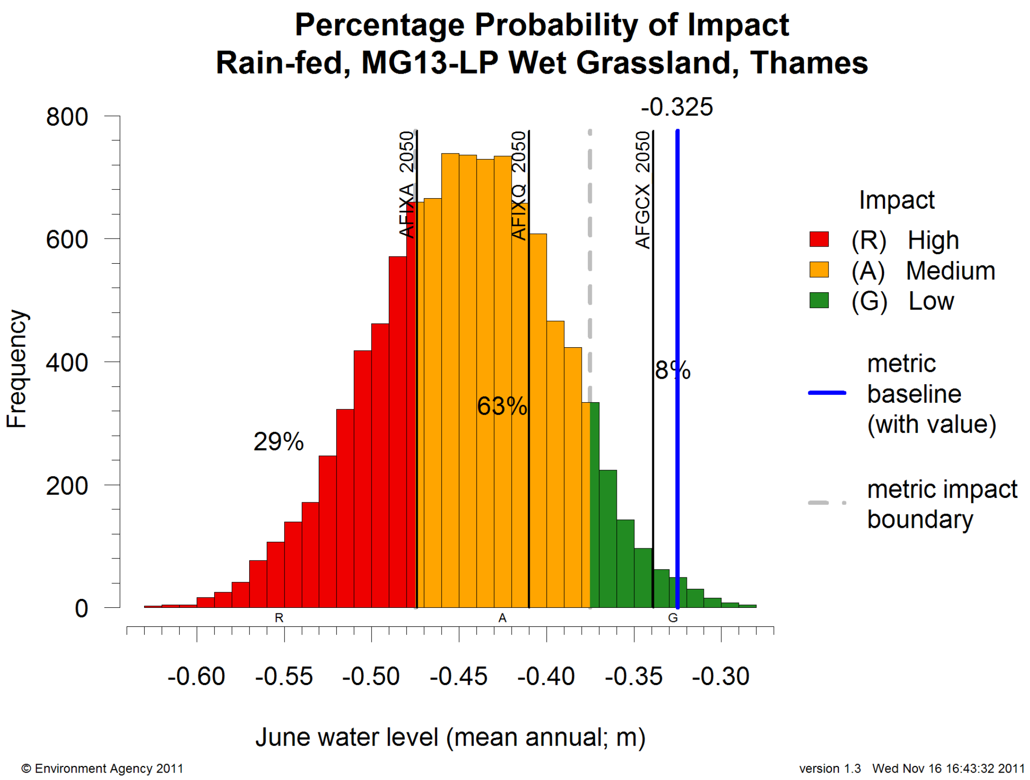


Figure 7 Comparison of results from Tier 1 and Tier 3 models at North Kent Marshes for mean June water level

Figure 7 shows the projections for mean June water level resulting from use of this Tier 3 model (black vertical lines) compared to the results from Tier 1 (histogram) at North Kent Marshes. It can be seen that all three Tier 3 results fall within the histogram, demonstrating consistency between the Tier 1 and Tier 3 models. AFGCX is consistent with low impact (green), AFIXQ lies within the medium (amber) impact zone, whilst AFIXA is on the medium/high (amber/red) boundary.

7.2 North Meadow, Cricklade, Wiltshire

North Meadow is designated a Special Area for Conservation (SAC) under the Habitats Directive on account of the species-rich grassland it holds, which is a prime example of traditional floodplain meadow. A hydrological model of the site had been previously developed (Gowing and Youngs, 1997; Gowing *et al*., 1998), which was used here to investigate the impact of future climate scenarios on the soil water regime of the site. The model has been validated against long runs of observational data from seven dipwells across the site, some of which have continuous data stretching back more than twenty years (Gowing *et al.,* 2002). The model solves drainage equations to simulate the shape of the phreatic surface between the two rivers that enclose the site. The meadow sits upon fine-textured, but well structured alluvium, up to one metre in depth, above terrace deposits of sand and gravel, which have high hydraulic conductivity and therefore act as a shallow aquifer, effectively connecting the two rivers hydraulically beneath the meadow. The soil-water regime is thus sensitive to variation in river level as pressure heads are propagated via the aquifer to all parts of the site. The site is a classic floodplain environment, in which the hydrology is determined by a combination of meteorological inputs, surface water regime and groundwater regime.

The model therefore needs to combine a variety of water-delivery mechanisms. It is an analytical model that runs at a field scale and takes the stage levels of the surrounding water-courses to be boundary conditions. It runs on a weekly time-step to suit the assumptions of a quasi-equilibrium state required to solve the underlying equations. Inputs to the model are precipitation, potential evapotranspiration and the stage level in each river. The meteorological data were drawn from the climate scenarios under investigation. The river stage data were based on flow predictions made by CEH using catchment-response models for the two adjacent rivers (Thames and Churn.) The flow predictions were converted into stage levels using Crump equations developed for a gauging weir on each river close to the site. The gradient along the river was estimated from field observations (Gowing and Youngs, 1997.) Mean weekly values of river levels were used to solve the seepage equations within the model, whilst maximum weekly levels were used to run its flood routines.

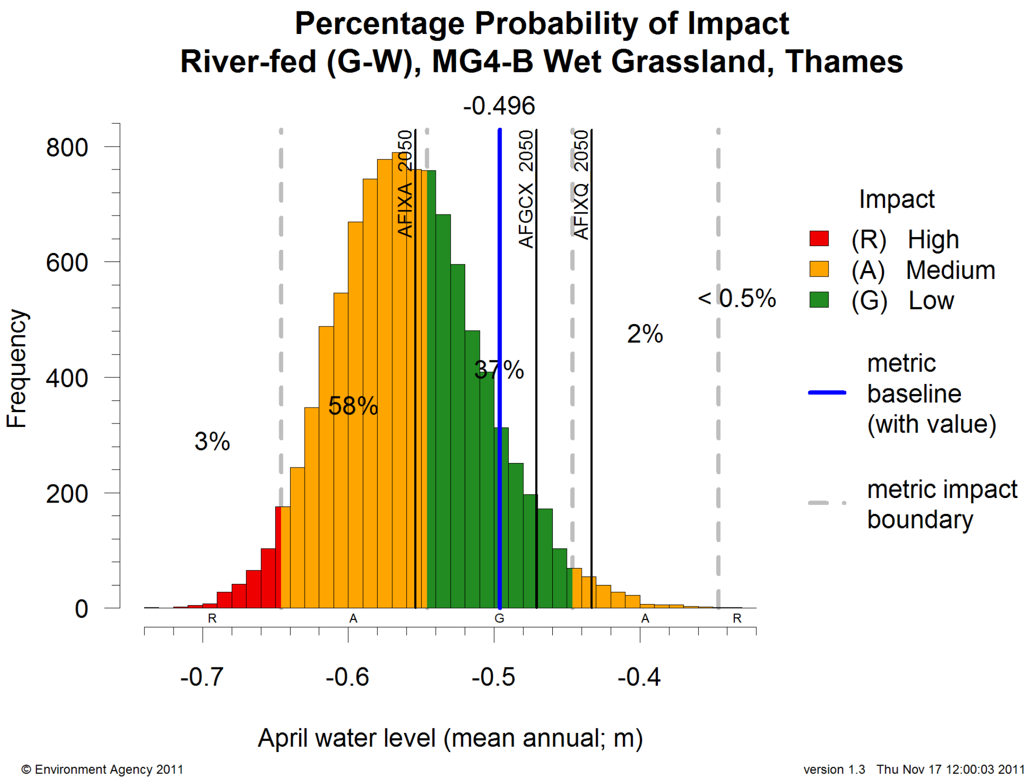


Figure 8 Comparison of results from Tier 1 and Tier 3 models at North Meadow for mean April water

Being based on analytical solutions of drainage equations, the model can be applied to any point in the meadow, which is 44 ha in extent. To represent the spatial variation within the site, which arises from factors such as distance from river, microtopography, depth of alluvium etc., twenty random points were selected. For each of these points, a precise surface elevation and spatial position were known. Soil depth and soil hydraulic properties were inferred by interpolation from sample measurements across the site (Gowing *et al*., 1998). The model runs a flood routine when the maximum stage level of either river exceeds bank height. Water is assumed to flow across the meadow to the same level as the river and then to return to the river once stage levels fall below bank level, except where it is retained within local basins. Each modelled position was thus assigned a flood-retention level to reflect the depth of retained water following a flood event. Retained water then either drains via the soil profile and aquifer or evaporates, unless there was a subsequent flood.

The output of the model is composed of weekly water-table depths over a thirty-year period for each of the selected positions for each of the scenarios.

Figure 8 shows the projections for mean April water level resulting from use of this Tier 3 model (black vertical lines) compared to the results from Tier 1 (histogram) at North Meadow. It can be seen that all three Tier 3 results fall within the histogram, demonstrating consistency between the Tier 1 and Tier 3 models. AFIXA shows a decrease in mean April water level with a medium impact (just in the amber zone). Both AFGCX and AFIXQ project slight increases in mean April water level with AFGCX showing a low impact (green) and AFIXQ showing a medium (amber) zone.

7.3 Great Cressingham Fen, Norfolk

Great Cressingham Fen is a groundwater-fed wetland site located in a tributary valley of the River Wissey, near the village of Great Cressingham in Norfolk (National Grid Reference TF848022). One of the best remaining examples of calcareous spring-fed valley-fen in west Norfolk; it has retained the full series of vegetation types, which range from dry unimproved grassland on the highest slopes, through wet, species-rich fen grasslands where springs emerge to tall fen vegetation in the valley bottom (see Figure 9). The site supports a very large number of plants including several uncommon species. The site covers an area of approximately 13.7 ha at an elevation of between 25 and 30 m AOD. The fen is groundwater-fed, by springs and seepages from the Chalk via granular alluvial deposits. Surface inputs are from direct rainfall and limited rainfall-generated runoff. The eastern part of the fen floods at times, however this may be due to backing up of water draining from the fen rather than inundation from the River Wissey. The site supports important vegetation communities that are recognised under the European Habitats Directive:

- Alkaline Fens (M13 *Schoenus nigricans-Juncus subnodulosus* mire);
- Calcareous fens with *Cladium mariscus* and species of the *Caricion davallianae* (S25 *Phragmites australis – Eupatorium cannabium* tall-herb fen);
- *Molinia* meadows on chalk, peat, clay or silt-laden soils (M24 *Molinia caerulea-Cirsium dissectum* fen meadow).

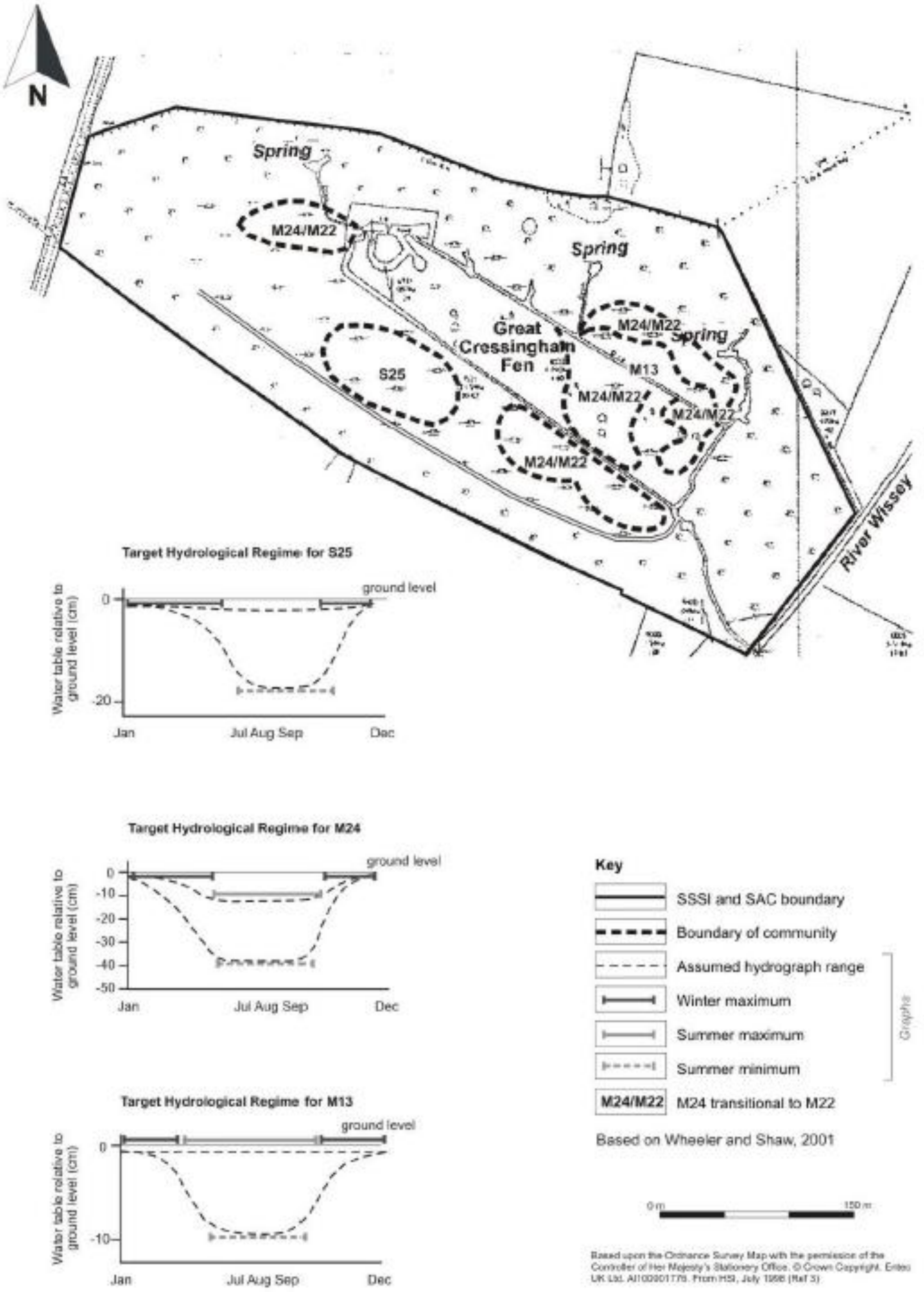


Figure 9 Great Cressingham Fen (Whiteman et al. 2004)

The Environment Agency has responsibility to assess potential hydrological impacts and ecological effects of new and existing consented activities on sites designated under the Habitats Directive. As part of its Review of Consents, the Agency commissioned detailed studies at Great Cressingham Fen. In 2003, the main issues affecting ecological features within the site were believed to be associated with the 30 current abstraction licenses within a 6 km radius of the site (Whiteman *et al*., 2004). These include groundwater abstractions for public water supply (PWS) and spray irrigation. Geological logs and recorded water levels suggested that sand and gravel alluvium deposits located on the northern edge of Great Cressingham Fen are in direct connection with the Chalk aquifer. Large groundwater springs and seepages are located along the northern and north western boundaries to the fen and where ponds and drains intersect the water table that occurs in the Chalk and overlying superficial deposits. The studies involved hydrogeological assessments carried out using a range of methods including a time variant distributed numerical groundwater model constructed using MODFLOW (McDonald and Harburgh, 1988) by ENTEC (2003).

