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

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1. Statement of the aims

This report outlines a monitoring plan for the Mires-on-the-Moors project. The aim of this monitoring is to assess the hydrological and hydrogeological impacts of an extensive peat cutting and gully blocking exercise that will be conducted across Dartmoor National Park to 2015. This monitoring plan will primarily focus on water quantity. A water quality monitoring strategy has been developed in parallel by Dr. Richard Brazier who is based at the University of Exeter.

2. Introduction

The monitoring strategy outlined in this plan will allow the Mires-on-the-Moors project to assess the impact of gully blocking on the hydrological and hydrogeological project objectives, produce a comparative dataset with the two Exmoor monitoring sites (i.e. Aclands and Spooners), provide a comprehensive baseline dataset for future collaborations/research opportunities, be modified for use across other peat restoration sites and contribute to the current understanding of peat groundwater and surface water processes beyond the scope of this project.

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 who are South West Water (SWW), Exmoor National Park Authority (ENPA), Dartmoor National Park Authority (DNPA), Natural England (NE) and the Environment Agency (EA):

- 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 the rate of 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 gully 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 project objectives requires the assessment of hydrological and hydrogeological processes at both the localised surface water pool-scale (Section 4.2) and the gully-scale (Section 4.3). The numerous hydrological and hydrogeological components that require accurate quantification to assess the success/failure of the Mires-on-the-Moors project objectives are considered below in greater detail (Section 4.1).

The hydrological and hydrogeological monitoring site on Dartmoor has been selected (Section 6) and further information relating to this site, which is called Wildbanks, is outlined in Appendix A (Page. 32).

4.1 Equipment requirements

4.1.1 Rainfall

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 and reduce the possibility of data misinterpretation when assessing the impacts of the gully blocking activities.

Numerous Environment Agency rain gauges have been measuring historical precipitation levels across Dartmoor 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 not located close enough to the Wildbank monitoring site to provide the level of accuracy required for this project.

Spatial: Standard rain gauges (measuring average monthly rainfall) will be combined with tipping bucket rain gauges (measuring rainfall intensity) and positioned along a south-westerly transect at both a suitable topographically high and low point of the monitoring 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. The approximate proposed locations of the rain gauges to be installed at the Wildbanks monitoring site are shown on Figure 13.

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 the Wildbank monitoring site. 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.

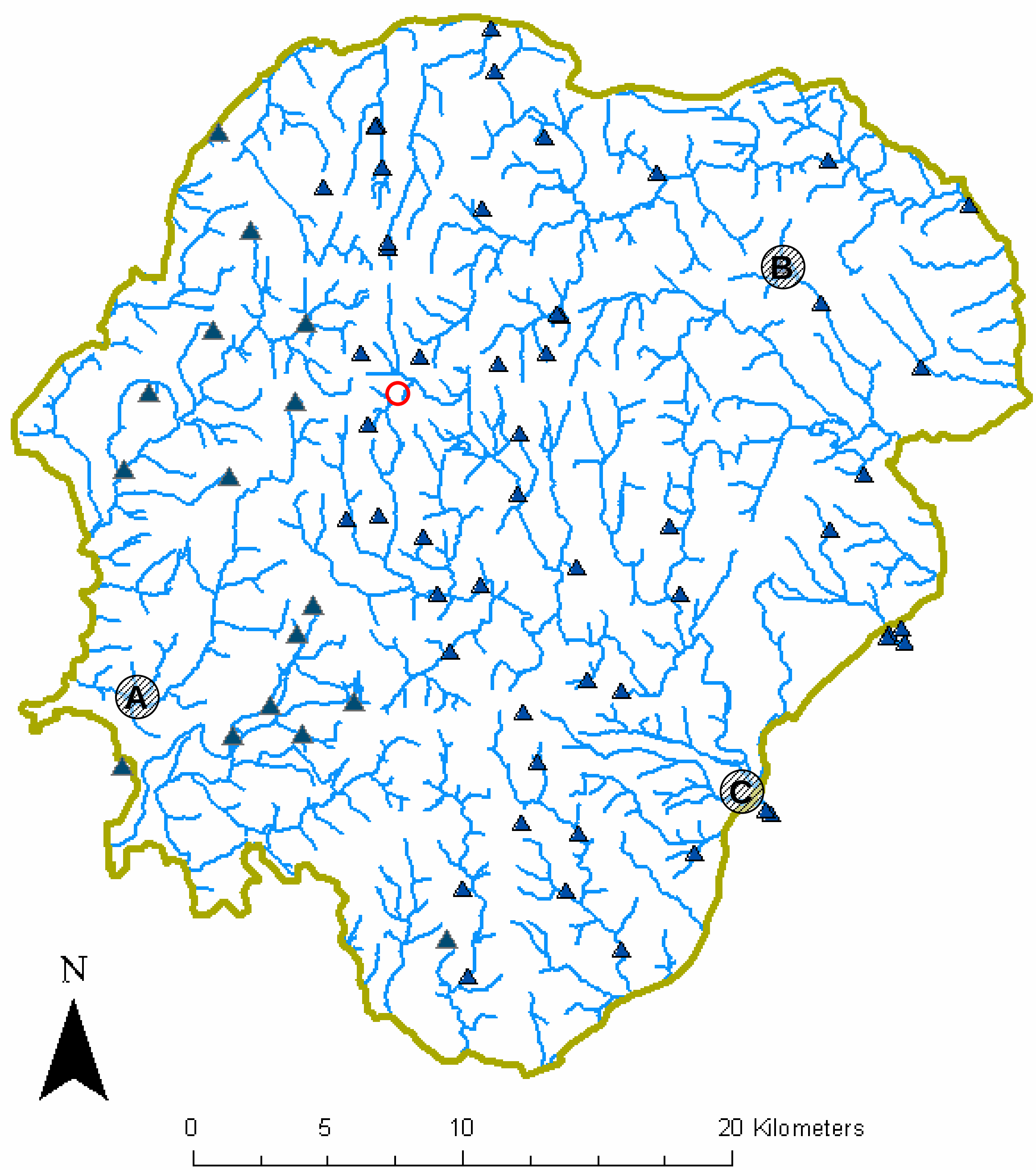

Figure 1. Location of Environment Agency monitored rain gauges across Dartmoor national park (A = Horrabridge, B = Moretonhampstead and C = Buckfastleigh). The location of Wildbanks monitoring site is highlighted by the red circle.

