Hydrological Assessment and Monitoring of Wetlands

AU1

Rob Low, Gareth Farr, Derek Clarke, and David Mould

Contents

R. Low (✉)
Rigare Ltd, Abergavenny, Cardiff, Wales, UK
e-mail: rob@rigare.co.uk

G. Farr
British Geological Survey, Tongwynlais, Cardiff, UK
e-mail: garethf@bgs.ac.uk

D. Clarke
University of Southampton, Southampton, UK
e-mail: D.Clarke@soton.ac.uk

D. Mould
Water Management Team, Canal & River Trust, Warwickshire, UK
e-mail: david.mould@canalrivertrust.org.uk

C.M. Finlayson et al. (eds.), *The Wetland Book*,
DOI 10.1007/978-94-007-6172-8_294-1

Introduction

AU2

The physical and chemical characteristics which favor wetland plant communities, primarily high soil water levels and anaerobic soil chemistry, are related directly to the hydrology/hydrogeology of the wetland and often its surrounding catchment. Appreciation and successful management of a wetland therefore almost always requires an understanding of its hydrological functioning, including the influences on hydrological functioning which often lie beyond the designated boundary of the site.

AU3

This section introduces **ecohydrological conceptual models** as a repository for knowledge about the combined ecological and hydrological functioning of a wetland and then provides a starting point (or initial framework) for the development of such a model. Also introduced are **hydro-environmental supporting conditions** (HSCs) that allow us to describe specific hydrological conditions required to support wetland plant communities. A suite of techniques for ecohydrological investigation and characterization of wetlands are described, the results from which can be used to develop and refine the ecohydrological conceptual model.

Ecohydrological Conceptual Models

An important requisite for appreciation and successful management of any system is a sufficiently detailed understanding of the relevant aspects of its form and function. For example, mechanics must use their basic knowledge of the form and function of a car engine in order to diagnose and remedy faults. The same is true in relation to appreciation and management of the hydrological environment, and specifically in this context wetland hydrology, where an understanding of the hydrological form and function of a wetland is called a **conceptual model**. And since the work is at the interface between ecology and hydrology, it is often called an **ecohydrological conceptual model**.

Some of the key characteristics of an ecohydrological conceptual model are:

- It only needs to include critical elements and mechanisms, in only as much detail as is necessary, of the ecohydrological functioning of the wetland; only a sufficient understanding of the complexity of a natural system is required.
- It must be recorded, for continuity of knowledge, through maps, diagrams, narrative description, and key data, such as water levels and vegetation surveys (Fig. 1).
- The ecohydrological conceptual model should be continually tested against new data and information and revised and refined as necessary.

AU4

As a starting point for an ecohydrological conceptual model, it is useful to identify the mechanisms of **water supply** to the wetland, **water retention** within the wetland, and **water loss** from the wetland. All wetlands will have at least one

