Exmoor Hydrological and Hydrogeological monitoring plan for the Mires-on-the-Moors project

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1. Executive Summary
This report outlines a monitoring plan for the forthcoming Mires-on-the-Moors project. The aim of this monitoring is to assess the hydrological and hydrogeological impacts of an extensive ditch blocking exercise that will be conducted across Exmoor National Park. A monitoring plan for Dartmoor National Park is currently being developed. This monitoring plan will primarily focus on water quantity. A water quality monitoring strategy is currently being developed by Dr. Richard Brazier who is based at the University of Exeter.

2. Introduction
This monitoring plan will allow us to assess the impact of the ditch blocking on the numerous hydrological and hydrogeological project objectives, provide a comprehensive baseline dataset for future collaborations/research opportunities and will contribute to the current understanding of peat groundwater and surface water processes.

3. Summary of stakeholder objectives
Summarised below is a list of the hydrological and hydrogeological objectives provided by the Mires-on-the-Moors project partners (South West Water; Exmoor National Park Authority; Dartmoor National Park Authority, Natural England and the Environment Agency):

- Retention of groundwater within the mire system.
- Re-establishment of natural stream flows, for example:
  1. A lowering of peak flows and an increase of baseflow.
  2. A reduction in water velocity at peak flows which should reduce the rate of gully erosion.
- Reduction in gully erosion.
- Quantification of groundwater-surface water interactions that occur between the newly formed surface water pools which will be created by ditch blocking and the groundwater system leading to an increased understanding of the impacts on downstream surface water flow regimes.

4. Monitoring approach
The recommended monitoring approach for addressing the Mires-on-the-Moors project objectives requires the assessment of hydrological and hydrogeological processes at both the localised surface
water pool-scale (Section 4.2) and catchment-scale via a water balance methodology (Section 4.3). The water balance approach requires the accurate measurement of inputs, outputs, and changes in storage across a study site that will consist of a small headwater catchment (Ca. 1-3 km²) over a selected period of time. The numerous hydrological and hydrogeological components that will require accurate quantification for both the surface water pool-scale monitoring and catchment-scale monitoring will be considered in greater detail below (Section 4.1).

4.1 Equipment requirements

4.1.1 Rainfall (input) (Figure 11; A)

**Why:** The accurate quantification of precipitation is fundamental to each and every one of the hydrological and hydrogeological project objectives as antecedent precipitation levels will control the height, rate and volume of surface water and groundwater systems. Accurate results will place groundwater and surface water processes into context, reduce the possibility of data misinterpretation when assessing the impacts of ditch blocking activities and contribute towards the accuracy of the water balance calculations (Section 4.3).

Numerous Environment Agency rain gauges have been measuring historical precipitation levels across Exmoor National Park for many years (Figure 1). These rain gauges will provide a good indication of long term trends and seasonal variations; however they are unlikely to be located close enough to the monitoring sites to provide the level of accuracy required for this project.

**Spatial:** Advice on the placement and type of rain gauges will be sought from the EA Hydrology and Hydrometry & Telemetry (H&T) teams based at Exminster House. Assessment of MET Office rainfall radar data at 1 km² resolution should be undertaken to identify if the monitoring sites are located in ‘typical’ rainfall locations across Exmoor National park.

**Temporal:** Once the location of the rain gauges has been decided they should be installed as soon as possible to provide the longest possible precipitation record at each monitoring site. Standard rain gauges (measuring average monthly rainfall) will be combined with tipping bucket rain gauges (measuring rainfall intensity) and positioned at both a suitable topographically high and low point of each site to contribute to the understanding of gully erosion processes, provide accurate measurements of rainfall patterns and allow cross-checks to be performed on the equipment.
Figure 1. Location of Environment Agency monitored rain gauges across Exmoor National Park (A = Simonsbath and B = Dulverton).
The measurement of precipitation levels at the tipping bucket rain gauges should be recorded on a breakpoint basis (i.e. every tip of the bucket is recorded) to ensure that even the most intense rainfall events are effectively captured as this data can easily be aggregated into any required time-step, such as 15 minutes, 60 minutes, daily, weekly, monthly, etc.

**Other considerations:** A preliminary investigation into precipitation patterns across the monitoring sites will be undertaken at the start of the project which will involve the positioning of numerous (Ca. ten) rain gauges simultaneously across each monitoring site for a set period of time by David Luscombe the Exeter PhD student and the Exeter Knowledge Transfer Partnership (KTP) Associate. The results of this investigation will contribute to our understanding of:
1. Rainfall patterns across each of the monitoring sites.
2. Topographic controls on precipitation levels across each of the monitoring sites.
3. The accuracy of the areal rainfall readings at the topographically high and low rain gauges (Pardo-Iguzquiza, 1998).

**Summary:** The accurate collection and measurement of rainfall data is fundamental to the accuracy of the water balance calculations and assessing the impact on the hydrological and hydrogeological project objectives. In particular, accurate rainfall data will help understand the relationship between rainfall intensity and gully erosion (Section 4.1.6).

4.1.2 Weather station and Evapotranspiration station (output) (Figure 11; B)

**Why:** A weather station located in each hydrological/hydrogeological monitoring site will assess the impact of meteorological conditions on the surrounding water environment and place these into context. The weather station should measure all the basic meteorological parameters such as wind speed, wind direction, temperature and evapotranspiration rates. Evapotranspiration sensors and the associated software should be added to the weather stations as this is an important measurement required for the water balance approach. The EA H&T team based at Exminster House has recommended the use of Casella Automatic Fixed Weather Stations for the measurement of meteorological conditions (http://www.casellameasurement.com/cl_ne_weatherstation.htm).

**Spatial:** Advice on the type and placement of the weather station will be sought from the EA Hydrology and H&T teams. The weather station will be located at a topographically high point of each monitoring site and adjacent to a tipping bucket and Octapent rain gauge (Section 4.1.1).
Temporal: Meteorological readings should be recorded at 15-minute intervals.

Other considerations: The ability to measure atmospheric pressure should be incorporated into the weather station as barometric effect can cause changes in groundwater levels (Section 4.1.3) and these need to be accounted for. Evapotranspiration rates are influenced by seasonal changes in vegetation cover and the measurement of these will allow an observed decrease/increase in groundwater levels to be confidently attributed to ditch blocking activities and not episodes of vegetation growth/decay.

Summary: Meteorological readings will be important for placing fluctuations of the water environment into context and for the accurate measurement of evapotranspiration rates which are fundamental to the accuracy of the water balance calculations.