Other considerations: A preliminary investigation into precipitation patterns across the monitoring site should 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. The results of this investigation will contribute to our understanding of:

1. Rainfall patterns across the monitoring site.
2. Topographic controls on precipitation levels across the monitoring site.
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 assessment of the 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

Why: A weather station located at the 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, barometric pressure and evapotranspiration rates. Meteorological sensors and associated software will be used to determine evapotranspiration rates to allow an observed decrease/increase in groundwater levels to be confidently attributed to gully blocking activities and not episodes of vegetation growth/decay. The EA H&T team based at Exminster House has recommended the use of a Casella Automatic Fixed Weather Station (http://www.casellameasurement.com/cl_ne_weatherstation.htm) for the measurement of meteorological conditions.

Spatial: The weather station will be located at a topographically high point of the Wildbanks monitoring site and adjacent to a tipping bucket and Octapent rain gauge (Section 4.1.1). The approximate proposed location for the weather/evapotranspiration station at Wildbanks monitoring site is shown on Figure 13.

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.

Summary: Meteorological readings will be important for placing fluctuations of the water environment into context and the measurement of evapotranspiration rates will account for changes in vegetation growth/decay during the assessment of groundwater levels in relation to the gully blocking activities.

4.1.3 Groundwater retention

Why: The retention of groundwater within the peat is a major objective of the Mires-on-the-Moors project. Gully blocking should result in surface water in the gully, 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) and possibly reduce peak flows during wet periods and increase baseflow levels during dry periods (Section 4.1.9).

Spatial: The dipwell transect should be positioned within the restoration area (Figure 13) and span across a number of drainage channels as shown in the idealised transect displayed in Figure 2. The size, number of transects and the positioning of the dipwell array will be controlled by the complexity of the drainage channels, the intensity of peat damage, the proposed dam locations and topography. Dipwells positioned in this type of array will provide an accurate indication of:

1. Changes in total water storage under several drainage channels;
2. Changes in total water storage as a result of gully blocking activities;
3. The direction of groundwater flow paths; and
4. Groundwater responses to gully blocking activities in both undisturbed peat (furthest from the drainage channel) and disturbed/restored peat (closest to the drainage channel).

Dipwells should extend through the majority of the peat system (*Ca.* 4 - 5 metres) 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.

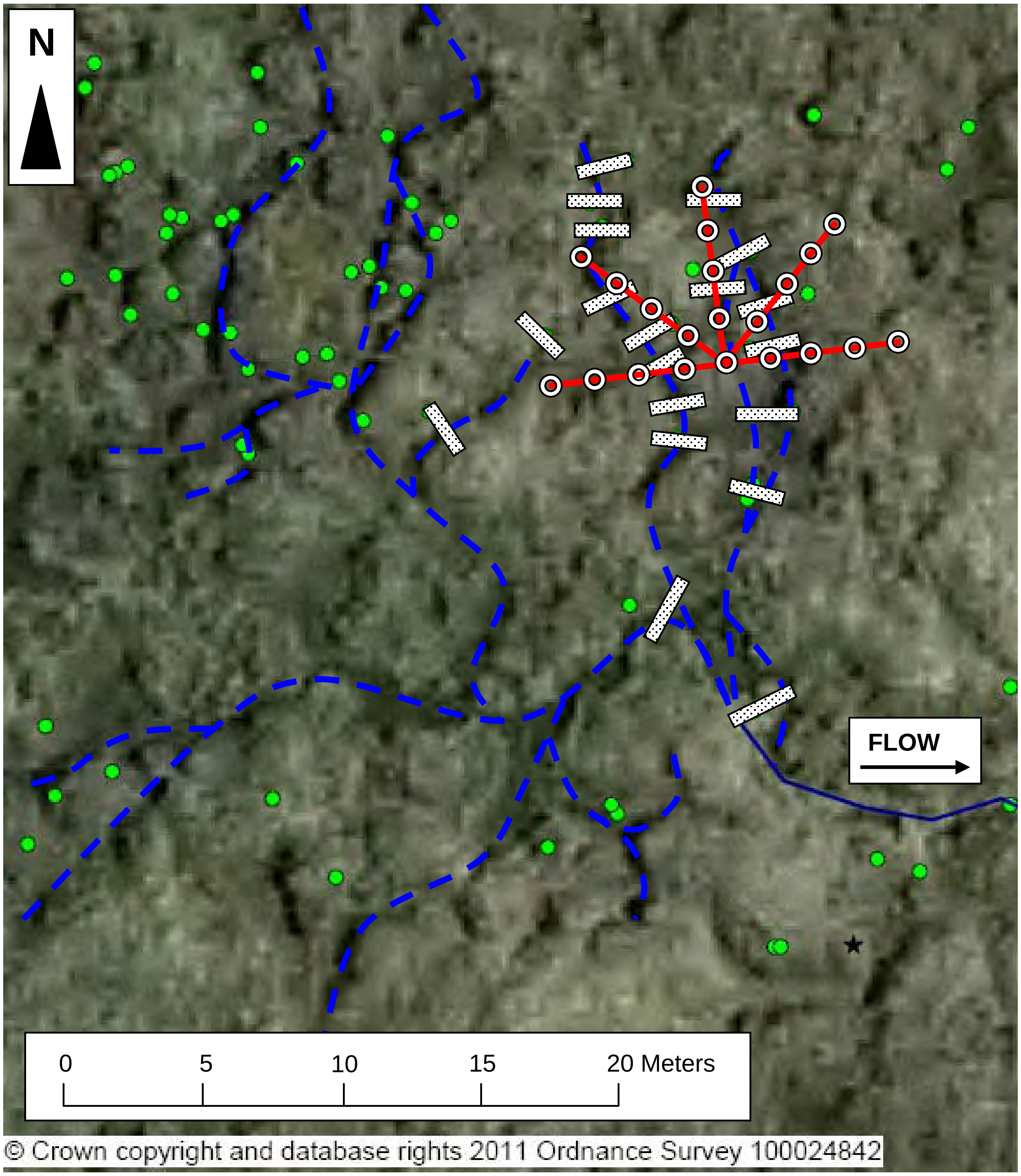

Figure 2. Proposed groundwater level monitoring array at Wildbanks on Dartmoor (hatched blue lines are the dendritic drainage channels, green dots/hashed boxes are the proposed locations of peat dams and red lines indicate the position of the groundwater level monitoring array).

Ideally, geophysical analysis should be conducted along the 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 extent of the mineral substrate and lower limits of the mineral substrate and the presence/formation of peat pipes that will strongly influence surrounding groundwater levels.

Temporal: Groundwater levels need to be monitored before and after gully 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 gully blocking activities on the surrounding water environment.

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).

A 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 become detached 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. I believe 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 gully blocking activities and not to seasonal variations in the height of the peat surface as the latter can be accounted for and eliminated.

