NEC04470 Boxford Pathfinder Project

Wetland Hydrological Monitoring

Overview

and

Boxford Water Meadows case study

Report by

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1. Aims and Objectives

The aim of this report is to provide the reader with the information required to make informed decisions about the best and most appropriate way to monitor a wetland site.

To achieve this aim, the report has the following objectives:

- To outline the need and purpose for monitoring.
- To summarise the methods used to identify and categorise wetland types.
- To describe the broad types of monitoring that may be undertaken.
- To give detailed information about the range of wetland monitoring techniques available.
- To provide guidance on how to select the most appropriate monitoring techniques.
- To illustrate, using the Boxford wetland as a case study, how the techniques described in this report can be applied, and what challenges and solutions are encountered.

2. Scope of this report

The RAMSAR convention (Ramsar, Iran, 1971), which is the globally recognised treaty for the conservation and sustainable use of wetlands, uses a broad definition of the types of wetlands covered in its mission, including lakes and rivers, swamps and marshes, wet grasslands and peatlands, oases, estuaries, deltas and tidal flats, near-shore marine areas, mangroves and coral reefs, and human-made sites such as fish ponds, rice paddies, reservoirs, and salt pans.

It is not possible, and arguably not relevant, to attempt to discuss all of these wetland types in this report and we therefore look only at freshwater wetlands, and in particular those of a natural or semi-natural character.

Similarly, it would not be possible to cover every single technique available for monitoring. We recognise that new techniques are being developed constantly and for that reason this report will benefit from periodic updates. We do however aim to cover the most relevant currently adopted techniques for the monitoring of wetlands.

3. The need and purpose for monitoring wetlands

It is estimated wetlands cover at least 6 % of the Earth's surface (Junk et al., 2012). They were once viewed as unproductive wastelands and sources of disease and their values, until recently, were poorly understood. Drainage, deforestation, river embankment and urbanisation were carried out in wetland areas in order to increase their value. During the 17th century major drainage schemes converted thousands of square kilometres of British wetlands into what is today some of the most productive farmland in the country (Cook and Williamson, 1999). Throughout the twentieth century, as demand for food increased and technology advanced, the rate of conversion from wetland to agricultural land increased. As a result, throughout the UK there is now a range of modified and degraded wetland landscapes (Acreman and José, 2000).

Wetlands are now widely recognised as biodiversity hotspots. A 1991 survey by the U.S. Fish and Wildlife Service listed 595 plant and animal species as threatened or endangered and 256 (43 %) of these are dependent upon wetland habitats. The survey also identified that wetlands provide 60 % of all threatened species and 40 % of all endangered species listed in 1991 with essential habitat (Niering, 1988). Increasingly there is awareness of the full range of benefits that wetlands provide and the concept of 'Ecosystem Services' (MEA, 2005) has been developed giving a framework for accounting for all of the benefits that humans get from an ecosystem. Benefits include everything from provision of freshwater, flood alleviation and carbon storage to providing places of natural beauty, growth of timber and crops and supporting biodiversity.

In order to understand how these benefits respond to change, we need to understand their key drivers and an obvious driver in the case of wetlands is hydrology. By studying the interactions between hydrology and ecosystem services we can begin to understand how hydrological changes (either natural or man-made) to a landscape can impact on the benefits to mankind. In recent years there has been a strong move towards trying to quantify and understand the full range of ecosystem services, in the hope of minimising their future degradation (Barbier *et al.*, 1997). The desire to find the right balance between exploitation of services and their conservation led to the concept of 'Wise use of wetlands', a more considerate and sustainable approach to living with wetland habitats (Maltby, 1992). For these reasons, in the UK and throughout Europe, considerable efforts are being made to protect, restore and in places recreate wetland habitats (Klötzli and Grootjans, 2001).

Collection of useful data is a key component in all steps in the sequence of identifying, carrying out, and evaluating conservation and/or restoration activities. In the initial stages it identifies and quantifies pressures and/or opportunities, and sets a baseline condition. During the activity it captures exactly what is done and the response to action. Post-activity it provides the information necessary to evaluate success or failure. In its entirety, monitoring provides the defensible information required to make robust decisions and to learn from our experience. A fit-for-purpose monitoring programme should increasingly be seen as a necessary, not optional, component of all restoration activities.

4. Inventory, Assessment and Monitoring.

A monitoring programme is normally triggered as a result of identification of an information need. Examples of those who may have an information need include policy makers, regulators, site managers and scientific researchers. The monitoring programme is likely to be set in context by and build upon information collected through processes of inventory and assessment. The Ramsar Convention defines wetland inventory, wetland assessment and wetland monitoring as follows (Ramsar Convention Secretariat, 2010):

- Wetland Inventory: the collection and/or collation of core information for wetland management, including the provision of an information base for specific assessment and monitoring activities.
- Wetland Assessment: the identification of the status of, and threats to, wetlands as a basis for the collection of more specific information through monitoring activities.
- Wetland Monitoring: the collection of specific information for management purposes in response to hypotheses derived from assessment activities, and the use of these monitoring results for implementing management. The collection of time-series information that is not hypothesis-driven from wetland assessment is here termed surveillance rather than monitoring.

Note that the term ‘research’ does not appear in the above text, however by simply exchanging the word ‘research’ for ‘management’ the definitions become more relevant to the scientific process.

5. Developing an initial conceptual understanding

Designing a monitoring network from scratch can be daunting. In order to progress from a ‘blank sheet’ to a first draft, a simple conceptual understanding of how the wetland behaves is extremely useful. This will identify the key processes that drive the hydrological conditions. A desk-based assessment, consulting existing data sets such as surface topography, nearby waterways, geological maps and meteorological data, is likely to be the quickest and easiest way to achieve this. A Geographic Information System (GIS) is an extremely useful and powerful tool in analysing the spatial relationships that exist between wetland habitats and their surrounding environment and can assist in providing key preliminary data on the type and abundance of wetland habitats, and potential drivers and pressures at both a regional and national scale.

The information provided by this initial assessment will be the basis for the conceptual understanding, and this in turn may be used to assign the wetland within one of the may wetland ‘typologies’ that exist (Table 1). Acreman *et al.,* (2010) have carried out an extensive review of wetland typologies and the information presented here is based largely on their original text. The reader is recommended to consult the original publication for more information.

All wetlands are unique to some extent. However, broad types reflecting common characteristics can aid assessment and prediction. Existing typologies have been developed for a range of purposes. One of the earliest UK classification schemes was developed by Goode (1972) for peatlands, or mires, *based primarily on topographical setting. Since then, numerous typologies have been devised and a sample of wetland classification schemes that were considered most appropriate to UK conditions, together with the objectives that led to their development, is presented in Table 1. For obvious reasons, botanists tend to use vegetation classifications such as the National Vegetation Classification (NVC; Rodwell, 1991-2000); whilst soil scientists may differentiate between organic soils, such as peat, and mineral soils, such as gleyed soils. Geochemists may classify wetlands according to pH (e.g. Ratcliffe, 1977) or nutrient status (e.g. Wheeler and Shaw, 1995a), whilst catchment planners may use hydrological functions as a means of classification (e.g. Bullock and Acreman, 2003).*

Table 1 Examples of wetland typologies (from Acreman *et al.,* (2010))

Authors	**Typology name**	**Objective**	**Wetland characteristics**	**Geographical scope**
Goode (1972)		Selecting wetland nature reserves	Landscape situation	Peatlands, UK
Novitsky (1978)		Functional analysis	Connectivity with channel and groundwater	Wisconsin, USA
Cowardin *et al* (1979)		Inventory	Associated water body, hydrological regime, substrate type and many others	USA
Lloyd *et al* (1993)		Wetland vulnerability assessment	Hydrological mechanism	East Anglia
Wheeler and Shaw (1995b)		Resource evaluation	Landscape situation	England and Wales
Acreman (2005)		Hydrological impact assessment	Landscape location and water supply mechanism	England and Wales
Wheeler *et al* (2009)	WETMECS	To link hydrology and vegetation	Landscape situation, water supply mechanism, pH, soil fertility	England and Wales
SNIFFER (2009)			Biological and hydrological types	Scotland

6. The Wetland Water Balance

When the conceptual understanding is sufficiently well-developed, a conceptual hydrological model can be drawn identifying the most significant hydrological components (Figure 1). This will in turn direct those components that require monitoring. Remember that at any stage the conceptual understanding and model can be revised and neither should be seen as definitive.