Great Cressingham Fen was selected as part of the current study as an example of a groundwater-fed wetland that had an existing Tier 3 model based on available water level data and physical properties of the geology. The Fen falls within the 70 x 70 km area covered by the Ely Ouse regional groundwater model, represented by a single 200 m by 200 m horizontal grid cell. The groundwater model comprises of a rainfall-runoff model (4R; Heathcote et al., 2004) running at a daily time step and a saturated zone flow model (MODFLOW) running at a monthly timestep. ENTEC (2011) was commissioned to use the groundwater model to assess the impacts of climate change on groundwater levels. The model has five vertical layers: (i.) near surface sand and gravel deposits or thin peat in certain areas (including the Fen); (ii.) clay dominated deposits, such as Boulder Clay; (iii.) granular deposits beneath the Boulder Clay; and (iv.) two layers representing the regional Chalk aquifer. The model was run to simulate monthly groundwater levels over the baseline time period with no abstractions (1961 to 1990) and for the 2050s (2040 to 2069). Three combined representations of baseline and future climate were run (from an ensemble of 11 from the Regional Climate Model) representing standard (AFGCX), low sensitivity (AFIXA) and high sensitivity (AFIXQ) conditions.

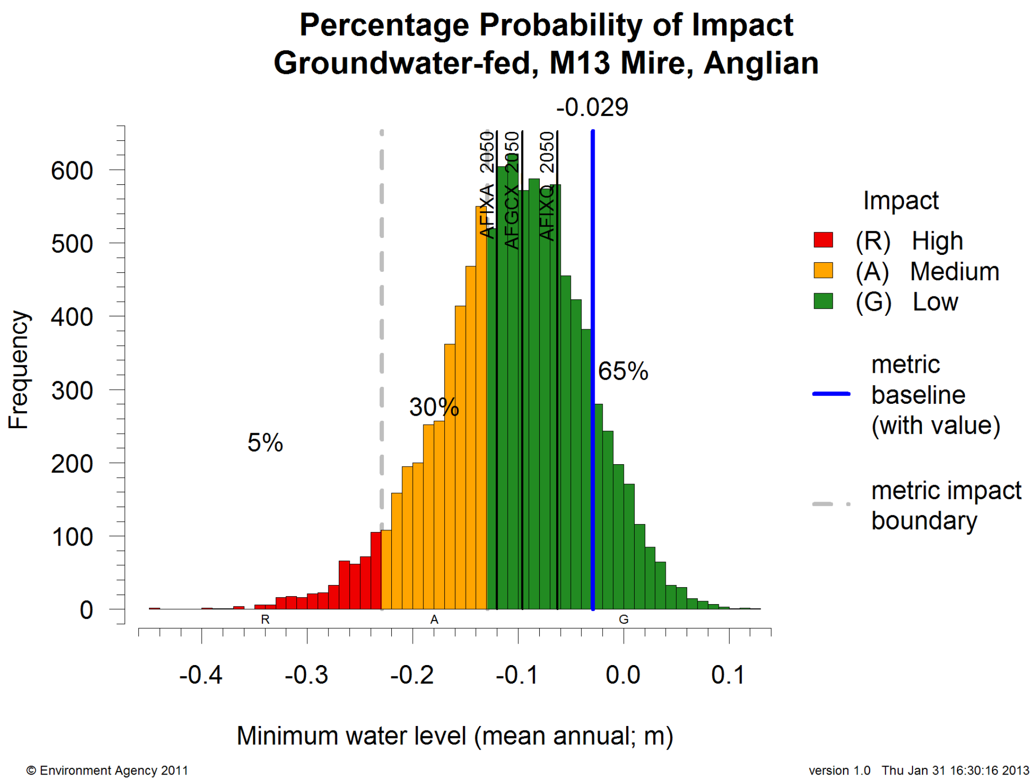


Figure 10 Comparison of results from Tier 1 and Tier 3 models at Great Cressingham Fen for mean annual minimum water level

Figure 10 shows the projections for mean annual minimum water level resulting from use of this Tier 3 model (black vertical lines) compared to the results from Tier 1 (histogram) at Great Cressingham Fen. It can be seen that all three Tier 3 results fall within the histogram, demonstrating consistency between the Tier 1 and Tier 3 models. AFIXA shows a decrease in mean annual minimum water level with a low impact (but near the amber-green boundary). AFGCX projects a low impact with a decrease in mean annual minimum water level similar to the histogram median value as projected using the UKCP09 data. AFIXQ projects a somewhat smaller decrease in mean annual minimum water level, again with a low impact (green).

Although results for this particular metric show good agreement between the Tier 1 and Tier 3 models, several factors complicate comparison between the modelling tiers at Great Cressingham Fen: (i.) the Tier 1 model is constrained by data availability to a 1980 to 1990 baseline period (see Annex 2) and a corresponding 11-year 2050s future period, whilst the Tier 3 model simulates the full 1961 to 1990 baseline period and corresponding 2040 – 2069 future period; (ii.) the Tier 3 groundwater model grid cell representing Great Cressingham Fen covers several vegetation communities including M13 mire, M24/M22 fen meadow transition and possibly S25 tall-herb fen; therefore the modelled groundwater levels are an average response across the Fen for the combined communities; and (iii.) although the groundwater observation borehole used to generate the Tier 1 results represents naturally occurring conditions and the Tier 3 model used is the ‘naturalised’ version (i.e. with the effects of abstraction removed), it is still possible that some difference may be due to the naturalisation approach employed by the Tier 3 model.

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Annex 1

Climate change scenarios

The current set of climate change information for the UK is called UKCP09, which was published in 2009. UKCP09 includes an estimation of modelling uncertainty quantified through the use of a perturbed physics ensembles (PPE), which explores variation in model parameters related to atmospheric and oceanic processes, the Sulphur cycle, and the Carbon cycle. In addition, downscaling uncertainty is explored by generating a PPE from the regional climate model HadRM3. Further, to capture differences in the way that different international global climate models represent the physics of climate, a multi-model ensemble was used, thus incorporating structural error (discrepancy) into the probabilistic projections. The result was to produce not just one, but 10,000 realisations of each climate scenario.

The Projections are presented for three different future scenarios representing High, Medium and Low greenhouse gas emissions. They provide temperature, precipitation, air pressure, cloud and humidity data for locations across the UK. In this study we selected the Medium emissions scenario. For full details, see: http://ukclimateprojections.defra.gov.uk/ and Murphy et al. (2009).

Tier 1 and Tier 2 wetland model formulation

Rain-fed wetlands

The model broadly follows that developed by Acreman et al. (2009). There are three basic water transfer mechanisms controlling the hydrology of these wetlands (Figure A1): precipitation (P – mainly rainfall in UK), evaporation (E) and outflow (OF). The volume of water, and hence the water table levels, within the wetland will depend on the balance between the three processes. When precipitation exceeds evaporation, the water table will rise, up to a maximum threshold level, above which any further potential water level rise will be lost as surface water outflow. The rate of rise (ΔWL) will be dependent on the available pore space in the soil. For example, if the pore space is 50% then 10 mm excess rainfall will lead to a 20 mm rise.

$$\Delta WL = (P - E) / SY$$

If new $WL > WL_{MAX}$ then $WL = WL_{MAX}$

where SY is the specific yield[1], a dimensionless scalar. P, E, WL_{MAX} and ΔWL are in mm.

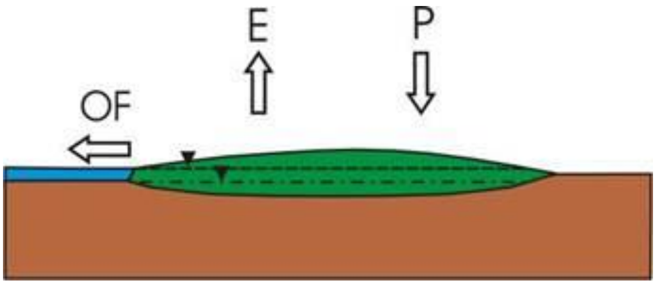

Figure A1 Schematic cross section of a rain-fed wetland showing key water transfer mechanisms (after Acreman, 2004).

Evaporation crop coefficients, used to adjust modelled *potential* evaporation (for a reference crop) to *actual* evaporation for a particular wetland vegetation type, e.g. wet grassland, were assembled from the literature (e.g. Acreman, 2004). It is also recognised that maximum evaporation occurs when the water table is near the surface and declines as water table levels fall. This can be represented by an evaporation extinction function. Following Acreman et al. (2009), a function taking the form shown in Figure A2 was used to reduce reported evaporation rates. This approach assumes that there is a water table level at which evaporation starts to decline and a water level at which evaporation is zero. It was assumed that some water could pond on the surface of the wetland in hollows, but any water above this level would flow out. The model thus contains the following parameters:

- Specific yield
- Threshold water table level at which evaporation starts to decline
- Threshold water table level at which evaporation is zero
- Maximum depth of surface water

[1] Specific yield is the volume of water released from storage by gravity per unit surface area per unit water table decline (Freeze and Cherry, 1979).

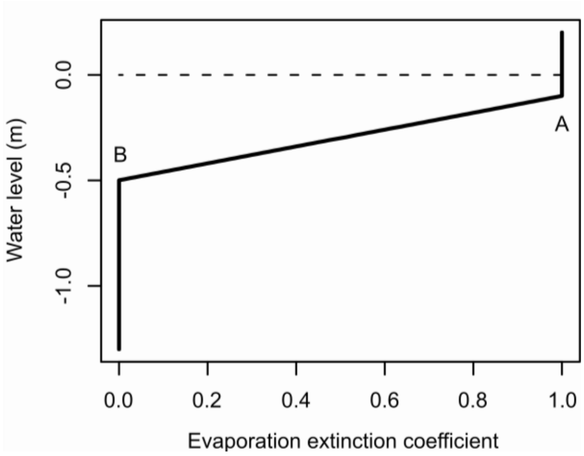

Figure A2 Relationship between water table level and evaporation extinction coefficient (after Acreman et al. 2009).

Separate models were set-up for each UK region (Figure 3) and each wetland type (based on NVC community). Potential parameter values were taken from the literature for each wetland type. Water table levels simulated by the models were plotted on the appropriate plant community water regime diagrams (Figure 4). The model uses monthly total precipitation and mean air temperature data, employing the Oudin et al. (2005) method to derive potential evaporation from temperature. For baseline climate conditions (1961 - 1990), parameters were then optimised in a semi-automated calibration processes to ensure that water table levels were predominantly within the desirable band, occasionally within the 'tolerable' band and rarely in the 'unacceptable' band (consistent with the approach for deriving the water regime diagrams).

<u>River-fed wetlands</u>

The model broadly follows that developed by Acreman et al. (2009).There are four basic water transfer mechanism controlling the hydrology of these river margin wetlands (Figure A3): lateral movement of water from the river to the wetland (L); drainage of water from the wetland to the river (D); overbank flow of water from the river (OB); and outflow of surface water back to the river. It is noteworthy that this model is not intended to simulate precipitation or evaporation or interaction with any aquifers.