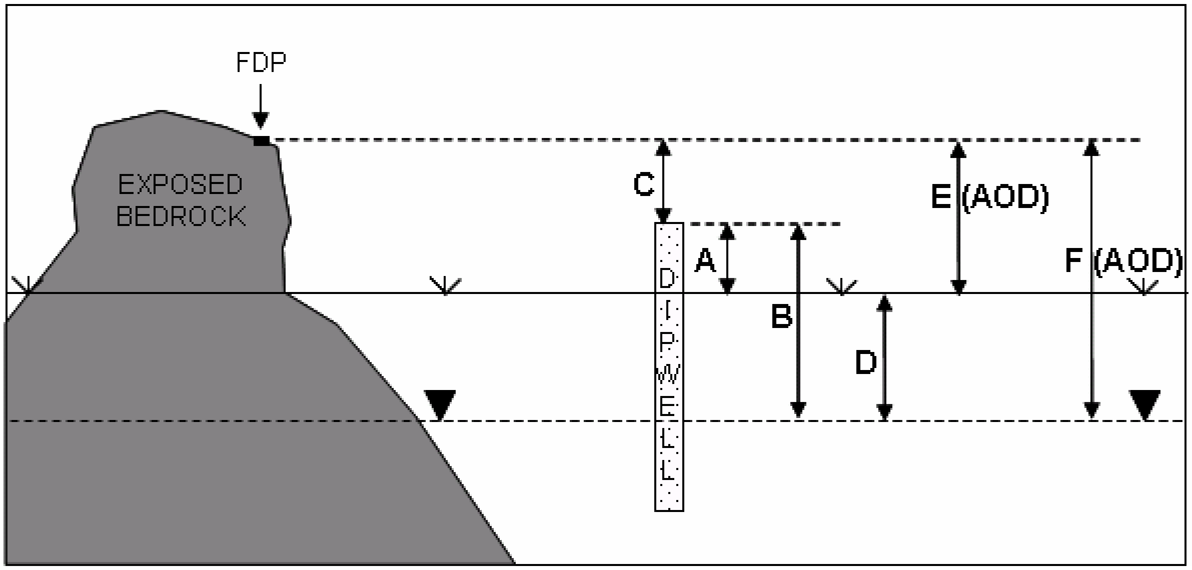

Figure 3. The measurements required to account for seasonal variation in the height of the peat surface (FDP = Fixed Datum Point and ▼ indicates the groundwater level).

2. Groundwater fluctuations will not be underestimated and therefore subsequent water storage estimates will be more 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 changes in groundwater storage.

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 are important when assessing the project objectives and can 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

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 and this process will 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. The damming of deep erosional gullies should reduce surface water flow rates and increase the residence time of water traversing across the monitoring site which will almost certainly increase the quantity of surface water infiltrating through the beds of the newly formed surface water pools into the highly fractured underlying Granite bedrock that underlies the majority of Dartmoor. 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. I recommend that the Mires-on-the-Moors project follows 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) tend to be 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 Wildbanks 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

Method	Equipment	Spatial	Temporal	Additional comments
Visual observations	No in-situ equipment.	Across the monitoring site.	Start, pre-restoration and end. Snapshot survey.	Groundwater may be identified flowing into the surface water pools from seeps and springs at the margins or through the bed.
Thermal signatures	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 *et al*., 2007).
Head difference	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 and then reduced to monthly.	Groundwater levels measured in dipwells (B; Fig. 5) can be compared against the stage height of adjacent surface water pool 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.

Table 2. Direct methods

Method	Equipment	Spatial	Temporal	Additional comments
Volumetric Stream flow method	No in-situ equipment.	Experimental Pools (Section 4.2).	Post-restoration. Accurate readings will be obtained during stable flow conditions.	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.
Automated mini-piezometers	Three automated stilling well type mini-piezometers.	Experimental Pools (Section 4.2).	Seepage rates will be logged at 15-minute intervals.	This method would provide an accurate estimate of vertical hydraulic gradient, hydraulic conductivity and specific flow through the base of the surface water pool (Baxter and Hauer, 2003) (Figure. 6).

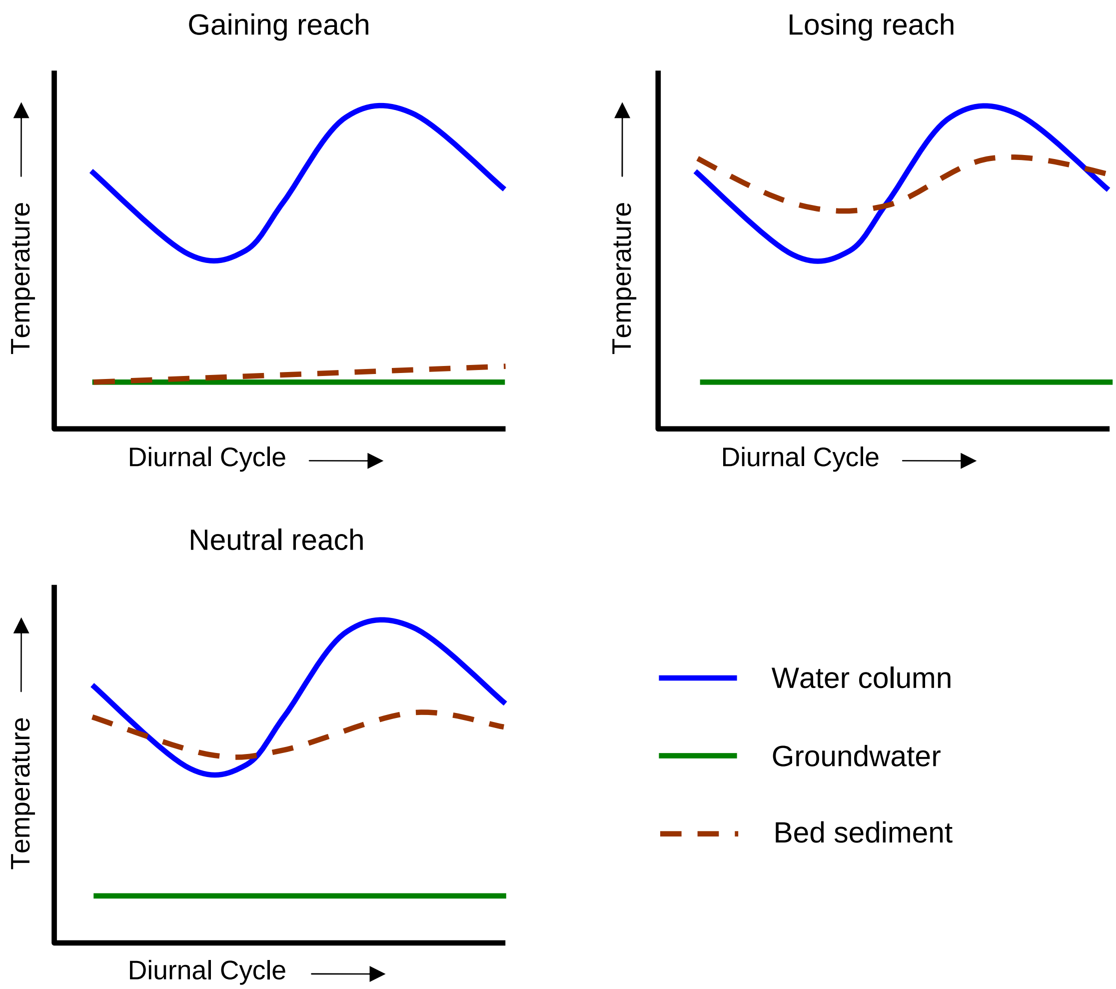

Figure 4. Thermal signatures of groundwater, bed sediment and water column temperatures of a gaining, losing and neutral pool (adapted from Silliman and Booth, 1993).

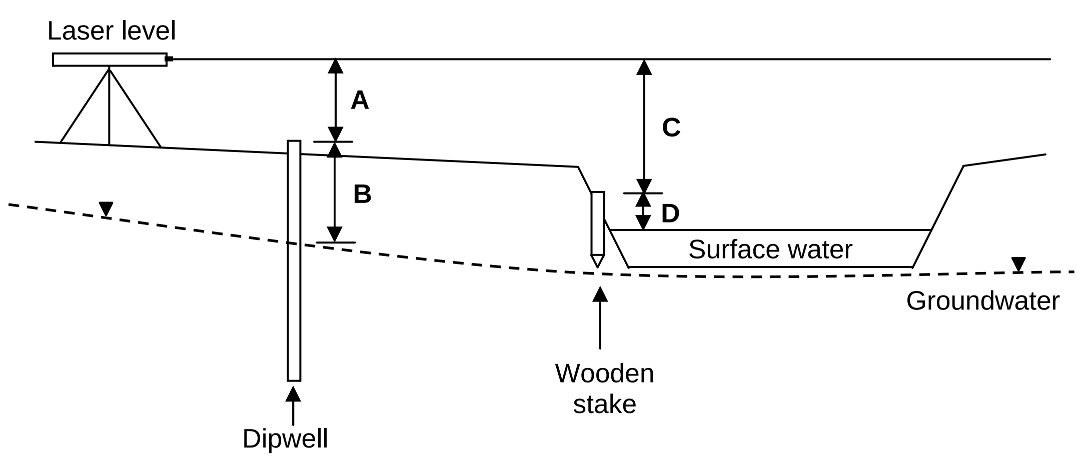

Figure 5. Head difference assessment via the comparison of groundwater level and stage height.

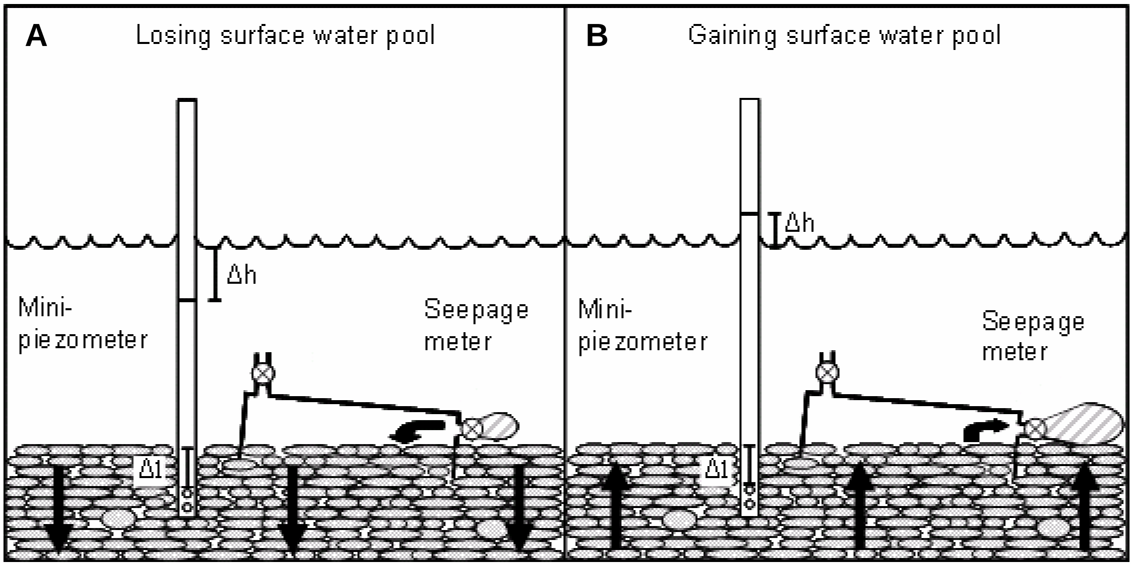

Figure 6. The principles of mini-piezometers and seepage meters in a (A) losing and (B) gaining surface water pool (Lee and Cherry, 1978; Baxter and Hauer, 2003).

<u>4.1.5 Water velocity</u>

Why: A reduction in surface water velocity rates after gully blocking in the dendritic drainage channels across the Wildbanks monitoring site was highlighted by South West Water as a major objective of the Mires-on-the-Moors project. The installation of numerous peat dams across the restored area should reduce surface water velocity rates across the monitoring site especially during times of peak flow. However, this reduction may only be evident across and immediately downstream of the monitoring site as other factors, such as variations in streambed friction, stream debris, riverbed elevation, tributary inputs from un-restored areas and growth of aquatic vegetation, will be more dominant.

Spatial: Surface water velocity rates will be recorded within the dendritic channels by a surface water velocity meter located at the Experimental Pools (Section 4.2 & Figure. 13) and at the downstream flow gauging station via a fixed bed-mounted surface water velocity meter (Section 4.1.9). This will allow the assessment of surface water velocity rates at certain points of the monitoring site and the comparison of flood peaks traveling across the monitoring site during pre and post-restoration periods. Furthermore, chemical tracing experiments could also be used to measure surface water velocity rates across the monitoring site as these experiments are already being undertaken to assess throughflow processes (Section 4.1.8). The downstream surface water velocity meter will be positioned at the flow gauging station. The location of the flow gauging station will be strongly influenced by site specific factors that 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 that 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.

The proposed location of the Wildbanks flow gauging station is shown in Figure 13.

Temporal: Water velocity readings should be recorded at 15-minute intervals.

Summary: The installation of peat dams across the monitoring site may reduce surface water velocity rates immediately downstream of the restoration/monitoring site. However, these reductions could be impacted by other factors, which may have a much greater influence over surface water flow velocity rates.

4.1.6 Gully erosion

Why: A reduction in the rate of gully erosion of peat and non-peat material is a major objective of the Mires-on-the-Moors project. The rate of gully erosion will be impacted by the velocity of flowing water across the peat surface, which should reduce as a result of gully 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.

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

1. Topographic and photographic surveys that focus on areas of potential gully development, such as gullies, sheep tracks, hollows, footpaths, ravines, etc.
2. Water samples that are collected at the Experimental Pools and the downstream flow gauging station (Figure. 13) for the comparison of flow and suspended sediment concentration (SSC) before and after gully blocking (Please note - storm samples can also be used for water quality (i.e. mineral and organic particulate content) and carbon analysis).

Temporal:

1. A detailed topographic and photographic 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 objectives of the restoration work are to assess the rates of surface runoff across the monitoring site that may reduce during post-restoration and so will erosional properties which in turn could 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. This would provide adequate time to organise the prompt collection of water samples (Please note - SSC samples will also be used for dissolved organic content and colour analysis therefore after a rainfall event samples will need to be collected/analysed ASAP). A flood forecasting point could be set-up for the Wildbanks monitoring site.

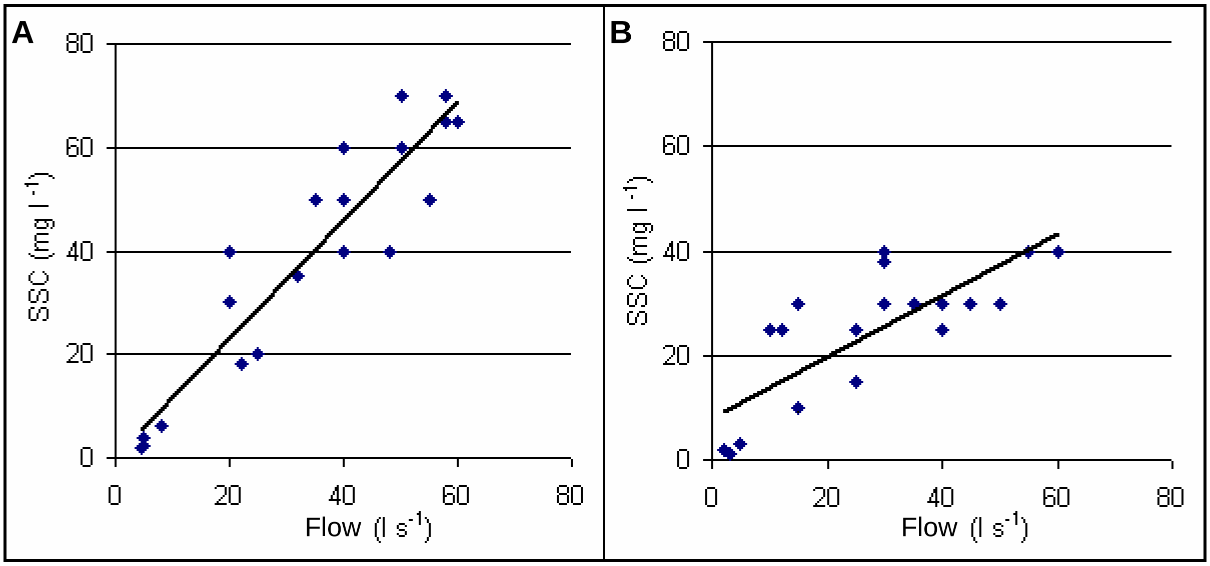

Figure 7. Scatter plots illustrating the potential changes in flow rates (l s^{-1}) and suspended sediment concentrations (SSC) (mg l^{-1}) during (A) pre restoration and (B) post restoration periods.

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

Summary: A reduction in downstream sedimentation and colmation rates will be beneficial to all the surface water systems that originate from Dartmoor National Park, such as the River Teign, East Dart River, West Dart River, River Plym, East Lyn River, Cowsic River, Blackbrook River, River Tavy, River Lyd, River Okement and the River Taw.

<u>4.1.7 Overland flow</u>

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 gully erosion processes across the monitoring site and may highlight where future restoration efforts need to be focused. This assessment will be undertaken at the Experimental Pools (Section 4.2).

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

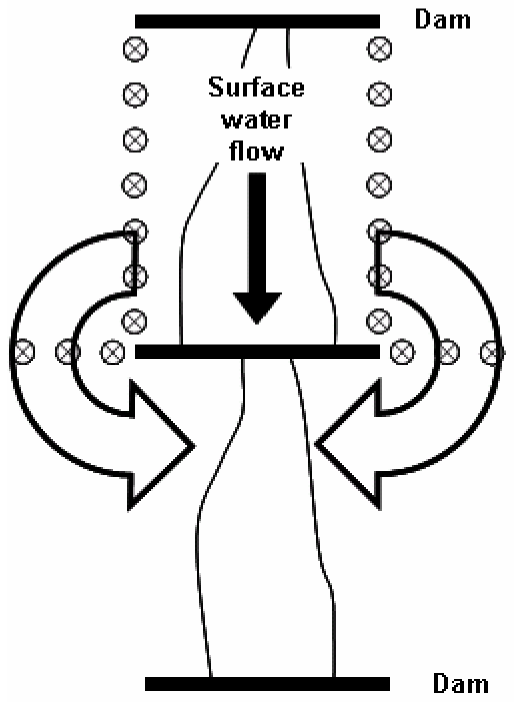

Figure 8. Plan view showing the grid of the capacitance probes for the measurement of the occurrence, duration, extent and direction of overland flow events (⊗ = capacitance probe).

Temporal: The capacitance probes will be set up to log the presence/absence, depth and duration of water at 15-minute intervals.

Summary: The measurement of overland flow processes are important to the Mires-on-the-Moors project objectives, may highlight where future restoration efforts need to be focused 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 positioned in dipwells. This will be undertaken at the lower Experimental Pool (Section 4.2).

Spatial: Transects of dipwells need to extend beyond the dam of the lower Experimental Pool 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).

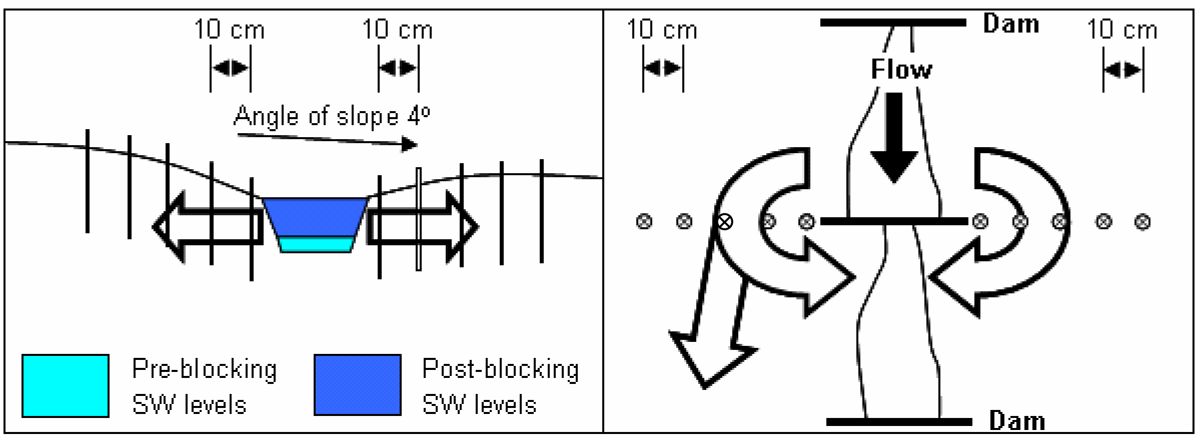

Figure 9. The dipwell array that will measure the rate and extent of through flow processes at the lower Experimental Pool (Section 4.2).

A preliminary investigation will need to 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 during both pre and post restoration periods.

Other considerations: Chemical tracing experiments can also be used to measure surface water velocity rates across the monitoring site (Section 4.1.5), flows in turbulent headwater streams and these tracing experiments could contribute towards the calibration of surface water flows 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 surrounding mire vegetation.

4.1.9 Flow

Why: Restored peat maybe 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.

Spatial: The characteristics of the gully will influence the type and location of flow gauging station that will be installed at the hydrological and hydrogeological monitoring site. The proposed approximate location for the placement of the downstream flow gauging station is shown in Figure 13.

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 restoration area to capture the full impact of the gully blocking activities.
2. Far enough from the restoration area 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 sections of the monitoring site will distort the results.

4. Account for anthropogenic activities, such as surface water (SW) abstractions abstractions/discharges, groundwater (GW) abstractions/discharges, which are expected to be sparse in these headwater catchments.

Temporal: Flow readings should be recorded at 15-minute intervals as they will accurately assess the hydrological project objectives, such as the lowering of peak flows and increased baseflow levels.

Other considerations: Chemical tracing experiments using conservative ionic tracers, such as sodium chloride (NaCl), will be used to assess the rate of through flow at the lower Experimental Pool (Section 4.2). This technique can also be used to measure flow rates in turbulent headwater streams (Church, 1975), calibrate flow rates at the downstream flow gauging station and to assess surface water velocity rates during pre and post-restoration periods (Section 4.1.5).

Numerous discussions have taken place on site relating to the most appropriate method of gauging surface water flows at Wildbanks, which would also need to account for the following;

- The underlying peat structure is approximately 4 - 5 metres in depth which may result in flows traversing underneath and around the sides of the flume.
- The flume being washed away during an intense rainfall event.
- Peat debris blocking the flume.

Summary: The restoration effort aims to stabilise flow regimes which will have a range of positive benefits on 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 (Section 3). As a result, two Experimental Pools (EP) will be established across the Wildbanks monitoring site for the high temporal and spatial monitoring of seepage flux rates (Section 4.1.4), surface water velocity (Section 4.1.5), overland flow processes (Section 4.1.7) and through flow processes (Section 4.1.8). Surface water temperatures, groundwater temperatures, flow measurements and SSC will also be recorded at the EPs which will contribute to our understanding of gully blocking across a range of scales and changes to the hydrological and hydrogeological system at a localised scale during both pre and post restoration periods.

The two EPs located on the Wildbanks monitoring site will be carefully positioned to account for the two different types of historical damage and future restoration that will be undertaken (Figure. 13). Therefore, the Lower EP will monitor the hydrological and hydrogeological impacts of blocking a large erosional gully feature (Section 4.2.1) and the Upper EP the blocking of peat cuttings and associated dendritic drainage channels (Section 4.2.2).

4.2.1 Lower Experimental Pool

Spatial: The main erosional gully feature that will be monitored at Wildbanks is similar to the type of damage observed across the two Exmoor monitoring sites (i.e. Aclands and Spooners) and the layout of the lower EP will be similar (Figure. 10) to the Exmoor EPs to provide a comparative dataset across the two moors.

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 Lower Experimental Pool will be consistent with the other monitoring equipment and record hydrological and hydrogeological processes at 15 minute intervals.