4.1.3 Groundwater retention (storage) (Figure 11; C)

Why: The retention of groundwater within the peat is a major objective of the Mires-on-the-Moors project. Ditch blocking should result in an observed increase in groundwater levels, an increase in water storage across the site, which in turn should decrease water velocities (Section 4.1.5), lower peak flows during wet periods and increase baseflow levels during dry periods (Section 4.1.9). The accurate quantification of groundwater levels will also provide data for changes in the water storage component of the water balance methodology (Section 4.3).

Spatial: Transects should be positioned perpendicular to a drainage ditch and span across Experimental Pool 1. The number of transects and dipwells in each transect will be controlled by the complexity of the surface water system, the intensity of peat damage, topography and the size of the monitoring site. Dipwell transects should span across an entire drainage ditch as this will provide an accurate indication of:

1. Changes in total water storage as a result of ditch blocking activities;
2. The direction of groundwater flow paths; and
3. Groundwater responses to ditch blocking activities in both undisturbed peat (furthest from the drainage ditch) and disturbed/restored peat (closest to the drainage ditch).
Dipwells should be positioned across the drainage ditch as shown in the idealised transect displayed in Figure 2. The dipwells are installed at a higher spatial resolution when located in close proximity to the drainage ditch (Ca. < 2 m intervals) as this is where groundwater levels are likely to display the greatest fluctuations. Increased spatial monitoring of groundwater levels in this location will significantly enhance the accuracy of the two-dimensional groundwater profiles, which in turn will improve estimated changes in water storage before and after ditching blocking. These results need to be as accurate as possible as any inconsistencies will be greatly exacerbated when the results are interpolated across other restored regions of Exmoor National Park.

**Figure 2.** The justification behind the increased spatial monitoring of groundwater levels closest to the drainage ditches. For example, drainage ditches that are approximately 20 metres apart will have dipwells positioned at 0.5, 1, 2, 3, 5, 10, 15, 17, 18, 19 and 19.5 metres.

Dipwells should extend through the majority of the peat system which will ensure that the full maximum and minimum range of groundwater fluctuations are monitored. Care should be taken during the installation of the dipwells to avoid puncturing through the confining layer of clay or attaching the dipwells to the underlying mineral substrate which will restrict the vertical movement of the dipwells and result in an underestimation of groundwater fluctuations.

Ideally, geophysical analysis should be conducted along the proposed line of transects before the installation of the dipwells and on an annual basis thereafter, as the GPR results will provide detailed information on the depth of the underlying water table, the upper and lower limits of the clay layer and the presence/formation of peat pipes that will strongly influence surrounding groundwater levels. Ralph Fyfe who is a geophysicist based at the University of Plymouth is already involved in the Mires-on-the-Moors project.
**Temporal**: Groundwater levels need to be monitored before and after ditch blocking. Automated loggers should record groundwater levels at 15-minute intervals. Only a high temporal measurement period, such as 15-minute intervals, will clearly identify and confidently assess the impact of the ditch blocking activities on the surrounding water environment. Tim Allott and Martin Evans who are based at the University of Manchester have recommended the use of TruTrack data-loggers ([http://www.trutrack.com/WT-HR_apps.html](http://www.trutrack.com/WT-HR_apps.html)) for the measurement of groundwater levels for the Mires-on-the-Moors project.

**Other considerations**: In order to account for seasonal variations in the height of the peat surface the dipwells need to be designed to record the following measurements:

1. The top of the dipwell to the peat surface (A; Fig. 3).
2. The top of the dipwell to the groundwater level (B; Fig. 3).
3. The top of the dipwell to a fixed datum point (FDP) that is surveyed into AOD (C; Fig. 3).

A number of simple calculations can then be used to determine:

4. The peat surface to the groundwater level (D; Fig. 3).
5. The height of the peat surface in relation to the fixed datum point (AOD) (E; Fig. 3).
6. The height of the groundwater level in relation to the fixed datum point (AOD) (F; Fig. 3).
7. Seasonal variations in the height of the groundwater level (AOD).
8. Seasonal variations in the height of the peat surface (AOD).

Figure 3. The measurements required to account for seasonal variation in the height of the peat surface (FDP = Fixed Datum Point and ▼ indicates the groundwater level).
The fixed datum point should be positioned either on an exposed section of bedrock or two posts that are driven into the mineral substrate. The height comparison of two posts will show if one of the posts has detached itself from the underlying mineral substrate. The height difference between the top of the dipwell to the fixed datum point (C; Fig. 3) should be measured as often as possible by a laser level. Ideally, an automated system that records the height difference between the top of the dipwells and the fixed datum point at 15-minute intervals should be utilised. However, the author believes that such a system does not currently exist.

Care should be taken to avoid damage to the dipwells and the surrounding peat system by people and cattle. Periodic checks should be undertaken to ensure the dipwells remain vertical and the results of these checks should dictate when rehabilitation work is required.

Dipwells that are designed to account for seasonal variations in the height of the peat surface will be essential to the project as:

1. Variations in groundwater levels which result in increased water storage capacity across the monitoring site can be confidently attributed to ditch blocking activities and not to seasonal variations in the height of the peat surface as the latter can be accounted for and eliminated.
2. Groundwater fluctuations will not be underestimated and therefore subsequent water storage and water balance calculations will be accurate.
3. Accurate groundwater level readings will allow for a detailed review of dipwell performance including the identification of peat/debris blockages and/or surface water infiltration.
4. Assessing the height of the peat surface during pre and post-restoration periods will provide a useful indication of peat development.

The vast majority of peat restoration projects focus on the depth of the underlying groundwater in relation to the peat surface (D; Fig. 3) as this is the most important measurement in terms of peat growth. However, the Mires-on-the-Moors project also has a number of important hydrological and hydrogeological objectives that would be difficult to accurately monitor and assess without the collection of the above measurements.

**Summary:** Accurate groundwater level measurements will be important when assessing the project objectives, contribute to the accuracy of the water balance methodology and reveal a great deal about the hydrological and hydrogeological processes across the monitoring site.
4.1.4 Quantification of groundwater-surface water interactions within the newly created surface water pools (input/output) (Figure 11; D)

Why: The quantification of groundwater-surface water interactions between the newly created surface water pools and the underlying groundwater system is a major objective of the Mires-on-the-Moors project, will contribute towards the accuracy of the water balance calculations and influence other hydrological and hydrogeological objectives, such as the retention of groundwater within the mire system and the re-establishment of natural surface water flow regimes.

Previous peat restoration projects appear to have overlooked the potential impact of groundwater-surface water interactions within the newly created surface water pools which may influence other interrelated hydrological and hydrogeological processes. The damming of deep erosional gullies will reduce surface water flow rates across the monitoring site and almost certainly increase seepage rates through the beds of the newly formed surface water pools into the highly fractured underlying Sandstone bedrock that underlies the majority of Exmoor. Substantial surface water losses from the newly formed surface water pools could impact on surrounding groundwater levels and influence downstream surface water flow regimes.

Surface water commonly is hydraulically connected to groundwater, but interactions tend to be difficult to observe and measure (Winter et al., 1998; Sophocleous, 2002). To overcome these difficulties the majority of projects tend to use a range of methods (Negrel et al., 2003; Oxotobee and Novakowski, 2002; Dumouchelle, 2001) to identify and quantify the rate of groundwater inputs or surface water losses. The Mires-on-the-Moors project should follow suit.

Spatial and temporal: The temporal and spatial factors of the methods proposed are outlined in Tables 1 and 2. Indirect methods (Table. 1) are generally used to identify groundwater-surface water interactions and direct methods (Table. 2) are used to understand and quantify seepage flux rates (i.e. the rate and direction of water movement at the interface between surface water and groundwater systems). Both the indirect and direct methods will be assessed at the Experimental Pools (Section 4.2).

Summary: These methods are relatively simple to use, inexpensive and provide information on the occurrence, velocity and seepage rate of groundwater inputs and surface water losses.
### Table 1. Indirect methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Equipment</th>
<th>Spatial</th>
<th>Temporal</th>
<th>Additional comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Visual observations</strong></td>
<td>No in-situ equipment.</td>
<td>Across the monitoring site.</td>
<td>Start, pre-restoration and end. Snapshot survey.</td>
<td>Groundwater may be identified flowing into the surface water pools from seeps and springs at the margins or through the bed. <strong>Thermal signatures</strong> Mini-temperature loggers installed in both the water column and the sediment. Experimental Pools (Section 4.2). Fifteen minute intervals. Thermal signatures can provide information on the occurrence of neutral pools, groundwater inputs or surface water losses (Figure. 4). The optimum period for thermal surveys is when the greatest temperature difference occurs between the surface water and groundwater systems which tends to be mid summer and mid winter. It can sometimes be difficult to identify between losing or neutral surface water pools using this method. This method can also be used to calculate seepage flux rates (Lowry <em>et al.</em>, 2007). <strong>Head difference</strong> In-situ wooden peg inserted into the bed of the surface water pool and an adjacent dipwell (Figure. 5). Experimental Pools (Section 4.2). Readings should be recorded weekly until an appreciation of head difference is obtained then reduced to monthly. Groundwater levels measured in dipwells (B; Fig. 5) can be compared against the stage height of adjacent surface water pools via a wooden stake (D; Fig. 5) which will provide an indication to the potential of groundwater inputs or surface water losses. Height differences between the top of the dipwell (A; Fig. 5) and the top of the wooden stake (C; Fig. 5) can be measured by a laser level.</td>
</tr>
</tbody>
</table>

### Table 2. Direct methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Equipment</th>
<th>Spatial</th>
<th>Temporal</th>
<th>Additional comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Volumetric Stream flow method</strong></td>
<td>No in-situ equipment.</td>
<td>Experimental Pools (Section 4.2).</td>
<td>Post-restoration, Accurate readings will be obtained during stable flow conditions.</td>
<td>Differences in flow at the inlet and the outlet of a surface water pool should equate to surface water losses or groundwater inputs through the pool bed. A small notch could be cut into the top of the wooden dams that would create a temporary single cascade for flow measurement purposes. Checks for seepage under and around each dam will have to be undertaken as unmeasured seepages would create false positives.</td>
</tr>
<tr>
<td><strong>Automated mini-piezometers or a seepage meter</strong></td>
<td>Three automated stilling well type mini-piezometers or a seepage meter.</td>
<td>Experimental Pools (Section 4.2).</td>
<td>Seepage rates will be logged at 15-minute intervals.</td>
<td>This method will provide an accurate estimate of vertical hydraulic gradient, hydraulic conductivity and specific flow through the base of each surface water pool (Baxter and Hauer, 2003) (Figure. 6).</td>
</tr>
</tbody>
</table>
Figure 4. Thermal signatures of groundwater, bed sediment and water column temperatures of a gaining, losing and neutral pool (adapted from Silliman and Booth, 1993).

Figure 5. Head difference assessment via the comparison of groundwater level and stage height.
Figure 6. The principles of mini-piezometers and seepage meters in a (A) losing and (B) gaining surface water pool (Lee and Cherry, 1978; Baxter and Hauer, 2003).

4.1.5 Water velocity

**Why:** A reduction in surface water velocity rates after ditch blocking was highlighted by South West Water as a major objective of the Mires-on-the-Moors project. The installation of numerous dams across the restored area should reduce surface water velocity rates across the monitoring site especially during times of peak flow. However, this reduction will only be evident in the surface water system immediately downstream of the monitoring site as other factors, such as variations in streambed friction, stream debris, riverbed elevation and growth of aquatic vegetation, will be more dominant. This data will not contribute to the water balance calculation.

**Spatial:** Surface water velocity will either be recorded directly or derived from other factors recorded at the flow gauging station (Section 4.1.9). The positioning of the flow gauging station will be influenced by site specific factors which will need to account for the following;
- Finding a suitable cross-section for a flow gauging station.
- Inflowing tributaries originating from other un-restored parts of the catchment will most likely react differently and may conceal any measurable differences.
- Surface water velocity rates will be impacted by other factors, such as variations in streambed friction, debris/obstructions, riverbed elevation, growth of aquatic vegetation, etc.

**Temporal:** Water velocity readings should be recorded at 15-minute intervals.
Summary: The installation of dams across the site is expected to result in a reduction of surface water velocity immediately downstream of the restoration/monitoring site. However, these reductions will only be evident over a short reach length as other factors will have a much greater influence over surface water flow velocity rates.

4.1.6 Gully erosion

Why: A reduction in the rate of gulley erosion is a major objective of the Mires-on-the-Moors project. The rate of gully erosion will be controlled by the velocity of flowing water across the peat surface, which should reduce as a result of ditch blocking activities. Sediment that originates from gully erosion processes will enter headwater streams and impact on a number of downstream hydrological and hydrogeological processes through the process of colmation (i.e. the blocking of interstitial spaces), which could:

- Increase the size and frequency of flood events.
- Decrease the flow capacity of the surface water channel.
- Lead to a deterioration of downstream water quality.
- Disconnect the surface water and groundwater systems which will impact on nutrient exchanges, baseflow, spawning sites of Atlantic salmon (Salmo salar) and Brown trout (Salmo trutta) and water supply mechanisms to riparian based groundwater dependent terrestrial ecosystems, such as marshes, fens, alluvial woodland, etc.

This data will not contribute to the water balance calculation.

Spatial: The rate of gully erosion should be measured across the monitoring sites via the following techniques:

1. Topographic surveys that focus on areas of potential gully development, such as ditches, sheep tracks, hollows, footpaths, ravines, etc.
2. Water samples that are collected at the three Experimental Pools and the downstream flow gauging station for the comparison of flow and suspended sediment concentration (SSC) before and after ditch blocking. Note-storm samples can also be used for water quality (i.e. mineral and organic particulate content) and carbon balance analysis.

Temporal:

1. A detailed topographic survey should be conducted at the start, prior to restoration and at the end of the five-year project.
2. Water samples will either be collected at certain points along the storm hydrograph or at fifteen-minute intervals (24 samples X 15 minute intervals = 360 minutes/6 hour coverage) by an automated ISCO water sampler when an automated stage/flow trigger value is activated during the rising limb of a storm event. Ideally, water samples will be collected during eight to ten storm events per annum. The decision when to collect the water samples (i.e. across the storm hydrograph or at fifteen minute intervals) will be data led.

Analysis of the sediment samples will be undertaken in the sediment laboratory at the University of Exeter and the results will allow the development of scatter plots showing flow rates versus SSC. The gradient of the linear trend-line should decrease after ditch blocking (i.e. less sediment input with increased flow rates) as water velocities should reduce across the monitoring site and so will erosional properties which in turn will lower the amount of suspended sediment entering the surface water system (Figure. 7). Richard Brazier who is based at the University of Exeter has developed a technique to account for the wide distribution of SSC points during this type of analysis.

The Environment Agency has developed a flood forecasting system that sends out an automated warning message 24 and 36 hours prior to an intense rainfall event which would provide adequate time to organise the prompt collection of the water samples (Note- after a rainfall event the SSC water samples need to be collected and analysed ASAP). A flood forecasting point should be setup for the two Exmoor hydrological and hydrogeological monitoring sites.

Other considerations: The breakpoint rainfall intensity data supplied by the two tipping bucket rain gauges (Section 4.1.1) at each monitoring site will significantly contribute to our understanding of the relationship between precipitation events and gully erosion/sedimentation deposition before and after ditch blocking.

Summary: A reduction in downstream sedimentation and colmation rates will be beneficial to all the surface water systems that originate from Exmoor National Park, such as the River Bray, the River Quarme, the River Barle, the River Heddon, the East Lyn River, the West Lyn River and the River Exe.
Figure 7. Scatter plots showing an illustration of potential changes in flow rates (l s\(^{-1}\)) and suspended sediment concentrations (SSC) (mg l\(^{-1}\)) during (A) pre restoration and (B) post restoration periods.

4.1.7 Overland flow

**Why:** Overland flow is an important surface water process across peat systems that will most likely influence the structure of the underlying vegetation, impact on the retention of groundwater across the monitoring site and may highlight where future restoration efforts need to be focused. This data will not contribute to the water balance calculation and this assessment will be undertaken at the Experimental Pools (Section 4.2).

**Spatial:** Depending on the topographical setting around the Experimental Pools a grid of ten capacitance probes will be positioned on the surface and will run along both sides of each Experimental Pool and then extend beyond the dams as shown in Figure 8. The capacitance probes will measure the occurrence, duration, depth (and therefore extent) and direction of each episode of overland flow.

**Temporal:** The capacitance probes will be set up to log the presence/absence, depth and duration of water at 15-minute intervals.
Figure 8. Plan view showing the grid of the capacitance probes for the measurement of the occurrence, duration, extent and direction of overland flow events (⊗ = capacitance probe).

Summary: The measurement of overland flow processes are important to the project objectives, could highlight where to focus future restoration efforts and will increase our understanding of the relationship between overland flow and the structure of mire vegetation.

4.1.8 Through flow

Why: The through flow of surface water into the surrounding groundwater system will most likely influence groundwater retention within the mire system which is a major objective of the Mires-on-the-Moors project. Quantifying the rate and extent of through flow processes during pre and post restoration periods will be undertaken by episodic chemical tracing experiments and a transect of mini-conductivity loggers. This data will not contribute to the water balance calculation and this assessment will be undertaken at the Experimental Pools (Section 4.2).

Spatial: Transects of dipwells need to extend beyond the dams of the Experimental Pools as shown in Figure 9. The dipwells should infiltrate the majority of the peat structure to ensure the lateral extent of the through flow process is effectively monitored. Ten mini-conductivity loggers need to be activated and inserted into the dipwells to a similar depth, such as 30 cm below ground level,
before introducing the conservative (i.e. un-reactive with suspended sediment, aquatic vegetation or the bed of the surface water pool) ionic tracer into the upstream surface water course via the integrated/gulp injection method. Church (1975) defines chemical tracing as the introduction of a substance (i.e. sodium chloride (NaCl)) into a circulating medium (i.e. surface water) allowing its course to be followed by some singularly identifiable characteristic (i.e. an increase of ionic tracer concentration recorded by the mini-conductivity loggers in the dipwell transects).

![Diagram](image)

Figure 9. The dipwell array that will measure the rate and extent of through flow processes at the Experimental Pools (Section 4.2).

A preliminary investigation will be undertaken at the start of the project to assess the lowest amount of ionic tracer that will produce a signal at the mini-conductivity loggers. This will entail entering an ever increasing amount of ionic tracer into the surface water system at hourly intervals until a signal is observed. The tracer will be entered into the upstream surface water course at a distance of seven times the width of the surface water channel at the dipwells to ensure the tracer is fully absorbed into the surface water system before it reaches the dipwells and the mini-conductivity loggers.

**Temporal:** Repeating the chemical tracing experiments at three monthly intervals (i.e. winter, spring, summer and autumn) will assess through flow processes across an annual cycle and during both pre and post restoration periods.

**Other considerations:** Chemical tracing experiments can also be used to measure flows in turbulent headwater streams and these tracing experiments could contribute towards the calibration of surface water flow rates at the downstream flow gauging station (Church, 1975) (Section 4.1.9).
Summary: The improved understanding of through flow processes is important to a number of Mires-on-the-Moors project objectives and could lead to a greater understanding of the impact of groundwater and surface water processes on the mire vegetation.

4.1.9 Flow (output) (Figure 11; E)

Why: Restored peat tends to be associated with the lowering of peak flows during storm events and increased baseflow levels during low flow periods, which are both major objectives of the Mires-on-the-Moors project (Section 3). As a result, accurate flow measurements are required as this data will be used to measure the success or failure of the numerous project objectives and will be a very important component of the water balance calculation (Section 4.3).

Spatial: The characteristics of the surface water channel will influence the location and type of flow gauging station that will be installed at each hydrological and hydrogeological monitoring site. Advice on the type and placement of flow gauging stations will be sought from the EA Hydrology and H&T team based at Exminster House.

A number of other factors must also be considered when positioning the flow gauging station. For example, the flow gauging station needs to be positioned;

1. Close enough to the monitoring site to capture the full impact of the ditch blocking activities.
2. Far enough from the monitoring site for the groundwater flow paths not to traverse around the flow gauging station.
3. On a first order stream as inputs originating from un-restored or unmonitored sections of the monitoring site will distort the water balance calculations.
4. Account for anthropogenic activities, such as SW abstractions/discharges, GW abstractions/discharges, which are expected to be sparse in these headwater catchments.
5. Ideally, where the surface water system flows over an impermeable layer and groundwater flows will rise to the surface to eliminate the loss of unrecorded lateral groundwater flows leaving the monitoring site (Fig. 11; F). Structures will also be constructed to funnel these lateral groundwater flows through the flow gauging station.

Temporal: Flow readings should be recorded at 15-minute intervals, which will;

1. Accurately assess the hydrological project objectives, such as the lowering of peak flows and increased baseflow levels.
2. Provide detailed hydrological datasets for the purposes of accurate water balance calculations.

**Other considerations:** Chemical tracing using conservative ionic tracers, such as sodium chloride (NaCl), will be used to assess the rate of through flow at the Experimental Pools (Section 4.2). This technique can also be used to measure flow rates in turbulent headwater streams (Church, 1975) and the same tracing experiment could be used to calibrate flow rates at the downstream flow gauging station.

**Summary:** The restoration effort aims to stabilise flow regimes which will have a range of positive benefits on the downstream aquatic flora and fauna.

### 4.2 Experimental surface water pools

**Why:** A number of the Mires-on-the-Moors project objectives can only be assessed at the individual pool-scale. As a result, three surface water pools, which will be termed Experimental Pools, will be selected for high temporal and spatial monitoring to quantify seepage flux rates (Section 4.1.4), overland flow (Section 4.1.7) and through flow processes (Section 4.1.8) as shown in Figure 10. Surface water temperatures, groundwater temperatures, flow measurements and SSC will also be recorded at each Experimental Pool which will contribute to our understanding of ditch blocking at a nested approach and changes across the hydrological and hydrogeological system at a localised scale during both pre and post restoration periods.

**Spatial:** The Experimental Pools will be positioned in a transect across each monitoring site and situated above a range of peat depths, for example, Experimental Pool 1 above deep peat, Experimental Pool 2 above shallow peat and Experimental Pool 3 will be situated along the main surface water channel. The dipwell transect outlined in Section 4.1.3 will span Experiment Pool 1 as this will provide a valuable link between the pool-scale and the catchment-scale monitoring, produce interrelated datasets and monitor a range of hydrological and hydrogeological processes and interactions.

**Temporal:** With the exception of the chemical tracing experiments, which will be performed at three monthly intervals, the monitoring equipment installed in and around the Experimental Pools will record at 15 minute intervals.
Summary: Monitoring at the localised pool-scale will effectively assess a number of project objectives, contribute towards a nested approach, provide a valuable link between pool-scale and catchment-scale monitoring and assess a range of hydrological and hydrogeological interactions.

4.3 Methodology of the water balance approach

The water balance approach is based on the principle of the conservation of mass and requires the accurate quantification of inputs, outputs and changes in water storage over time (Figure. 11 and Table 3). The selection of suitable headwater catchments is fundamental to the success of this approach as all of the surface water outputs are required to drain past a single flow measurement point which will be monitored by a flow gauging station. The water balance equation can be expressed as:

\[
\text{Sum of inputs} = \text{Sum of outputs} + \text{Change in storage}
\]

\[
P_{\text{net}} + Q_{\text{in}} + G_{\text{in}} + S_{\text{in}} = E + Q_{\text{out}} + G_{\text{out}} + S_{\text{out}} + \Delta s
\]
where $P_{net}$ is precipitation (Fig. 11; A), i.e. the amount of precipitation that reaches the ground; $Q_{in}$ and $Q_{out}$ are surface water flows (Fig. 11; E) in and out of the study site; $G_{in}$ and $G_{out}$ are groundwater flows (Fig. 11, F) in and out of the study site; $S_{in}$ and $S_{out}$ are seepage fluxes (Fig. 11; D) in and out of the study site; $E$ is evapotranspiration (Fig. 11; B); and $\Delta S$ changes in water storage (Fig. 11; C).

Figure 11. The methodology of the water balance approach (A = rain gauges (Section 4.1.1), B = weather/evapotranspiration station (Section 4.1.2), C = dipwells (Section 4.1.3), D = seepage meter/mini-piezometers (Section 4.1.4), E = flow gauging station (Section 4.1.9) and F = groundwater flows).

Seepage, evapotranspiration and surface water flow values listed in Table 3 all represent losses when calculated against rainfall inputs. Rainfall can be temporarily retained in groundwater storage and then released in a successive time step. Negative groundwater storage values represent a loss from the rainfall total and an increase in groundwater storage. Positive values represent a decrease in groundwater storage and water being released to the surface water flow component.
Table 3. An example of the water balance methodology. Litres in the table are equivalent to the quantity of the water in relation to the measured inputs, outputs and changes in storage at each monitoring site over a ten day period.

<table>
<thead>
<tr>
<th>Timestep</th>
<th>Rainfall (A; Fig. 11)</th>
<th>Seepage (D; Fig. 11)</th>
<th>Evapo-tran (B; Fig. 11)</th>
<th>SW flow (E; Fig. 11)</th>
<th>GW Storage (C; Fig. 11)</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Litres %</td>
<td>Litres %</td>
<td>Litres %</td>
<td>Litres %</td>
<td>Litres %</td>
<td>Litres %</td>
</tr>
<tr>
<td>1-10 Nov 10</td>
<td>+10000 +100</td>
<td>-300 -3</td>
<td>-200 -2</td>
<td>-9500 -95</td>
<td>0 0</td>
<td>0 0</td>
</tr>
<tr>
<td>11-20 Nov 10</td>
<td>+8000 +100</td>
<td>-400 -5</td>
<td>-400 -5</td>
<td>-6720 -84</td>
<td>-400 -5</td>
<td>80 1</td>
</tr>
<tr>
<td>21-30 Nov 10</td>
<td>+5000 +100</td>
<td>-50 -1</td>
<td>-150 -3</td>
<td>-4600 -92</td>
<td>-100 -2</td>
<td>100 2</td>
</tr>
<tr>
<td>1-10 Dec 10</td>
<td>+9000 +100</td>
<td>-450 -5</td>
<td>-450 -5</td>
<td>-8100 -90</td>
<td>0 0</td>
<td>0 0</td>
</tr>
<tr>
<td>11-20 Dec 10</td>
<td>+2500 +100</td>
<td>-75 -3</td>
<td>-150 -6</td>
<td>-2375 -95</td>
<td>0 0</td>
<td>-100 -4</td>
</tr>
<tr>
<td>21-30 Dec 10</td>
<td>+10000 +100</td>
<td>-300 -3</td>
<td>-300 -3</td>
<td>-9400 -94</td>
<td>+500 +5</td>
<td>500 5</td>
</tr>
<tr>
<td>31-9 Jan 11</td>
<td>+5000 +100</td>
<td>-100 -2</td>
<td>-250 -5</td>
<td>-4700 -94</td>
<td>+50 +1</td>
<td>0 0</td>
</tr>
<tr>
<td>10-20 Jan 11 – Ditch Blocking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21-30 Jan 11</td>
<td>+10000 +100</td>
<td>-500 -5</td>
<td>-500 -5</td>
<td>-8300 -83</td>
<td>-1000 -10</td>
<td>-300 -3</td>
</tr>
<tr>
<td>31-9 Feb 11</td>
<td>+8000 +100</td>
<td>-320 -4</td>
<td>-240 -3</td>
<td>-7200 -90</td>
<td>-160 -2</td>
<td>80 1</td>
</tr>
<tr>
<td>10-19 Feb 11</td>
<td>+10000 +100</td>
<td>-500 -5</td>
<td>0 0</td>
<td>-10000 -100</td>
<td>0 0</td>
<td>-500 -5</td>
</tr>
</tbody>
</table>

The water balance calculations will account for variations in weather conditions during the monitoring as variations in hydrological and hydrogeological compartments will be transformed and presented in both absolute values and percentages (Table 3). Analysis of the percentage values will allow us to assess the impact of the ditch blocking on the numerous hydrological and hydrogeological compartments irrespective of antecedent weather conditions. For example, the green text highlighted in Table 3 shows a substantial increase in groundwater storage immediately after ditch blocking which would be clearly highlighted when presented in percentages. The most representative timestep at each monitoring site will be ascertained by assessing monitoring data from storm events and the overall behaviour of the hydrological and hydrogeological system.

A number of assumptions can be made by using small headwater catchments and therefore eliminated (highlighted above in red text) from the water balance calculations (Gilman, 1994);

- Surface water inflows will not enter the study site due to the topographically high catchment boundaries;
- Groundwater inflows will not enter the study site due to the underlying impermeable clay layer;
- Groundwater outflows will not leave the study site due to the presence of the underlying impermeable clay layer and the careful positioning of the flow gauging station. Furthermore, structural wings will be installed at the downstream end of each site to direct any lateral groundwater flows through the flow gauging station.
Care must be taken to avoid un-monitored cross-catchment transfers as they will distort the results of the water balance assessment. For example;

- Drainage ditches that traverse the catchment divide should either be blocked below the divide or impermeable barriers erected along the divide as dams will increase the stage height of the surface water pools and surface water flows maybe re-directed into the adjacent catchment.
- Peat pipes may create cross-catchment transfers (Holden, 2002). GPR analysis could be used to survey sections of the catchment divide to confirm the presence/absence of peat pipes.

The accuracy of the monitoring equipment will control the effectiveness of the water balance methodology. For example, if flow readings are generally +/- 10% of actual flow rates then water balance outputs will be approximately +/- 10%. The use of uncertainty ratings will be investigated.

4.4 Monitoring duration
The water balance approach should reduce the need for long-term baseline monitoring that is dependent on antecedent weather conditions as this approach should account for any atypical climatic conditions. However, it would be advantageous to collect baseline monitoring data over a twelve to eighteen month period to place the pre and post-ditch blocking hydrological and hydrogeological patterns into context and to assess the accuracy of the water balance outputs across a range of flows.

4.5 Temporal logging resolution
To accurately assess the project objectives a temporal logging resolution of 15-minutes has been recommended for all the automated monitoring equipment. A fifteen minute logging rate will capture all the necessary groundwater and surface water processes across a monitoring site, such as the lowering of peak flows and an increase of baseflow levels after ditch blocking. A greater temporal logging interval is likely to miss important information, such as peak flow rates, as surface water systems that drain peat regions are notoriously flashy.

4.6 Estimated equipment costs
Table 4 lists the estimated costs of the monitoring equipment that will be installed at each Exmoor monitoring site. They exclude installation costs. However, the construction of the flow gauging
station platform will be the only major installation. This cost is difficult to ascertain at this time as it will depend on the range of flows that need to be recorded and the subsequent size of the flow gauging station. Flow range assessments are currently being undertaken by the Devon and Cornwall-Hydrology Team.

Table 4. The estimated cost of the monitoring equipment at each monitoring site.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Number</th>
<th>Approx cost (£)</th>
<th>Minimum cost (£)</th>
<th>Maximum cost (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Personal digital assistant (PDA)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hand held unit</td>
<td>1</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rainfall</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard rain gauge</td>
<td>2</td>
<td>650</td>
<td>1300</td>
<td>1300</td>
</tr>
<tr>
<td>Tipping bucket rain gauge</td>
<td>2</td>
<td>700</td>
<td>1400</td>
<td>1400</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Climate and Evapotranspiration</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weather station + sensors + software</td>
<td>1</td>
<td>7000</td>
<td>7000</td>
<td>7000</td>
</tr>
<tr>
<td>40 Watt solar panel</td>
<td>1</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Groundwater levels</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation of fixed datum point + survey</td>
<td>1</td>
<td>2000</td>
<td>2000</td>
<td>2000</td>
</tr>
<tr>
<td>Groundwater dipper</td>
<td>1</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Laser level</td>
<td>1</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Dipwells</td>
<td>22</td>
<td>100</td>
<td>2200</td>
<td>2200</td>
</tr>
<tr>
<td>Groundwater level equipment</td>
<td>22</td>
<td>900</td>
<td>19800</td>
<td>19800</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>GW-SW interactions (3 pools)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mini-temperature loggers</td>
<td>18</td>
<td>105</td>
<td>1890</td>
<td>1890</td>
</tr>
<tr>
<td>Automated seepage meter</td>
<td>3</td>
<td>4000</td>
<td>12000</td>
<td>12000</td>
</tr>
<tr>
<td>Dipwells</td>
<td>2</td>
<td>100</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Groundwater level equipment</td>
<td>2</td>
<td>900</td>
<td>1800</td>
<td>1800</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Overland flow (3 pools)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitance probes</td>
<td>60</td>
<td>80</td>
<td>4800</td>
<td>4800</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Through flow (3 pools)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conservative tracer</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>Dipwells</td>
<td>30</td>
<td>50</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Mini-conductivity loggers</td>
<td>30</td>
<td>100</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.7 Work plan

The following table identifies who will be monitoring which pieces of hydrological and hydrogeological monitoring equipment at each site, how often and over what time period (Table 5).

Table 5. Who is monitoring what, how often and over what time period.

<table>
<thead>
<tr>
<th>Parameter &amp; monitoring (it is assumed that battery power will also be monitored)</th>
<th>No</th>
<th>EA or Exeter</th>
<th>Site visits</th>
<th>Project start date</th>
<th>Project end date</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rainfall</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage (Octapent) rain-gauge</td>
<td>2</td>
<td>EA</td>
<td>*W to M</td>
<td>1st Oct 2010</td>
<td>31st Mar 2015</td>
</tr>
<tr>
<td><strong>Climate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Climate station + evapotranspiration + additional sensors (i.e. leaf wetness)</td>
<td>1</td>
<td>EA</td>
<td>*W to M</td>
<td>1st Oct 2010</td>
<td>31st Mar 2015</td>
</tr>
<tr>
<td><strong>Groundwater</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total survey station survey + Installation of fixed datum point</td>
<td>1</td>
<td>Contractor</td>
<td>Once at the start</td>
<td>Prior to the 1st Oct 2010</td>
<td>31st Mar 2015</td>
</tr>
<tr>
<td><strong>GW-SW interactions (3 pools)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual observations</td>
<td>N/a</td>
<td>Exeter</td>
<td>Quarterly</td>
<td>1st Oct 2010</td>
<td>31st Mar 2015</td>
</tr>
<tr>
<td>Mini-temperature loggers (6 X 3 pools)</td>
<td>18</td>
<td>Exeter</td>
<td>*W to M</td>
<td>Site &amp; flow dependent</td>
<td>31st Mar 2015</td>
</tr>
<tr>
<td>Equipment Description</td>
<td>Number</td>
<td>Location</td>
<td>Frequency</td>
<td>Start Date</td>
<td>End Date</td>
</tr>
<tr>
<td>-----------------------</td>
<td>--------</td>
<td>----------</td>
<td>-----------</td>
<td>------------</td>
<td>----------</td>
</tr>
<tr>
<td>Stage recording equipment (1 X 3 pools)</td>
<td>3</td>
<td>Exeter</td>
<td>*W to M</td>
<td>1 Oct 2010</td>
<td>31 Mar 2015</td>
</tr>
<tr>
<td>Volumetric stream flow measurements (2 X 3 pools)</td>
<td>6</td>
<td>Exeter</td>
<td>*W to M</td>
<td>Post ditch blocking</td>
<td>31 Mar 2015</td>
</tr>
<tr>
<td>Seepage meter or mini-piezometers (1 X 3 pools)</td>
<td>3</td>
<td>Exeter</td>
<td>*W to M</td>
<td>Site &amp; flow dependent</td>
<td>31 Mar 2015</td>
</tr>
<tr>
<td>Evaporation pans (1 X 3 pools)</td>
<td>3</td>
<td>Exeter</td>
<td>*W to M</td>
<td>1 Oct 2010</td>
<td>31 Mar 2015</td>
</tr>
<tr>
<td>Overland flow (3 pools)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitance probes (20 X 3 pools)</td>
<td>60</td>
<td>Exeter</td>
<td>*W to M</td>
<td>1 Oct 2010</td>
<td>31 Mar 2015</td>
</tr>
<tr>
<td>Through flow (3 pools)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical tracing</td>
<td>N/a</td>
<td>Exeter</td>
<td>Quarterly</td>
<td>1 Oct 2010</td>
<td>31 Mar 2015</td>
</tr>
<tr>
<td>Mini-conductivity loggers (10 X 3 pools)</td>
<td>30</td>
<td>Exeter</td>
<td>Quarterly</td>
<td>1 Oct 2010</td>
<td>31 Mar 2015</td>
</tr>
<tr>
<td>Gully erosion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automated water sampler (1 X 3 pools + 1 adjacent to the flow gauging station)</td>
<td>4</td>
<td>Exeter</td>
<td>Post storm</td>
<td>1 Oct 2010</td>
<td>31 Mar 2015</td>
</tr>
<tr>
<td>Total survey station survey for topographic changes</td>
<td>N/a</td>
<td>Contract</td>
<td>Start, mid &amp; end</td>
<td>1 Oct 2010</td>
<td>31 Mar 2015</td>
</tr>
<tr>
<td>Flow (including stage)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow gauging station</td>
<td>1</td>
<td>EA</td>
<td>*W to M</td>
<td>1 Oct 2010</td>
<td>31 Mar 2015</td>
</tr>
<tr>
<td>Water velocity</td>
<td>1</td>
<td>EA</td>
<td>*W to M</td>
<td>1 Oct 2010</td>
<td>31 Mar 2015</td>
</tr>
<tr>
<td>Solar panel</td>
<td>1</td>
<td>EA</td>
<td>*W to M</td>
<td>1 Oct 2010</td>
<td>31 Mar 2015</td>
</tr>
</tbody>
</table>

* Initially weekly for approx 6 weeks then reduced to monthly site visits (in the above table this is indicated as W to M). EA = The Environment Agency and Exeter = The University of Exeter.

4.8 Advantages and disadvantages of the water balance approach

4.8.1 Advantages

1. The water balance approach will confidently assess the Mires-on-the-Moors objectives. Inferior monitoring plans will make it inherently difficult to confidently attribute an increase in groundwater levels to either ditch blocking activities, a precipitation event or a reduction in evapotranspiration rates as a result of changes in vegetation cover.

2. This monitoring plan negates the need for long-term weather dependent baseline monitoring as results will not be influenced by antecedent weather conditions. However, it would be advisable to collect twelve to eighteen months of baseline monitoring data to place the pre and post-ditch blocking hydrological and hydrogeological data into context and to assess the accuracy of the water balance approach across a range of flows.

3. The accuracy of the monitoring equipment can be calibrated and assessed by investigating datasets provided by the other field equipment that are monitoring different components of the hydrological and hydrogeological water balance. For example, precipitation levels (input)
should be equivalent to evapotranspiration (output) and flow (output) rates over a set period of time. If not, some of the field equipment may not be monitoring to the required standard.

4. Future collaborations/research opportunities will require the collection of accurate hydrological and hydrogeological datasets. This will be fundamental in attracting future project partners to develop and extend the Mires-on-the-Moors project beyond its initial five-year funding period.

5. The results provided by this monitoring plan will contribute to and further our understanding of peat groundwater and surface water processes. For example, the quantification of surface water losses and groundwater inputs through the beds of the newly created surface water pools and the comprehensive spatial and temporal monitoring in and around the Experimental Pools.

4.8.2 Disadvantages

1. Greater costs will be associated with the water balance approach as additional equipment, such as a weather station and evapotranspiration sensors will be required at each monitoring site.

2. The monitoring strategy may require some fine-tuning to provide the most accurate results and water balance outputs.

3. Undetected/unknown hydrological and hydrogeological processes may create imbalances between inputs and outputs, such as subterranean peat pipes creating un-monitored cross-catchment transfers.

4. Hydrological and hydrogeological variations may be within the accepted accuracy of the monitoring equipment.

5. Recommendations for ditch blocking across the monitoring sites

Below are a number of recommendations for ditch blocking across the monitoring sites-

A. Dams should be installed manually instead of using heavy and unwieldy mechanical excavators that may damage the monitoring equipment.

B. Dams should be inserted across the entire monitoring site as quick as feasibly possible to increase the likelihood of observing a signal across the hydrological and hydrogeological compartments as a result of the ditch blocking.

C. Where possible monitoring equipment should remain in-situ and continue logging during the ditch blocking as this data should provide us with an invaluable insight into the transition period between pre and post restoration.
6. Site selection
The site selection process was based on (1) the outputs of a GIS screening tool, (2) site specific factors and finally (3) site visits.

1. Approximately thirty hydrological/hydrogeological monitoring sites, which comprised of small headwater catchments (1 - 3 km²) as shown in figure 12, were identified across Exmoor National Park by a GIS screening tool. The GIS screening tool utilised a number of digitized GIS layers, such as the digital terrain model, detailed river network and potential restoration areas across Exmoor. The GIS screening tool also provided an indication of;
   - The complexity of the surface water system;
   - Topography;
   - Intensity and extent of damage to the peat structure; and
   - An anthropogenic activity, such as GW abstractions, SW abstractions, SW discharges, etc.

2. These thirty selected field sites were then assessed by David Smith who is the Exmoor National Park restoration project officer for access rights, site accessibility (i.e. proximity of roads, footpaths and bridleways), health & safety implications, inaccessible terrain, etc. Approximately 20 sites were excluded during this assessment.

3. Site visits were undertaken to the ten remaining sites by Environment Agency staff, Exmoor National Park Authority staff and the University of Exeter staff. Many of these sites were deemed unsuitable due to limited peat damage, steep topography, etc. Two final monitoring sites that were selected as shown in Appendix 1 & 2.

7. Overall Summary
This monitoring plan has been developed to accurately assess the impact of ditch blocking activities on the Mires-on-the-Moors hydrological and hydrogeological project objectives (Section 3). However, during the development of this monitoring plan other benefits have transpired, for example the use of a water balance to reduce long-term weather dependent baseline monitoring. This is a major advantage for a five-year project as the full impact of the ditch blocking on downstream flow regimes (i.e. a reduction of peak flows and an increase in baseflow levels) may not be evident for between three to five years.
Figure 12. Outputs of the GIS screening tool for Exmoor (purple lines indicate drainage ditches, green hatched polygons are small headwater catchments/potential monitoring sites and red polygons are damaged peat regions/restorable areas within each small headwater catchment).
8. Recommendations

It is recommended that the Mires-on-the Moors steering group should adopt this monitoring plan as failure to do so will result in a long weather dependent baseline monitoring period, present problems when assessing the impact of the ditch blocking activities on the hydrological and hydrogeological project objectives and will make it inherently difficult to place the datasets into context.

9. Acknowledgements

Many thanks to Tim Allott, Joseph Holden, Richard Brazier, Martin Evans, Ralph Fyfe and all the other numerous consultees for contributing to this monitoring plan. Thanks to David Smith, Frances Cooper, Chris Underwood and Mary-Rose Lane for allowing me the opportunity to work on the Mires-on-Moors project. Many thanks to Kate Bowers, Tim Shipton, Paul Mason and Paul Smith for providing me with sound technical advice and the estimated costs of the field monitoring equipment.
References


Appendix 1

Site 1

Site description: This site has been significantly damaged by 19th and early 20th century ditch cutting with the aim of draining the site for agricultural use. The drainage ditches are spaced approximately 20 to 21 metres apart, 30-100 cm deep and 30-100 cm wide. A number of drainage ditches also run perpendicular through the site to form a lattice of drainage ditches across the monitoring catchment. The site has a catchment area of 0.136 km².

As a result of extensive anthropogenic damage across the monitoring site, the main surface water channel tends to be dry for prolonged periods of time. This will preclude the use of the water balance approach during these dry periods as no outputs will be measured. However, this site should be included in the monitoring strategy of the Mires-on-the-Moors project as it is typical of damaged sites across Exmoor National Park and changes in the hydrological and hydrogeological regime as a result of the ditch blocking will be very evident.

Other factors: The location of the downstream flow gauging station will be determined by capturing the largest possible monitoring site with consideration given to an area of raised peat, which is most likely fed by underground spring sources, at the downstream end of the monitoring site. Water in the outflow channel will disperse through this valley mire system which will result in a dampening of the discharge hydrograph and negates the possibility of situating the flow gauging station downstream of this groundwater fed ecological feature.
Appendix 2
Site 2

Site description: The left flank (facing upstream) of this monitoring site has been significantly damaged by ditches typical of late 19th and early 20th century moorland drainage activity across Exmoor National Park. The drainage ditches are spaced approximately 20 to 21 metres apart, 30-100 cm deep and 30-100 cm wide. The drainage ditches tend to increase in depth and width from the top to the bottom of the monitoring site. The topographically high areas of the monitoring site have also been extensively damaged by 16th century domestic peat cuttings. The right flank (facing upstream) of the monitoring site is damaged to a lesser degree and encompasses a patch of grassland that is located above mineral rich soil. This monitoring site has a catchment area of 0.47 km².

Surface water flows appear to be present in the main channel all year round, which is conducive to the water balance approach.

Other factors: The confluence of a tributary, which originates on the topographically high region of the left flank (facing upstream), is located immediately downstream of the flow gauging station. Some consideration was given to the inclusion of this tributary into the monitoring site. However, substantial flows were observed in this tributary that could either be created by peat pipes or other unknown hydrological and hydrogeological processes. Whatever the water supply mechanisms, it was decided that it should not be included within the monitoring catchment.