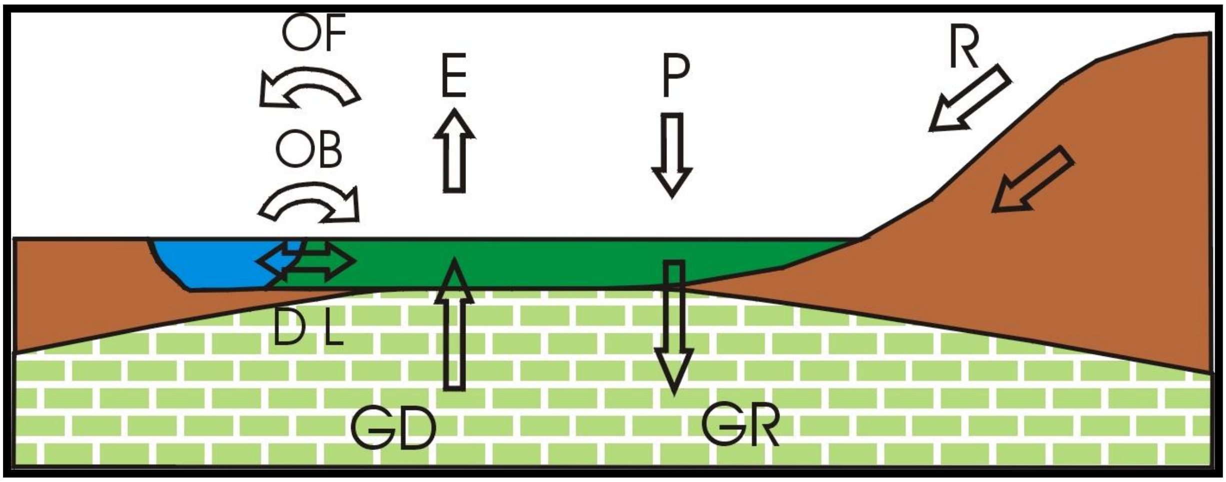

Figure 1 Conceptual hydrology of a combined groundwater and surface water fed wetland system.

The components of the water balance in Figure 1 are describe below:

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
GD:	groundwater discharge into the wetland

Water transfer mechanism outputs from the wetland	
E:	evaporation from the wetland
D:	drainage
OF:	overland outflow
GR:	groundwater recharge to aquifers

In addition to these components, the wetland itself stores water. Storage is possible in both saturated and unsaturated conditions and measurement of the water stored is crucial in understanding the water balance. Water storage is normally denoted by the letter S and change in water storage by ΔS.

The wetland water balance for the example given above is:

$$(P + R + L + OB + GD)_{\text{inputs}} = (E + D + OF + GR)_{\text{outputs}} + \Delta S$$

In words, this means that for a given time period, the sum of hydrological inputs to the wetland is equal to the sum of hydrological outputs from the wetland plus the change in amount of water stored in the wetland.

7. Monitoring techniques for the wetland water balance

The aim of this section is to present and discuss the currently recommended methods for measuring the different components of the wetland water balance. Measurement of topography is also included. The pros and cons of different techniques are also presented along with suggestions for where some techniques will work better than others.

7.1.Rainfall

The measurement of meteorological variables is well documented. The following text is from the UK Meteorological Office report 'National Meteorological Library and ArchiveFact sheet 17 — Weather observations over land' (UK Met Office, 2010):

'Many different types of rain-gauge have been designed and used. Most consist of a circular collector, delineating the area of the sample, and a funnel that channels the collected rain into a measuring mechanism or into a reservoir where it may be measured at a later time. As the name implies, rain gauges measure rain not snow, hail or other forms of frozen precipitation. The entrance to the gauge through the funnel is narrow to avoid debris clogging the mechanism and undesirable evaporation in hot weather. However, the gauge rapidly becomes blocked in snow and any readings at the time, and during thawing events when melted snow gradually trickles into the gauge, should be treated with caution. Where an observer is present to make a daily precipitation reading, the water equivalent of freshly fallen snow is reported.

Since the earliest years of weather records, the de facto standard for the measurement of daily rainfall has been the 0900 UTC reading made by an observer from a 5 inch storage rain-gauge. The gauge has a sharp brass or steel rim of diameter 5 inches (127 mm), sited 30 cm above ground level with a funnel that collects rain in a narrow necked bottle placed in a removable can.

To make the rainfall measurement, the observer empties the collected rain into a graduated glass rain measure. As automated instruments were introduced across the synoptic network in the 1980s and 1990s the 5 inch gauge was still deployed alongside the tipping bucket gauge to continue a long consistent record of measurements for climate purposes.

In recent years this practice has proved impractical and many automatic sites now only report rainfall amount from a tipping bucket gauge. Storage gauges are still used widely at non automated climate stations and rainfall-only stations. Where an observer is not available to provide daily rainfall, readings may be made at weekly or monthly intervals.'

Measurement of rainfall in a wetland should follow the Meteorological Office guidance. It is important to select a location that will give a representative measurement for the study area. Unlike a purpose built met site, the rain gauge in the wetland is likely to be surrounded by more natural vegetation and this will need to be kept in check so that it doesn't interfere with the rain falling on the gauge. In order to avoid a 'rain shadow' effect, the standard rule of thumb is that the distance from the rain gauge to the nearest vegetation should be at least 2.5 times the maximum height of the vegetation (John Roberts *pers. comm.*). This is likely to influence both the positioning of the rain gauge and also the maintenance of the area around the gauge.

Figure 2 A tipping bucket raingauge

Various types of gauge exist, from manually read storage rain gauges (giving the total quantity of rain that has fallen since the previous measurement) to automatically logged tipping bucket rain gauges (Figure 2). Where possible it is recommended to install both an automatically logged tipping bucket raingauge, which gives the time of each bucket tip (typically either 0.2 mm or 0.5 mm), and a manual storage gauge as a backup check. It may also be possible to obtain rainfall data from existing sources. Any of these methods generally have a cost that reflects the effort required to obtain the data and the quality and spatial and temporal frequency of the data.

Table 2 Summary of different rainfall measurement techniques

Direct Measurement	**Existing Datasets**	**Suitability/Cost**
• Manual storage rain gauge. • Weekly or monthly values.	• Local amateur enthusiast • Monthly MORECS 40 km^2 gridded data.	• Low detail. • Rapid assessment. • £
• Single logging rain gauge.	• Local MET station • Monthly MORECS data for a single location. • Daily MORECS data for a 40 km^2 grid square.	• More detailed but possibly lacking some spatial or temporal variation. • ££
• Multiple logging rain gauges, giving spatial coverage.	• MET Office individual rain gauge hourly or daily data.	• Very detailed • Fine-scale assessment. • £££

7.2.Evaporation and Evapotranspiration

Evaporation is one of the most difficult elements of the hydrological cycle to measure (Shaw, 1994). Multiple factors affect the quantity of water that moves from the land surface to the atmosphere. It is important to distinguish between evaporation and evapotranspiration, and also between the potential, reference and actual quantity. Brief definitions are given below:

Evaporation. The physical process of water changing from a liquid to a gas or vapour. In the water cycle the liquid water is present in open water bodies (oceans, lakes, rivers) and wet or moist substrates (damp soil, wet sand etc).

Evapotranspiration. This is the sum of evaporation (as defined above) and transpiration, which includes direct evaporation of intercepted precipitation and transpired water on plant surfaces (Shaw, 1994).

Potential. The amount of evapotranspiration from a surface with an unlimited water supply.

Reference. The amount of evapotranspiration from a hypothetical well-watered grass reference crop.

Actual. The amount of evapotranspiration that actually takes place from the surface in question.

Evaporation can be time-consuming and costly to measure accurately and it is often more simple to calculate evaporation using methods such as those developed by Thornthwaite, Blaney-Criddle, Penman and Penman-Monteith (see Shaw (1994) for more details). All of these methods give an indication of the ‘potential evaporation’ (PE) rate that could occur, and assume that there is an adequate supply of water available to the plant. In reality, various factors (including water availability) affect the rate at which the plant evaporates and it is more accurate to use ‘actual evaporation’ (AE) in the water balance calculation. However AE is more difficult to measure and the instruments required to do this are expensive both to purchase and operate. Techniques such as Bowen ratio (Peacock and Hess, 2004), Eddy Covariance (Acreman et al., 2003) and Scintillometry (McJannet, 2011) have been used very effectively to measure AE.

Choosing a suitable method for measuring evapotranspiration in a wetland will depend on the characteristics of the wetland. For example, the size, topographic variation in the vegetated and non-vegetated surface, homogeneity of vegetation will guide the choice of technique. Scintillometry can be nicely applied in there are large flat expansive open areas - provides near ideal conditions – where there are large trees included in the footprint then the scintillometer beam should be much higher than the tree tops.

Eddy covariance also needs to be away from trees, as this can cause additional turbulence and complication of the evaporation calculation. Eddy covariance was successfully applied to Wicken Fen (Kelvin, 2011) in a large open area of reeds. There are also difficulties of applying energy balance over areas of open water, and improvements are required to get advection & storage terms right.

Table 3 Summary of different evapotranspiration measurement techniques.

Direct Measurement	Existing Datasets	Suitability/Cost
• Evaporation Pan. Direct measurement of open water evaporation – *assumes labour from volunteer workforce to keep costs down, but acknowledges that this may affect data quality.*	• Calculation of potential evaporation using met data from a nearby station such as Local enthusiast/ RAF station/airfield.	• Gives an approximate measure, unlikely to account for site-specific factors. • Rapid assessment. • £
• Calculation of potential evaporation using Penman Monteith formula or similar using on-site automatic weather station data.	• Monthly MORECS data • Average for 40km square. • Monthly totals	• Improved representation of site-specific factors. • Intermediate level assessment. • ££
• Direct measurement of evaporation over the land surface using eddy covariance and gas path analysis, or scintillometry.	• MET Office individual weather station daily data.	• Accurate, site-specific quantification of evapotranspiration. • Detailed assessment. • £££

7.3.Surface Flows

Surface flows are dealt with separately to channel flows (e.g. rivers and ditches). By surface flows, we mean overland flows that include surface runoff, overbank inflow and overbank outflow. Unlike measurement of channel flows surface runoff can be shallow, over areas of mixed land cover, and spread over a large area. Surface flows can be very unevenly distributed as preferential pathways develop and carry the majority of flow, so it may be misleading to monitor the flow in only one small area and to extrapolate from that point.

Measurement in the field can therefore be difficult and traditional methods are unlikely to address the issues identified above. In addition, most current meters will struggle with the shallow and turbulent nature of the flow. Electro-magnetic current meters and acoustic Doppler velocity meters may perform better in such conditions but will ultimately face similar limitations. The very intermittent nature of these flows and potentially sudden high flows (e.g. when a river overtops its banks) further make use of these instruments difficult and potentially dangerous. Alternative direct measurement techniques have been trialled for small areas using collector pipes, such as a perforated tube or lengths of gutter, laid flush with the ground surface and perpendicular with the direction of flow in order to catch the surface water and direct it to a bespoke measurement chamber. This may be a simple storage unit in which the volume can be regularly recorded or a more advanced flow cell in which the inflow is measured in real time.

Accurate determination of surface flows over larger areas is likely to require a combination of topographic data, soil and land cover data and water level data. Some of this data will be available from existing (possibly remotely sensed) data sets however this may only be accurate enough to merit fairly rough flow estimates using equations such as that for a broad-crested weir. For a more detailed site investigation, a topographic survey, land cover survey and detailed water level information are likely to be required and it may then be possible to carry out a more accurate calculation using the Manning formula. Probably the most advanced but also labour intensive solution for large areas is to construct a 3 dimension hydraulic model however the data requirements of this are likely to be very large. Assessment of which solution is most appropriate should consider the likely improvement in conceptual understanding that will be provided by each.

Table 4 Summary of surface flow measurement techniques

Direct Measurement	**Existing Datasets**	**Suitability/Cost**
• Basic field instrumentation, such as collection pipe and storage gauge, may be low-cost to setup but will require considerable staff effort. *Only low cost if staff costs are minimal.*	• Off the shelf rainfall/runoff models and datasets such as the FEH Handbook and LowFlows Enterprise taking into account contributing catchment area.	• Very general, indicative value. • Suitable for rapid assessment. • £
• Use on-site monitored rainfall and evaporation data, plus soil and land surface properties to model runoff.	• Use existing rainfall and evaporation data sets plus indicative soil properties (e.g. HOST) to model runoff.	• Improved representation of site conditions, but may not account for preferential flow paths etc. • Intermediate level assessment. • ££
• Extensive site investigation and instrumentation making sure that all major flow pathways are accounted for. Use this data to setup and calibrate a hydraulic model to calculate the flow.	• Not applicable. Existing site-specific data for detailed surface flow analysis are unlikely to exist.	• Accurate quantification of surface flows into the study site. • Suitable for very detailed assessment. • £££

7.4.Subsurface flows

Subsurface flows are distinguished from groundwater interactions as they involve local shallow water tables whose influence on the study site is due to topography and differences in hydraulic head. They include subsurface runoff from surrounding uplands, downslope drainage to lower-lying areas, and lateral subsurface exchanges with open water bodies (e.g. rivers, lakes and ditches). These flows are not visible at the surface and are difficult to measure directly. The two basic measurement methods use either a tracer to establish the velocity of water movement, or the difference in water level between two points along with hydraulic conductivity to calculate the potential flow velocity using Darcy's Law. An estimate of the width and saturated thickness of the porous medium is then used in addition to the velocity in order to calculate the flow volume.

Many different tracers exist including physical properties such as water temperature, hydro-chemical signature, artificially introduced dye tracers, and specially designed bacteriophage tracers. The basic principal is to measure the time taken for the tracer to travel a certain distance and it is assumed that this is representative of the flow velocity for the study area. This velocity is then multiplied by the cross-sectional area to get a volumetric flow rate. It is important to select a tracer appropriate to the study in question. In heterogeneous substrates the tracer injection and detection points may have a large influence on the flow velocity recorded as large preferential flow paths may or may not be intercepted. Interpretation of results should take this into account.

The alternative method of measuring water levels or potentiometric heads and calculating the flow using Darcy's law is likely to be more straightforward than using a tracer, but it only tells you the calculated potential movement of water, not the actual movement. The measurement of water levels in the subsurface is generally quite straightforward, although installation of wells in some media can be difficult.

Measurement of hydraulic conductivity can also be problematic in some soil types. Soils with a heterogeneous structure (e.g. some peats) have been shown to have a highly scale-dependent hydraulic conductivity (Bromley et al., 2004). Various methods exist for field measurement of hydraulic conductivity (Falling head test and Guelph Permeameter).

Table 5 Summary of subsurface flow measurement techniques.

Direct Measurement	**Existing Datasets**	**Suitability/Cost**
• Use a small number (<3) of dipwells and open water monitoring stations to establish the general slope of the water table. Use the Darcy flow equation with off the shelf values of hydraulic conductivity to estimate subsurface flow.	• Existing datasets are likely to be scarce, but very rough indicative values might be available through datasets such as HOST or LowFlows Enterprise.	• Rough indication only – unlikely to account for any heterogeneity in the subsurface. • Rapid assessment. • £
• Detailed piezometry using multiple (~ 5 to 15) monitoring stations. • On site measure of hydraulic conductivity. • Calculation of subsurface flow using the Darcy flow	• Not applicable. Existing site-specific data for subsurface flow analysis are unlikely to exist.	• Better representation of site-specific factors and heterogeneity. • Intermediate to detailed level assessment. • ££ to £££

equation.		
• Full tracer testing to establish flow velocity. • Combination with saturated thickness to calculate flow volume.	• Not applicable. Existing site-specific data for subsurface flow analysis are unlikely to exist.	• Capable of giving an accurate quantification of flow velocity. • Intermediate to detailed level assessment. • ££ to £££

7.5.Groundwater Discharge and Groundwater Recharge

Groundwater discharge and recharge are distinguished from interaction with subsurface flows as they deal with defined groundwater bodies rather than near-surface undefined movements of water. The measurement of exchanges between the surface water and groundwater systems can be done using various methods. Tracer tests, as described in the previous section, are sometimes used to identify areas in which discharge or recharge are occurring.

Piezometry is commonly used, comparing the potentiometric water level in the different layers of the system. Two or more piezometers are installed in the subsurface in close proximity to each other (typically around 1 metre) so that each intercepts the desired layer of interest. A simple set up might for example include measurement of the surface water level and the groundwater level. More complex systems might have more layers, each with its own properties and degree of hydraulic connectivity with the adjacent layers.

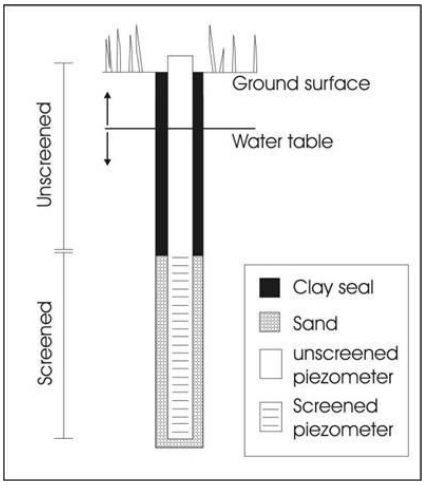

Figure 3 Piezometer with screened and unscreened sections.

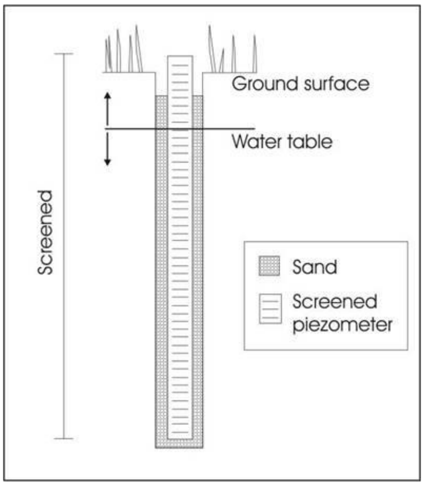

Figure 4 Simple screened piezometer.

Since the objective here is to look for differences in water levels between layers, it is necessary to maintain the isolation between layers. This is achieved by using slotted/screened pipe and highly permeable gravel in the layer where the water table is to be observed, and non-slotted/unscreened pipe and very low permeability bentonite clay in the non-observed layers (Figure 3). Where the water table in the surface layer is being observed, a simple slotted pipe will often suffice (Figure 4), although a small seal around the top may still be required to prevent the preferential flow of surface water down the sides of the pipe.

Table 6 Summary of groundwater discharge and recharge measurement techniques.

Direct Measurement	Existing Datasets	Suitability/Cost
• Measurement of groundwater and surface water temperature during times of surface water temperature extremes (e.g. winter and summer) can identify areas where interactions are occurring.	• Geological Maps can identify key groundwater aquifers and where these may have a connection with surface water systems.	• Qualitative or semi-quantitative indication of groundwater discharge and/or recharge. • Rapid assessment. • £
• Detailed piezometry and field and/or lab measurement of the hydraulic conductivity of relevant layers.	• It is possible that some existing groundwater and surface water monitoring data are available for the study site, and these could be used to estimate	• Quantitative estimate of groundwater discharge and/or recharge. • Intermediate to detailed assessment. • ££ to £££
• As above, but combined with detailed geophysical investigation to develop a more thorough understanding of subsurface layers and their likely effect on groundwater discharge and/or recharge.	• Not applicable. Existing site-specific data for groundwater discharge and/or recharge analysis are unlikely to exist.	• Likely to provide the most accurate quantification of groundwater discharge and/or recharge. • Highly detailed assessment. • £££

7.6.Measurement of water level

Water levels can be measured manually or automatically. To gain a broad understanding of the seasonal fluctuations in water table and of the general shape of the water table across a site, weekly or monthly manual water level ‘dip’ measurements may well be sufficient. These are best collected with a dip meter, which consists of an electrical sensor that makes a sound when in contact with water, connected to a length of tape which is generally marked at centimetre and millimetre intervals. The level recorded is that from the top of the monitoring pipe to the water level (the point at which, upon lowering it into the tube, the sensor first makes a sound). In order to make sense of the water levels across a site, it will also be necessary to measure accurately the elevations of the tops of the monitoring wells (and also ground level if the water level is to be described in relation to the ground surface).

For a more detailed understanding of the behaviour of the water table, for instance how it responds to rainfall events, it may be necessary to monitor the water level at a higher frequency. Figure 5 shows a time series of water level. The red dots are the levels recorded by weekly manual dips and the blue line is the level recorded hourly by an automatic logger. It can clearly be seen that whilst the overall trend is picked up by the weekly dips, a great deal of variation (sometimes up to 25 cm in this case) is only picked up by the automatic logger.

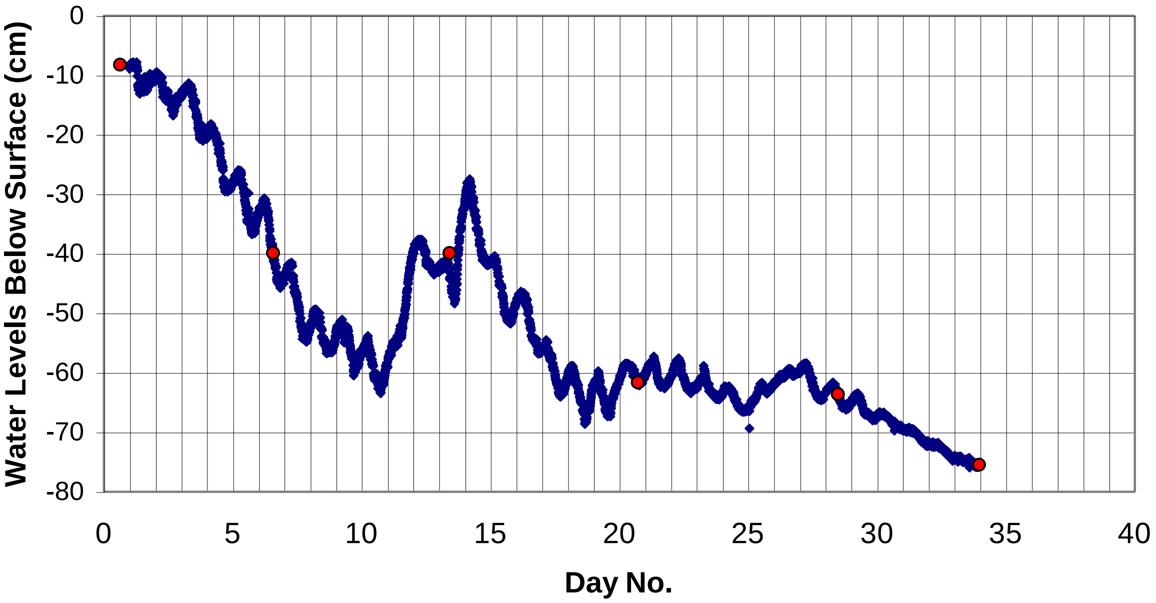

Figure 5 Time series of water level recorded showing weekly manual dips and hourly automatic logger results.

Various automatic loggers exist and selection of the appropriate type is important. A comprehensive review of some of the leading loggers currently on the market is given below in Appendix A.

7.7.Storage

The final element of the wetland water balance is storage. Water is stored in the wetland in two ‘zones’ - the saturated zone and unsaturated zone and this section considers both to be unconfined and in good contact with the surface water system. The water stored in the saturated zone is more straightforward to measure and this is generally done using a simple screened piezometer (Figure 6). The water level in the piezometer reflects the water table and this, in combination with a measure of the drainable porosity (defined below) of the medium, will enable quantification of hydrological storage. In describing the volume of water that can be stored in a wetland substrate it is useful to define the following:

Total porosity. This is a measure of the amount of open space in the soil and is typically given as a percentage calculated by dividing the volume of pores in the sample by the total volume of the sample (Hillel, 1998). The *Porosity* tells us nothing about how well connected those pores are and it is possible to have a substance with high porosity but which if submerged will only accommodate a small volume of water. They may also have a relatively low permeability (e.g. pumice).

Effective Porosity. This describes the amount of interconnected pore space and is defined as the porosity available for fluid flow (Fetter, 1994).

Drainable Porosity (generally used interchangeably with the term Specific Yield). This is the ratio of the volume of water that drains from a saturated rock or soil owing to the attraction of gravity to the total volume of the rock (Meinzer, 1923). This value is generally less than or equal to the *effective porosity*. It is described by Beavan *et al.* (2008); 'If a fully saturated waste material is allowed to drain under gravity, its water content will decrease as drainable pores empty. It will eventually reach a state (termed the field capacity) when no further drainage occurs.'

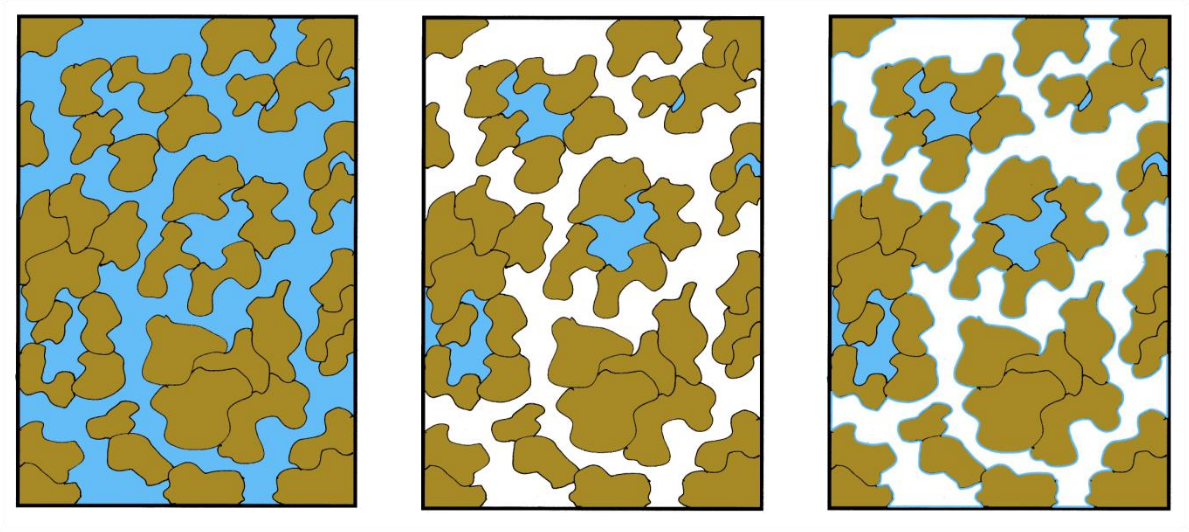

Figure 6 Illustration of total porosity (left), effective porosity (middle) and drainable porosity (right). Light brown shading indicates soil particles, light blue shading is water, and white is empty pore space.

Measurement of the water content in the unsaturated zone involves monitoring the moisture content in the layers above the water table. Moisture content can be determined as a percentage of weight (gravimetric) or as a percentage of volume (volumetric). Measurement methods can be destructive, involving field sample collection and laboratory analysis, or non-destructive, using sensors to detect the soil moisture content.

Field samples are collected using specially designed steel rings, which are inserted into the soil and a sample of known volume of soil is extracted. The sample is put in an airtight bag and returned to the lab, where it is weighed, dried in an oven (normally at 105 °C) and then re-weighed. The difference in weight equates to the mass of water that was present in the sample.

Non-destructive detection methods generally make use of either the electrical properties or neutron scattering properties of the moist substrate. Electrically-based methods include Electrical Resistance Tomography (ERT) and capacitance (e.g. Delta-T Theta probe or profile paper), and neutron scattering methods include the neutron probe (using an active neutron source) and COSMOS (using the naturally occurring cosmic ray source).

7.8.Topography

Measurement of topography is important in order to capture variations in the surface of the study area and also to measure the elevation measurement stations and notable features. Two widely recognised techniques for measuring elevation are differential GPS, and total station (a traditional theodolite combined with a distance measurement device). The details of each are set out below.

Table 7 Comparison of dGPS and Total Station surveying techniques.

	Principle of measurement	Accuracy	Advantages	Disadvantages
Differential GPS	Receiving and processing signals from satellites to obtain absolute x, y, z position.	± 1 cm	Gives an absolute measure of elevation and position and therefore doesn’t require existing benchmarks or survey markers.	Requires good coverage and geometry of satellites in order to achieve the most accurate results.
Total Station	Sending and receiving signals to and from a reflective target to obtain relative x, y, z position.	± 0.5 cm	Once set up, very quick to operate. If wanting to collect many high accuracy points, the total station is likely to be quicker than the dGPS	Only gives relative elevation and position. To set the survey data in wider context, or carry out repeat surveys, permanent survey makers need to be installed.

8. Boxford Water Meadows Case Study

This section aims to describe the approach taken to monitoring the Boxford Water Meadows and to use the experiences gained from this work to provide examples of some of the successes and difficulties encountered.

8.1.Preliminary Analysis and Categorisation of Wetland Type

Desk study and initial site investigations identified that the Boxford site sits adjacent to the river Lambourn and within a permeable chalk catchment. The river is fed predominantly by groundwater. The site is low-lying and is likely to receive water from multiple sources (rainfall, river and groundwater. A hillslope and dry valley to the east both have a role in the wetland water balance of the north-eastern area of the site. The generalised wetland stratigraphy is chalk overlain by gravel overlain by peat. A small channel, connected to the main river at both ends, runs through the site.

The following excerpt from the SSSI designation (1986) gives some additional general information:

'Boxford Water Meadows comprise a series of flood pastures and disused water meadows along the River Lambourn. Patches of alder and sallow scrub occur. The site overlies alluvium and the soils consist of calcareous alluvial gleys.

Traditionally the water meadows would have been managed as pasture for cattle or horses, controlling flooding along specially constructed carrier streams providing a supply of warm water in spring to encourage early growth from the sward. The water meadows at Boxford have not been grazed, with the exception of the southern-most field, for between 5 and 20 years and the vegetation types present reflect both this and the gradient in soil moisture, the plant communities grading from *Carex acutiformis* swamp and fen to *Cynosurus cristatus-Caltha palustris* flood-pasture and water-meadow vegetation southwards across the site.'

In terms of typology the Boxford water meadows would be classed as a *Groundwater depression wetland'* occurring where a depression intercepts the water table. The wetland receives direct precipitation, runoff and groundwater inflow. There is no surface drainage away from the wetland. According to the typology developed by Acreman and Miller (2007), the Boxford water meadows would be classed as *Valley bottom wetland Groundwater-fed*, in direct contact with underlying aquifer.

Having developed a very basic understanding of the wetland and an initial hydrological conceptual model, the key hydrological processes and hence monitoring requirements were identified. The water transfer mechanisms that should be monitored, along with an initial impression of the significance of each, are summarised in Table 8.

Table 8 Water transfer mechanisms potentially needing consideration in monitoring plan.

	Water Transfer Mechanism	**Likely Significance**	**Comment**
Inputs	Precipitation	High	
	Surface and shallow subsurface inflow to the wetland	Medium to low	Likely to be variable significance across the site. Medium in the northern wetland area, low in the southern wetland.
	Lateral inflow	Medium to low	May be significant adjacent to the river.
	Overbank flow	Low	River level unlikely to rise enough to cause widespread overbank flow.
	Groundwater discharge	High	Connectivity with groundwater body uncertain by likely to be significant.
Outputs	Evapotranspiration	High	
	Drainage	Medium to low	Surface water drains not evident at the outset. The Westbrook stream may collect water from the wetland.
	Overland outflow	Low	Within site topography is unlikely to promote significant overland outflow.
	Groundwater recharge	High	Connectivity with groundwater body uncertain by likely to be significant.
	Storage	High	Storage is very likely to vary in each layer of the wetland system.

To further refine the monitoring plan it proved useful to consider the questions that we might like to address as these will likely influence the monitoring that is required. We started off by asking ‘What are we interested in?’ and the following were identified:

- Can we quantify the water balance of this wetland habitat – input, attenuation (storage) and output?
- What role does the wetland have on the hydrology of the local area?

- What relationship exists between wetland vegetation type and abundance, and the hydrological regime?
- What is the impact of environmental events such as flooding and drought?

- What are the physio-chemical properties of this wetland?
- Migration / movement of water throughout the wetland habitat. How does the quantity and quality of water change as it moves through the wetland?

- How well connected are water levels in the peat and the superficial geology?
- What is the relationship between the wetland and the River Lambourn?

- How do the topographic characteristics of the wetland changes over time as a result of fluctuations in the hydrological regime of the habitat?

8.2.Proposed and implemented monitoring plan

Based on the information collected (and presented in section 8.1), a proposed monitoring plan was drawn up (Figure 7). The aim of the plan was to adequately capture the processes identified. It was always recognised that further refinements were likely, but this was felt to be the best starting point.

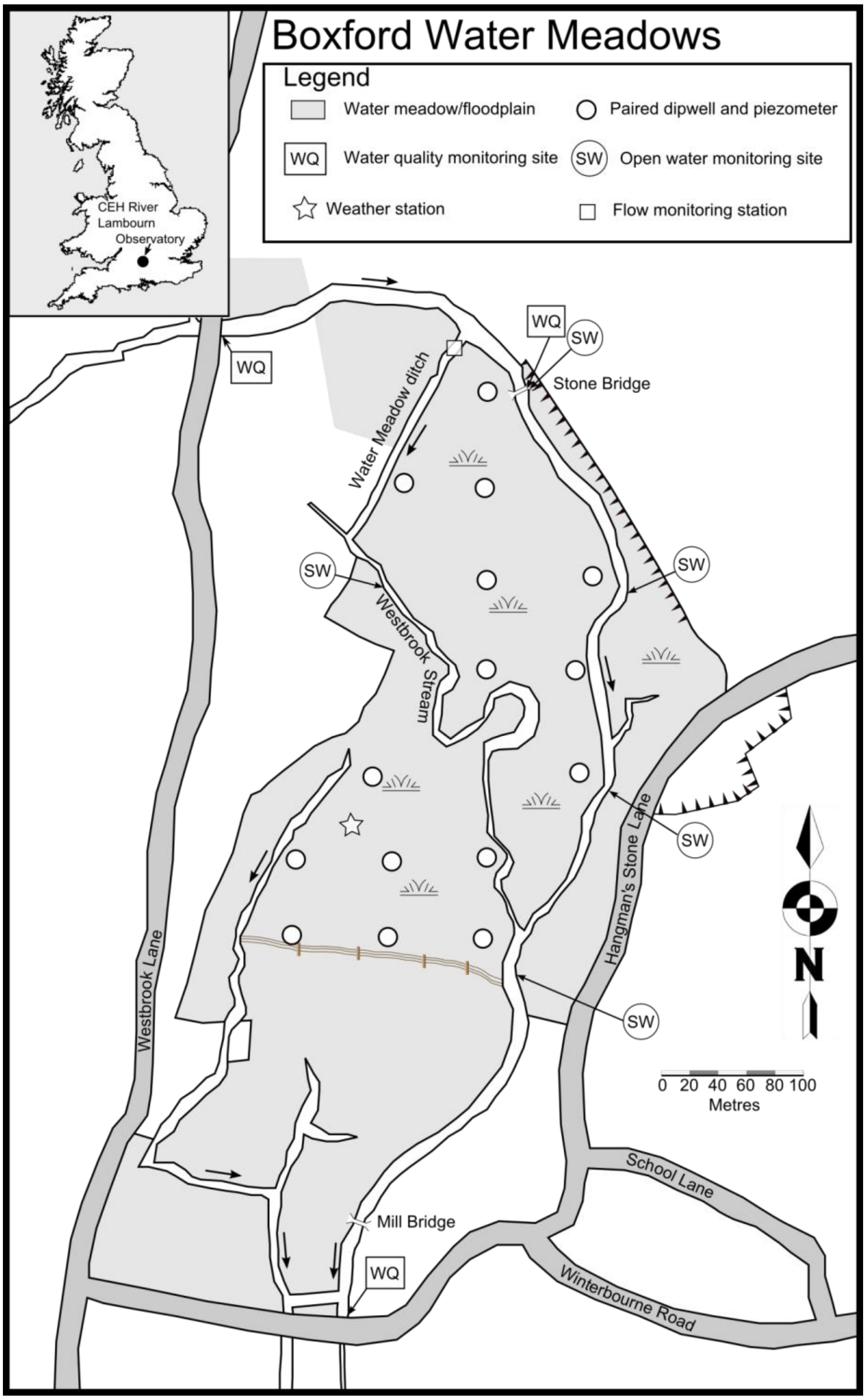

Figure 7 Proposed monitoring setup for Boxford Water Meadows(© NERC (CEH) © Crown copyright and database rights 2009 Ordnance Survey 100017572).

The plan includes the following elements:

Water Transfer Mechanism	**Importance**	**Method**
Precipitation	High	Automatic weather station, to collect rainfall data and report at hourly intervals. A storage check gauge was also installed as a backup.
Surface and shallow subsurface inflow to the wetland	Medium to low	As this monitoring plan focussed on the southern wetland area, any surface and shallow subsurface flows would be intercepted by the open water channels and do not therefore require dedicated monitoring. Multiple surface water level monitoring points are included in the plan.
Lateral inflow	Medium to low	This is likely to be confined to the area of wetland bordering the open water areas. Monitoring for inflow will initially be as part of the dipwell and piezometer network.
Groundwater discharge	High	Movement of groundwater from the chalk and gravel aquifers into the wetland will be detected using the dipwell and piezometer network.
Evapotranspiration	High	The automatic weather station includes a multi-spectral radiometer for accurate quantification of solar radiation flux and improved estimation of evapotranspiration.
Drainage	Medium to low	The extent and state of drainage channels are currently poorly understood, but it is thought that the Westbrook stream may collect some water from the wetland. To test for this, flow monitoring along the Westbrook stream will be carried out.
Groundwater recharge	High	Movement of groundwater from the wetland into the chalk and gravel aquifers will be detected using the dipwell and piezometer network.
Storage	High	Quantification of storage in the wetland is by measurement of the water levels in the gravel and peat layers, using the dipwell and piezometer network. The network was fully instrumented with automatic water level loggers.

In the absence of better information, the paired dipwells and piezometers were laid out in a grid pattern with a spacing of approximately 60 m. At each installation site, soil cores were collected and logged both in the field and then in finer detail back in the lab. This information gave a first impression of the stratigraphic variability across the site. The thickness of gravel and peat were found to vary considerably across the site. Also found were layers of low permeability putty chalk in places at the chalk/gravel interface and gravel/peat interface. The significance of these layers is that hydrological connectivity may vary across the site and the hydrological response in some areas may differ greatly from that in others. An example of a field log is shown in Figure 8.

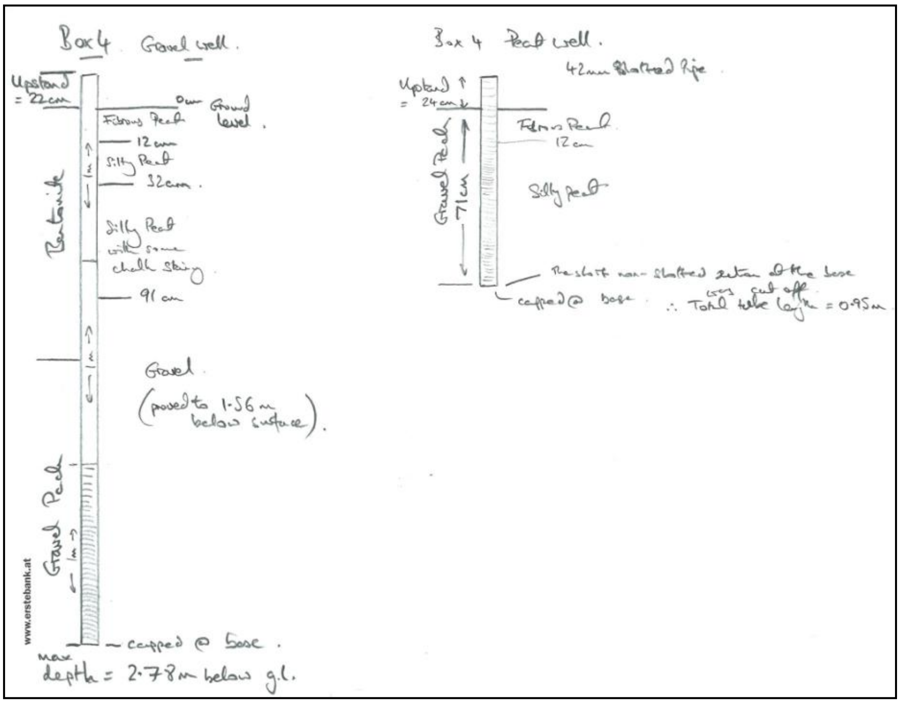

Figure 8 Example of a soil profile log collected during dipwell and piezometer installation. The elevation of sections of screened pipe, gravel pack and bentonite seal are also recorded.

Repeat topographic surveys of the site have been carried out in order to establish the surface elevation and whether it varies over time, and also to provide accurate positional information for any of the monitoring locations and interest features. The fully integrated survey method was used, combining the dGPS and Total Station, which gave the benefits of knowing absolute position (from the dGPS) of the site, and very accurate within-site measurement (from the Total Station).

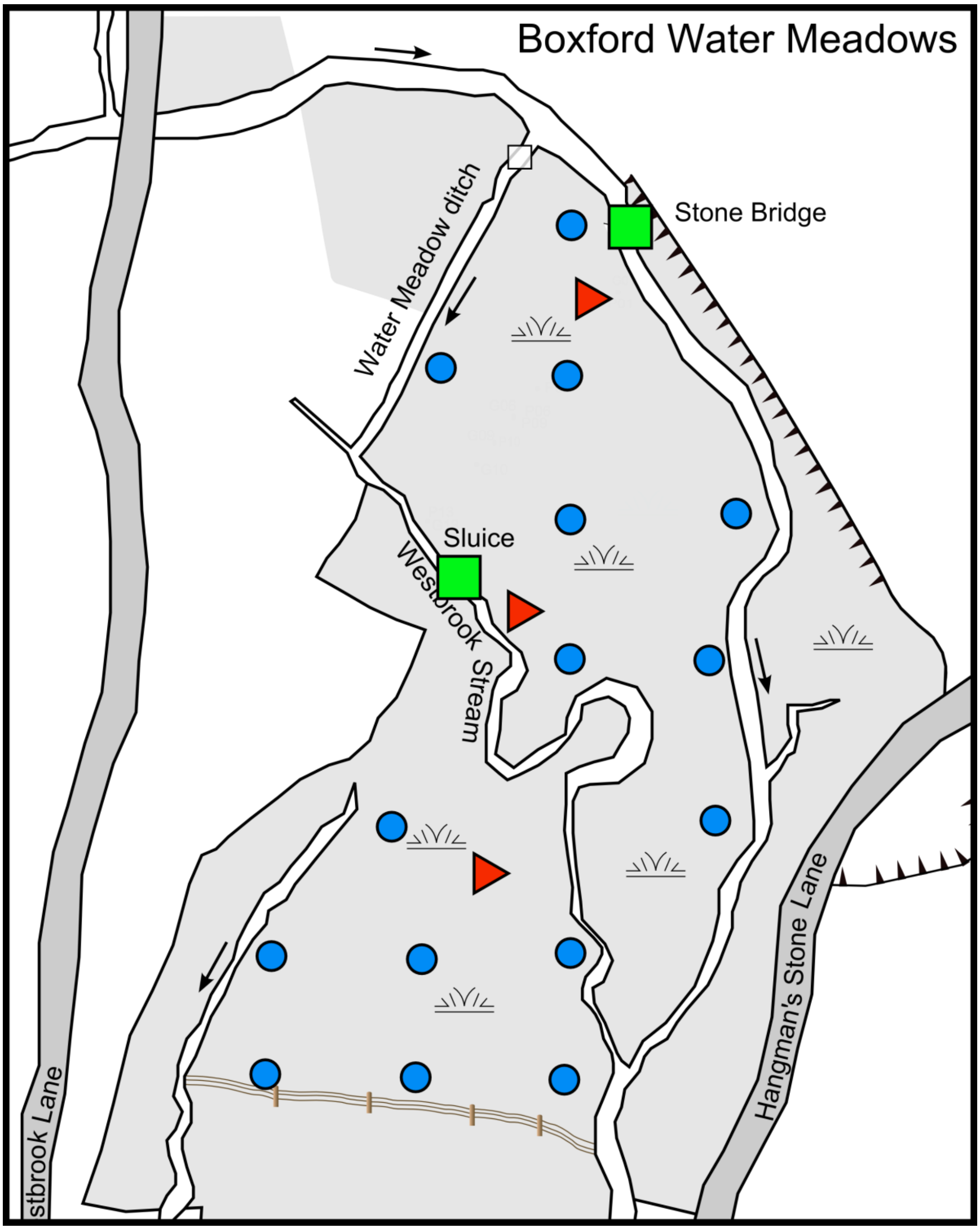

Figure 9 Locations of permanent survey markers (green squares), Total Station setups (red triangles), and surveyed monitoring points (blue circles). (© NERC (CEH) © Crown copyright and database rights 2009 Ordnance Survey 100017572).

Full coverage of the site was achieved with 3 separate setup points, two in the northern wetland and one in the south (Figure 9). Setup was achieved using a combination of dGPS control points and two fixed observation points, one on the stone bridge and the other on the sluice. These were two of the only areas of hard standing within the wetland area. The dGPS control points measured using the 3 minute Observation Point setting and a bipod to keep the staff still during measurement. Previous tests using this approach have shown repeat measurements over time are typically within ±0.7cm of each other. Foresights and backsights to the fixed observation points were taken from each setup point so that potential error in location, most importantly elevation, could be minimised. At each monitoring location, the top of pipe for of gravel and peat piezometers was measured.

The wider topographic survey was carried out using primarily the dGPS. This reliably has a positional accuracy of c.20mm and will normally provide ample precision for a survey of this kind. However in some locations, such as where dense vegetation obscures the satellite signal, the Total Station was used to fill in points. The integrated set-up provides the most reliable solution for this type of work. As the survey progressed around the site the Total Station was relocated and repositioned as necessary. The resulting dataset consisted of 3101 survey points and this has provided a baseline for further spatial analysis (

Figure 10).

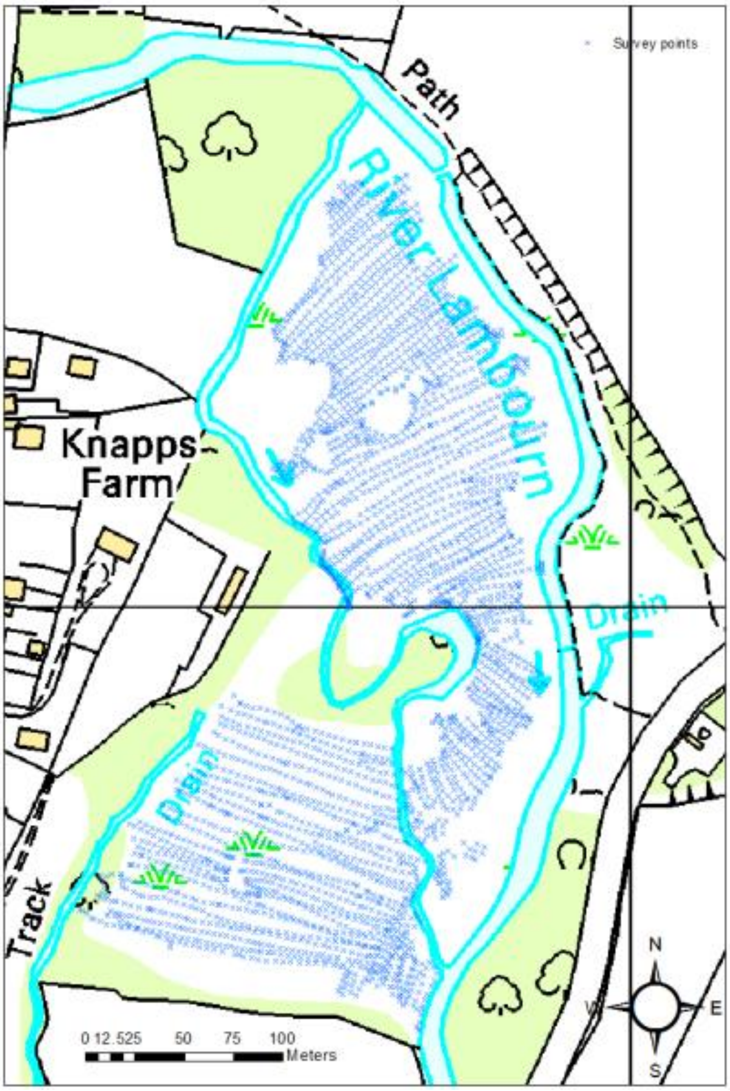

Figure 10 Coverage of topographic survey points

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Appendix A

Comparison of water level loggers

There are currently a multitude of commercially available transducers which range considerably in both performance and price. To assess which model would be most suitable for use at the Lambourn Observatory, a field comparison of four different transducers was undertaken – Micro-Diver, Mini-Diver, INW PT2X and Level Troll 500. The INW PT2X and In-Situ Level Troll (LT) 500 were selected based on positive results in Sorensen and Butcher (2010; 2011) and the Divers were selected as they have traditionally been used at many BGS and CEH research sites. The Divers and PT2X are non-vented sensors and the LT 500 is a vented sensor.

Methodology

One model of each transducer was installed at a similar depth below water at a peat dipwell (DW1) adjacent to the River Lambourn (442919, 172160). A further Mini-Diver, PT2X and LT 500 were installed at similar depths below water at another peat dipwell (DW2) in the centre of the wetland (442866, 172109). All transducers were set to log at five minute intervals and were left in-situ for 33 days beginning on 7th October 2011.

Results

Changes in water pressure recorded by all transducers are shown in Figure A1. All data are referenced to the last pressure reading for comparative purposes. The figure highlights the clear disparity in transducer precision (or noise), with greatest noise in the Micro-Diver data and least in the LT 500 data. Moreover, the noise is so significant in all the Diver data that accurately quantifying water level changes due to daily evaporative losses is challenging. Estimates of transducer precision based upon Figure are provided in Table.

Table A1 Transducer precision (mm)

Transducer	DW1	DW2
Micro-Diver	10	-
Mini-Diver	6	6
PT2X	2	2
LT 500	<1	<1

There are no manual data available to assess transducer accuracy. Sensor drift was also not specifically investigated for this study due to the limited timeframe available to leave the transducers in-situ. Figure confirms differences between the sensors over time were minimal.

The noise recorded by non-vented transducers is a combination of both the submerged and atmospheric sensors. Figure contrasts the two atmospheric sensors over a five-day period. It is evident there is a relatively constant difference in recorded pressure of c. 10 mm. Moreover, the Baro-Diver is more imprecise and has a lower resolution.

Conclusion

The most precise instrument is the LT 500. Divers do no capture water level changes with sufficient precision to monitor water level changes resulting from evaporation.

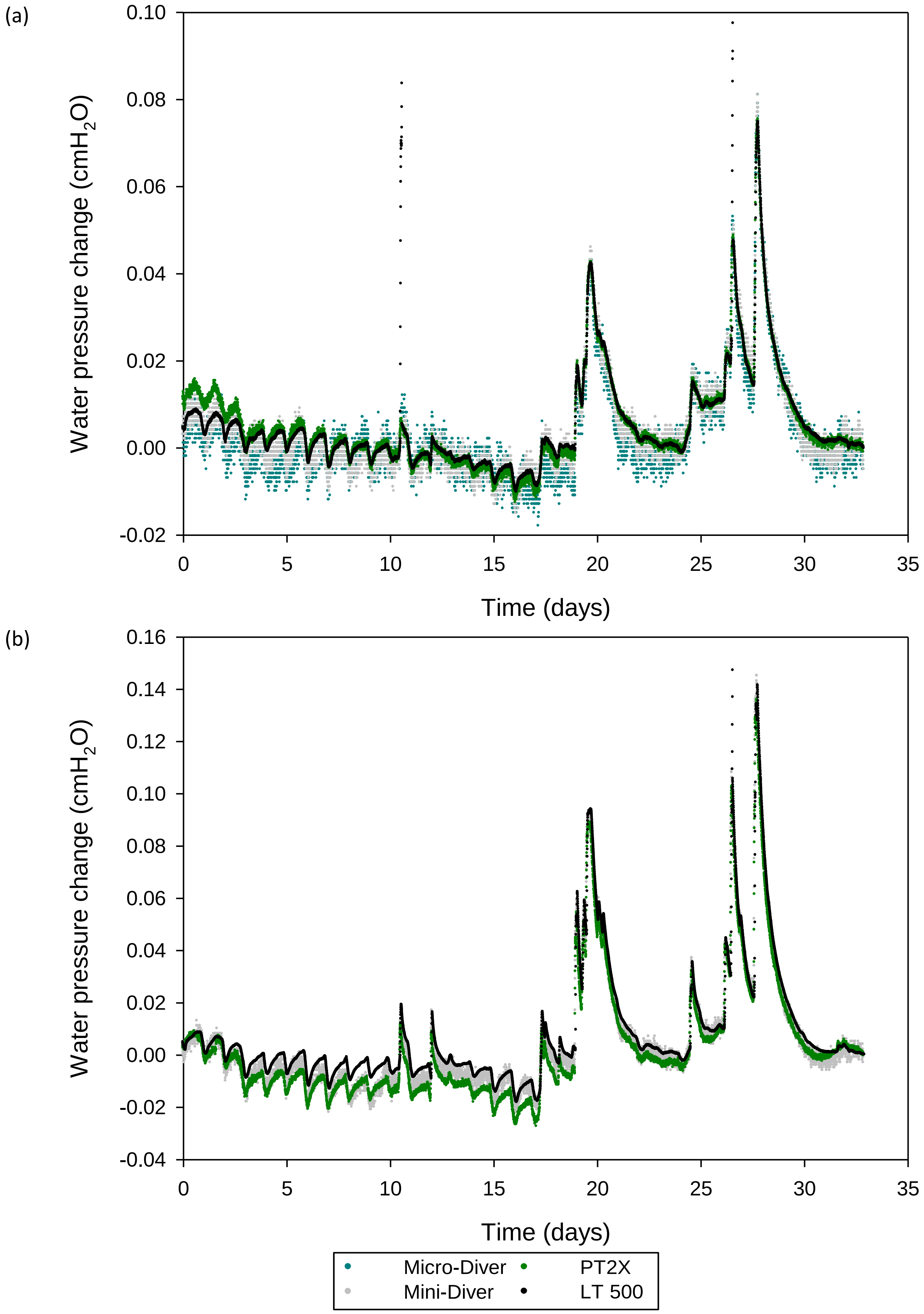

Figure A1 Changes in water pressure recorded by transducers in (a) DW1 and (b) DW2

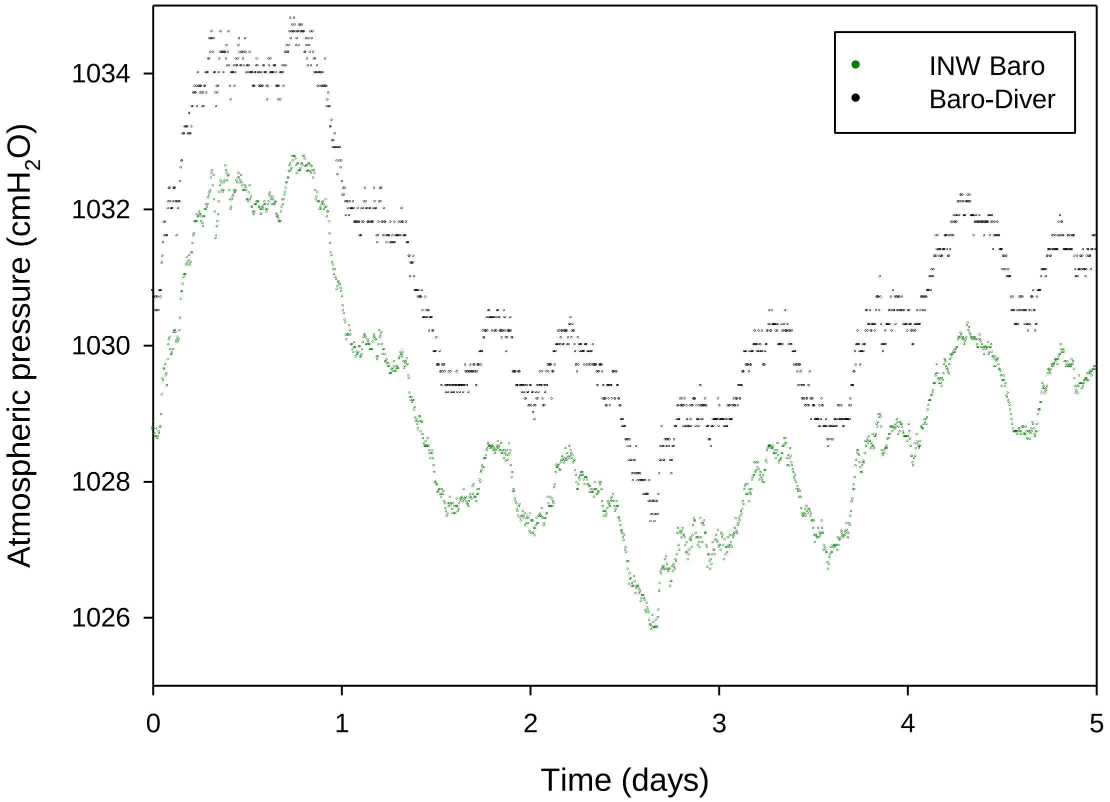

Figure A2 Recorded atmospheric pressure over 5 days by two pressure