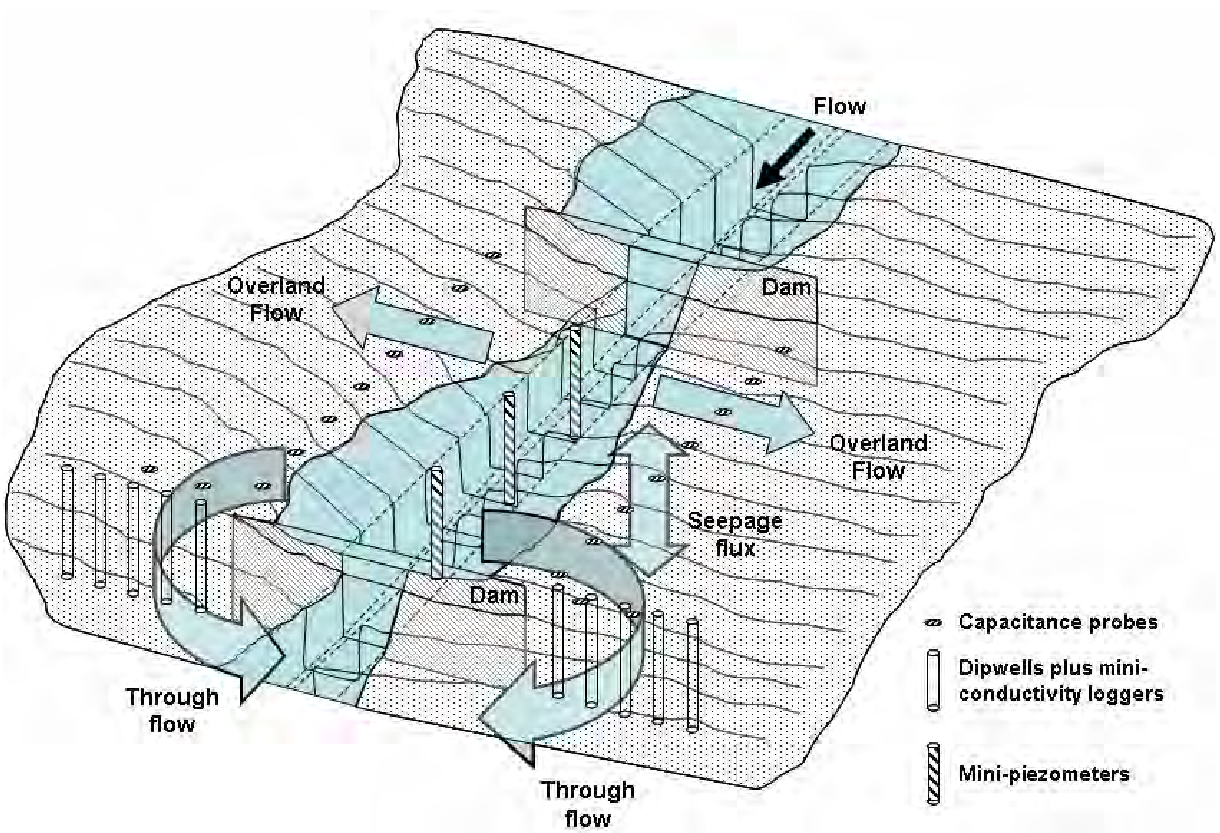

Figure 10. Equipment and the processes which will be monitored in and around the Lower Experimental Pool at the Wildbank monitoring site on Dartmoor.

4.2.2 Upper Experimental Pool

Spatial: The Upper EP will be positioned in a topographically high region of the Wildbanks monitoring site and will monitor the impact of restoration activities across a peat cutting and associated dendritic drainage channels (Figure. 13). The monitoring equipment installed in this region will be representative of the heterogeneous nature of the peat cuttings and drainage channels across Dartmoor.

Three mini-piezometers (Black; Fig. 11) will monitor stage height and surface water temperature within the peat cutting. Approximately thirty other sensors will monitor temperature, groundwater levels and overland flow events around the peat cutting and adjacent dendritic channels. For example, 10 sensors will be positioned between - 0 to 0.5 metres (Red; Fig. 11), 10 sensors - 0.5 m to 2 metres (Green; Fig. 11) and 10 sensors - 2 to 5 metres (Pink; Fig. 11) from the dendritic drainage channels and peat cuttings. This approach will enable us to investigate hydrological and hydrogeological processes in comparative locations across what is essentially a very complicated and heterogeneous system.

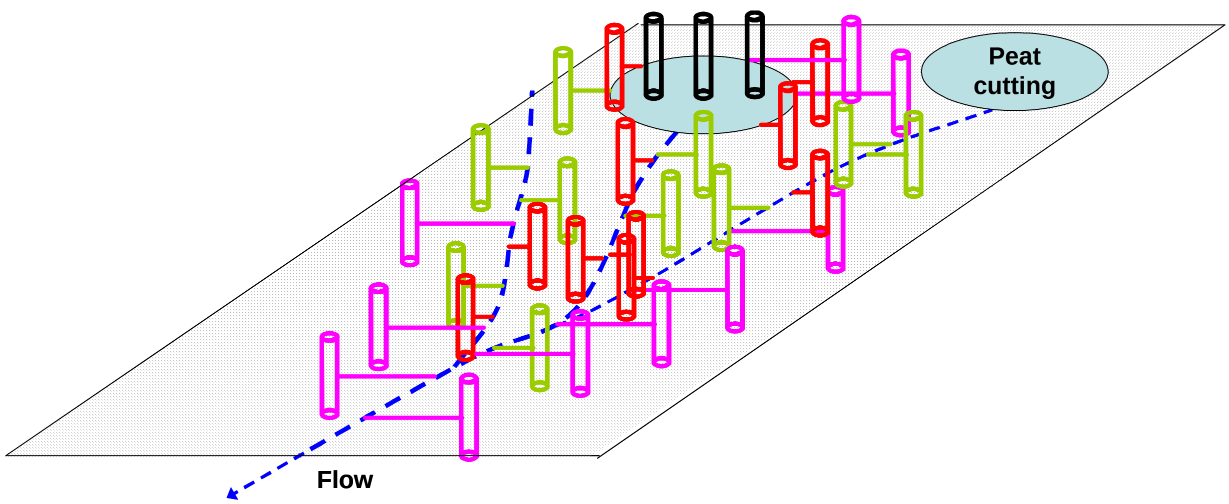

Figure 11. An illustration showing the proposed array of monitoring equipment in and around the Upper Experimental Pool at Wildbanks. Three mini-piezometers (Black; Fig. 11) and thirty overland flow / groundwater level sensors will be positioned approximately 0 - 0.5 metres (Red; Fig. 11), 0.5 - 2 metres (Green; Fig. 11) and 2 - 5 metres (Pink; Fig. 11) from the dendritic drainage channels and peat cuttings.

Temporal: The monitoring equipment installed in and around the Upper Experimental Pool will be consistent with the other monitoring equipment located across the Wildbanks monitoring site and record hydrological and hydrogeological processes at 15 minute intervals.

Summary: Monitoring at the localised pool-scale will effectively assess a number of project objectives, contribute towards a nested monitoring approach and assess a range of hydrological and hydrogeological processes and interactions.

4.3 Gully-scale monitoring

Why: Surface water flows in the main gully will need to be monitored during pre and post restoration periods to assess the success/failure of numerous Mire-on-the-Moors project objectives. Furthermore, the positioning of the Lower Experimental Pool along the upper reaches of the main gully (Figure. 13) will provide a valuable link between the pool-scale and gully-scale monitoring as well as producing interrelated hydrological and hydrogeological datasets at a range of scales.

Spatial: The monitoring gully stretches from the restoration area (SX6136881246) to the main channel (SX6146281221) and is approximately 0.5 metres wide, 0.5 - 1 metre deep and 100 metres in length (Figure 13).

Temporal: Monitoring equipment installed in and around the Experimental Pools and along the monitoring gully should record at 15 minute intervals as this high temporal resolution should effectively capture all the important hydrological and hydrogeological processes.

Summary: Monitoring along the main gully should capture all the necessary hydrological and hydrogeological information required for assessing the Mire-on-the-Moors project objectives and provide a valuable link between the pool-scale and gully-scale monitoring.

4.4 Monitoring duration

It would be advantageous for the Mires project to install monitoring equipment this coming Sept/Oct 2011, which would allow the collection of baseline monitoring over a period of 1.5 - 2 years and provide sufficient time for the hydrological and hydrogeological patterns during the periods of pre and post-gully blocking to be placed into context and to assess the accuracy of the field data across a range of flows. Ideally, post restoration monitoring of 2.5 - 3 years should be undertaken as some project objectives are linked to the development of the underlying peat structure, which will require time to mature.

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 across the Wildbanks monitoring site. A fifteen minute logging rate will effectively capture all the necessary groundwater and surface water processes, such as the lowering of peak flows and an increase of baseflow levels, during the periods of both pre and post gully 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 Summary of equipment costs

Table 3 (below) lists the estimated costs of the monitoring equipment that will be installed across the Wildbanks monitoring site. The estimates exclude an exact cost for the flow gauging station as this depends on the type of flow gauging station selected and the range of flows to be measured.

Table 3. The estimated cost of the monitoring equipment for the Wildbanks monitoring site.

Parameter	Number	Approx (£)	Min (£)	Max (£)
Personal digital assistant (PDA)				
Hand held unit	1	1200	1200	1200
Total			1200	1200
Rainfall				
Standard rain gauge	2	650	1300	1300
Tipping bucket rain gauge	1	700	700	700
Total			2000	2000
Climate and Evapotranspiration				
Weather station + sensors + software + TBR	1	7000	7000	7000
40 Watt solar panel	1	500	500	500
Total			7500	7500
Groundwater levels				
Installation of fixed datum point + survey	1	2000	2000	2000
Groundwater dipper	1	100	100	100
Laser level	1	100	100	100
Dipwells	21	50	1050	1050
Groundwater level equipment	21	900	18900	18900
Total			22150	22150

Table. 3 (cont)				
Parameter	**Number**	**Approx (£)**	**Min (£)**	**Max (£)**
Lower Experimental Pool -				
GW-SW interactions				
Mini-temperature loggers	6	105	630	630
Mini-piezometers	3	800	2400	2400
Dipwells	1	100	100	100
Groundwater level equipment	1	900	900	900
Total			4030	4030
Overland flow				
Capacitance probes	20	80	1600	1600
Total			1600	1600
Through flow				
Conservative tracer	N/a	100	100	100
Dipwells	10	50	500	500
Mini-conductivity loggers	10	100	1000	1000
Total			1600	1600
Gully erosion				
Automated water sampler	1	5000	5000	5000
Automated water sampler cabinets	1	100	100	100
Total			5100	5100
Upper Experimental Pool -				
GW-SW interactions & Overland flow				
Mini-piezometers	3	800	2400	2400
GW level / Overland flow sensors	30	400	12000	12000
Total			14400	14400
Gully erosion				
Automated water sampler	1	5000	5000	5000
Automated water sampler cabinets	1	100	100	100
Total			5100	5100
Flow (presence, stage and velocity)				
Trapezoidal flume (construct + install)	1	18000 - 20000	18000	20000
Stage height sensor	1	3000	3000	3000
Bed mounted velocity meter	1	5000	5000	5000
Surface water velocity meter for EPs	1	5000	5000	5000
40 Watt solar panel	1	500	500	500
Total			31500	33500
Gully erosion				
Automated water sampler	1	5000	5000	5000
Automated water sampler cabinets	1	100	100	100
Total			5100	5100
Minimum to maximum costs			101280	103280
Average costs			102280	

4.7 Work plan

Table 4 identifies that the University of Exeter will be responsible for the monitoring of Wildbanks and displays how often checks should be performed and over what time period.

Table 4. What parameter is being monitored, how often and over what time period?

Parameter (including battery checks)	No	Frequency	Start date	End date
Rainfall				
Storage (Octapent) rain-gauge	2	*W to M	1st Oct 2011	March 2015
Tipping bucket rain gauge	2	*W to M	1st Oct 2011	March 2015
Climate				
Climate station + evapotranspiration + additional sensors (i.e. leaf wetness)	1	*W to M	1st Oct 2011	March 2015
Solar panel	1	*W to M	1st Oct 2011	March 2015
Groundwater				
Total survey station survey + Installation of fixed datum point	1	Once at the start	Prior to the 1st Oct 2011	March 2015
Groundwater level	21	*W to M	1st Oct 2011	March 2015
Associated dips	21	*W to M	1st Oct 2011	March 2015
Groundwater dipwells to AOD	21	*W to M	1st Oct 2011	March 2015
GW-SW interactions				
Visual observations	N/a	Quarterly	1st Oct 2011	March 2015
Mini-temperature loggers	6	*W to M	Site & flow dependent	March 2015
Groundwater level	1	*W to M	1st Oct 2011	March 2015
Associated dip	1	*W to M	1st Oct 2011	March 2015
Stage recording equipment	1	*W to M	1st Oct 2011	March 2015
Volumetric stream flow measurements	2	*W to M	Post ditch blocking	March 2015
1 seepage meter/3 mini-piezometers	1	*W to M	1st Oct 2011	March 2015
Evaporation pan	1	*W to M	1st Oct 2011	March 2015
Overland flow				
Capacitance probes	20	*W to M	1st Oct 2011	March 2015
Through flow				
Chemical tracing	N/a	Quarterly	1st Oct 2011	March 2015
Mini-conductivity loggers	10	Quarterly	1st Oct 2011	March 2015
Gully erosion				
Automated water sampler	2	Post storm	1st Oct 2011	March 2015
Total survey station and photographic survey for topographic changes	N/a	Start, mid & end	1st Oct 2011	March 2015
Flow (including stage)				
Flow gauging station	1	*W to M	1st Oct 2011	March 2015
Water velocity	1	*W to M	1st Oct 2011	March 2015
Solar panel	1	*W to M	1st Oct 2011	March 2015

* Initially weekly for approx 6 weeks then reduced to monthly site visits (in the above table this is indicated as W to M).

5. Recommendations for gully blocking across the monitoring site

Below are a number of recommendations for gully blocking across the Wildbank monitoring site-

A. Peat dams around the monitoring equipment should be installed very carefully using the same mechanical excavators as the rest of the monitoring site which will make the gully blocking representative to the rest of the restoration efforts.
B. Blocks should be installed across the entire monitoring site as quick as feasibly possible to increase the likelihood of observing hydrological and hydrogeological signals as a result of the gully blocking.
C. Where possible monitoring equipment should remain in-situ and continue logging during the gully blocking activities as this data will provide an invaluable insight into the transition 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 (3) site visits.

1. