Hydrological impact assessment of wetlands

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ABSTRACT

It is the hydrological regime of wetlands, with varying wet and drier periods, that makes them different from terrestrial and fully aquatic ecosystems. Even slight changes in hydrology may result in significant alteration of wetland processes, species composition and ecological functions. Under national and European legislation, such as the Habitats and Water Framework Directives, EU member states need to assess the impact on wetlands of hydrological changes caused by, for example, abstractions and river engineering works and how these may affect ecological status. Reducing abstraction or restoring engineering modifications can be very costly, but failure to address impacts may put important biodiversity at risk; consequently, a consistent and robust assessment framework is required. A major problem is that wetlands are complex systems covering many types of habitat including mires, fens, floodplains, blanket peats and salt marshes. This paper reports on work undertaken in the UK to develop a consistent hydrological impact assessment approach for wetlands. It is based on fundamental hydrological principals and integrates four important concepts: (1) building a sound conceptual understanding of the hydrological processes that control water movement into and out of the wetland and can be tested by a water balance; (2) using a risk-based approach, which employs the simplest tool that is fit for the purpose of the study; (3) recognising a hierarchy of tools from simple to complex that require different amounts of data, different user time and deliver different levels of confidence; (4) although some sources of water for a wetland may be small, they may be critical at certain times, such as droughts, or in determining water quality. Although, developed in the UK, the approach has wide applicability to other countries that need to make objective judgements about hydrological impacts on wetlands.

1. INTRODUCTION

Since the UNCED Conference in Rio in 1992 it has become widely recognised that the lives of people and the environment are profoundly inter-linked. Ecological processes keep the planet fit for life providing our food, air to breathe, medicines and much of what we call "quality of life" (Acreman, 2003). Wetlands in particular are achieving increasing local, national and international attention for the wide range of goods and services they provide. The wide range of species wetlands support are important for fisheries, fuel-wood, timber, medicines and the local and global biodiversity (Dugan, 1993), providing high ecological, cultural and economic value through recreation and tourism. Wetlands also exert a significant influence on the hydrological cycle (Bullock and Acreman, 2003); altering flood flows, low flows and groundwater recharge. Scientific understanding of wetlands is rapidly improving and we recognise that the hydrology of wetlands is the most important element that distinguishes wet from terrestrial habitats (Mitch and Gosselink, 2000).

Some wetlands have isolated hydrological systems, controlled by rainfall and evaporation, such as upland blanket bogs. However, most wetlands are connected hydrologically to other water bodies including rivers, lakes, estuaries, groundwater or the sea. For example, the floodplains of the Senegal River valley recharge the underlying aquifer (Hollis, 1996), the delta of the Indus (Maynell and Qureshi, 1991) and the Sofala Bank near-shore marine ecosystem at the mouth of the Zambezi (Gamelsrod, 1993) all depend on freshwater from the river basin upstream. The Azraq oasis in Jordon (Fariz and Hatough-Bouran, 1998) and Las Tablas de Daimiel wetlands in Spain (Llamas, 1989) are fed by groundwater.

Alteration of the catchment hydrology, including abstraction from surface and groundwater, impoundment or diversion of rivers or landuse change can have a significant impact on wetlands and the functions they perform. To maintain the goods and services provided by wetlands, there is a need to assess and where necessary control these impacts.

This paper provides a framework for the hydrological impact assessment of wetlands developed in the UK (Acreman, 2004); i.e. for assessing the impacts of changes in catchment hydrology on wetlands water regimes and dependent ecosystems.

2. POLICY DRIVERS FOR WETLAND IMPACT ASSESSMENT

In many countries around the world an Environmental Impact Assessment (EIA) is required for major projects. An EIA provide a means of drawing together, in a systematic way, an assessment of a project's likely significant environmental effects and it enable environmental factors to be given due weight, along with economic or social factors, when planning applications are being considered. Environmental Impact Assessment (EIA) is required in EU states under EU Directive 97/11/EC. Other European legislation provides an example of how impact assessment is evolving with respect to wetlands. The European Habitats Directive (92/43/EEC) aims to achieve the conservation of natural habitats and of wild fauna and flora through designation of Special Areas of Conservation (SACs) that must be maintained at, or restored to, 'favourable conservation status'. Likewise, the Birds Directive (79/409/EEC) contains special measures to conserve the habitats of listed species in Special Protection Areas (SPAs). The Water Framework Directive (2000/60/EC) aims to achieve 'good status' in all water bodies (or good potential depending on the precise designation), within which wetlands are parts of surface water or groundwater bodies. Implementation of these Directives requires that hydrological impacts on wetlands are assessed and where necessary addressed.

Under the International Convention on Wetlands, contracting parties are required to maintain the ecological character of wetlands (Davis, 1993). To address this the convention's Scientific and Technical Review Panel is developing guidance on the understanding of the relationships between wetland and catchment hydrology (Acreman, 2005) and the role of wetlands in water resources management (MacKay *et al,* 2002). Some guidance is available for EIAs in development projects (OECD, 1992). In addition, OECD (1996) has produced specific guidelines on development projects and tropical and sub-tropical wetlands.

3. ASSESSMENT COMPLEXITY AND UNCERTAINTY

Impact assessment depends on understanding how a wetland works hydrologically and how changes to the wider hydrological system will impact on the wetland water regime. It is recognised that we will never achieve absolute knowledge of our environment; there will always be some uncertainty. In broad terms, the more data available and research undertaken the better the understanding, although employing a complex approach does not guarantee less uncertainty. Undertaking an impact assessment involves a trade-off between avoiding unnecessary work, and the costs of achieving an acceptable level of understanding, such that decisions can be made with reasonable confidence. For example, if a wetland is underlain by a thick layer of low permeability sediment, such as estuarine clay, it is unlikely that abstraction from any nearby aquifer will have an impact; and it is not always necessary to undertake a detailed groundwater study to realise this. In contrast, where a wetland is separated from an underlying aquifer by thin, irregular sediments of varying permeability, it may be necessary to collect site -specific data and undertake a detailed assessment using complex tools.

The basic principle is to start with simple approaches and adopt more complex techniques if necessary; i.e. use the simplest approach that gives an acceptable level of confidence, moving to a higher level if there is a high degree of uncertainty in the results. It thus becomes useful to specify different levels of analysis: 1. simple, 2. intermediate and 3. detailed. Within each level an iterative process is undertaken, whereby conceptual understanding of the wetland is developed and tested, improved and tested again until the best conceptual understanding is reached given the available data and limitations of the assessment tools used (Fig. 1). The spiral within each modelling element of Fig. 1 represents iterations in model development and testing. A decision can then be made either to accept the model as fit for the purpose of the assessment or to move to higher level of analysis. As more detailed analysis is undertaken, more data are needed and costs increase, but confidence in the results is improved.

4. DEVELOPING CONCEPTUAL UNDERSTANDING

Any analysis or modelling exercise needs to begin with a simple conceptualisation of how the system works. *i.e.* the nature of the different components of the hydrological cycle relevant to the wetland and how they interact. In wetlands, the components will include the wetland soils, as well as the underlying rocks and their characteristics, such as permeability that control their interaction with groundwater.

The interaction between groundwater and wetlands can vary significantly between individual wetlands, even ones that are close to one another. For example, there are three wetlands in Eastern England

(Langmere, Ringmere and Fenmere) that are visually similar and geographically close to each other (Fig. 2), but they are hydrologically different (Acreman and Jose, 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 lining of organic matter (an aquitard), but is still largely controlled by groundwater. In contrast, Fenmere is isolated from the Chalk aquifer by a clay layer (an aquiclude) and its water levels are controlled exclusively by rainfall and evaporation.

The movement of water between aquifers and wetlands can be expressed as one of two principle hydrological functions, depending on the direction of water movement. Upward flow of water from an aquifer to a wetland is termed groundwater discharge and downward flows from a wetland to an aquifer is called groundwater recharge. Discharge occurs when the groundwater level (or the piezometric head) is above the water level of the wetland, recharge occurs when the wetland level is high than the groundwater level. Functional links between groundwater and wetlands are thus dependent on the geology (presence of an aquiclude or aquitard) and relative water levels in the wetland and in the aquifer.

The interaction can vary over time and space, hence site-specific investigations are usually needed to identify and confirm local interactions. Groundwater levels vary naturally in time depending on previous recharge. Additionally, management of water levels in either the wetland or the aquifer, such as abstraction, can alter the relative water levels. Both these factors can change the functional relationship as shown in the following example.

Las Tablas de Daimiel wetlands in central Spain are fed by the upper Guadiana river and water discharging from the La Mancha aquifer when groundwater levels are high; but when groundwater levels are low the direction of groundwater flow is reversed and water moves downwards from the wetlands to recharge the aquifer (Llamas, 1989). Until the 1970s the functional relationship was predominantly based on groundwater discharge. However low rainfall and pumping of the aquifer for irrigated agriculture has caused groundwater levels to drop and recharge dominated during the 1990s. This led to severe desiccation of the wetlands. In recent years, water has been transferred to Las Tablas de Daimiel from the Tagus River basin as an emergency plan, however this has led to some physio-chemical and ecological changes to the wetland due to the different characteristics of the transferred water (Cirujano *et al.*, 1996).

As water flows through a Chalk or limestone aquifer it dissolves minerals in the rock, such as calcium, sodium, bicarbonate and chloride. As a result, the chemical and thermal properties of groundwater are often quite different from those of surface water. Thus wetlands fed from these aquifers often have different floral and faunal communities than those fed purely by surface water. Indeed, in some cases the presence or absence of specific species known to be groundwater-reliant can be an indicator of whether or not a wetland is strongly dependent on groundwater. Furthermore, although groundwater may be volumetrically a minor source of water for some wetlands, even a small quantity of groundwater can have a significant impact on water quality and hence on ecological processes and biota in the wetland. At Wicken Fen in the UK, changes in ecological character were first attributed to drying out of the wetland. However, hydrological analysis showed that reduced inundation from the groundwater-fed high pH river due to flood management activities had altered the acidity of the wetland (McCartney *et al*, 2000).

5. UNDERSTANDING GROUNDWATER-RELATED WETLANDS

A prerequisite to assessing the implications for a wetland of any external hydrological impacts is to understand the ways in which water enters and leaves the wetland, termed water transfer mechanisms and quantifying the associated rates of water movement. Most wetland managers are very familiar with geographical (horizontal or plan-form) analysis of wetlands, using maps of open water bodies and vegetation zonation. However, understanding interactions with groundwater requires a geological view in a third dimension, i.e. looking at vertical sections through the soils and rocks that lie beneath the wetland. Annex 1 provides details of the 14 water transfer mechanisms depicted schematically in the form of vertical sections. They show that groundwater can enter a wetland indirectly via a spring (spring flow), by lateral movement from an adjacent aquifer (seepage) or by upward movement from an underlying aquifer (discharge). Water usually moves from a wetland to an aquifer by downward movement (recharge).

The first step in understanding wetland hydrology involves identifying which water transfer mechanisms are operating at a wetland and which of these are the most important in maintaining the ecology present. Whether movement of groundwater to or from a wetland is an important mechanism depends not only on the presence of an aquifer, but also on the nature of the soils and rocks between the aquifer and the wetland. If the wetland is in direct contact with the aquifer, exchange of water is very likely. However, if there is an aquitard or aquiclude between a wetland and an underlying aquifer, there may be little or no exchange of groundwater.

To aid the user to identify water transfer mechanisms, a hydrological typology of wetlands has been developed by Acreman (2004), based on landscape location. This is described in Annex 2. The wetland under study is unlikely to be precisely like any of the wetland types shown and may exhibit characteristics of more than one type; nevertheless the typology provides an indication of most common situations.

The outcome of a hydrological investigation should be a conceptual diagram of the wetland under study showing water transfer mechanisms and the soils and rocks underlying the wetland. Real wetlands are often complex, exhibiting many water transfer mechanisms simultaneously, although certain mechanisms will often dominate in different zones of an individual wetland.

Fig. 3 shows a cross-section of a hypothetical wetland where different water transfer mechanisms dominate in different zones of the wetland. Hydrological inputs to Zone A are dominated by spring flow (S) and outputs by pumping (PU), whereas in Zone B over-bank flow from the river (OB) dominates. Zone C is an area of exchange with groundwater (GD, GR), whilst the hydrology of Zone D is dominated by precipitation (P) and evaporation (E). In Zone E inputs come from groundwater seepage (GS) and runoff from the adjacent slopes (R). Cross-section diagrams will probably need to be produced for different periods (most notably for wet or dry seasons) since the water transfer mechanism may change, for example the interaction between the aquifer and wetland may alter discharge and recharge as water table levels change.

Because aquifers are hidden from view is it very difficult to measure accurately the nature and extent of any groundwater interaction with wetlands. There are various ways in which information can be gathered. The intensity and scope of information-gathering activities will depend on the confidence in the results and degree of quantification required. A scoping study to identify the potential (presence/absence) for significant connectivity between a wetland and related groundwater bodies may only require an initial desktop assessment. However, to determine the sustainable yield and permitted abstraction from an aquifer is likely to require site-specific field studies and monitoring over time. In general, there are three levels of assessment that can contribute to understanding and quantifying water transfer mechanisms:

1. **Desk based information.** Investigations normally start with information available in the office. Spatial data will often include topographical, land use/vegetation and geological maps and photographs taken from aircraft or satellites. Old photos have proved to be very useful in explaining hydrological links with wetlands in Costa Rica, where restoration practices benefit from historical knowledge. Geological maps can reveal the proximity of aquifers to the wetlands. However, these maps are generally drawn by extrapolating information from limited geological data (such as cores). Hence in parts of these maps the presence and thickness of impermeable strata lying between a wetland and an aquifer may be very uncertain. In addition, the permeability (or hydraulic conductivity) of the strata will not be evident from the map.

2. **Field visits.** Field visits should be undertaken at an early stage in any investigation. Where possible the field team should be multi-disciplinary including a hydrologist, hydro-geologist and botanist. Botanists may be able to identify plants that may indicate groundwater discharge to the site; however, this assumes that the present vegetation truly reflects the current wetland hydrology. It is particularly advisable to try and visit the wetland (a) after prolonged rainfall to see if springs or ephemeral water courses can be identified and (b) after a prolonged dry spell when vegetation patterns may indicate areas where the wetland is reliant on groundwater during the dry season or droughts. Photographs should be taken to record specific features, such as weirs or sluices, vegetation distribution and channel networks. Auger holes can also be dug to investigate the soil properties of the wetland, particularly to identify areas of permanent water-logging in the dry season that may reflect reliance on groundwater. Where possible, local people, such as site managers and farmers should be interviewed to gain anecdotal information about potential water transfer mechanisms or changes to the site, eg. are there springs feeding the wetland and are these perennial? This information should provide on-the-ground confirmation of the office-based conceptual model or identify new aspects that have not been covered.

3. **Field measurement and monitoring programmes.** The quantification of groundwater exchanges with wetlands requires field data. Whilst some data, such as groundwater levels may be available from hydrometric services, most wetland studies require the collection of field data for the site in question. These data may include dip well or piezometer levels from the wetland soil or the underlying aquifer and soil properties, such as specific yield or hydraulic conductivity. Based on initial understanding, field monitoring programmes will need to be established to collect the necessary data i.e. over a specific time period rather than a one-off assessment. The data will support the generation of more comprehensive understanding and the use of more detailed assessment tools.

Although these three levels of information collection are presented as sequential steps, it is not always the case that they must be followed in this order. Furthermore, the process may be cyclical. For example, it may be recognised at an early stage in a wetland impact assessment that a detailed model will be required, so collection of appropriate data and model development can start. Later anecdotal information could be collected that refines or changes previous understanding, *e.g.* the identification of springs during a wet season visit.

6. TESTING UNDERSTANDING THROUGH WATER BALANCES

Once an understanding of how a wetland works hydrologically has been established in principle and a cross-section diagram like in Fig. 3 has been produced, the understanding needs to be tested and confirmed or refined. Estimating a water balance, which involves quantifying water transfer rates, provides a means of testing hydrological understanding. The principle of balancing inputs, storage and outputs provides a check that all water transfers have been accounted for and quantified.

The water balance is a key quantitative test of hydrological understanding, but is normally only a first step because it deals with bulk water volume transfers and not with wetland water levels which may be the key control on wetland flora and fauna. Thus, it will not in itself provide full answers to assessments of impacts of regime changes on wetlands. Although simple in principle, quantifying a water balance is not always straightforward. Many wetlands have a multitude of natural and man-made surface channels providing links to water courses or have a complex association with an underlying aquifer; these need to be taken into account in the water balance.

The water balance of a wetland is based on comparing the total quantity of water transferred into a wetland with the total quantity of water transferred out (see Fig. 4). By using the list of water transfer mechanisms in Annex 1, the water balance of a wetland can be summarised by a simple addition of inputs to and outputs from the wetlands as expressed in equation [1]

$$\underset{\textbf{inputs to the wetland}}{(P + R + L + OB + PU_i + S + GD + GS + TI)} - \underset{\textbf{outputs from the wetland}}{(E + D + OF + PU_o + GR + TO)} = \delta V \qquad [1]$$

Thus if inputs exceed outputs, storage (V) will increase and the water level in the wetland will rise. If inputs are less than outputs, storage (V) will decline and the water level in the wetland will fall.

Some water transfer mechanisms may not occur in any particular wetland and thus will have a zero value in the water balance. If the total inputs of a water balance are not approximately equal to the total outputs, then this may indicate that a potentially significant water transfer mechanism either has been omitted or not measured accurately. Hence the water balance can help to identify specific areas where additional or more detailed investigations are required.

It is not possible to measure any rates of water transfer exactly, and thus it is inevitable that quantification of the water balance will not be precise. Although uncertainty is often perceived as a negative issue (often associated in people’s minds with user error), it is a fact of life, especially when dealing with natural systems, and should be presented explicitly rather than hidden. Where possible, the uncertainty (or level of confidence) associated with any water transfer mechanism should be estimated. Future effort can then be focused on the better measurement of the most uncertain mechanisms. One approach to the estimation of uncertainty is to quantify the rate of flow in each water transfer mechanism using various different methods. The range in results generated using different methods helps define the certainty with which the water transfer mechanism has been defined.

The water balance is tested by comparing the volume of inputs with the volume of outputs. If the volumes match approximately, then the water balance is said to be "closed" and the conceptual understanding of the wetland hydrology can be considered plausible; it does not however prove the conceptual understanding. Since all measurements of water transfer mechanisms have some uncertainty, the water balance will never close exactly. In practice, the balance is thought to be satisfactory if the imbalance is within the uncertainty of the measurements. If the volumes of water do not balance, then alternative conceptual understanding should be considered.

There is often a temptation in water balance studies to assume that any differences between inputs and outputs (or unaccounted-for volume of water) must be equal to a particular water transfer mechanism that is thought to occur, but for which data are not available. For example, if in a wetland that is thought to be fed by groundwater, the precipitation is less than the various outflows, it is tempting to conclude that the groundwater discharge must be equal to the difference between precipitation and outflow. However, this apparently unaccounted-for water may be a result of inaccurate rainfall or outflow data, or input from another mechanism, such as a spring which has not been recognised. Consequently, every water transfer mechanism should be estimated independently, however uncertain this may be, and checked using the water balance. Defining a water balance can thus be an iterative process, in common with developing the whole conceptual understanding of the wetland.

An example of a water balance is given in Annex 3.

7. PREDICTING HYDROLOGICAL CHANGE IN A WETLAND

The water balance approach as described above can assist with testing which water transfer mechanisms may be present and the volume of water moving into and out of the wetland. However, it is hydrological factors, such as water table level and soil moisture, that ultimately determine the impacts of an external change on the wetland itself. The water balance indicates the change in water storage within the wetland, but does not include water table levels and a more detailed approach is required to predict water level changes, often involving the use of a model. However, there are no 'off the shelf' models designed specifically for wetland impact assessment, and so a degree of interpretation is necessary to translate the model outputs into an assessment of impact on the wetland itself.

At the simplest level, analytical equations provide an estimate of the impacts of drawdown in a well on water table levels in the aquifer. Theis (1935) provided the first mathematical solution of drawdown in a confined aquifer using parameters for transmissivity, storativity and distance from the well. Hantush (1964) provided equations for leaky or semi-confined aquifers which allows for vertical and horizontal hydraulic conductivity. Neuman (1972) gives solutions for unconfined aquifer drawdown. The Hantush leaky model was used on the assessment of Great Cressingham Fen, UK (Whiteman *et al.,* 2004). However, because these equations assume an infinite aquifer with no source of water, they have limited application for wetland impact assessment.

At a slightly more complex level IGARF is a spreadsheet tool for evaluating the Impact of Groundwater Abstraction on River Flows. Whilst IGARF also provides estimates of drawdown in the aquifer due to groundwater abstraction, it includes more realistic boundary conditions, eg. no flow, and allows consideration of both fully and partially penetrating rivers.

For impermeable wetlands (e.g. clay), Gasca-Tucker and Acreman (1999) developed a model of ditch water level and surface flooding called PINHEAD for application to the Pevensey Levels; this only has very simplistic surface groundwater interactions and does not model water tables explicitly.

In the steady state situation, the relationship between soil water storage and water table level depends on the soil's specific yield (Gilman, 1994).

$$\delta s = S/100\ \delta h \qquad [2]$$

where

δs is the change in soil water storage

S is the specific yield (expressed as a percentage)

δh is the change in water table level

The specific yield is different from the soil water content (which for a peat may be 80-95%); it is the amount of water released from the soil when the water table drops (which may be 30-50% for peat). Boelter (1969) defines a similar property called the water yield coefficient.

Armstrong and Rose (1999) combined a water balance approach with soil porosity to produce the DRAIN model for predicting water table levels. Various models have been developed using land drainage and soil physics theory (Youngs *et al.*, 1989) to examine the impact of land-drain spacing on water table elevation. Many of the factors required for impact assessment are included in these models including volume of flux due to rainfall and evaporation, water table height and specific yield. For example, Gowing *et al*. (1997) studied the water regime requirements of wetland vegetation communities using SCHAFRIM, the hydrology for which is based on Young's equations. These models tend to predict water table levels as discrete values, *i.e.* not related to each other. Further development of this modelling approach to produce contour maps of water table levels was made by Youngs *et al.* (1991).

8. MODELLING SPATIAL HYDROLOGICAL PATTERNS

Full understanding of spatial and temporal hydrological patterns requires the use of models that have explicit representation of water table gradients and groundwater flow and how these change with time thus requiring the solution of partial-differential equations. MODFLOW[1] is a finite difference, 3-dimensional time varying sub-surface flow model that has become the industry standard for groundwater modelling. MODFLOW has been widely used to model regional aquifers, in some cases including a representation of a local wetland, such as Great Cressingham Fen, UK (Whiteman *et al,* 2004) to determine

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[1] MODFLOW is available free of charge; see http://water.usgs.gov/nrp/gwsoftware/modflow.html

the impact on water levels of draw-down in the aquifer due to abstraction. Other groundwater models similar to MODFLOW have also been used, such as Aqua 3D employed in the Messara valley, Greece (Acreman *et al*, 2000). There are three limitations to the application of these models. First, it is difficult to represent satisfactorily in a single model the important characteristics of both the large regional scale aquifer and the small local scale wetland. For example, the grid-size appropriate for modelling a regional aquifer in MODFLOW may be 500 m; this may be reduced to say 200m in specific areas, but this still means that a wetland may be represented by only a few grid squares and local heterogeneities in hydraulic conductivity would not be represented. The object orientated groundwater modelling tool ZOOM-3D (ref) attempts to overcome this problem by dynamically coupling objects of different resolutions. A river module is being developed for ZOOM-3D, but no wetland module is currently available or being developed. Second, whilst it may be considered acceptable to predict groundwater levels in a regional aquifer to an accuracy of 1 m, this is not acceptable for wetland impact assessment since wetland soil water level predictions within 0.1 m may be required to determine likely changes to communities. Third, these models do not incorporate surface runoff or evaporation explicitly. However, a wetland "module" has been developed for MODFLOW (Restrepo *et al.*, 1998) that allows simple representation of flow in rivers and sheet flow in areas of dense vegetation (Kadlec, 1990). However, this approach requires spatially distributed estimates of surface roughness and variations in local topography. Nevertheless, MODFLOW has also been used to simulate within-wetland water levels (e.g. Gerla and Matheney, 1996; Bradley, 2002; Bradford and Acreman, 2003).

An alternative attempt is given with the much more flexible spatial discretisation realised by triangles in the finite element approach (Diersch and Michels, 1996). An example of this model type is the *FEFLOW 3D* model of wetland-catchment interactions used in Germany. Additionally, the HPP-GMS[2] finite element calculation code has been used to simulate the hydrological dynamics of the Rhine floodplain and to evaluate the role of that wetland in denitrification (Sanchez-Pérez and Trémolières 1997). However, the effort required for parameterisation of such large coupled groundwater models is immense.

In many wetlands water levels are influenced not just by external water transfer but by infrastructure within the wetland such as penning boards and sluices. In such situations, models that explicitly link surface and groundwater are required. However, they tend to be still at the research stage and require large numbers of data to be calibrated. Mansell *et al.* (2000) developed and applied a transient, coupled saturated-unsaturated, 2D numerical model to study the link between groundwater and cypress ponds in the Coastal Plain forest region, USA. Crowe *et al.* (2004) developed a 2D model for simulation of groundwater-wetland interactions. An example of coupling surface and groundwater models was given by Krause and Bronstert (2004), who coupled the surface water model WASIM-ETH-I and the groundwater model MODFLOW to simulate hydrological processes in a low lying sub-catchment of the Havel, Germany. A similar method was employed by Thompson *et al* (in press) for the analysis of wetlands. They applied the hydrological model MIKE SHE and the hydraulic model MIKE 11 together to the North Kent Marshes as part of the SHYLOC project (Al-Khudhairy *et al.*, 2001). These coupled hydraulic river models and groundwater models are examples of "regional" scale modelling, where the wetland is part of a much larger hydrological system. Nevertheless, it is important to note that merely collecting more data and using a more complex model does not in itself guarantee that understanding will be improved. Even where it is anticipated that a

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complex model will be required eventually, analysis should always start with a simple conceptual picture of the wetland that becomes more complex as understanding develops. It is essential that there is first a correct conceptual understanding of the water transfer mechanisms.

9. RELATING WATER LEVEL CHANGE TO ECOLOGICAL IMPACT

The prediction of water level is not normally the end-point of wetland studies. Impact assessment requires quantification of the response of plants and animals to hydrological change, since these govern the designation of the site under the Ramsar Convention, the European Habitats and Birds Directives and dominate the determination of good ecological status under the Water Framework Directive. Research on the water requirements of wetlands has been led predominantly by wetland botanists, focusing on the water regimes of plant communities. Wheeler and Shaw (2001) identify three environmental gradients that influence community assemblages in freshwater wetlands:

a) acidity: ranging from acid (or base-poor) to base-rich (coming from a chalk aquifer);
b) fertility: related to availability of nutrients (primarily N and P): ranging from oligotrophic to eutrophic;
c) hydrological regime: ranging from highly variable water level, such as floodplains of flashy catchments to stable water levels fed by groundwater.

Ellenberg (1988) presented broad water requirements of European plant species and communities. Other research has focused on the water regime requirements of specific wetland plant community types, including wet grasslands (Gowing *et al*, 1997) and fens (Wheeler and Shaw, 2001). The hydrological regime has been characterized by the Sum Exceedance Value, where periods of low water (drought stress) and high water (aeration stress) are accumulated from water table time series (Gowing *et al.*, 2002). De Becker *et al.* (1999) found that the spatial distribution of vegetation in an alluvial groundwater-fed fen was best explained by mean groundwater level and groundwater amplitude. The UK research experience on water requirements of key wetland vegetation communities (wet grasslands, fens/mires and swamps/ditches) has been brought together as *Ecohydrological Guidelines* that can be applied directly to impact assessment (Wheeler *et al*, 2005). Fig. 5 provides an example for MG13 type wet grasslands; water levels in the green zone are "desirable" for this plant community, water levels in the amber are "tolerable for limited periods", whilst water levels in the red are "unacceptable". Following work on additional wetland types including wet woodland and dune slacks is underway.

Newbold and Mountford (1997) defined water conditions for some wetland birds, amphibian and dragonflies. Ausden *et al* (2001) examined the impact of water levels on macro-invertebrates as prey for wading birds. Less attention has been paid to the relationship between water regime and wetland microbes. Microbes are essential in many wetlands in determining the availability of nutrients as well as toxins to other life forms, sometimes even actually delivering these in symbiosis. Francez *et al* (2000) and also McNamara *et al* (2004) have shown that methane output is higher during water logging of wetlands than during dry periods.

Little research has also been undertaken on the impact of the water regime on the physical structure of the wetlands, although there is a vast bank of knowledge on the impact of surface water flow on the geomorphology and associated plant growth in wetlands that are part of surface water bodies, such as floodplains, estuaries and shallow rivers. Bendjoudi et al (2002) however used a different time scale approach (millennia, centuries and decades) to study the historical development of riparian wetlands along the Seine and the Aube rivers in France. Peat soils in particular are oxidised when dry, leading to soil wastage and ground surface lowering. Data from the UK suggests peat wastage of 0.44-0.79 m over the past 100 years (Brunning, 2001), where in The Netherlands studies show land levels lowering by 1 cm yr-1 under normal agricultural use. Subsidence of clay soils under varying hydrological regimes is now recognised as a major problem in large sedimentary basins including extensive parts of China.

10. CONCLUSIONS

Impact assessments are increasingly being required by international and national legislation to determine the implications of developments, such as abstraction of water from rivers and aquifers. Impact assessments of groundwater-fed wetlands provide a significant challenge. Several levels of approach can be taken. For academic studies, driven by deep understanding of hydrological processes, complex models may be developed and employed from the start. However, in regulatory agencies where many hundreds of wetlands must be assessed, it is necessary to have a structure framework. We make the following recommendations:

1) Conceptual understanding. Impact assessment should be based on the development of conceptual understanding of the hydrological processes that control water movement into and out of the wetland. Since all models are based on conceptual understanding there will be iterations of model building, testing and revision or confirmation of conceptual understanding. The landscape-based typology provides a guide to develop initial understanding.
2) Risk-based approach. Use the simplest level of assessment that is fit for the purpose of the study, moving only to more complex levels of assessment when uncertainty is too great. The acceptable level of confidence will depend on the consequences of the results being wrong. For assessments of designated sites, with rare or endangered species, and where water is short and altering or relocating abstractions would be prohibitively costly, a higher level of confidence is required than for non-designated sites in water-rich areas.
3) Hierarchy of tools. Normally, as more data are collected and more detailed analysis is undertaken, the confidence in the conceptual understanding increases and uncertainty decreases, but the costs increase. There is sometimes a temptation to start with a complex tool because it is a favourite or is very complex, so “must” be able to model any situation. We recommend developing a tool-kit containing a hierarchy of tools from simple to complex, so the most appropriate tool can be selected at each stage of the analysis. Indeed, merely collecting more data and using a more complex model does not in itself guarantee that results will be improved.
4) Water balances. Testing conceptual understanding at all levels should include development of a water balance, even when more complex models are used for prediction of impacts, as this can be used to verify that all key water transfer mechanisms, to and from the wetland, have been included.
5) Water transfer mechanisms. Some water transfer mechanisms may be volumetrically a minor source of water for some wetlands. However, for example, even a small quantity of groundwater may be significant during droughts and can have a major impact on water quality and hence on ecological processes and biota in the wetland.

6) The challenge of hydrological impact assessment. Despite the availability of various tools and approaches, translating predicted river flow alterations or water level changes in an aquifer or to a water level change on the wetland remains a major challenge. We will never be certain about how our environment works. Satisfactory calibration of a model, such as closure of the water balance, does not guarantee that the conceptual understanding is correct; rather it confirms that the conceptual understanding is plausible.

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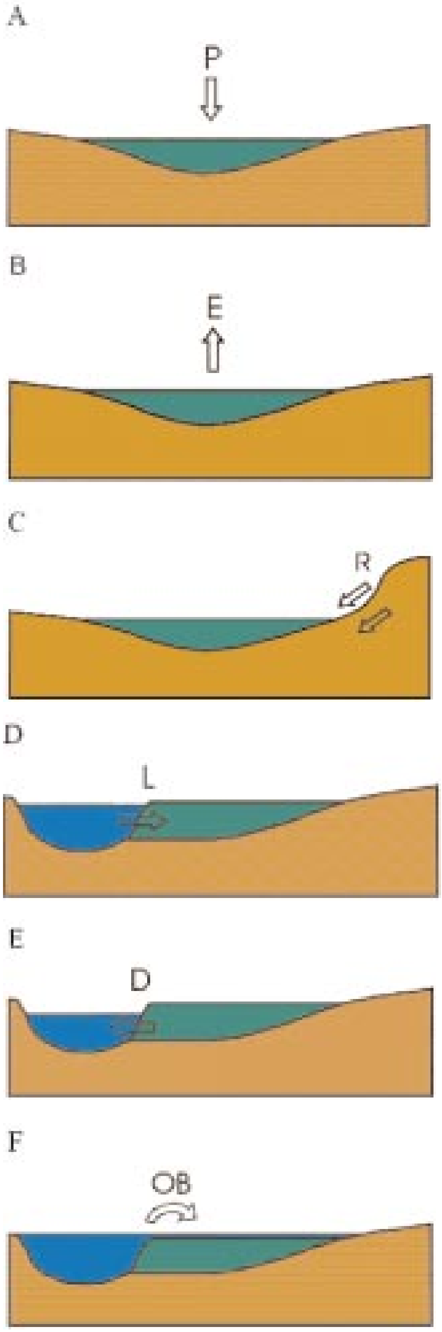
ANNEX 1. WATER TRANSFER MECHANISMS IN GROUNDWATER-RELATED WETLANDS

The ways in which water can move into or out of a wetland are called water transfer mechanisms. Figure A1 (a to n) presents a list of possible water transfer mechanisms together with their association to aquifers and less permeable strata. These mechanisms do not necessarily dictate the distribution of water within a wetland or the rate of movement, but rather define the hydrological interface with the surrounding environment. Any particular wetland will only be influenced by a sub-set of these mechanisms. Identification of the key mechanisms can be made by collecting information about the wetland's hydrology and geology.

KEY FOR FIGURES

Geological strata vary considerably in their permeability, or the rate at which water can pass through (also called hydraulic conductivity). Low permeability strata includes clay, whilst highly permeable strata include sand. The piezometric head is the level that groundwater would reach if not impeded by a low permeability layer above the aquifer (an aquiclude or aquitard). In un-confined aquifers the piezometric head may be equal to the observed water table.



P **precipitation**. Rain, sleet or snow falling directly onto the wetland and intercepted mist and condensation.

E **evaporation**. Water moving from the soil, open water or plant surfaces in the wetland to the atmosphere. It includes transpiration.

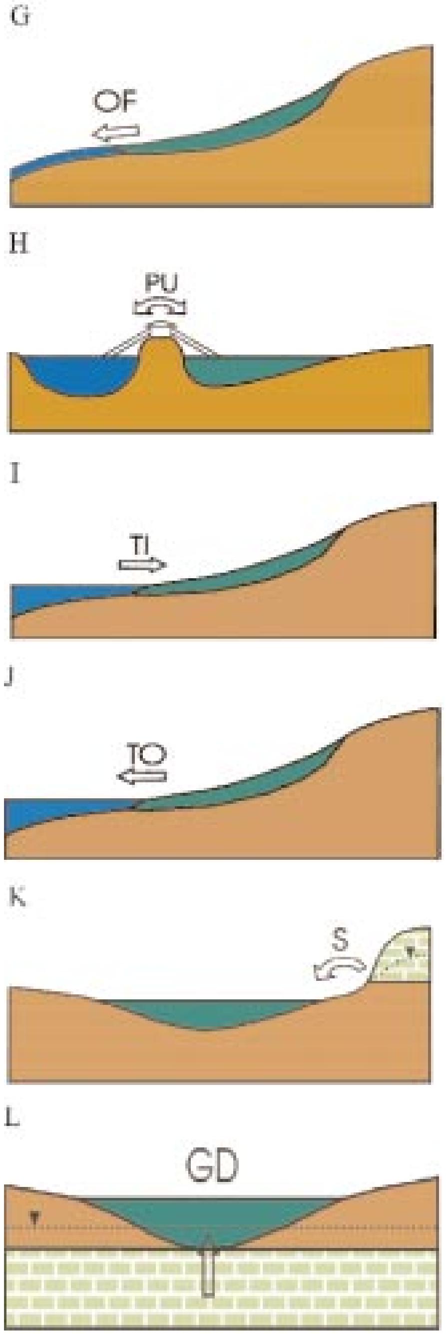
R **runoff**. Water moving down-slope across the land surface, in streams or through shallow layers of the soil into the wetland.

L **lateral inflow**. Water moving laterally through the soil from a ditch, river or lake into the wetland. The wetland water table level is lower than that in the issuing water body.

D **drainage**. Water moving laterally through the soil from the wetland to a ditch, river or lake. This may be natural or enhanced by artificial tile or mole drains. The wetland water table level is higher than that in the receiving water body.

OB **over-bank flow**. Water moving from a ditch, river or lake onto the wetland's surface. The water level in the issuing body is higher than the ground level of the wetland.

Figure A1 Wetland water transfer mechanisms



OF **out flow**. Water moving from a wetland down slope into a water course. This includes water flowing back to a river after over-bank flooding when the river level has dropped. The water course may start within the wetland.

PU **pumping**. Water moved between a wetland and a river, lake, ditch or the sea by a mechanical pump. Water may be pumped into or out of the wetland I

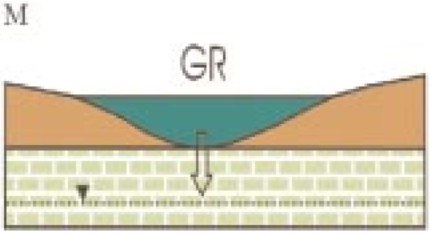
TI **tidal inflow**. Saline water entering a wetland from the sea as the tide rises

TO **tidal outflow**. Saline water moving from the wetland to the sea as the tide falls

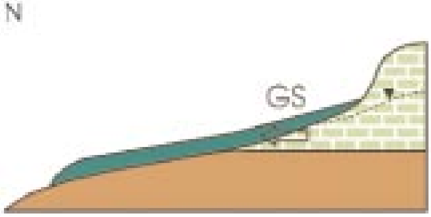
S **spring**. Water issuing from an aquifer onto the surface of a wetland. Often this is associated with the location of an aquiclude beneath the aquifer.

GD **groundwater discharge**. Water moving vertically upwards into a wetland from an underlying aquifer. The piezometric head/water level of the aquifer is higher than the water level in the wetland. There may or may not be a lower permeability layer between the wetland and the aquifer that could limit water flow.

Figure A1. Wetland water transfer mechanisms (contd)



GR groundwater recharge. Water moving vertically downwards from a wetland to an underlying aquifer. The piezometric head/water level of the aquifer is lower than the water level in the wetland. There may or may not be a lower permeability layer between the wetland and the aquifer that could limit water flow.



GS groundwater seepage. Water moving laterally into a wetland from an adjacent aquifer. There may or may not be a lower permeability layer between the wetland and the aquifer that could limit water flow.

Figure A1. Wetland water transfer mechanisms (contd)

ANNEX 2 LINKING LANDSCAPE LOCATION AND WATER TRANSFER MECHANISMS

The hydrological wetland typology adopted in these guidelines is based on landscape location and water transfer mechanisms. Landscape location produces seven types within the Ramsar definition (Figure A2.1). These can be further sub-divided on the basis of dominant water transfer mechanisms to produce 15 sub-types (Table A2.1). In particular, the sub-types are based on whether the likely dominant water transfer mechanism in each type is surface water or groundwater or a combination of the two. Figure A2.2 to A2.7 show diagrams of some example hypothetical wetlands in each sub-type. For wetlands in topographically flat areas, only the surface water sub-type is relevant.

Clearly, the sub-type may not be known at the outset of the study, as the contribution of groundwater to the wetland is difficult to determine. However, the typology can be used to guide understanding of hydrological mechanisms that can be tested by data.

Table A2.1 Wetland landscape location types and hydrological sub-types

Landscape location	**Sub-type based on water transfer mechanism**
Flat upland wetlands	Upland surface water fed
Slope wetlands	Surface water-fed
	Surface and groundwater-fed
	Groundwater-fed
Valley bottom wetlands	Surface water-fed
	Surface and groundwater-fed
	Groundwater-fed
Underground wetlands	Groundwater-fed
Depression wetlands	Surface water-fed
	Surface and groundwater-fed
	Groundwater-fed
Flat lowland wetlands	Lowland surface water fed
Coastal wetlands	Surface water-fed
	Surface and groundwater-fed
	Groundwater-fed

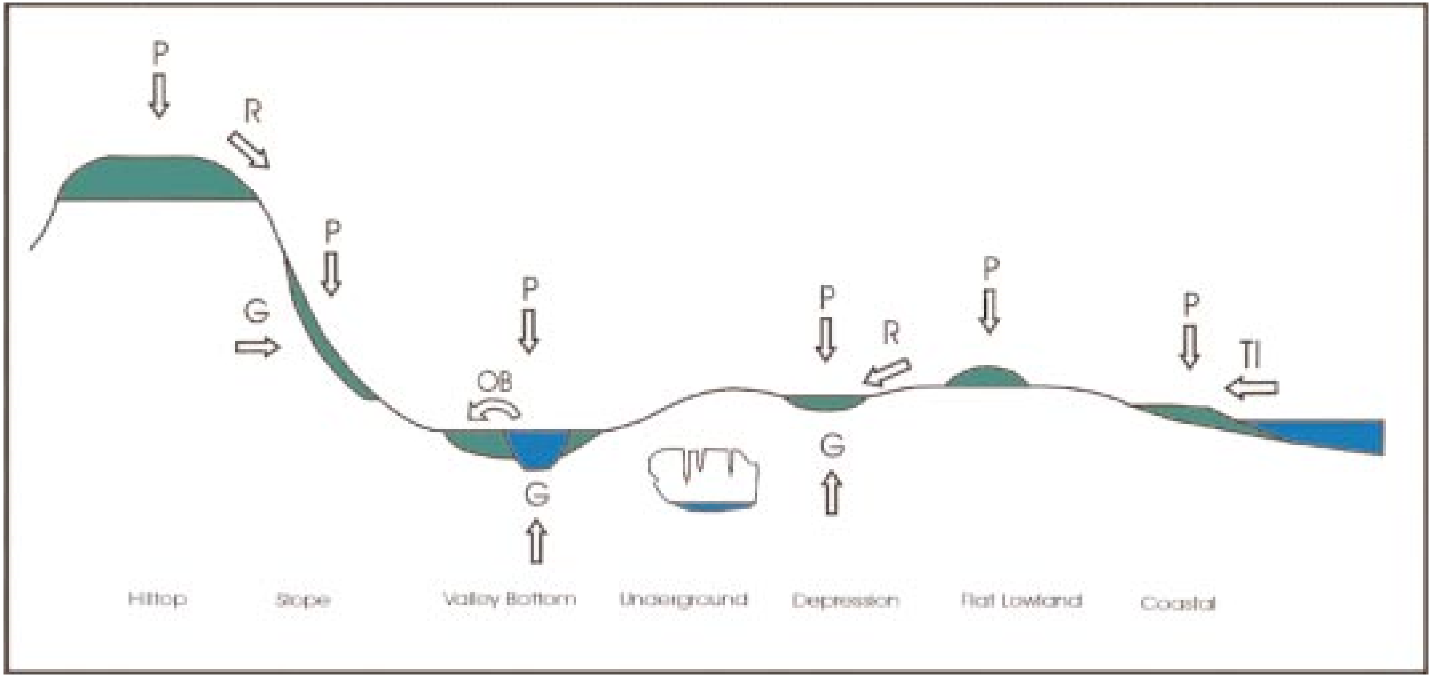
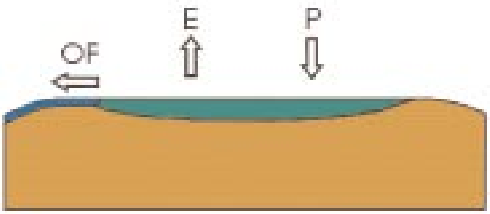


Figure A2.1 Landscape locations of wetlands

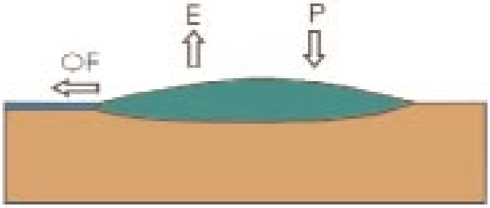


Upland flat area wetlands

Surface water-fed: Upland flat area wetlands

Surface water-fed: Wetland underlain by impermeable strata.

Input dominated by precipitation. Output by evaporation and surface outflow. Example: upland blanket bogs

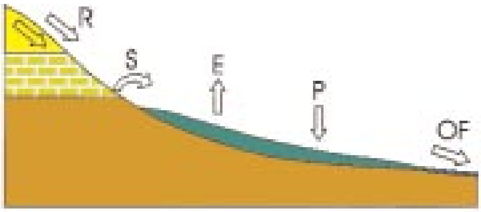


Lowland flat area wetlands

Surface water-fed: Wetland underlain by impermeable strata.

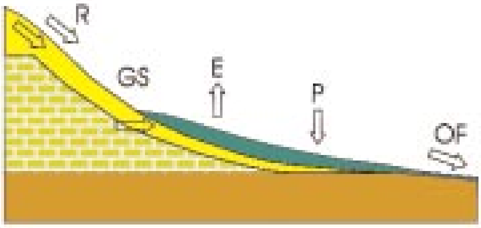
Input dominated by precipitation. Output by evaporation and surface outflow. Example: rain-fed domed mires.

Figure A2.2 Flat area wetlands (see Annex 1 for key to abbreviations)



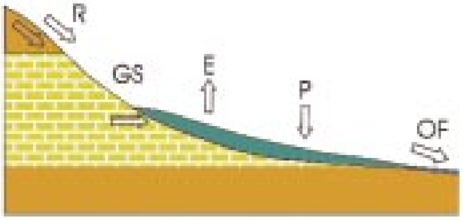
Slope wetlands

Surface water-fed: Wetland underlain by impermeable strata. Input dominated by precipitation, surface runoff and possible spring flow. Output by evaporation and surface outflow



Slope wetlands

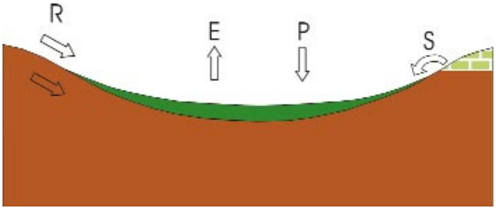
Surface and groundwater-fed: Wetland separated from underlying aquifer by lower permeability layer. Input from groundwater seepage, precipitation and surface runoff. Groundwater input may be restricted by lower permeability layer. Output by evaporation and surface outflow. Example:



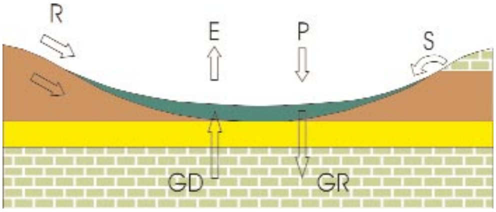
Slope wetlands

Groundwater-fed: Wetland in direct contact with underlying aquifer. Input dominated by groundwater seepage, supplemented by precipitation and surface runoff. Output by evaporation and surface outflow. Example:

Figure A2.3 Slope wetlands



Depression wetlands
Surface water-fed: Wetland underlain by impermeable strata. Input dominated by precipitation, surface runoff and possible spring flow. Output by evaporation only. Example:



Depression wetlands
Surface and groundwater-fed: Wetland separated from underlying aquifer by lower permeability layer. Input from groundwater discharge, when groundwater table is high, precipitation, surface runoff and possibly spring flow. Groundwater input may be restricted by lower permeability layer. Output by evaporation and groundwater recharge when groundwater table low. Example:

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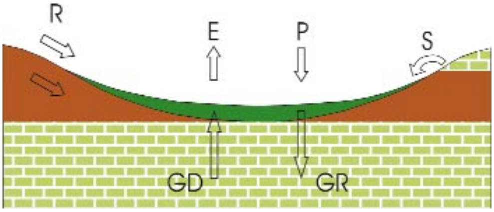
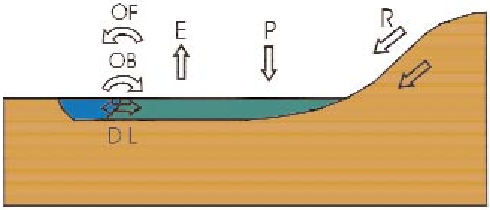


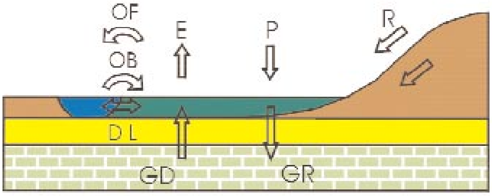
Depression wetlands
Groundwater-fed: Wetland in direct contact with underlying aquifer. Input dominated by groundwater discharge when groundwater table is high, supplemented by precipitation, surface runoff and spring flow. Output by evaporation and groundwater recharge when groundwater table low.

Figure A2.4 Depression wetlands



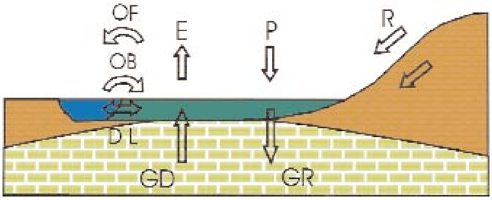
Valley bottom wetland

Surface water-fed: Wetland underlain by impermeable strata. Input dominated by over-bank flow and lateral flow, supplemented by precipitation and surface runoff. Output by drainage, surface outflow and evaporation. Inflows and outflows are controlled largely by water level in the river or lake. Example: alluvial floodplains



Valley bottom wetland

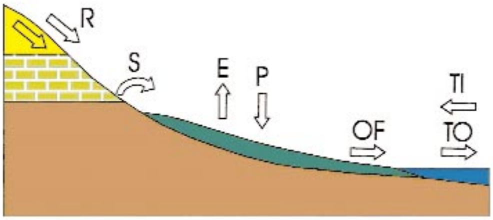
Surface and groundwater-fed: Wetland separated from underlying aquifer by lower permeability layer. Input from over-bank flow and groundwater discharge, supplemented by runoff and precipitation. Groundwater flow may be restricted by intervening low permeability layer. Output by drainage, surface outflow, evaporation and groundwater recharge. Example: floodplains on sandy substrate



Valley bottom wetland

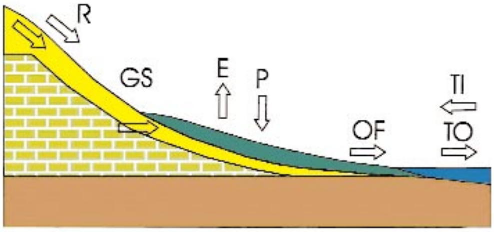
Groundwater-fed: Wetland in direct contact with underlying aquifer. Input dominated by over-bank flow and groundwater discharge, when groundwater table is high, supplemented by runoff and precipitation. Output by groundwater recharge when water table is low, drainage, surface outflow and evaporation. Example: floodplains in karst systems

Figure A2.5 Valley bottom wetlands



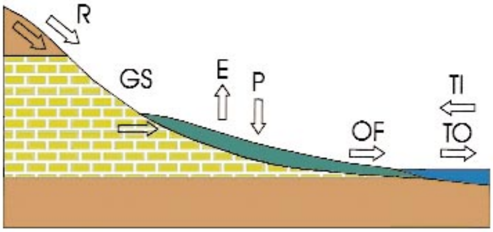
Coastal wetlands

Surface water-fed: Wetland underlain by impermeable strata. Input dominated by tidal flow, precipitation, surface runoff and possible spring flow. Output by evaporation and surface outflow



Coastal wetlands

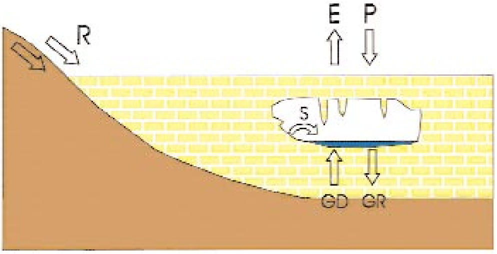
Surface and groundwater-fed: Wetland separated from underlying aquifer by lower permeability layer. Input from tidal flow, groundwater seepage, precipitation and surface runoff. Groundwater input may be restricted by lower permeability layer. Output by evaporation and surface outflow. Example:



Coastal wetlands

Groundwater-fed: Wetland in direct contact with underlying aquifer. Input dominated by groundwater seepage and tidal flow, supplemented by precipitation and surface runoff. Output by evaporation and surface outflow. Example:

Figure A2.6 Coastal wetlands



Underground wetlands

Groundwater-fed: Wetlands formed with solution caves in permeable rocks. Input dominated by spring flow and groundwater discharge. Output by groundwater recharge. Example:

Figure A2.7 Underground wetlands

ANNEX 3 WATER BALANCE EXAMPLE

Water balance example

At Sheringham and Beeston Regis Commons, UK, the main hydrological inputs to the wetland were considered to be rainfall (P), inflow from a stream that runs through the site (R) and discharge from the sand and gravel aquifer ($GD_{s\&g}$). It is also possible that small quantities of water enter the wetland from the Chalk aquifer (GD_{Chalk}), though the initial understanding to be tested was that this was negligible. The main outputs are evaporation (E) and outflow to the brook (OF). Change in storage of water within the wetland was also thought to be negligible. The water balance used takes the form:

$$\underset{\text{inputs}}{(\text{net rain }(P\text{-}E) + \text{stream inflow }(R) + GD_{s\&g} + GD_{Chalk})} = \underset{\text{outputs}}{(\text{stream outflow }(OF))} \qquad [A3.1]$$

Under current conditions (with groundwater abstraction from the Chalk aquifer), the annual mean water balance is (Ml/d):

$$\underset{\text{inputs}}{(0.112 + 0.110 + 0.423 + 0.0)} = \underset{\text{outputs}}{(0.6)} \qquad [A3.2]$$

This leaves a residual of 0.045 Ml/d (Table A3.1), which is very small compared to the volume of the inputs and outputs. The residual may be due to errors in estimation of each component or to an increase in storage of water within the wetland, but there are no data available to test this. The water balance confirmed the assumption that groundwater discharge from the Chalk aquifer was negligible under current conditions.

Water balances were also calculated for the long term average natural conditions and for droughts (Figure A3.1). Groundwater discharge from the Chalk is 1% of total inputs under natural conditions, but 4% in droughts. Effective rainfall (P-E) provides 25% of total input in drought conditions compared to only 17% in average natural conditions. Hence in dry years, Chalk groundwater and effective rainfall are more important in the water balance, which changes depending on climatic conditions. This enhanced understanding of the relationship between the wetland and associated groundwater can be used to design a water abstraction regime that is better suited to the wetland's water needs under different climatic conditions.

Table A3.1 Water balance for Sheringham and Beeston Regis Commons

	Mechanism	Long term	current	Drought
Inputs	P-E	0.112	0.112	0.070
	R stream	0.110	0.110	0.030
	GD drift	0.450	0.423	0.170
	GD Chalk	0.003	0	0.010
	total inputs	0.675	0.645	0.280
Outputs	OF stream	-0.600	-0.600	-0.400
Residual		0.075	0.045	-0.120

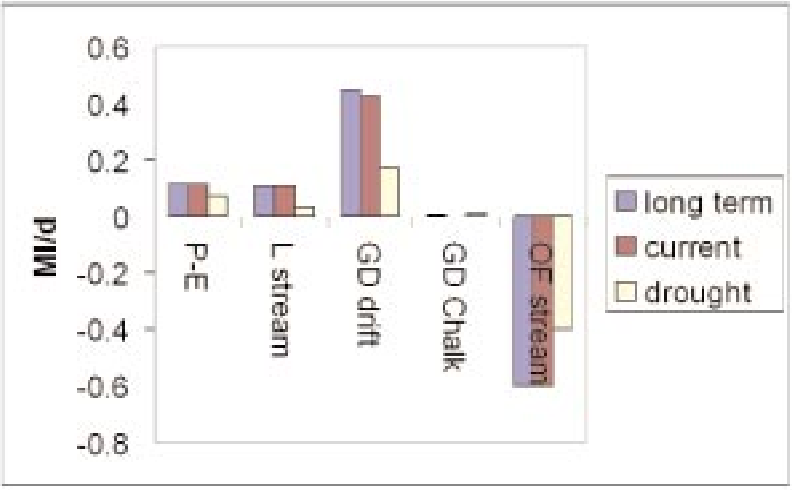


Figure A3.1 Graphical representation of water balances for Sheringham and Beeston Regis Commons

In Table A3.2, fictitious estimates of the uncertainty have been added to the data from Sheringham and Beeston Regis Commons, UK, for each water transfer mechanism to illustrate how these may alter the water balance. Upper and lower estimates were derived by adding and subtracting the uncertainty. The results are shown graphically in Figure A3.2. This provides three possible water balance scenarios for the wetland. The overall uncertainty is within the error of individual estimates and so is considered satisfactory.

It is essential to recognise that a water balance cannot be used to unequivocally prove the existence and precise magnitude of water transfer mechanisms. Instead, the water balance is used to discount errors in understanding and to identify gaps. If the inputs and outputs do not balance it is clear that understanding of the wetland hydrology is inadequate. If the inputs and outputs do balance, then current understanding is a possible explanation of how the wetland functions hydrologically. In most cases this can only be confirmed by site-specific investigation.

Table A3.2 Including uncertainty in water balance data

	Mechanism	long term	Uncertainty	upper estimate	lower estimate
Inputs	P-E	0.112	20%	0.134	0.090
	R stream	0.11	25%	0.138	0.083
	GD drift	0.45	50%	0.675	0.225
	GD Chalk	0.003	100%	0.006	0.000
	total inputs	0.675		0.953	0.397
Outputs	OF stream	-0.6	20%	-0.720	-0.480
Residual		0.075		0.233	-0.083

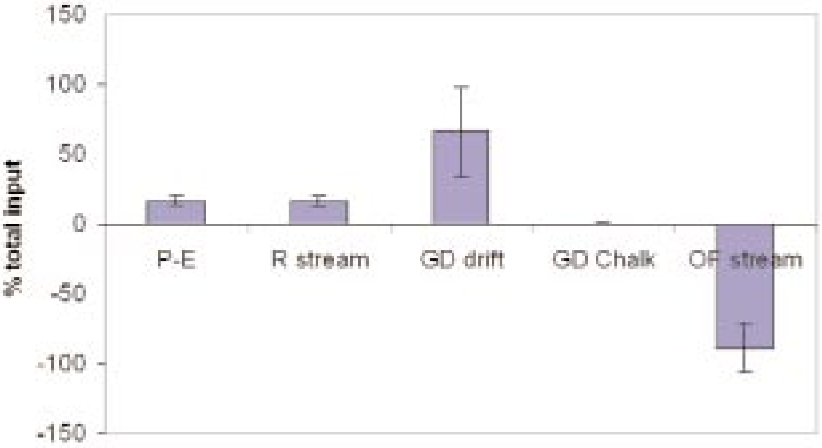


Figure A3.2 Hypothetical uncertainty estimates added to a water balance

Figures

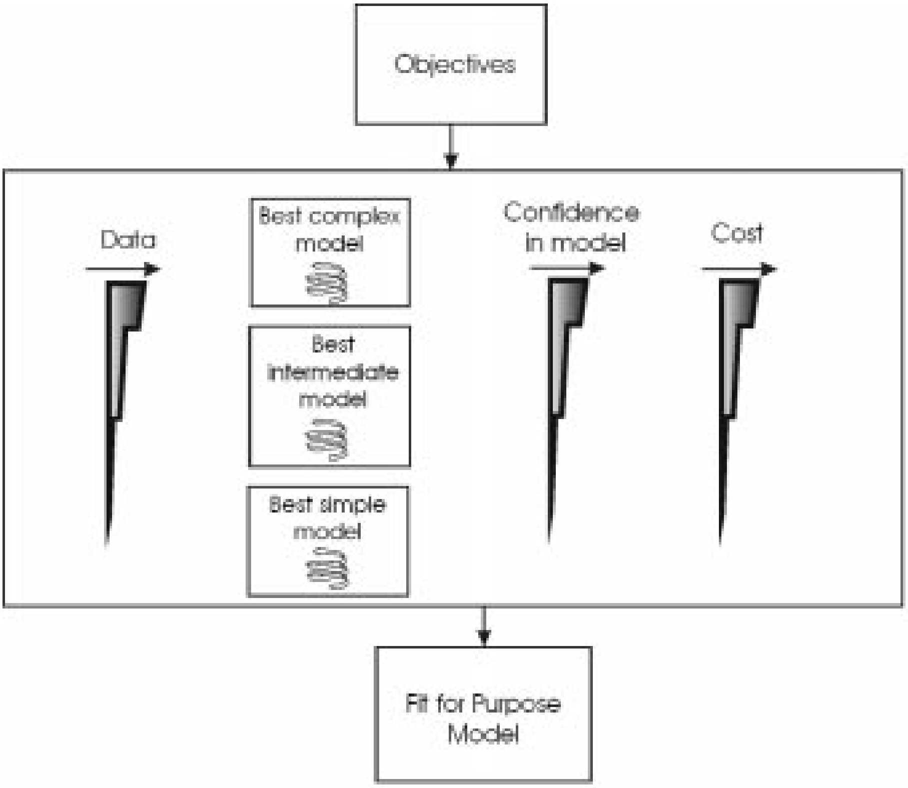


Figure 1 Risk-based approach to model development

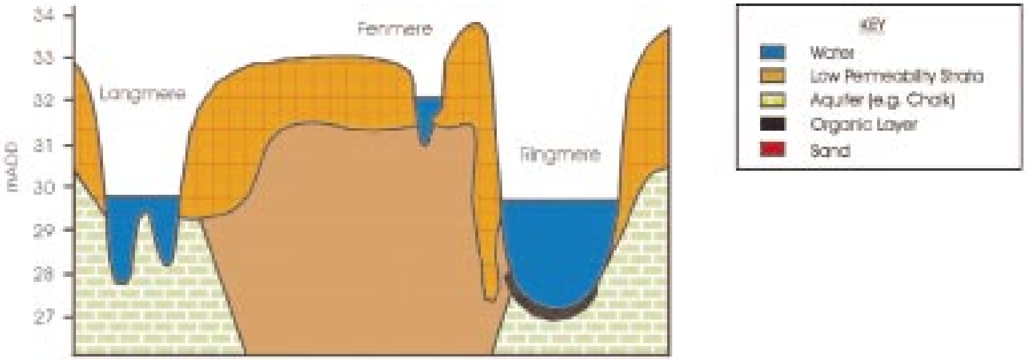


Figure 2 Geological cross-section through the Breckland Meres, UK

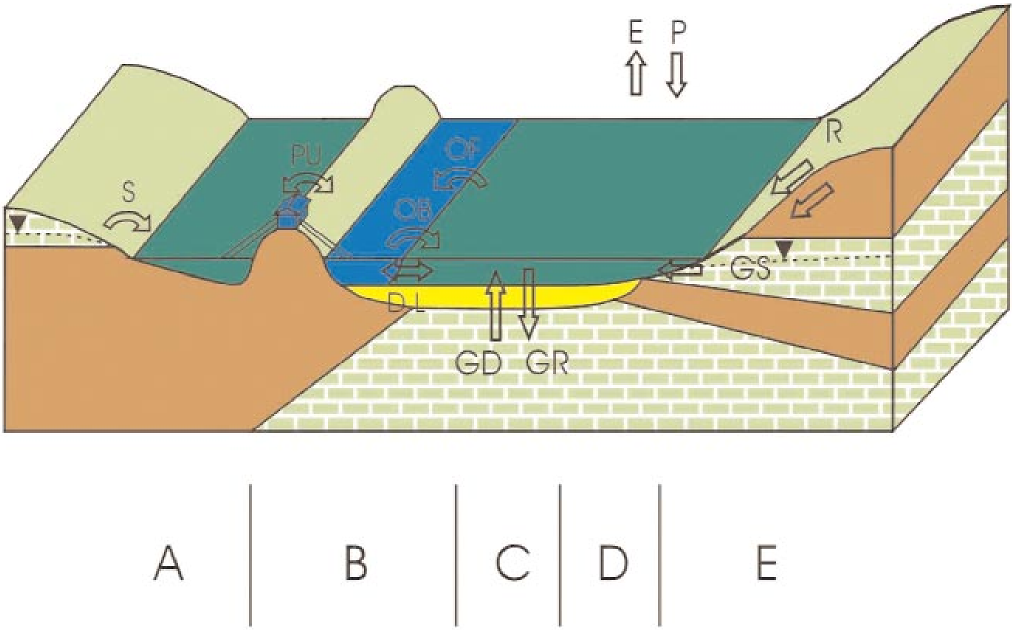


Figure 3 Block diagram of a hypothetical wetland showing water transfer mechanisms in different zones.

Water transfer mechanism inputs to the wetland

P: precipitation (rainfall, snow, dew etc) directly on the wetland +
R: surface and shallow subsurface inflow to the wetland +
L: lateral inflow +
OB: over-bank inflow +
PU_i: water pumped into the wetland +
S: spring flow +
GD: groundwater discharge into the wetland +
GS: groundwater seepage into the wetland +
TI tidal inflow from the sea to the wetland

=

Water transfer mechanism outputs from the wetland

E: evaporation from the wetland +
δV: change in volume of water stored within the wetland +
D: drainage +
OF: overland outflow +
PU_o: water pumped out of the wetlands +
GR: groundwater recharge to aquifers +
TO tidal outflow from the wetland to the sea

Where δV may be positive or negative

Figure 4 Balancing potential water transfer mechanism inputs to and outputs from a wetland

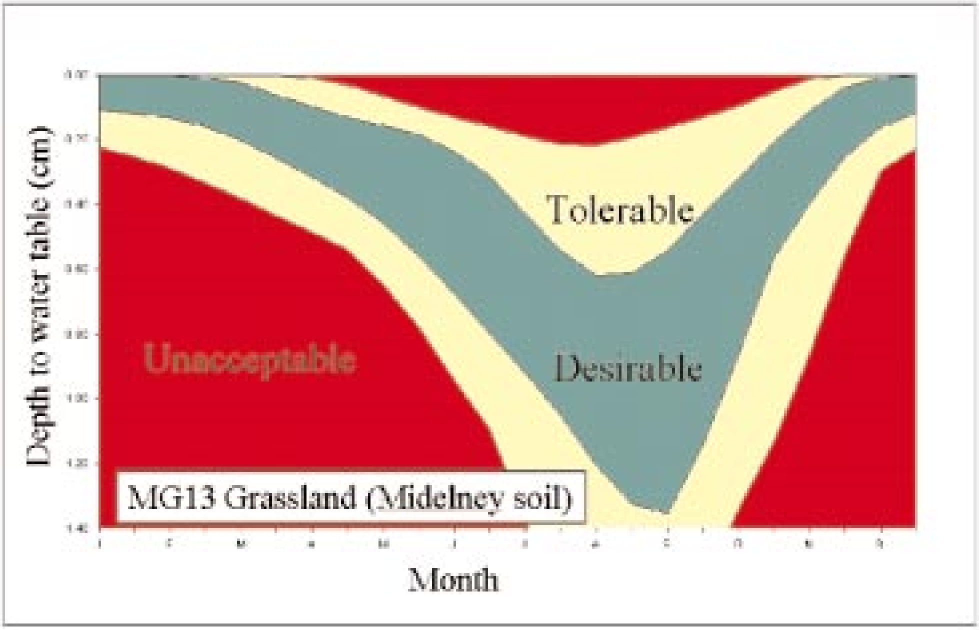


Figure 5 Water level requirements of MG13 wet grassland wetlands (after Wheeler et al, 2005).