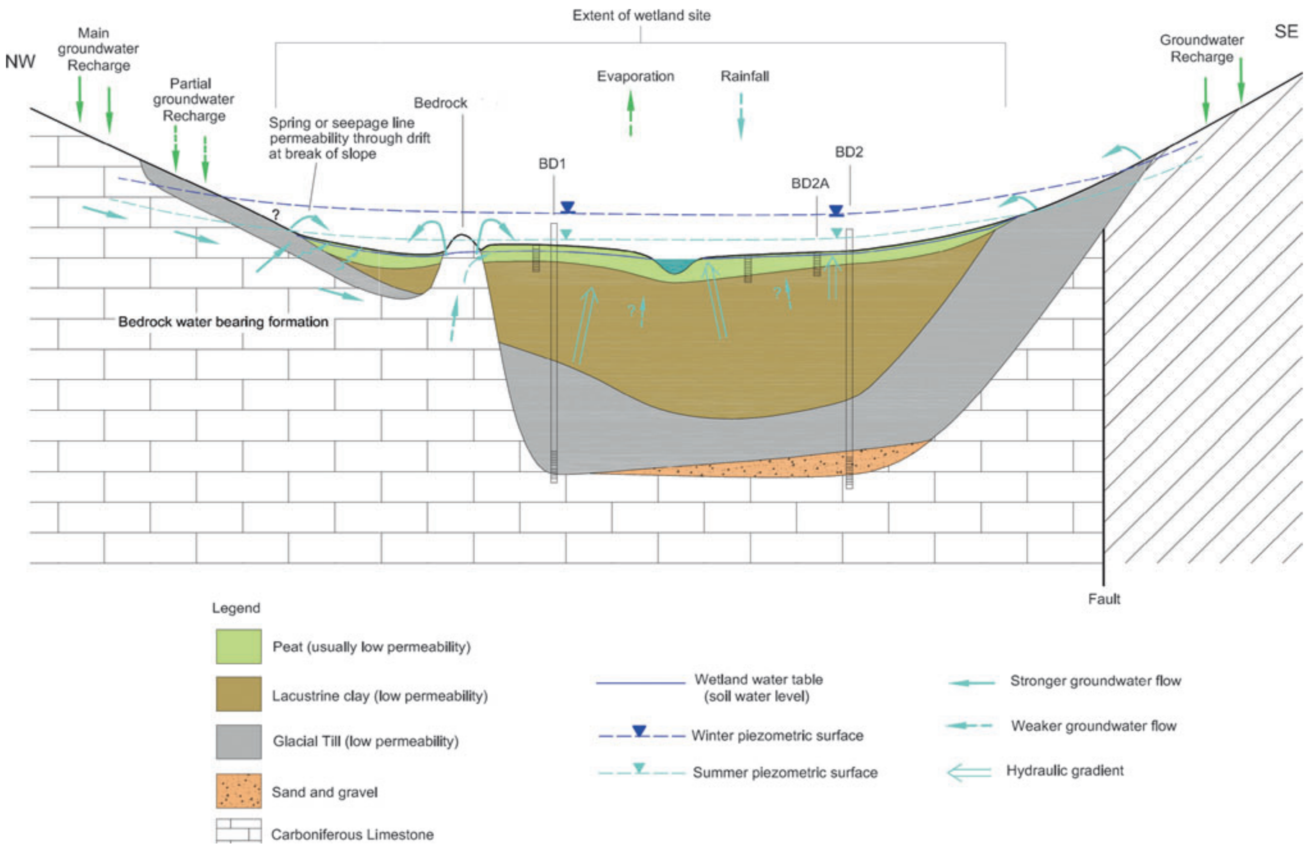

Fig. 1 Diagrammatic example of an ecohydrological conceptual model from Cors Bodeilio, part of the Anglesey and Llyn Fens NNR, Wales, UK (Schlumberger Water Services 2010)

mechanism under each of these headings, and this approach offers a useful initial framework for an ecohydrological conceptual model.

There are four primary mechanisms of **water supply** to a wetland:

1. Rainfall. Rainfall is the primary source of water for ombrotrophic systems, i.e., bogs, and is characterized by low pH and a low dissolved mineral content. Atmospheric deposition is the key pathway allowing nutrients such as nitrogen to enter ombrotrophic systems. Temporal variation of rainfall (short term, seasonal, longer term) can be an important overall determinant of wetland water levels.
2. Surface water. Water from streams and rivers, including seasonal surface water flooding, is an important supply for many floodplain wetlands. Flow characteristics and natural water quality are variable depending partly on the environmental factors within the catchment (e.g., topography, geology) and also the anthropogenic pressures (e.g., land use, drainage, and water abstraction). Suspended sediment load and deposition can be an important aspect of surface water supply.
3. Groundwater. Permeable aquifers can be important as a supply to wetlands, but ecohydrologically significant quantities of groundwater can emerge from most rocks or superficial deposits. The character of a groundwater discharge – rate, variability of flow, and water chemistry – is primarily determined by the nature of the rocks and sediments through which the groundwater flows.
4. Surface runoff. Direct surface-borne flow occurring when rainfall exceeds the surface infiltration capacity within the immediate surface water catchment of the wetland. The spatial distribution of surface runoff is dependent on microtopographic routing on surrounding slopes and can be redirected by boundary drainage systems. In agricultural catchments surface runoff from adjacent fields can often be the source of nutrient-enriched water.

Water retention within wetlands is caused primarily by the combination of low topographic (and hydraulic) gradients; the presence of poorly permeable deposits such as silt, clay, and peat; and the presence of water-retaining vegetation (e.g., *Sphagnum* mosses). Wetlands on steeper slopes also depend on a continuous supply of water to maintain wetness (soligenous systems). The mechanisms of water retention often only become apparent when they are compromised, for example, by the presence and effects of ditches that bypass the water retention mechanisms and accelerate water flow through a site.

There are three primary mechanisms of **water loss** from a wetland:

1. Evapotranspiration. The combination of direct evaporation from open water and soil surfaces and transpiration from plants. Evapotranspiration is often the predominant cause of lowered wetland soil water levels in the UK during warmer months.
2. Surface water. Discharge to streams and rivers flowing from or through wetlands.

3. Groundwater. In a natural condition, water loss to groundwater is relatively rare because of the landscape position and poorly permeable basal deposits associated with many wetlands.

Hydro-environmental Supporting Conditions

It is useful here to introduce the concept of hydro-environmental supporting conditions (HSCs). The term "hydro-environmental," rather than just "hydrological," is used to acknowledge the vital interaction of water with other environmental factors, such as geology, wetland substrate, and micro-topography, in producing favorable conditions. HSCs are the specific hydrological conditions, defined in terms of, for example, water levels, flow, or water chemistry, which are required to support a wetland plant community. At a basic level, HSCs are obvious – near-surface water levels are a requisite for peat-forming wetlands, and a base-rich groundwater supply is required for alkaline and calcareous fens. At a more detailed level, information on HSCs for many wetland plant communities can be obtained for, for example, lowland wetland communities (Environment Agency 2010), wet grassland communities (Gowing et al. 2002; see Box 1), and wet woodland communities (Barsoum et al. 2005). Since the recognition and application of HSCs is a relatively new and complex subject, the information in these sources is often incomplete and/or uncertain, and judgment based on experience is often required to determine and use HSCs.

Box 1 Hydro-environmental Supporting Conditions for Wet Grassland Communities (Gowing et al. 2002)

A very good example of the determination of HSCs for wetland plant communities is provided by the work of Professor David Gowing and others on wet grassland communities – it is based on extensive botanical and hydrological data collection at 18 sites throughout England. Two metrics were chosen to describe a wet grassland water level regime – sum exceedance value (SEV) for soil drying and SEV for soil waterlogging. The method relies on threshold water levels being specified, one defining the level at which the zone of densest rooting begins to become waterlogged and the other defining the level at which drying of the surface soil becomes detectable by plants. For each threshold, the SEV is the depth-time integration when the water table is above or below the threshold value, with waterlogging only being integrated between March and September, during the period of active grass growth – the concept is illustrated in the graph Fig. 6.

When data for the two SEVs (5-year means) were plotted against each other (Fig. 7), it was found that the water level regimes for wet grassland communities were distinct, suggesting that the water level regime is an important, perhaps the most important, determinant of plant community composition. The water level regime information is therefore very useful for management of wet grassland sites.

An important criterion for recognition of successful hydrological management of a wetland is therefore the presence of favorable spatial and temporal distributions of HSCs for the target wetland plant communities. It follows that an ecohydrological conceptual model should include an understanding of the processes which combine to produce these HSCs at critical times and places within the site; these processes are likely to act at a variety of scales, both within and outside the wetland. An appropriately detailed understanding of these processes should aid identification of causes of hydrological problems within a wetland that could result in unfavorable wetland condition.

Understanding the hydrological functioning of most wetlands is easier when equipped with a basic understanding of groundwater flow theory, including principles such as hydraulic head, hydraulic gradient, hydraulic conductivity, and Darcy's law, as described in any basic hydrogeology textbook (e.g., Price 1996; Hiscock 2006). It is also very useful to have an understanding of the wider-scale environmental water cycle because hydrological conditions within a wetland are often significantly influenced by processes operating beyond the site boundary.

Developing and Refining the Ecohydrological Conceptual Model

Desk Study

Many investigations will start with the collation and review of existing information, often in the form of a short written report. This is called a "desk study" and is an important first step toward gathering the information needed to develop a wetland ecohydrological conceptual model. The desk study should be undertaken in advance of any new information being collected or before fieldwork or a walkover survey is undertaken. Table 1 lays out a step-by-step list of sources of information to be included within the desk study phase. This information will be vital to support the ecohydrological conceptual model and to help identify potential HSCs.

Walkover Survey

There is a limit to the conceptual understanding that any desk-based assessment can provide, and following the desk study, it is almost always important that a site visit or "site walkover survey" is undertaken. As the realm of ecohydrological investigations and the identification of HSCs are still relatively modern, it is advisable to involve both an ecologist and a hydro(geo)logist in the walkover survey; this cross-disciplinary approach is a theme that runs throughout the entire ecohydrological conceptual modeling process.

The walkover survey facilitates collaboration between the ecologist and the hydro (geo)logist, and basic data such as observations on the presence, levels, and flows of water in relation to key wetland vegetation communities can be recorded. The survey provides a platform for the discussion of ideas, thoughts, and theories that can

Table 1 Desk study sources of data and potential uses to inform a hydroecological conceptual model

Source of data	Example of data and use
Site managers and local experts	The range and depth of information that can be gained from site managers and local experts can be an important starting point for the desk study
Published literature	Peer-reviewed literature
Gray literature	Site descriptions and reports and notes on the ecology, hydrology, management, and historic and current pressures
Vegetation survey	Vegetation maps (e.g., those produced using the National Vegetation Classification or NVC in Britain) will provide a baseline from which to monitor change. For example, certain communities that are more groundwater dependent maybe used to indicate areas where groundwater is an important HSC
Geological maps	Bedrock and superficial geology can be used to characterize the wetland, and if detailed enough, a geological cross section may be produced
Borehole archives	Stratigraphical data that can be used to create geological cross sections of the wetland (as above) and to understand the depositional history of the wetland
Soil maps	Soil map and properties
Water chemistry	Nutrient levels, e.g., nitrate and phosphate, ions, and physical parameters such as pH, dissolved oxygen, and electrical conductivity are all part of characterizing HSC at any wetland
Rainfall	Rainfall data from an on-site or local monitoring point may also include other climatic variables such as wind speed, moisture, and sunshine
Groundwater level and chemistry data	Existing boreholes installed with hydrometric monitoring could provide information on the local or wider supporting aquifer/s
Groundwater models or maps	Groundwater flow direction and catchment-scale conceptual model
Aerial photographs	Historical and current hard copy or digital photographs ideal for seeing land use and vegetation changes
Air pollution information	Modeled or measured deposition of atmospheric nutrient loading

support the understanding of HSCs, can underpin detailed site investigation, and ultimately can enable further development of the ecohydrological conceptual model.

Before engagement with the site at a detailed level, the position of the wetland within the wider landscape should be considered. What generic type of wetland is under consideration (bog? fen?), what are the related wetland plant communities, and what are the likely HSCs? Is the site likely to be supported by rainfall, groundwater, surface water, or a combination thereon? What are the main water retention and loss mechanisms? Does the immediate catchment or landscape setting suggest potential anthropogenic pressures such as agriculture, urban development, or industry?

During the walkover survey, the hydro(geo)logist might consider questions such as: What are the main water supplies to the site? How is water retained within the site, and how can water be lost from the site? Looking for evidence of groundwater inflow to the site (springs, seepages, etc.), estimates of flow can be made, and basic field parameters (pH, electrical conductivity, and dissolved oxygen) can be collected. Hand augers can provide an affordable, quick, and easy way to characterize the near subsurface in both geological and hydrogeological terms, informing potential locations for dipwells to monitor groundwater levels and chemistry.

An ecologist will often be able to provide surrogate hydrological evidence whereby the presence and condition of certain plant communities or species can be used to infer the existence of certain hydrological mechanisms, regimes, and conditions (HSCs). For example, the presence of ombrotrophic vegetation in central areas of a fen will suggest that rainfall is the predominant source of water in those areas, which in turn has implications for the interpretation of water flow through the site.

Site Investigation and Monitoring

Information requirements from site investigations will vary between wetland sites and will be influenced by the results of the cross-disciplinary desk study and the walkover survey. Figure 2 represents a generic wetland with some common pressures on the right-hand side (e.g., groundwater abstraction, nutrient enrichment, and drainage) with the left-hand side illustrating a selection of the more common wetland monitoring techniques.

Wetland Substrate

It is important to survey the wetland substrate and to compare it with any published geological and soil maps; the distribution and nature of substrate types are important determinants of hydrological conditions within a wetland.

Peat probes are an inexpensive tool for determining the thickness of peat deposits. If you suspect there is a thickness of peat then a peat probe – basically a long thin rod – can be pushed through until a more resistive material, such as gravel or clay, is encountered. Peat probes can be used safely to prove peat deposits up to around 6 m in thickness and sometimes more. Repeat measurements across a site can quickly result in an understanding of the thickness and lateral continuity of a peat deposit and also the general shape of the underlying mineral surface, which in turn often allows the history of peat accumulation to be inferred.

Hand augers are another low-cost method to characterize near-surface superficial deposits. The operational depth of a hand auger depends upon the material and the strength of the user, but retrieval of material from greater than 2 m depth can often be challenging! The auger head will retrieve about 20 cm of material for each insertion, allowing the user to create a geological log of the near-surface deposits.

Drill rigs are a more expensive option; however, they can offer deeper investigation, retrieval of sediment/bedrock cores, and the option of installation of monitoring wells. The most common issue with drilling at wetland sites will be arranging safe access for the drill rig and avoiding causing damage to any interest features.

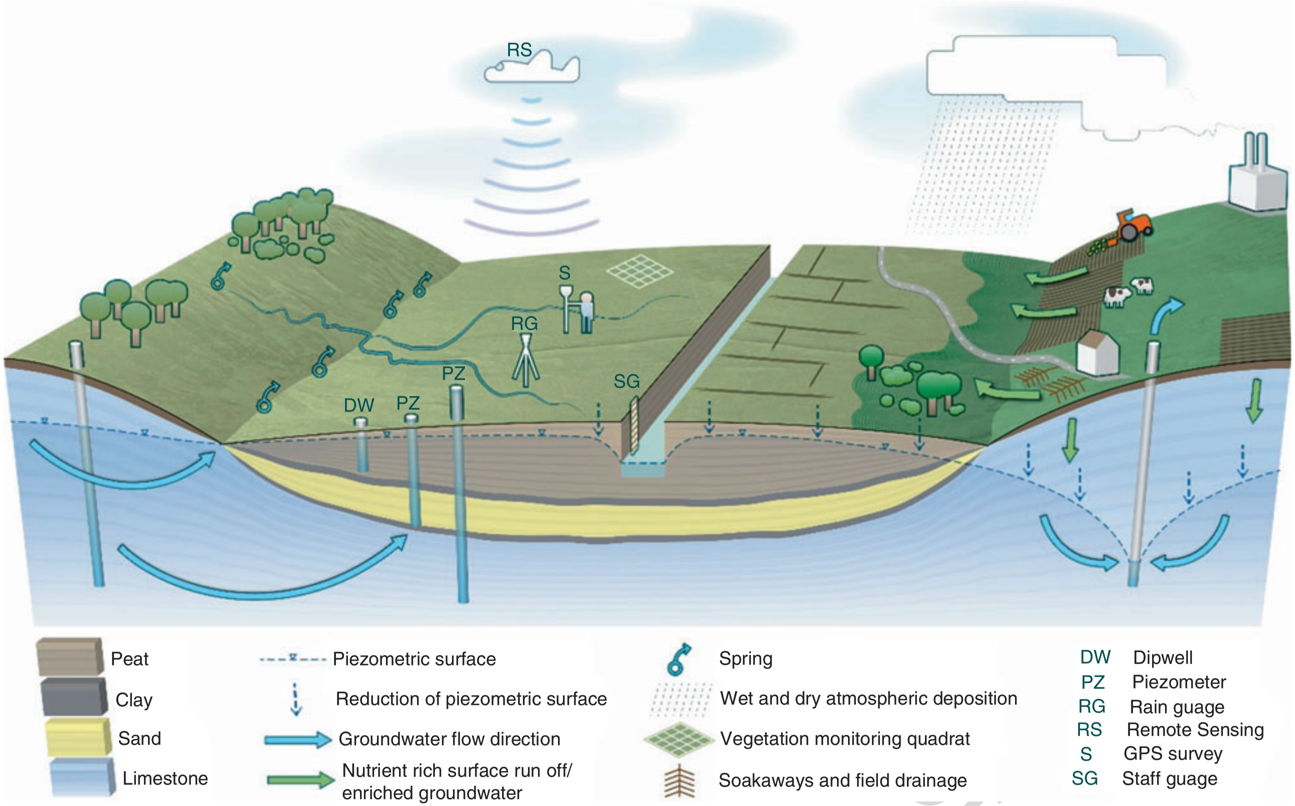

Fig. 2 Generic pressures (*right-hand side*) and common site investigation techniques for wetlands (*left-hand side*) (Image: BGS© NERC)

Geophysical methods such as ground-penetrating radar and electrical resistivity can be used as nonintrusive methods to characterize large areas of the wetland substrate. Geophysics can be expensive but can also help inform suitable areas for the installation of monitoring wells. Geophysical data can also be collected from airborne surveys, although the cost of this is significant and airborne surveys are often used to look at landscape-scale rather than site-scale detail. Beamish and Farr (2013) show that airborne geophysics can be useful to help characterize wetlands on a landscape scale, potentially helping to guide ground investigations. The attenuation of airborne radiometric data can identify areas of water saturation near the surface, while conductivity data appears capable of mapping the occurrence of clay concealed beneath peat.

Vegetation Classification Systems

In Britain, a common standard of vegetation classification, called the National Vegetation Classification (NVC), is used (see Rodwell 2006). The NVC was the product of a commissioned research project in 1975 funded by the Nature Conservancy Council (NCC), designed to be used by all the conservation bodies in Britain, allowing comparable datasets to be gathered and compared for similar plant communities. NVC data will not exist for all wetlands; it can be timely and costly to collect over entire wetland sites. Where however it does exist, it can offer useful information with respect to development of the ecohydrological conceptual model. The presence of many NVC communities can be used to infer the presence of specific HSCs, as noted above.

A large number of countries have a similar vegetation classification system which defines vegetation associations based variously on floristic, ecological, and physiognomic criteria, for example, the Canadian and US vegetation classification systems; mapping of wetlands according to these types of systems will provide similar useful information in relation to development of conceptual models.

Water Levels

Water level with respect to the ground surface is often a key parameter describing HSCs for wetlands and will form an important part of any ecohydrological site investigation and conceptual model. It is worth giving careful consideration as to when and where water level data will be collected. Firstly, information gathered from the desk study should be consulted and used in conjunction with on-site ground condition and vegetation data. Discussion between the hydrologist and ecologist should be undertaken to ensure the water level monitoring data informs both the HSCs and also the hydrology near or within key vegetation areas. Siting of water level monitoring points next to important areas of vegetation or where repeat vegetation surveys occur will only increase the value of both of these datasets. The period of water level monitoring is also an important consideration if, for example, hydrological extremes such as drought and flood are to be recorded or if changes in vegetation linked to changing HSCs are to be identified. Data from monitoring periods of less than 1 year are often limited in their usefulness, and long-term monitoring periods of several years or longer may be required to produce meaningful datasets.

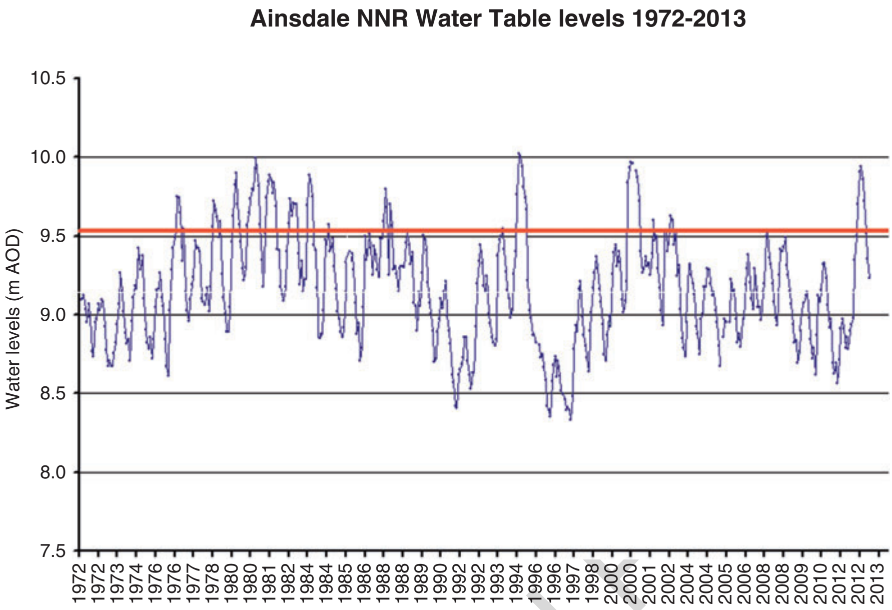

Fig. 3 Long-term groundwater level record from well 11 at Ainsdale Sand Dunes National Nature Reserve, Merseyside, UK

The data set shown below (Fig. 3) is the monthly water table variation over a 40 year period in an undisturbed coastal sand dune system in the UK. Over the whole period, there is no long-term upward trend (which might be due to sea level rise) or decline (which might be due to higher temperatures/climatic change). However there are significant inter-decadal changes. Take, for example, the period 1972–1982, which shows a definite and continuous increase in water table levels. Such a 10 year data set will produce a statistically significant positive upward trend. However the next 10 years (1983–1993) shows the direct opposite – a statistically significant downward trend. A similar sequence is also apparent after 2000, when increased awareness of climate change might make us state that this is definite proof of climate change, if we did not have the proceeding 30 years of data.

Short-term sudden changes in water level may be relatively easy to identify, and their cause may be readily found, such as increased well pumping or raised reservoir water levels. Changes in groundwater level over several months or years are more difficult to explain – is there a slow but gradual change in the rainfall pattern, is the land use (hence evapotranspiration) changing, or are there slow long-term mechanisms such as sea level rise in play?

In reality, a calibrated aquifer recharge model exists for the system presented in Fig. 3 (Clarke and Sanitwong 2010). The model shows that interannual variability of rainfall is the main driver of these changes and no definite climate change signal is apparent. The lesson learned here is that changes in the medium term (5–10 years) should not be used to prove or demonstrate the influence of a single driver of change.

Fig. 4 Dipwells can be manually installed (*left*), deeper dipwells and piezometers can be installed into more competent material using portable hand-powered drills (*middle*), and larger percussion drills are used to install deeper boreholes and piezometers into bedrock

Climate change is a slow and incremental process and is usually described within time steps of 30+ years, and during this period, natural variability may be an order or magnitude or more than any climate change influence.

When monitoring water levels at a wetland, it is most likely that you will also want to monitor surface water, such as a ditch, pond or pool, or soil or groundwater. Measurements can be made manually or electronically with an in situ water pressure data logger. Surface water levels can be monitored using similar techniques to groundwater levels.

Techniques for monitoring groundwater levels include (Fig. 4):

Dipwells are inexpensive plastic tubes, ranging in diameter from 12 to 50 mm, with holes or slots to allow water ingress. They can be installed manually using a hand auger, usually to between 1 and 3 m depth. Dipwells can come with a variety of "geotextile" membrane covers which can be selected based upon the sediment into which they are being installed. Finer geotextile membrane covers are used where there are fine-grained sediments such as silts or fine sands to limit the ingress of this material into the dipwell as much as possible. When dipwells are installed in peat, they are sometimes attached to a tube driven into competent underlying material such as a basal clay or bedrock, to allow the vertical position of the dipwell to be maintained. Water levels and soil water levels can be measured in dipwells by using an electronic water level dip tape or by installation of an electronic water pressure data logger.