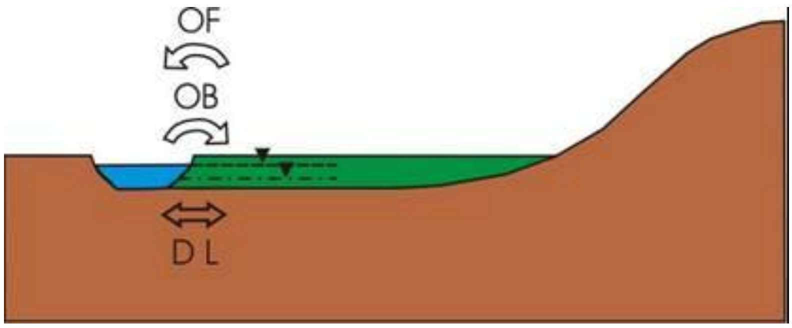

Figure A3 Schematic cross section of a river-fed wetland showing key water transfer mechanisms (after Acreman, 2004).

As the water level in the river rises, water will move laterally into the wetland at a rate controlled by the difference between river water level and wetland water table level (i.e. difference in head) and the permeability (hydraulic conductivity of the soil). The difference in levels, combined with permeability, will also control the rate at which water drains back into the river as the river level falls. When the river level exceeds bank-full, water will flow rapidly onto the surface of the wetland and the wetland water level will be the same as that for the river. When the river falls back below bank-full level it is possible for some water to remain on the wetland surface as the model formulation allows low river levees to be represented. Water table levels will decline from this height according to permeability and relative water levels as the river level is back within bank. River level (H) is related to river flow (Q) by a rating equation in the form:

$$Q = CH^b$$

The river-fed wetland model thus contains the following parameters:

- Hydraulic conductivity of the soil
- Height of the levée
- C in rating equation
- b in rating equation
- Bankfull discharge

Separate models were set-up for each UK region (Figure 3) and each wetland type (NVC community). Each region is represented by a 'typical' surface-water-fed river catchment and, where appropriate to the regional geology, a 'typical' groundwater-fed catchment. Initial parameter values were found in the literature for each wetland type. Water table levels simulated by the models were plotted on the appropriate plant community water regime diagrams (Figure 5). The model requires daily river flow data; these were provided by CEH from a previous Defra contract (Crooks *et al.,* 2009). For baseline climate conditions (1961 – 1990), parameters were then optimised using a semi-automatic calibration processes to ensure that water table levels were predominantly within the desirable band, occasionally within the ‘tolerable’ band and rarely in the ‘unacceptable’ band.

<u>Groundwater-fed wetlands</u>

There are three possible ways that groundwater can interact with a wetland that have been incorporated in this model (Figure A4): upward movement (discharge) of groundwater from the aquifer to the wetland (GD), downward movement (recharge) of water from the wetland to the aquifer (GR) and lateral movement or seepage (GS) of groundwater from the aquifer to the wetland. It is worth noting that this model is not intended to simulate precipitation, surface flow from an up-slope spring, evaporation or river-wetland interactions nor any down-slope outflow from the wetland.

As the water level in the aquifer rises above that in the wetland, water will move vertically (or laterally) into the wetland at a rate controlled by the difference between the groundwater head and wetland water table level, the permeability (hydraulic conductivity) of the wetland and the permeability of any aquitard separating the aquifer and the wetland. The difference in levels (change in hydraulic head) and permeability will also control the rate at which wetland water recharges groundwater as the aquifer water level falls below the wetland water level.

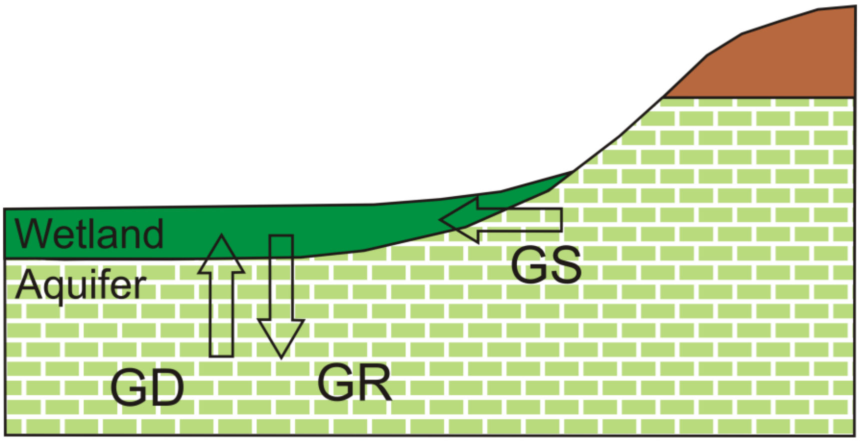

Figure A4 Schematic cross section of a groundwater-fed wetland showing key water transfer mechanisms, combining elements of slope, depression and valley bottom wetlands (after Acreman, 2004).

To provide a simple modelling scheme similar to that for river-fed wetlands, the wetland water level response to changing groundwater levels was modelled using a calibrated 'hydraulic head transfer rate' factor (k; m/m). This factor has been used to combine the effects of wetland, aquifer, and any aquitard, permeability and the relative specific yields and scales of the wetland and the aquifer:

$$WL_{WETLAND,t} = WL_{WETLAND,t-1} + k(WL_{GROUNDWATER,t} - WL_{WETLAND,t-1})$$

where WL is water level (m) relative to the wetland surface and t is the model timestep.

Although it would have been possible to introduce a term into this equation to specifically account for a variable lag in the timing of the response of the wetland water level to changes in the groundwater level, this was not implemented. The scale of the wetland is assumed to be minor relative to the scale of the aquifer and hence it should be relatively quick to respond to changes in groundwater head in the underlying aquifer. The groundwater-fed wetland model thus contains the following parameters:

- Wetland surface elevation (mAOD)
- Wetland-aquifer 'hydraulic head transfer rate' factor, k (m/m)

Initial conditions for the wetland water level were set to the March optimum value from the relevant ecohydrological water level requirements (e.g. Figure 5). This allowed for a nine month run-in period to reduce the influence of initial conditions on simulation results. Climate change metrics were calculated for each calendar year (January to December).

Separate models were set-up for each UK region (Figure 3), for each major aquifer, i.e. Chalk, Jurassic Limestone and/or Permo-Triassic Sandstone (North West England, Solway, Northumbria, Humber, Western Wales, Dee, Severn, Anglian, South West England, Thames and South East England regions) and for each wetland type (NVC community). Initial parameter values were found in the literature for each wetland type. Water table levels simulated by the models were plotted on the appropriate plant community water regime diagrams (e.g. Figure 5). The model uses monthly groundwater level data. These were provided by the models developed for the Future Flow and Groundwater Levels project and the location of the point scale models are shown on Figure A5. These locations were chosen to represent naturalised groundwater conditions without significant effects of abstraction.

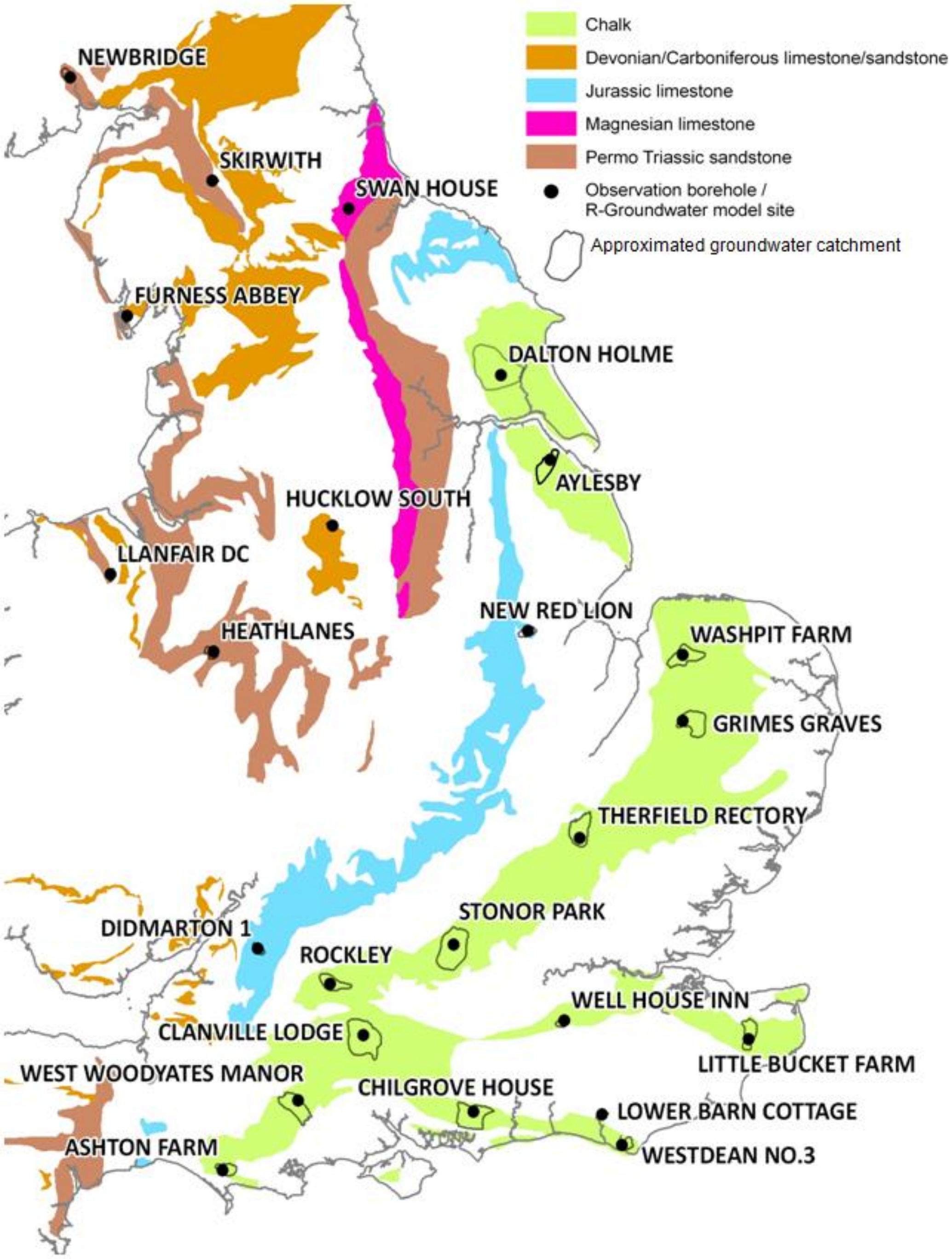

Figure A5 Map of principal aquifers and borehole locations, available data from which were used to model the impacts of climate change.

For baseline climate conditions (1980 – 1990), parameters were then optimised using a semi-automatic calibration processes to ensure that wetland water table levels were predominantly within the ‘desirable’ band, occasionally within the ‘tolerable’ band and rarely in the ‘unacceptable’ band. The degree of deviation from the ‘desirable’ band was quantified by calculating root mean squared deviation, allowing a consistent amount of deviation to be calibrated for each region-aquifer combination. The calibration was limited to summer (June, July and August) and winter (December, January and February) periods as, for the communities considered, water requirements are less certain for the spring and autumn periods. It should be noted that the baseline period for the groundwater-fed wetlands is shorter than that for the rain- or river-fed wetlands as data for the full time-period was not available for all groundwater borehole locations. Therefore, to allow unbiased comparison of the groundwater-fed results between both aquifers and regions, the baseline was standardized to the overlapping time period only. This should also be considered when evaluating results for the same region for different water supply mechanisms, i.e. rain-, river- and groundwater-fed. Furthermore, it has only been possible to calculate the *plant communities:* d*eparture from water level requirements regime* metrics for the summer and winter months, rather than for the whole year, meaning that these metrics are limited to a maximum value of six for groundwater-fed wetlands.

Impact metrics

The following table provides a list of the metrics defined for each interest feature, along with thresholds of change in those metric that were considered to be

green – minor change in metric, low impact

amber – intermediate change in metric, medium impact

red – major change in metric, high impact

The thresholds were based on available literature and expert consensus.

Table A1 Impact metrics and thesholds

Interest feature	Wetland metric	Limits
Hydrology (minimum and maximum water levels)	Minimum water level *mean annual**	Green < 0.1 m below baseline Amber 0.1 to 0.2 m below baseline Red > 0.2 m below baseline
	Minimum water level *over 30 years***	Green < 0.2 m below baseline Amber 0.2 to 0.4 m below baseline Red > 0.4 m below baseline
	Maximum water level *mean annual**	Green < 0.1 m above baseline Amber 0.1 to 0.2 m above baseline Red > 0.2 m above baseline
	Maximum water level *over 30 years***	Green < 0.2 m above baseline Amber 0.2 to 0.4 m above baseline Red > 0.4 m above baseline
Hydrology (eco-related)	Spring (May) water level *mean annual**	Green < 0.1 m from baseline Amber 0.1 to 0.2 m from baseline Red > 0.2 m from baseline
	Late summer (August) water level *mean annual**	Green < 0.2 m below baseline Amber 0.2 to 0.3 m below baseline Red > 0.3 m below baseline
	Late summer (August) water level *minimum over 30 years***	Green < 0.2 m below baseline Amber 0.2 to 0.4 m below baseline Red > 0.4 m below baseline
Hydrology (water balance)	No. months per year with positive or neutral water balance *mean annual**	Green < 1.0 month different than baseline Amber 1.0 to 3.0 months different from baseline Red > 3.0 months different from baseline
	No. months per year with positive or neutral water balance *minimum over 30 years***	Green < 2.0 months different than baseline Amber 2.0 to 4.0 months different from baseline Red > 4.0 months different from baseline
	Gross annual water balance (rainfall - actual evaporation (mm)) *mean annual**	Green < 10% change from baseline Amber 10 to 25% change from baseline Red > 25% change from baseline
	Gross annual water balance (rainfall - actual evaporation (mm)) *minimum over 30 years***	Green < 20 % change from baseline Amber 20 to 40 % change from baseline Red > 40 % change from baseline
Plant communities	Departure from water level requirements regime: Σ (1.0 × N ‘unacceptable’ months, 0.5 × N ‘tolerable for short periods’ months) *mean annual**	Green < 2 Amber 2 to 4 Red > 4
	Departure from water level requirements regime: Σ (1.0 × N ‘unacceptable’ months, 0.5 × N ‘tolerable for short periods’ months) *maximum over 30 years***	Green < 2 Amber 2 to 4 Red > 4

Historic environment	No. months per year with soil saturation (below gwl, ignoring capillary fringe) at 35 cm below surface *mean annual**	Green	12 (highly conducive to preservation of organic archaeological remains)
		Amber	< 12, ≥ 9 (organic archaeological remains slowly deteriorating over ~10-15 years)
		Red	< 9 (rapid deterioration of existing organic remains should be expected)
	No. months per year with soil saturation (below gwl, ignoring capillary fringe) at 35 cm below surface *minimum over 30 years***	Green	12 (highly conducive to preservation of organic archaeological remains)
		Amber	< 12, ≥ 9 (organic archaeological remains slowly deteriorating over ~10-15 years)
		Red	< 9 (rapid deterioration of existing organic remains should be expected)
	No. months per year with soil saturation (below gwl, ignoring capillary fringe) at 70 cm below surface *mean annual**	Green	12 (highly conducive to preservation of organic archaeological remains)
		Amber	< 12, ≥ 9 (organic archaeological remains slowly deteriorating over ~10-15 years)
		Red	< 9 (rapid deterioration of existing organic remains should be expected)
	No. months per year with soil saturation (below gwl, ignoring capillary fringe) at 70 cm below surface *minimum over 30 years***	Green	12 (highly conducive to preservation of organic archaeological remains)
		Amber	< 12, ≥ 9 (organic archaeological remains slowly deteriorating over ~10-15 years)
		Red	< 9 (rapid deterioration of existing organic remains should be expected)
Birds	No. months, April to July, with surface water *mean annual**	Green	< 1 month more than baseline
		Amber	1 to 2 months more than baseline
		Red	> 2 months more than baseline
	No. months, April to July, with surface water *maximum over 30 years***	Green	< 1 month more than baseline
		Amber	1 to 3 months more than baseline
		Red	> 3 months more than baseline
	No. months, November to March, without surface water *mean annual**	Green	< 1 month more than baseline
		Amber	1 to 2 months more than baseline
		Red	> 2 months more than baseline
	No. months, November to March, without surface water *maximum over 30 years***	Green	< 1 month more than baseline
		Amber	1 to 3 months more than baseline
		Red	> 3 months more than baseline
	April water level *mean annual**	Green	< 0.05 m from baseline
		Amber	0.05 to 0.15 m from baseline
		Red	> 0.15 m from baseline
	April water level *minimum over 30 years***	Green	< 0.2 m from baseline
		Amber	0.2 to 0.4 m from baseline
		Red	> 0.4 m from baseline
	June water level *mean annual**	Green	< 0.05 m below baseline
		Amber	0.05 to 0.15 m below baseline
		Red	> 0.15 m below baseline
	June water level *minimum over 30 years***	Green	< 0.2 m below baseline
		Amber	0.2 to 0.4 m below baseline
		Red	> 0.4 m below baseline

* Mean annual values over the simulated 30 year time period, e.g. mean of the annual minima. These give an indication of long-term sustainability under a changing climate

** The maximum/minimum value for the 30 year time period, i.e. highest and lowest records. These indicate the effect of extreme events (floods/droughts) under a changing climate

Selecting wetland water supply mechanism by vegetation type

It is often very difficult to identify the presence of groundwater as a supply mechanism to wetlands. Even wetlands that are located adjacent to known aquifers may be separated from them by thin semi-permeable or non-permeable layers that reduce or preclude hydrological connectivity. Likewise, wetlands that are thought to be totally surface water fed can have a significant groundwater contribution. For example, Pulfin bog in Yorkshire, which lies in the meander bend of the River Hull and was thought to be fed soley by the river; however analysis of borehole data showed that the underlying Chalk aquifer provide significant water to the wetland.

NVC Communities indicative of groundwater - after Wheeler *et al (*2004)

WETMEC: Permanent Seepage Slopes

- **M13** *Schoenus nigricans - Juncus subnodulosus* Mire

WETMEC: Intermittent and Part-Drained Seepages

- **M24** *Molinia caerulea - Cirsium dissectum* Fen Meadow
- **S24** *Phragmites australis-Peucedanum palustre* Tall-herb Fen

WETMEC: Fluctuating Seepage Basins

- **M24** *Molinia caerulea - Cirsium dissectum* Fen Meadow
- **S24** *Phragmites australis-Peucedanum palustre Tall*-herb Fen
- **S2** *Cladium mariscus* Swamp

WETMEC: Seepage Percolation Basins

- **M24** *Molinia caerulea - Cirsium dissectum* Fen Meadow
- **S24** *Phragmites australis-Peucedanum palustre* Tall-herb Fen
- **S2** *Cladium mariscus* Swamp

WETMEC: Surface-water Percolation Floodplain

- **S2** *Cladium mariscus* Swamp

Table A2 provides a tabulation of *NVC* types against WETMECs related to broad habitat type (wet woodland, swamp, fen, bog, wet heath and grassland) and water supply mechanism (precipitation, flooding, groundwater, percolation).

Habitat type	Amplitude of WT	Precipitation and direct run off	Fluvial flooding	Groundwater from aquifer	Percolation (sub-irrigation) from surface water bodies
Woodland	Hi		5, (7) **W6, W8**	(8), 11 12d-e **W4**	7 **W4, W6**
	Lo	18, 20 **W3**	**W1-3**	8, 9, 10, 12a-c, 13, 14, 16, 17 **W1-3, W5**	6 **W1-3, W5, W7**
Swamp	Hi		5, (7) **(S4) (S26) S28**	(8), 11 12d-e	7 **(S4) (S26) S28**
	Lo	20 **S9, S10, S11**	**S1-19, S24-7**	8, 9, 10, 12a-c, 13-17 **S1-19, S24-7**	6 **S1-19, S24-7**
Mire (including fen)	Hi		5, (7) M24	(8), 11 12d-e	
	Lo	3, 18, 19, 20 **M4-9, M24-5, M29-30**		8, 9, 10, 12a-c, 13-17 **M10-14, M22, M26, M35-38**	6 **M13, M23-28**
Mire (including bog & wet heath)	Hi	4 M19			
	Lo	1-3, 18-19 **M1-3, M15-18, M20-21 H5, H21**			
Grassland	Hi	**U5, OV31, OV34-6**	**OV28-31 SD17, MG4, MG7C, MG9, M11-13**	(8), 11	7 **MG4, MG9**
	Lo		**S22-23**	8, 9 **MG8, MG10**	6 **MG8, MG10, SD17,** *Agrostis Carex* community, **S22-23**
Measure of water regime		Water balance	Frequency and seasonality of flood	Consistency of discharge	Median stage height in growing season
Critical limits		Positive • Every month • >9 months • <9 months	• >1 in 20 • >1 in 3 • at least one flood annually • at least one flood in growing season annually	• Continuous • Intermittent • all interruptions < 1 month • some interruptions > 1 month	• field elevation • within 5 cm of field • within 25 cm of field • >25 cm freeboard • >50 cm freeboard

Table A2 Relating NVC and WETMECS to broad habitat type and water source

__Note__: Blue numerals represent Wetmecs types (Wheeler & Shaw); NVC types in brackets reflect situations where the type may occur but where its typical occurrence is under some other regime

NVC Communities indicative of groundwater
After Rodwell (1991-2000)

Summary derived from Table A2 (*i.e.* Groundwater from aquifer (GWA) and percolation (sub-irrigation) from surface water bodies (PSW)) and thence compared (supplementary details) from the description in Rodwell

Woodland:

GWA:

W1 *Salix cinerea-Galium palustre* woodland – no mention of groundwater made in *NVC*

W2 *Salix cinerea-Betula pubescens-Phragmites australis* woodland - – no mention of groundwater made in *NVC*

W3 *Salix pentandra-Carex rostrata* woodland - – no mention of groundwater made in *NVC*

W4 *Betula pubescens-Molinia caerulea* woodland – said to be locally present where soligenous conditions present in valley mires and irrigated by rather base- and nutrient-poor water

W5 *Alnus glutinosa-Carex paniculata* woodland – said to be often occurring on floodplain mires where there is a strong influence of calcareous groundwater, and more locally where there are seepage lines above basin mires

PSW:

W1 *Salix cinerea-Galium palustre* woodland – as GWA

W2 *Salix cinerea-Betula pubescens-Phragmites australis* woodland – as GWA

W3 *Salix pentandra-Carex rostrata* woodland – as GWA

W4 *Betula pubescens-Molinia caerulea* woodland – as GWA

W5 *Alnus glutinosa-Carex paniculata* woodland – as GWA

W6 *Alnus glutinosa-Urtica dioica* woodland – no mention of groundwater or percolation made in *NVC*

W7 *Alnus glutinosa-Fraxinus excelsior-Lysimachia nemorum* woodland - no mention of groundwater or percolation made in *NVC*

Mires:

GWA:

M10 *Carex dioica-Pinguicula vulgaris* mire – strictly calcicolous and in soligenous/groundwater fed situations, flushed with oligotrophic water (Scotland and northern parts of Wales and England)

M11 *Carex demissa-Saxifraga aizoides* mire –open stony flushes, moderately base-rich on steep slopes (Scotland and the Lakes)

M12 *Carex saxatilis* mire – high montane flushes that are base-rich and calcareous (Scotland only)

M13 *Schoenus nigricans-Juncus subnodulosus* mire – strongly soligenous, highly calcareous and oligotrophic, below springs and seepages

M14 *Schoenus nigricans-Narthecium ossifragum* mire – notably soligenous with moderately base/calcium-rich water in flushes in wet heath (manly south and southwest England)

M22 *Juncus subnodulosus-Cirsium palustre* fen-meadow – occurs under both soligenous and topogenous situations, including in and around well-developed springs, flushes and water-tracks

M26 *Molinia caerulea-Crepis paludosa* mire – only *locally* on soligenous flushed slopes

M35 *Ranunculus omiophyllus-Montia fontana* rill – springheads and rills that are circumneutral and oligotrophic (Wales and the Southwest)

M36 Lowland springs and stream-banks in shade situations – also circumneutral and oligotrophic, where flushing

M37 *Cratoneuron commutatum-Festuca rubra* spring – base-rich, calcareous and oligotrophic springs (Pennines, Snowdonia & Scotland)

M38 *Cratoneuron commutatum-Carex nigra* spring – montane, base-rich, calcareous and oligotrophic springs and flushes (Pennines & Scotland)

PSW:

M13 *Schoenus nigricans-Juncus subnodulosus* mire – as GWA

M23 *Juncus effusus/acutiflorus-Galium palustre* rush pasture – generally on gently-sloping ground at the margins of soligenous flushes and water-tracks

M24 *Molinia caerulea-Cirsium dissectum fen*-meadow – in both topogenous and soligenous situations at the margins of hollows and flushes

M25 *Molinia caerulea-Potentilla erecta* mire – on gently sloping ground, marking out seepage zones, flushed margins and water-tracks *etc*

M26 *Molinia caerulea-Crepis paludosa* mire – as GWA

M27 *Filipendula ulmaria-Angelica sylvestris* mire – in both soligenous and topogenous situations, typical of silting margins of slow-moving streams and soakways/flushes

M28 *Iris pseudacorus-Filipendula ulmaria* mire – freshwater seepage along upper edge of saltmarshes (mainly Scotland)

Note that the following mire types were classified as not occurring under groundwater influence or supplied via percolation, but are noted in the *NVC* as being found (at least occasionally) where there is some soligenous processes including spring-fed situations and seepages:

M4 *Carex rostrata-Sphagnum recurvum* mire – can occur in seepage areas on raw peat *i.e.* soligenous mires (mainly Wales and Scotland)

M5 *Carex rostrata-Sphagnum squarrosum* mire – locally in soligenous mires (also mainly N and W)

M6 *Carex echinata-Sphagnum recurvum/auriculatum* mire – generally on peats and peaty gleys that are irrigated or flushed on gentle to moderate slopes

M7 *Carex curta-Sphagnum russowii* mire – oligotrophic flushes in montane moss-heath (Scotland only)

M9 *Carex rostrata-Calliergon cuspidatum/giganteum* mire - occasional in small spring-fed basins and flushes within/by blanket mires

M15 *Scirpus cespitosus-Erica tetralix* wet heath – only very locally where soligenous

M16 *Erica tetralix-Sphagnum compactum* wet heath – locally where there is a high groundwater table

M21 *Narthecium ossifragum-Sphagnum papillosum* valley mire – within valley mires due to locally high groundwater tables

M29 *Hypericum elodes-Potamogeton polygonifolius* soakway – seepage and runnels in mires with low pH

M31 *Anthelia julacea-Sphagnum auriculatum* spring – acid water springs and soakways (Scotland, North Wales and the Lakes)
M32 *Philonotis fontana-Saxifraga stellaris* spring – circumneutral and oligotrophic springs and rills (as **M31** but more widespread)
M33 *Pohlia wahlenbergii* var. *glacialis* springs – oligotrophic situations at springheads and by snow melt (Scotland only)
M34 – *Carex demissa-Koenigia islandica* flush – very similar to **M32**, but with vigorous flushing (Western Isles)

Grasslands:

GWA: **MG8** *Cynosurus cristatus-Caltha palustris* grassland – seasonal flooding and below springs, flushes and seepage lines (see Eco-hydrological Guidelines)
MG10 *Holcus lanatus-Juncus effusus* rush-pasture – occasional waterlogging through groundwater or surface water

PSW: **MG8** *Cynosurus cristatus-Caltha palustris* grassland – as GWA
MG10 *Holcus lanatus-Juncus effusus* rush-pasture – as GWA
***Agrostis-Carex** community* **–** see Eco-hydrological Guidelines
S22 *Glyceria fluitans* water-margin vegetation – not cited by *NVC*
S23 Other water-margin vegetation – not cited by *NVC*
SD17 *Potentilla anserina-Carex nigra* dune-slack – assemblage (or some-thing extremely close) now known to occur inland in freshwater situations – slacks kept moist by the fluctuation of less base-rich ground-waters

Again the following grassland types were classified by DJGG/JOM as not occurring under groundwater influence or supplied via percolation, but are noted in the *NVC* as found (at least occasionally) where there is some soligenous processes:
MG9 *Holcus lanatus-Deschampsia cespitosa* grassland – occurs on groundwater gleys with fluctuating water-table

Note**:** **MG4** and **MG11-MG13** occur where there is surface flooding

Aquatic communities not dealt with – all dependent on (almost) permanent surface water

Swamps and tall-herb ferns:

The following swamps occur when supplied by groundwater from aquifer (GWA) and by percolation from surface water-bodies (PSW) – **S28** alone is only listed for the percolation category. Cross-comparison with the text of the *NVC* confirms that most true swamps (**S1-S19**) depend on (almost) permanent surface water, though the *NVC* does note that some (marked *F) are frequent where the water-level (water-table) fluctuates:
S1 *Carex elata* sedge-swamp - *F
S2 *Cladium mariscus* swamp and sedge-beds - *F
S3 *Carex paniculata* swamp
S4 *Phragmites australis* swamp and reed-beds - *F
S5 *Glyceria maxima* swamp - *F
S6 *Carex riparia* swamp - *F
S7 *Carex acutiformis* swamp - *F
S8 *Scirpus lacustris* ssp. *lacustris* swamp

S9 *Carex rostrata* swamp
S10 *Equisetum fluviatile* swamp
S11 *Carex vesicaria* swamp - *F
S12 *Typha latifolia* swamp
S13 *Typha angustifolia* swamp
S14 *Sparganium erectum* swamp
S15 *Acorus calamus* swamp
S16 *Sagittaria sagittifolia* swamp
S17 *Carex pseudocyperus* swamp - *F
S18 *Carex otrubae* swamp
S19 *Eleocharis palustris* swamp

Following two brackish-water types not included in DJGG/JOM table:
S20 *Scirpus lacustris* ssp. *tabernaemontani* swamp
S21 *Scirpus maritimus* swamp

For "grassy swamps" (**S22** and **S23**) – see grasslands

Remaining tall-herb fens are:
S24 *Phragmites australis-Peucedanum palustre* tall-herb fen – generally found in topogenous situations but see WETMECs above
S25 *Phragmites australis-Eupatorium cannabinum* tall-herb fen – as latter and often found on groundwater gley soils
S26 *Phragmites australis-Urtica dioica* tall-herb fen - as **S24/S25** and often found on groundwater gley soils
S27 *Carex rostrata-Potentilla palustris* tall-herb fen – occurs where there is lateral water flow and throughput or soligenous areas within an otherwise ombrotrophic mire
S28 *Phalaris arundinacea* tall-herb fen – typical of fluctuating water-levels

Tables from: Mountford and Chapman, 1993

Table A3 Categories of Dutch phreatophytes. (after Londo, 1988)

Z	Species that grow only in salt habitats.
A	Aphreatophytes - species not bound to the sphere of influence of the water-table.
D	Dune phreatophytes - species which are not limited to the sphere of influence of the water-table (where they are aphreatophytes), but grow exclusively or mainly within this sphere of influence in dunes and other sand areas
P	Local phreatophytes - species that grow above the sphere of influence of the water-table (also outside limestone areas) in much of their area of distribution, but depend on this sphere of influence in certain areas or places
K	Lime phreatophytes - species growing within the sphere of influence of the water-table (which is generally below the soil surface) but occurring above this sphere of influence on lime-rich soils
V	Species growing *mainly* or *almost* exclusively within the sphere of influence of the water-table, which is generally below the soil surface
F	Species growing *only* within the sphere of influence of the water-table, which is generally below the soil surface
W	Species requiring a water-table at the soil surface (in years with a normal water-table) or higher during part of the year or permanently for good development and completion of their life-cycle
H	Hydrophytes - species with vegetative parts submerged or floating on the water surface

Notes: Categories D, P, K and V are non-obligate phreatophytes
Categories F and W are obligate phreatophytes.

Table A4 Species recorded at Tadham Moor (1986-90) - Average Ellenberg moisture value (mF) within each Phreatophyte category of Londo

Aphreatophyte (A) [60 species].. 4.83

Non-obligate phreatophytes (V, K, P & D) [36 species] 7.07

Obligate phreatophytes (W & F) [26 species].. 8.64

Table A5 River flow gauging stations for which climate change scenario data and rainfall-runoff models are available from the Future Flows project

Station	Location		River name	Station name	area km^2
2001	299700	918100	Helmsdale	Kilphedir	551.4
4003	265467	869598	Alness	Alness	201
4005	228650	852750	Meig	Glenmeannie	120.5
6008	244900	830100	Enrick	Mill of Tore	105.9
7002	301853	858387	Findhorn	Forres	781.9
7004	288238	855059	Nairn	Firhall	313
7005	300541	848032	Divie	Dunphail	165
7006	313442	848903	Lossie	Torwinny	20
7009	303930	855845	Mosset Burn	Wardend Bridge	28.3
8004	318450	835200	Avon	Delnashaugh	542.8
8006	331850	851850	Spey	Boat o Brig	2861.2
8009	297722	824763	Dulnain	Balnaan Bridge	272.2
9001	353217	846431	Deveron	Avochie	441.6
9002	370551	849833	Deveron	Muiresk	954.9
9003	349350	850614	Isla	Grange	176.1
10002	410000	848650	Ugie	Inverugie	325
11001	388850	814150	Don	Parkhill	1273
12002	379800	798300	Dee	Park	1844
12003	334300	796350	Dee	Polhollick	690
12005	336423	794759	Muick	Invermuick	110
12008	368703	792800	Feugh	Heugh Head	229
13001	382550	773450	Bervie	Inverbervie	123
13005	365450	749400	Lunan Water	Kirkton Mill	124
13007	369940	764029	North Esk	Logie Mill	732
13008	359962	759665	South Esk	Brechin	488
13009	359152	768050	West Water	Dalhouse Bridge	127.2
14001	341450	715650	Eden	Kemback	307.4
15006	314700	736550	Tay	Ballathie	4587.1
15014	305619	763026	Ardle	Kindrogan	103
15023	301320	742158	Braan	Hermitage	210
15024	256401	731995	Dochart	Killin	239
15025	317405	747165	Ericht	Craighall	432
16003	276400	720350	Ruchill Water	Cultybraggan	99.5
16007	297508	715379	Ruthven Water	Aberuthven	50
17003	282298	680356	Bonny Water	Bonnybridge	50.5
17005	295050	679650	Avon	Polmonthill	195.3
17015	311503	704113	North Queich	Lathro	23.1
17016	322036	698514	Lochty Burn	Whinnyhall	14
18001	279225	705376	Allan Water	Kinbuck	161
18005	278591	697984	Allan Water	Bridge of Allan	210
19006	322792	673202	Water of Leith	Murrayfield	107
19011	333250	667950	North Esk	Dalkeith Palace	137
20001	358950	676650	Tyne	East Linton	307
21003	325750	640050	Tweed	Peebles	694
21006	349700	633350	Tweed	Boleside	1500
21009	389650	647700	Tweed	Norham	4390
21012	352150	615800	Teviot	Hawick	323
21013	347900	637400	Gala Water	Galashiels	207
21015	356450	638850	Leader Water	Earlston	239

21017	323400	613150	Ettrick Water	Brockhoperig	37.5
21021	375150	635400	Tweed	Sprouston	3330
21022	388100	655000	Whiteadder Water	Hutton Castle	503
21023	383750	639700	Leet Water	Coldstream	113
21027	382600	653050	Blackadder Water	Mouth Bridge	159
21031	392746	639703	Till	Etal	648
21032	391896	631027	Glen	Kirknewton	198.9
22001	423250	604450	Coquet	Morwick	569.8
22004	421200	612950	Aln	Hawkhill	205
22009	406713	601557	Coquet	Rothbury	346
23004	385604	564702	South Tyne	Haydon Bridge	751.1
23006	367194	561103	South Tyne	Featherstone	321.9
23011	364398	594599	Kielder Burn	Kielder	58.8
24002	421500	530650	Gaunless	Bishop Auckland	93
24005	425900	538800	Browney	Burn Hall	178.5
24009	428300	551150	Wear	Chester le Street	1008.3
25005	444550	512050	Leven	Leven Bridge	196.3
25007	428054	509990	Clow Beck	Croft	78.2
25019	458552	508592	Leven	Easby	14.8
25020	429250	523750	Skerne	Preston le Skerne	147
27002	442050	447400	Wharfe	Flint Mill Weir/Tadcaster	758.9
27007	435500	466950	Ure	Westwick Lock	914.6
27009	456950	455350	Ouse	Skelton	3315
27021	456950	404150	Don	Doncaster	1256.2
27034	418850	486000	Ure	Kilgram Bridge	510.2
27035	401300	445750	Aire	Kildwick Bridge	282.3
27041	473000	458850	Derwent	Buttercrambe	1586
27042	470480	485543	Dove	Kirkby Mills	59.2
27043	409050	449450	Wharfe	Addingham	427
27049	469450	479150	Rye	Ness	238.7
27055	456000	488300	Rye	Broadway Foot	131.7
27071	442500	473400	Swale	Crakehill	1363
27084	402050	445250	Eastburn Beck	Crosshills	43.4
28008	411270	339640	Dove	Rocester Weir	399
28018	423463	328840	Dove	Marston on Dove	883.2
28022	478850	359850	Trent	North Muskham	8231
28030	446787	316934	Black Brook	Onebarrow	8.4
28031	414006	350706	Manifold	Ilam	148.5
28033	406300	366857	Dove	Hollinsclough	8
28046	414625	350855	Dove	Izaak Walton	83
28055	431900	344800	Ecclesbourne	Duffield	50.4
28066	418300	287550	Cole	Coleshill	130
30018	493574	343412	Witham	Colsterworth	51.3
31010	496090	303049	Chater	Fosters Bridge	68.9
31020	493833	301804	North Brook	Empingham	36.5
33012	515500	263100	Kym	Meagre Farm	137.5
33014	575800	272900	Lark	Temple	272
33018	471405	248781	Tove	Cappenham Bridge	138.1
33019	587850	282850	Thet	Melford Bridge	316
33026	521650	266950	Bedford Ouse	Offord	2570
33027	533250	248500	Rhee	Wimpole	119.1
33029	571700	300450	Stringside	Whitebridge	98.8
33044	595720	285581	Thet	Bridgham	277.8
33049	583600	295250	Stanford Water	Buckenham Tofts	43.5
33063	596119	280974	Little Ouse	Knettishall	101

34002	622546	299339	Tas	Shotesham	146.5
34006	622900	281100	Waveney	Needham Mill	370
34011	592046	329254	Wensum	Fakenham	161.9
34014	602034	318386	Wensum	Swanton Morley Total	397.8
34018	594400	341350	Stiffkey	Warham All Saints	87.8
35008	605732	257933	Gipping	Stowmarket	128.9
36005	602500	242900	Brett	Hadleigh	156
36007	584755	242144	Belchamp Brook	Bardfield Bridge	58.6
37001	541500	188250	Roding	Redbridge	303.3
37011	562855	223356	Chelmer	Churchend	72.6
37019	551564	185336	Beam	Bretons Farm	49.7
38003	528350	213150	Mimram	Panshanger Park	133.9
38014	534366	193746	Salmon Brook	Edmonton	20.5
39001	517750	169650	Thames	Kingston	9948
39006	440200	201900	Windrush	Newbridge	362.6
39008	444350	208650	Thames	Eynsham	1616.2
39016	464750	170650	Kennet	Theale	1033.4
39034	444950	209850	Evenlode	Cassington Mill	430
39049	521645	189592	Silk Stream	Colindeep Lane	29
39057	510297	177783	Crane	Cranford Park	61.7
39076	429827	210695	Windrush	Worsham	296
39081	448100	196450	Ock	Abingdon	234
39090	420831	196910	Cole	Inglesham	140
39092	524047	189547	Dollis Brook	Hendon Lane Bridge	25.1
39096	519260	186260	Wealdstone Brook	Wembley	21.8
39103	447212	167181	Kennet	Newbury	548.1
39105	461200	205000	Thame	Wheatley	533.8
39131	514910	182277	Brent	Costons Lane Greenford	146.2
40003	570650	152850	Medway	Teston	1256.1
40011	611750	155550	Great Stour	Horton	345
40017	567891	124009	Dudwell	Burwash	27.5
40023	601500	140650	East Stour	South Willesborough	58.8
41011	485217	122904	Rother	Iping Mill	154
41022	493198	122308	Lod	Halfway Bridge	52
41026	537745	125887	Cockhaise Brook	Holywell	36.1
42012	437900	139450	Anton	Fullerton	185
43003	416010	114300	Avon	East Mills	1477.8
43005	415050	141450	Avon	Amesbury	323.7
43006	409700	130830	Nadder	Wilton	220.6
43007	411750	95850	Stour	Throop	1073
43021	415600	96900	Avon	Knapp Mill	1706
44002	391200	87750	Piddle	Baggs Mill	183.1
45001	293607	101668	Exe	Thorverton	600.9
45004	326209	95365	Axe	Whitford	288.5
45005	308700	88550	Otter	Dotton	202.5
45009	293500	126000	Exe	Pixton	159.7
45011	292689	125887	Barle	Brushford	128
46003	275081	65904	Dart	Austins Bridge	247.6
46005	265699	77478	East Dart	Bellever	21.5
46006	264171	53229	Erme	Ermington	43.5
47001	242450	72450	Tamar	Gunnislake	916.9
47008	239850	85550	Thrushel	Tinhay	112.7
47014	251314	69914	Walkham	Horrabridge	44.6
48003	192200	44850	Fal	Tregony	87
49001	201749	68094	Camel	Denby	208.8

50002	249950	118350	Torridge	Torrington	663
50006	266050	120950	Mole	Woodleigh	327.5
50007	267292	106816	Taw	Taw Bridge	71.4
51001	308760	142749	Doniford Stream	Swill Bridge	75.8
52004	336100	118800	Isle	Ashford Mill	90.1
52010	359150	131800	Brue	Lovington	135.2
53005	376250	161050	Midford Brook	Midford	147.4
53006	363740	177170	Frome(Bristol)	Frenchay	148.9
53017	368100	169850	Boyd	Bitton	47.9
53018	378550	167000	Avon	Bathford	1552
54001	378050	276300	Severn	Bewdley	4325
54008	359800	268500	Teme	Tenbury	1134.4
54018	346750	309350	Rea Brook	Hookagate	178
54022	285232	287197	Severn	Plynlimon flume	8.7
54036	402400	240800	Isbourne	Hinton on the Green	90.7
54038	325175	322475	Tanat	Llanyblodwel	229
54057	384400	227900	Severn	Haw Bridge	9895
55002	348350	238750	Wye	Belmont	1895.9
55003	353458	240974	Lugg	Lugwardine	885.8
55004	289050	246000	Irfon	Abernant	72.8
55007	307550	244450	Wye	Erwood	1282.1
55029	341650	224900	Monnow	Grosmont	354
56002	325829	188948	Ebbw	Rhiwderyn	216.5
56003	305014	229846	Honddu	The Forge Brecon	62.1
56005	332950	192400	Lwyd	Ponthir	98.1
56007	292815	225435	Senni	Pont Hen Hafod	19.9
56013	300318	230507	Yscir	Pontaryscir	62.8
56019	321000	201500	Ebbw	Brynithel	71.7
57004	307819	195756	Cynon	Abercynon	106
58005	290397	184430	Ogmore	Brynmenyn	74.3
58007	289096	185500	Llynfi	Coytrahen	50.2
58008	277861	200837	Dulais	Cilfrew	43
58012	277111	190989	Afan	Marcroft Weir	87.8
59001	268507	199849	Tawe	Ynystanglws	227.7
60002	250800	222379	Cothi	Felin Mynachdy	297.8
60004	229041	217543	Dewi Fawr	Glasfryn Ford	36.7
60006	243023	221914	Gwili	Glangwili	129.5
60009	271200	226550	Sawdde	Felin-y-cwm	77.5
61001	195250	217850	Western Cleddau	Prendergast Mill	197.6
62001	224550	241550	Teifi	Glan Teifi	893.6
62002	243487	240415	Teifi	Llanfair	510
63001	259133	277474	Ystwyth	Pont Llolwyn	169.6
63004	279042	273695	Ystwyth	Cwm Ystwyth	32.1
64001	274350	301900	Dyfi	Dyfi Bridge	471.3
64002	263145	306598	Dysynni	Pont-y-Garth	75.1
65001	259190	347790	Glaslyn	Beddgelert	68.6
65006	249419	362288	Seiont	Peblig Mill	74.4
65014	257476	350400	Colwyn	Hafod Wydr	6.6
66011	280300	358250	Conwy	Cwm Llanerch	344.5
67005	329447	337354	Ceiriog	Brynkinalt Weir	113.7
67010	284304	341988	Gelyn	Cynefail	13.1
67013	294575	334924	Hirnant	Plas Rhiwedog	33.9
68001	366950	363150	Weaver	Ashbrook	622
68003	366800	371750	Dane	Rudheath	407.1
68005	365300	343250	Weaver	Audlem	207

69042	385000	417450	Ding Brook	Naden Reservoir	2.2
71001	358950	430550	Ribble	Samlesbury	1145
71006	372200	439200	Ribble	Henthorn	456
71009	370200	437600	Ribble	New Jumbles Rock	1053
72004	352950	465450	Lune	Caton	983
72009	361494	470105	Wenning	Wennington	142
72014	348286	455408	Conder	Galgate	28.5
72015	361122	502941	Lune	Lunes Bridge	141.5
73003	350589	495729	Kent	Burneside	73.6
73005	350900	487550	Kent	Sedgwick	209
73006	336948	494063	Cunsey Beck	Eel House Bridge	18.7
73009	351423	496076	Sprint	Sprint Mill	34.6
73011	352352	494343	Mint	Mint Bridge	65.8
73013	337110	504200	Rothay	Miller Bridge House	64
73014	336097	503351	Brathay	Jeffy Knotts	57.4
74001	319550	489600	Duddon	Duddon Hall	85.7
74005	300777	506132	Ehen	Braystones	125.5
74006	303522	504570	Calder	Calder Hall	44.8
74007	313100	497783	Esk	Cropple How	70.2
75017	309750	538550	Ellen	Bullgill	96
76005	360381	528050	Eden	Temple Sowerby	616.4
76007	338850	557100	Eden	Sheepmount	2286.5
76008	348600	558100	Irthing	Greenholme	334.6
77002	339700	575100	Esk	Canonbie	495
77003	341448	575923	Liddel Water	Rowanburnfoot	319
77004	328388	569324	Kirtle Water	Mossknowe	72
77304	348435	587284	Lyne	Cliff Bridge	191
78003	319150	570350	Annan	Brydekirk	925
78005	309070	584485	Kinnel Water	Bridgemuir	229
78006	309954	601015	Annan	Woodfoot	217
78999	307639	602921	Annan	Woodfoot	217
79002	292450	585100	Nith	Friars Carse	799
79003	268450	612950	Nith	Hall Bridge	155
79006	285855	599366	Nith	Drumlanrig	471
80005	245069	578706	Dargall Lane	Loch Dee	2.1
81002	241300	565150	Cree	Newton Stewart	368
81005	210699	556333	Piltanton Burn	Barsolus	34.2
81007	259198	558998	Water of Fleet	Rusko	77
82001	221722	599667	Girvan	Robstone	245.5
83005	234350	636950	Irvine	Shewalton	380.7
83007	231579	642059	Lugton Water	Eglinton Castle	54.6
83010	253252	637188	Irvine	Newmilns	72.8
83011	265999	626168	Ayr	Wellwood	60
84003	283531	645323	Clyde	Hazelbank	1092.9
84004	292837	642386	Clyde	Sills of Clyde	741.8
84005	270435	657942	Clyde	Blairston	1704.2
84012	250050	662900	White Cart Water	Hawkhead	234.9
84013	267050	661750	Clyde	Daldowie	1903.1
84015	263770	673949	Kelvin	Dryfield	235.4
84016	273882	672532	Luggie Water	Condorrat	33.9
84018	289394	640326	Clyde	Tulliford Mill	932.6
84020	265646	676198	Glazert Water	Milton of Campsie	51.9
84022	293046	625977	Duneaton	Maidencots	110.3
84026	255800	673639	Allander Water	Milngavie	32.8
84029	276445	647059	Cander Water	Candermill	24.5

84037	285542	633341	Douglas Water	Happendon	97
85002	248448	686603	Endrick Water	Gaidrew	219.9
85003	232100	719550	Falloch	Glen Falloch	80.3
89003	223832	731054	Orchy	Glen Orchy	251.2
89004	215011	729889	Strae	Glen Strae	36.2
89005	219692	727471	Lochy	Inverlochy	47.7
89008	223886	727602	Eas Daimh	Eas Daimh	4.5
89009	220649	726481	Eas a' Ghaill	Succoth	9.7
90003	211592	774257	Nevis	Claggan	69.2
92002	179208	768812	Shiel	Shielfoot	256
93001	194100	843050	Carron	New Kelso	137.8
94001	186000	880300	Ewe	Poolewe	441.1
95001	214650	924950	Inver	Little Assynt	137.5
97002	313100	959500	Thurso	Halkirk	412.8
48005			Kenwyn	Truro	19.1

Table A6 Groundwater level observation borehole locations for which climate change scenario data are available from the Future Flows and Groundwater Levels project

WellMaster ID	Grid Reference	Location	Aquifer
SY68/34	3661 0880	Ashton Farm	Chalk
TA10/63	5194 4071	Aylesby	Chalk
SU81/1	4835 1143	Chilgrove House	Chalk
SU34/8D	4322 1490	Clanville Lodge Gate	Chalk
SE94/5	4965 4453	Dalton Holme	Chalk
ST88/62A	3827 1874	Didmarton 1	Inferior Oolite
SD27/6B	3216 4717	Furness Abbey	Permo-Triassic Sandstone
TL89/37	5817 2900	Grimes Graves	Chalk
SJ62/112	3619 3210	Heathlanes	Permo-Triassic Sandstone
SK17/13	4177 3775	Hucklow South	Carboniferous Limestone
TR14/9	6122 1469	Little Bucket Farm	Chalk
SJ15/13	3137 3555	Llanfair Dyffryn Clwyd	Permo-Triassic Sandstone
TQ41/82	5437 1132	Lower Barn Cottage	Lower Greensand
TF03/37	5088 3303	New Red Lion	Lincolnshire Limestone
NX97/2	2951 5788	Newbridge	Permo-Triassic Sandstone
SU17/57	4165 1717	Rockley	Chalk
NY63/2	3613 5325	Skirwith	Permo-Triassic Sandstone
SU78/45A	4741 1892	Stonor Park	Chalk
NZ21/29	4252 5199	Swan House	Magnesian Limestone
TL33/4	5333 2372	Therfield Rectory	Chalk
TF81/2A	5813 3196	Washpit Farm	Chalk
TQ25/13	5258 1552	Well House Inn	Chalk
TV59/7C	5529 0992	West Dean No. 3	Chalk
SU01/5B	4016 1194	West Woodyates Manor	Chalk

see:
http://www.bgs.ac.uk/research/groundwater/change/FutureFlows/sites.html

Notes explaining the shapes of particular groundwater-fed metric histograms

Metric 02: Minimum water level *over 11 years*
Metric 04: Maximum water level *over 11 years*
Metric 07: Late summer (August) water level *minimum over 11 years*
Metric 23: April water level *minimum over 11 years*
Metric 25: June water level *minimum over 11 years*

As illustrated in the Figure A7, histograms for these metrics can sometimes show a clustering of values around the simulation initial wetland water level value.

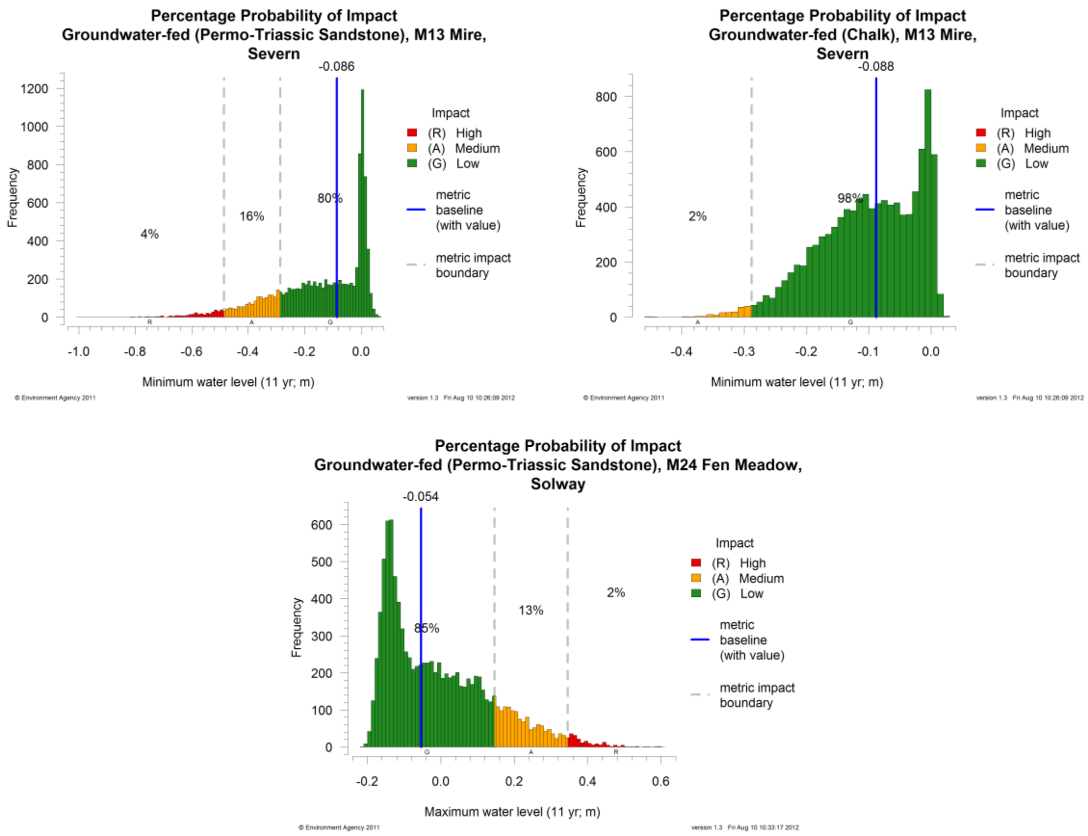

Figure A7 Example histograms showing metric clustering around the initial condition (wetland water level) values

In these simulations the initial wetland water level corresponds to the March 'optimum' value from the water level requirements data, i.e. 0.00 m for M13 mire, -0.01 m for M21 mire, -0.08 m for M24 fen meadow and 0.03 m for S24 tall-herb fen. The March value is used as the simulations employ a 9 month run-in period, ending in December, before the 11 year annual timeseries used for the climate change analysis.

One possible explanation for this clustering is that a number of the 10,000 climate change simulations are driven by groundwater levels predominantly higher than the initial wetland water level once the wetland ground surface offset is accounted for, implying that the 11 year minimum wetland water levels will be at or near the initial condition as the slowly responding wetland water levels will generally be increasing over time (affecting metrics 02, 07, 23 and 25). Conversely, if driven by groundwater levels predominantly lower that the initial wetland water level, accounting for the wetland ground surface offset, the 11 year maximum wetland water level will be at or near the initial condition as the slowly responding wetland water levels will generally be decreasing over time (affecting metric 04).

Although the metric clustering effect has persistence due to the relatively slow simulated response of groundwater-fed wetland water levels compare to river-fed or rain-fed wetlands, the effect is somewhat ameliorated by the 9 month run-in period employed in the simulations. The run-in length is the maximum possible given the available data and the need to use a consistent baseline timeseries for each of the region/aquifer combinations.

Metric 08: No. months per year with positive or neutral water balance *mean annual*

As illustrated in the Figure A8, histograms for these metrics can sometimes show a tendency for values to group together with some ranges on the histogram apparently over-represented and some under-represented (a 'hedgehog' appearance).

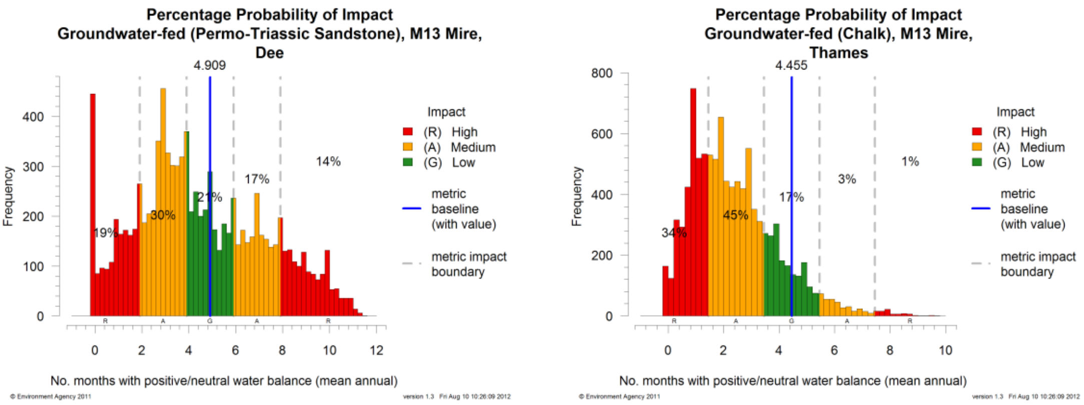

Figure A8 Example histograms showing grouping of metric values, apparently over-representing some ranges whilst under-representing others

Having checked and discounted the simple explanation that a number of the 10,000 climate change data sets have been accidentally duplicated, a potential explanation can be derived by considering seasonal and yearly variations in the groundwater level driving data. If groundwater level, relative to the wetland water level, varies consistently over time (see Figure A9), then the number of months with a positive or neutral water balance will smoothly vary with changing groundwater level.

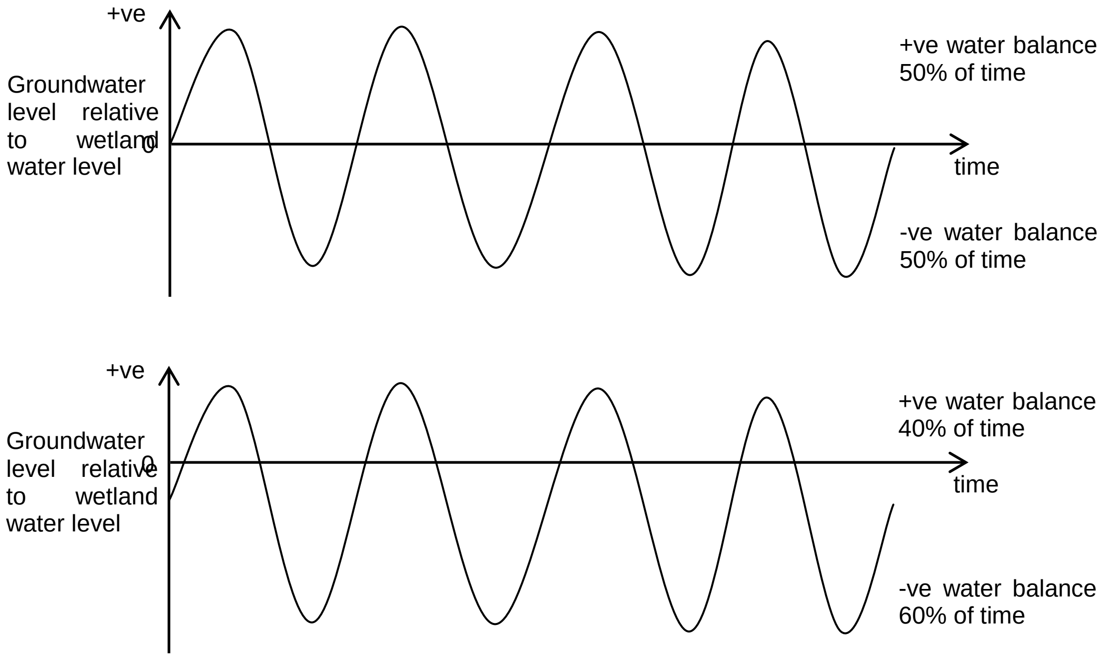

Figure A9 Hypothetical smooth variations of groundwater level over time and relationship to water balance

If however, groundwater level relative to wetland water level exhibits local minima or maxima, the number of months with a positive or neutral water balance will not vary smoothly with changing groundwater level. Instead the local minima/maxima will enhance the trend, causing grouping of the metric values. For example, as illustrated in Figure A10, with local maxima present in the driving groundwater data, if the groundwater level relative to the wetland surface experiences a general decline (as for example under one of the 10,000 climate change simulations) the decrease in the proportion of time with a positive water balance will be higher than expected than if the local maxima were not present. This is because if the local maxima were actually of full amplitude (as for example in Figure A9) they would still be counteracting the falling groundwater level in terms of the proportion of time with a positive water balance. Thus in this hypothetical illustration, metric values tend to group together around the 65% and 50% values, being apparently over represented, but are apparently under-represented between these values.

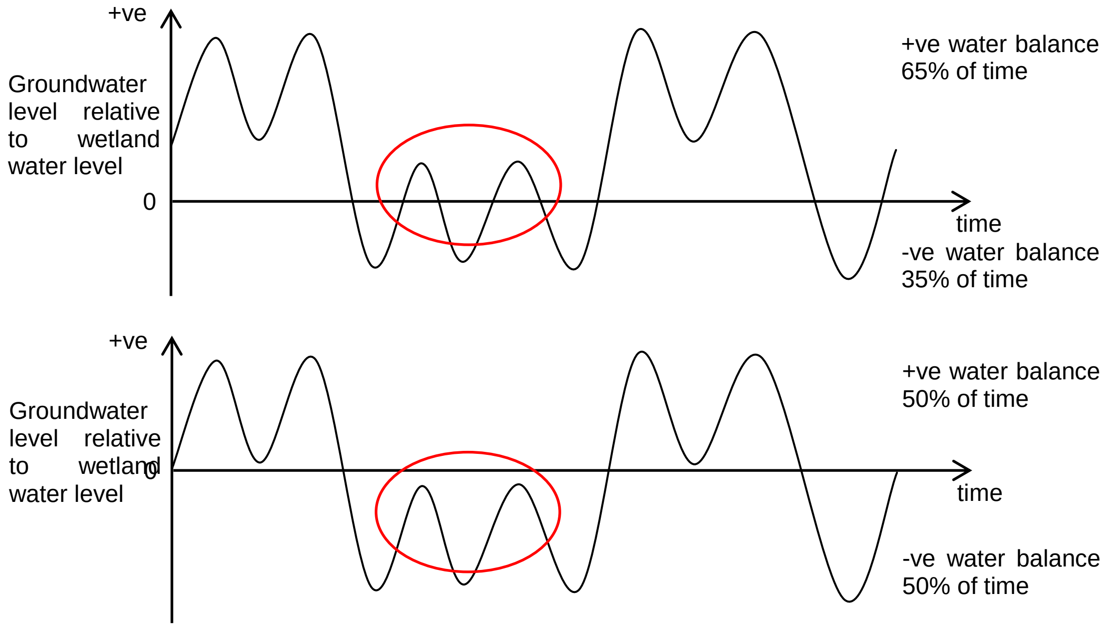

Figure A10 Hypothetical variations of groundwater level over time incorporating local maxima (circled) and minima for higher (top) and lower (bottom) groundwater conditions

The hypothesised explanation that local maxima/minima in the groundwater level driving data are responsible for the grouping of values for metric 08 can be tested by investigated the nature of the driving data for affected region/aquifer combinations. For example, Figures A11 and A12 show the baseline climate driving data for the Dee region with Permo-Triassic Sandstone and the Thames region with Chalk respectively.

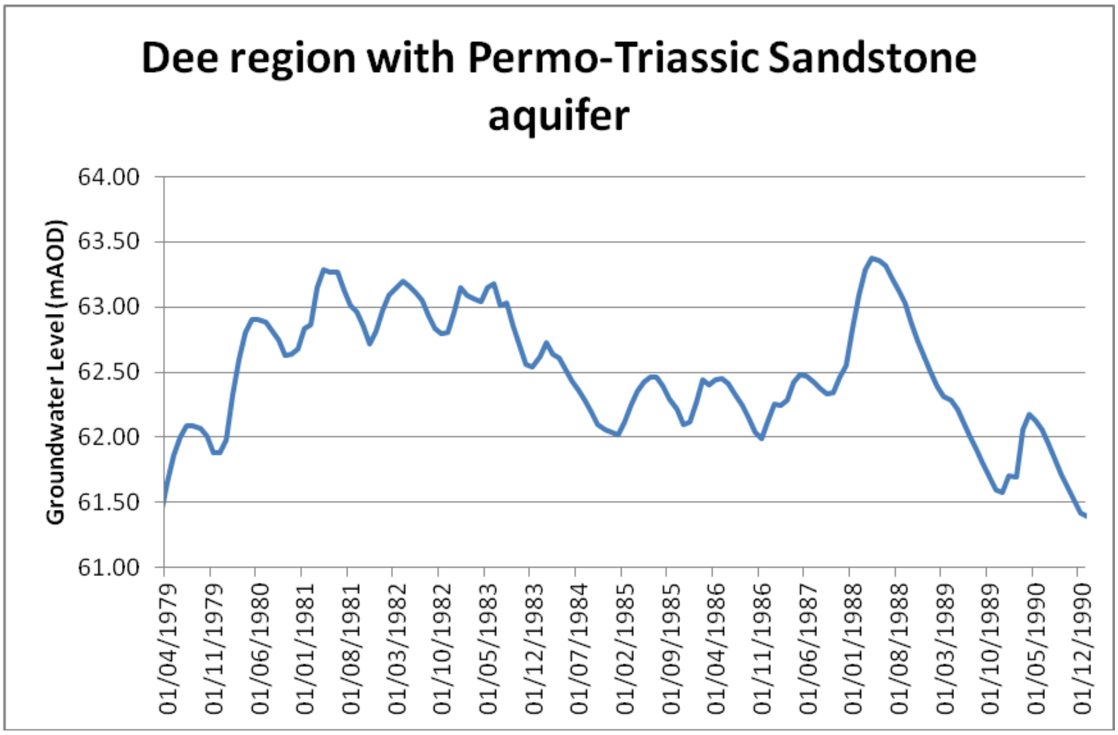

Figure A11 Baseline groundwater level data for Dee region with Permo-Triassic Sandstone aquifer

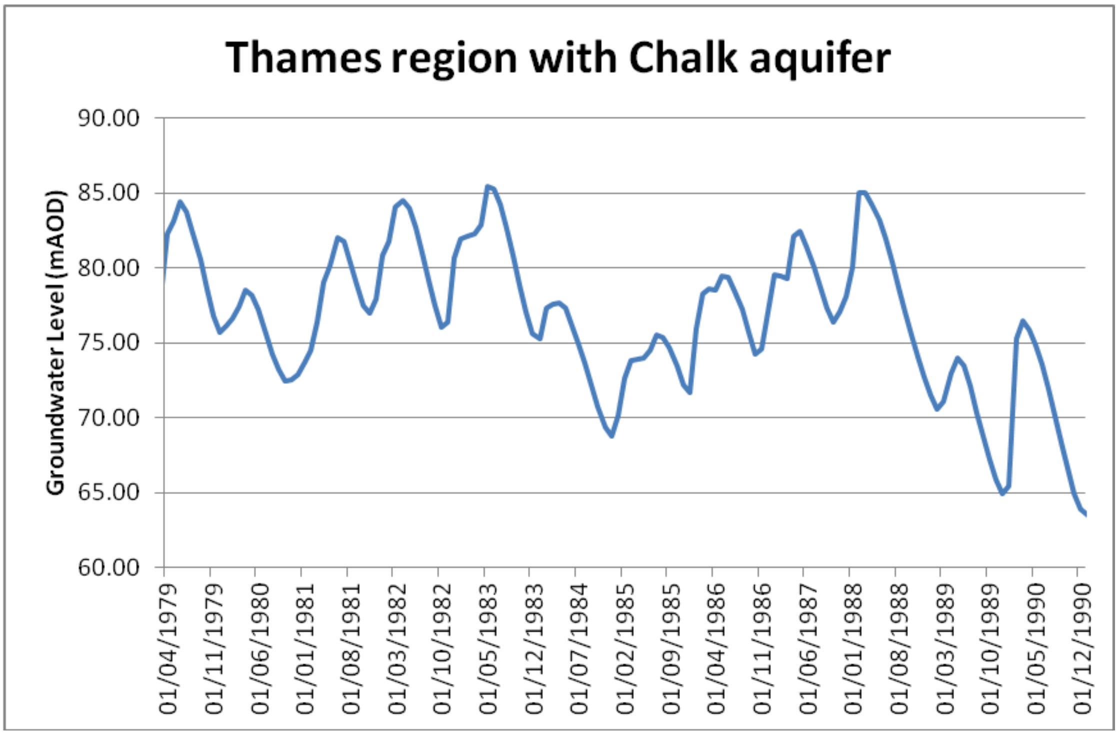

Figure A12 Baseline groundwater level data for Thames region with Chalk aquifer

These groundwater driving data both exhibit clear local maxima and minima, potentially explaining the metric 08 value grouping exhibited in Figure A8.

Conversely, Figure A13 shows the driving groundwater data for South West England with Chalk. This does not exhibit pronounced local maxima/minima and correspondingly the metric 08 histograms for this region/aquifer combination do not exhibit value grouping.

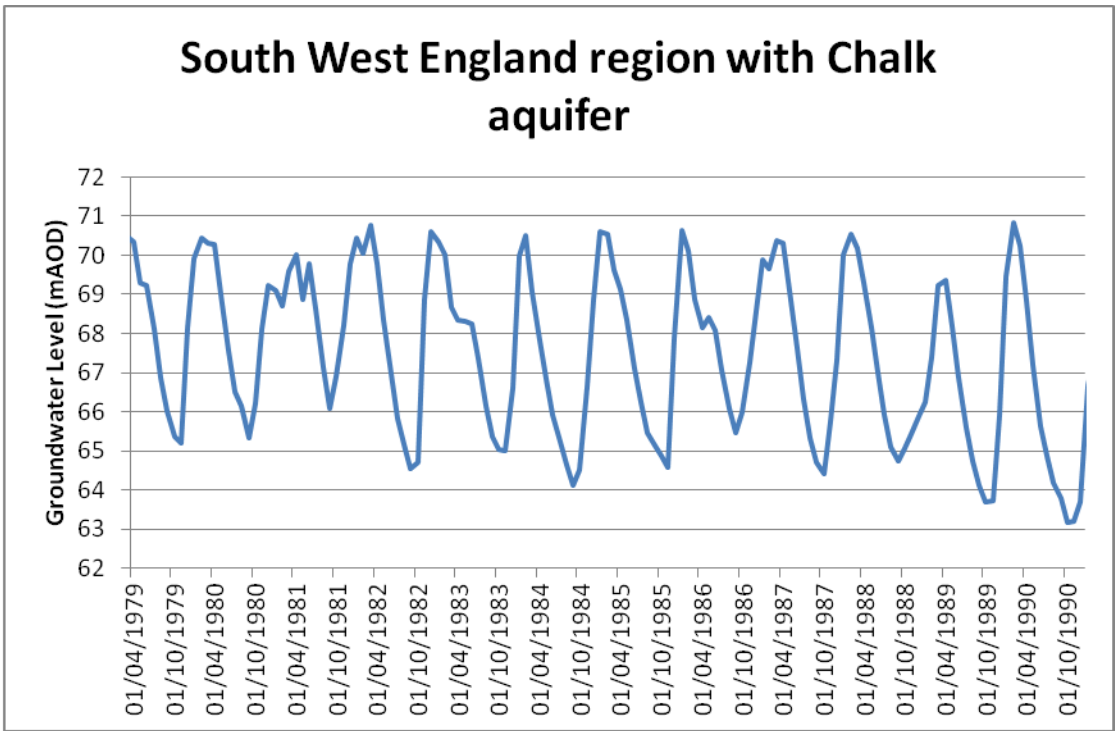

Figure A13 Baseline groundwater level data for South West England region with Chalk aquifer

Metric 12: Departure from water level requirements regime *mean annual*
Metric 13: Departure from water level requirements regime *maximum over 11 years*

As shown in Figure A14, histograms for these metrics can sometimes show a tendency for values to group together with some ranges on the histogram apparently over-represented and some under-represented (a 'hedgehog' appearance). In this case, it is not possible to postulate that this grouping of metric values is caused by local maxima/minima in the driving data (see above) as the effect occurs regardless of driving data form. For example South West England with Chalk (left plot in Figure A14) has relatively full range driving data (see Figure A13).

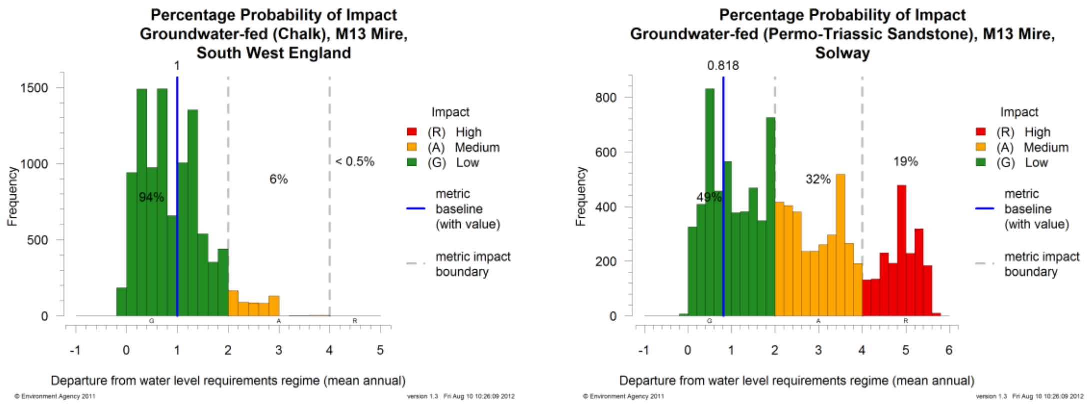

Figure A14 Example histograms showing grouping of metric values, apparently over-representing some ranges whilst under-representing others

One possible explanation for this behaviour focuses on the relative variability of the simulated wetland water levels over time compared to the ecohydrological water level requirements. In general, the simulated wetland water levels exhibit larger inter-annual variability compared to intra-annual variability. Given that the wetland water levels are relatively constant for any particular year, the degree of metric value grouping may relate to the degree of overlap between the green, amber and red zones of the water level requirements diagram for the particular community under consideration. As shown in Figure A15, this means that certain 'departure from water level requirements regime' values may be more frequent in the 11 year time series, causing grouping around particular values.

It should be noted that the maximum possible 'departure from water level requirements' value for the groundwater-fed wetland simulations is six as the metric is only evaluated for the combined Summer (June, July and August) and Winter (December, January and February) periods rather than the full twelve months. This is to ensure consistency between the less well quantified eco-hydrological water level requirements data available for the M13 and M21 mire communities compared to the better quantified M24 and S24 fen communities.

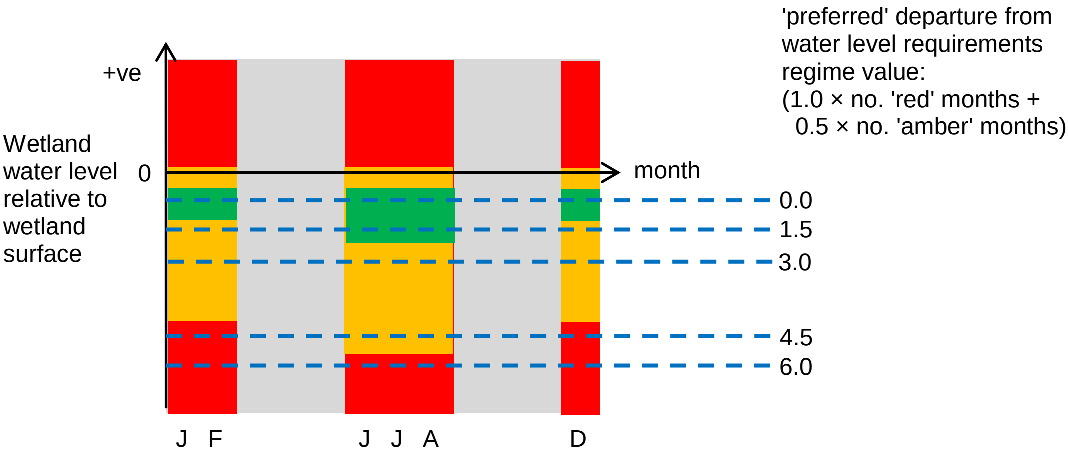

Figure A15 Hypothetical water level requirements plot illustrating relationship to 'preferred' departure from water level requirements regime metric values

Metric 18: No. months, April to July, with surface water *mean annual*
Metric 19: No. months, April to July, with surface water *maximum over 11 years*
Metric 20: No. months, November to March, without surface water *mean annual*
Metric 21: No. months, November to March, without surface water *maximum over 11 years*

As shown in Figure A16, histograms for these metrics can sometimes show values which tend to either end of the scale, i.e. surface water either present or absent for the all months considered.

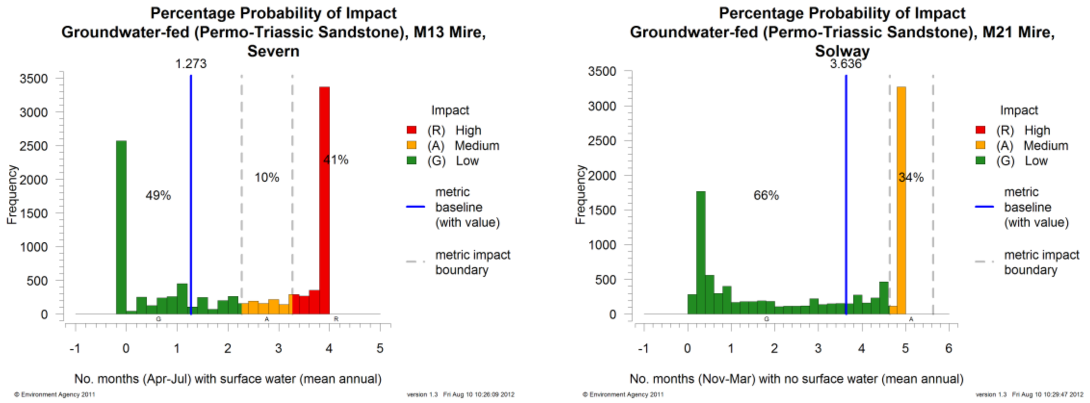

Figure A16 Example histograms showing bi-modal response

One possible explanation for this particular response focuses on the low intra-annual variation of the simulated groundwater-fed wetland water levels. Essentially the wetland water levels vary little over the course of any particular year. Therefore, the wetland water level is often either above the surface or alternatively below the surface for the entire period being considered. Given the low intra-annual variability there is a reduced possibility of the wetland water level switching from above ground to below ground or vice versa during the metric calculation period.