Boreholes are drilled using a large drill rig, of which there are various types; the scale of effort, cost, and the installations themselves are much larger than for dipwells. In the context of wetland investigations, boreholes are normally drilled to a maximum of 10 m, and depending on the drilling technique, the materials underlying the wetland can be examined and recorded with reasonable precision. A borehole can be completed either with slotted tube throughout its depth, allowing water ingress at all levels, or with slotted tube at a specific depth (usually the base), allowing water ingress and pressure measurement at that depth. The latter are called piezometers because they measure subsurface water pressure (piezometric pressure). Combinations of dipwells and piezometers can be used to help to characterize vertical hydraulic gradients, which indicate the potential for vertical flows of water, e.g., upwelling into wetland sites.

Survey and construction data should be recorded for each monitoring well. All dipwells, piezometers and boreholes should be surveyed to a common datum to allow the comparison of data from one well to another. This datum can be an arbitrary fixed point within or close to the site (a local benchmark) or if possible ordnance datum (OD) or sea level. It is vital that a borehole log is made for each well and should include the type and thickness of strata encountered, if possible recorded in line with an international standard or description. Borehole logs should also include survey elevation data, notes on the decisions made to install them in any given location, and notes on the vegetation or habitat they are associated with.

Instrumentation and Frequency of Data Recording

Regular manual water level recording is recommended at all wells to correct any data collected from in situ electronic pressure transducers. There are many proprietary pressure transducer systems on the market, and one should be selected based upon the water column (pressure) range, accuracy, and resolution that is required. For simplicity, it is recommended that all loggers should be set to record coincidentally and that they are set to run on standard time (e.g., GMT in the UK). The frequency of data measurement and recording should be decided according to the purpose of monitoring; a higher frequency (e.g., 15 or 30 min interval) yields data which will provide information about the short-term dynamic functioning of the system, whereas a lower frequency can be used for background monitoring.

Figures 5, 6, and 7 show an example of the increasing information obtained from higher-frequency sampling. This shows the shallow groundwater response to rainfall at a wetland site with constant groundwater recharge and a diurnal water table fluctuation driven by evapotranspiration. Note that the monthly and weekly sample rates do not pick up the rainfall events and that sub-daily (in this case hourly) sampling is needed to detect the diurnal pattern. Monitoring at a suitably high temporal resolution can allow estimation of evaporative loss (e.g., Gilman 1994; Mould et al. 2010) during periods of zero rainfall, when lateral flow is constant and evaporative loss is enough to drive a diurnal oscillation in water levels (assuming constant lateral or upward shallow groundwater flow). However producing unnecessarily large datasets can be problematic when information storage and analysis are considered. So a monitoring program should consider the cost versus benefit of monitoring frequency. AU5

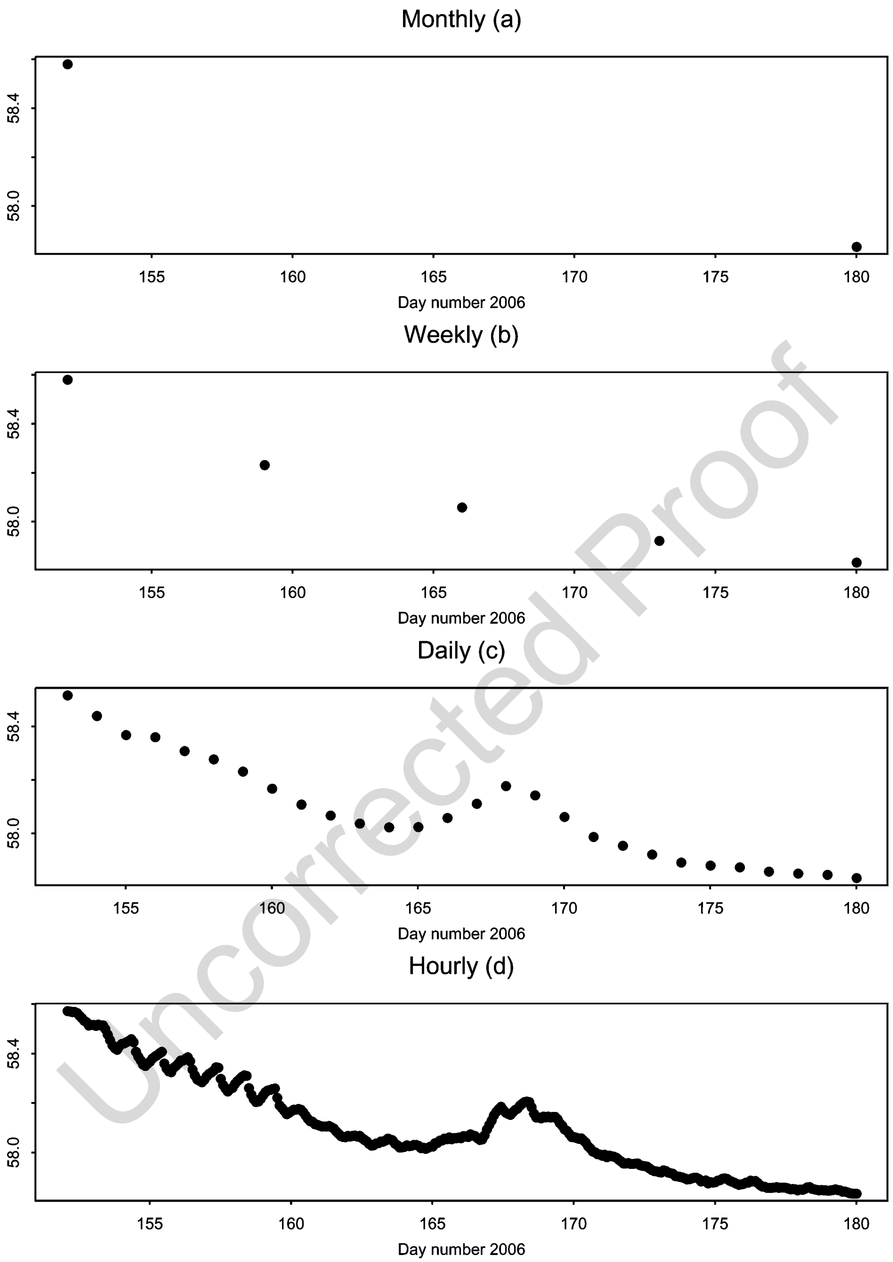

Fig. 5 Water level monitoring data from Otmoor, UK. The same data set is shown at four distinct sampling frequencies, with detail increasing as frequency increases

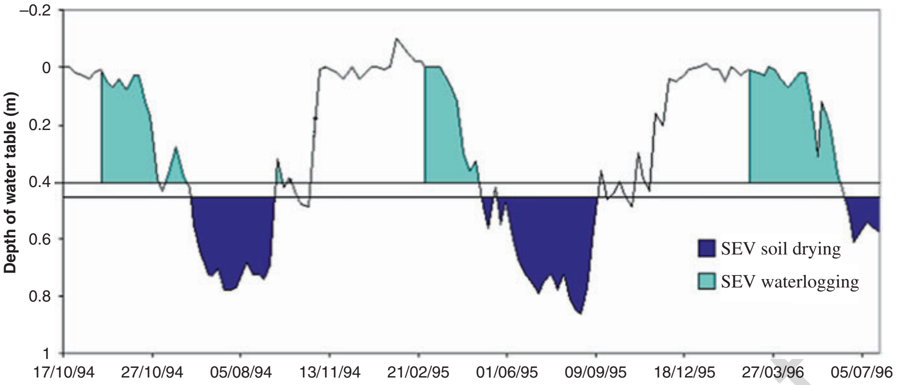

Fig. 6 Time series water levels relative to the ground surface. The *shaded areas* demonstrate how the SEV areas for soil drying and wetting are defined

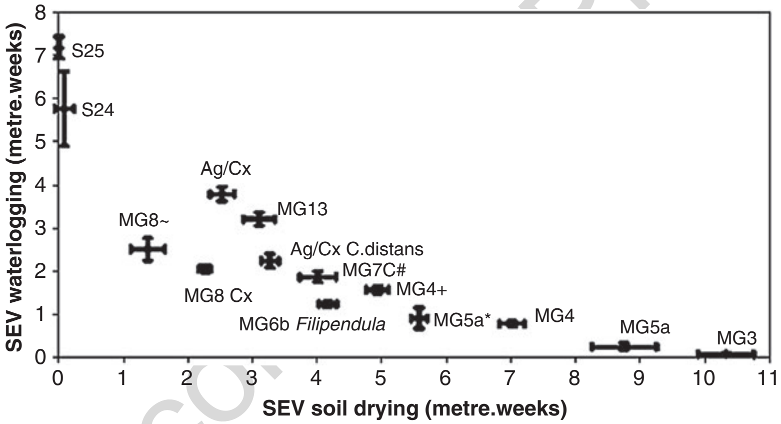

Fig. 7 SEV soil drying versus SEV soil waterlogging. The labeled points within the graph space represent separate wet grassland NVC communities

Water Chemistry

Water chemistry or quality is often, in conjunction with water levels, a key HSC for many wetland plant communities, e.g., alkaline and calcareous fens both depend on specific groundwater chemistries. An understanding of baseline chemistry and variation in chemistry through time are key to identifying risks (such as nutrient enrichment) and to underpin successful management of wetlands and wider catchments. For all sampling, a repeatable and defensible **methodology** should be implemented following best practice procedures. A **comparative analysis suite** should be used for all wetland investigations with agreed lower limits of detection for nutrients and sufficient ions to characterize groundwater facies or types. Table 2 shows the minimum analysis suite that has been agreed by the Water Framework Directive UK Technical Advisory Group (WFDUKTAG) for wetlands, the aim of which is to make results, especially for nutrients, directly comparable within the UK (WFDUKTAG 2004).

Where possible each sample point must be put "**in context**" which means it should be associated with a specific vegetation type or habitat, and a reason for its inclusion should be recorded. This information may already exist on the borehole log as described in the previous section.

In any wetland investigation, water chemistry samples may be obtained from surface water (e.g., ditches, ponds, runnels) and groundwater (e.g., seepages, springs, dipwells), each of which can pose their own difficulties. Low or diffuse flows in many wetland areas can be problematic but not prohibitive to sample. Simple tools such as a stainless steel jug (and some patience) will often allow samples to be collected from even the smallest of runnels or seepages. Portable low voltage submersible pumps can abstract water from dipwells, and syringes can be used to sample water from small ponded areas or seepages. Field readings for pH,

Table 2 Wetland water chemistry analysis suite (WFDUKTAG 2004)

Determinant	Units	Suggested minimum limit of detection
Alkalinity pH 4.5 – $CaCO_3$	mg/l	5 mg/l
Ammonia – N	mg/l	0.03 mg/l
Bicarbonate – HCO_3	mg/l	n/a
Calcium – Ca	mg/l	1 mg/l
Chloride ion – Cl	mg/l	1 mg/l
Conductivity at 25 °C	uS/cm	n/a
Hardness total – $CaCO_3$	mg/l	n/a
Iron – Fe	ug/l	30 μg/l
Magnesium – Mg	mg/l	0.3 mg/l
Manganese – Mn	ug/l	10 μg/l
Nitrate – N	mg/l	n/a
Nitrite – N	mg/l	0.004 mg/l
Nitrogen total oxidized – N	mg/l	0.2 mg/l
Orthophosphate – P	mg/l	0.02 mg/l
Oxygen dissolved – field measurement	mg/l	n/a
Oxygen dissolved – field measurement	%	n/a
pH – field measurement	pH	n/a
Phosphate	mg/l	0.02 mg/l
Potassium – K	mg/l	0.1 mg/l
Sodium – Na	mg/l	2 mg/l
Sulfate – SO_4	mg/l	10 mg/l
Temperature – field measurement	CEL	n/a
Redox potential – field measurement	Mv	n/a
Iron dissolved	ug/l	n/a
Manganese dissolved	ug/l	n/a

temperature, dissolved oxygen, and electrical conductivity need to be recorded on site using appropriate methods. Wherever possible, measurements should be taken of flowing water, with time allowed for instrument stabilization.

Novel Techniques

Novel groundwater analysis can help to characterize the HSCs at wetlands and to improve the ecohydrological conceptual model. It is possible to understand the recharge age of groundwater using several dating techniques. One technique that is applicable to wetlands, where waters are often less than 50 years old, is the dating of **chlorofluorocarbon** (**CFC**) **and sulfur hexafluoride** (**SF_6**) aerosols. This analysis can also help to infer groundwater mixing and likely groundwater flow mechanisms (Gooddy et al. 2006).

When a wetland is faced with problems of enrichment by nitrogen, then it is possible to use **nitrogen and oxygen stable isotopes**, often in conjunction with other analysis, to determine the source of nitrogen dissolved in groundwater (Saccon et al. 2013). The method works by comparing the ratios of the respective isotopes, ^{15}N to that of air ($\delta\ ^{15}N$ ‰) and ^{18}O relative to Vienna Standard Mean Ocean Water ($\delta\ ^{18}O$ ‰). The analysis can help to "fingerprint" various sources of nitrogen, including soil organic matter, inorganic fertilizers, and atmospheric deposition.

Future Challenges

Ecohydrology is an expanding subject in the UK, and it is an example of a subject where a truly bi- or multidisciplinary approach can pay significant dividends and is in fact essential. There are few people who have the complementary skill sets and knowledge to work alone and effectively in this field, and positive collaborations are therefore required. Appropriate education and training to provide ecohydrologists is encouraged.

More widespread monitoring and collation of ecohydrological data for wetlands, according to the guidelines above and more detailed sources, will allow the hydrological functioning of wetlands to be understood more clearly at both site-specific and generic levels and will also give information for characterization of HSCs. In turn, this will allow better wetland hydrological management.

Cross-References

- ▶ Monitoring of Wetlands, High Temporal Resolution Hydrological Monitoring (Mould)
- ▶ Monitoring of Wetlands, Long-Term Groundwater Monitoring (Clarke)
- ▶ Monitoring of Wetlands, Overview (Stratford)
- ▶ Wetland Assessment, Overview (Stratford)

References

Barsoum N, Anderson R, Broadmeadow S, Bishop H, Nisbet T. Ecohydrological guidelines for wet woodland – phase 1. English nature research report No.619, 2005.

Beamish D, Farr G. Airborne geophysics: a novel approach to assist hydrogeological investigations at groundwater – dependent wetlands. Q J Eng Geol Hydrogeol. 2013;v46:53–62.

Clarke D, Sanitwong Na Ayuttaya S. Predicted effects of climate change, vegetation and tree cover on dune slack habitats at Ainsdale on the Sefton Coast, UK. J Coast Conserv. 2010;14(2):115–25.

Environment Agency. Ecohydrological guidelines for lowland wetland plant communities. Fens and mires update, Mar 2010.

Gilman K. Hydrology and wetland conservation. Chichester: Wiley; 1994.

Gooddy DC, Darling GW, Abesser C, Lapworth DJ. Using Chlorofluorocarbons (CFCs) and Sulphur Hexafluoride (SF_6) to characterise groundwater movement and residence time in a lowland chalk catchment. J Hydrol. 2006;330(1–2):44–52. http://nora.nerc.ac.uk/4481/.

Gowing, DJG, Lawson CS, Youngs EG, Barber KR, Rodwell JS, Prosser MV, Wallace HL, Mountford JO and Spoor G. The water regime requirements and the response to hydrological change of grassland plant communities. Institute of Water and Environment, Silsoe, Beds. (2002), Project BD1310. Available from www.floodplainmeadows.org.uk

Hiscock KM. Hydrogeology: principles and practice. Oxford: Blackwell; 2006.

Mould DJ, Frahm E, Salzmann T, Miegel K, Acreman MC. Estimating the use of diurnal groundwater fluctuations for estimating evapotranspiration in wetland environments: case studies in southeast England and northeast Germany. Ecohydrology. 2010;3:294–305.

Price M. Introducing groundwater. London: Chapman and Hall; 1996.

Rodwell JS. National vegetation classification: users handbook. (2006). JNCC. http://jncc.defra.gov.uk/pdf/pub06_NVCusershandbook2006.pdf

Saccon P, Leis A, Marca A, Kaiser J, Campisi L, Böttcher ME, Savarino J, Escher P, Eisenhauer A, Erbland J. Multi-isotope approach for the identification and characterisation of multiple nitrate pollution sources in the Marano Lagoon (Italy) and part of its catchment area. Appl Geochem. 2013;34:75–89. doi:10.1016/j.apgeochem.2013.02.007.

Schlumberger Water Services. River basin planning through targeted investigations on selected Welsh groundwater dependent terrestrial ecosystems (GWDTEs): Cors Bodeilo and Merthyr Mawr. (2010). 1–274/R3 for Environment Agency.

UKTAG. Guidance on the identification and risk assessment of groundwater dependent terrestrial ecosystems. (2004). Version 5 http://www.wfduk.org/sites/default/files/Media/Characterisation%20of%20the%20water%20environment/Risk%20assessment%20of%20terrestrial%20ecosystems%20groundwater_Draft_210104.pdf

Index Terms: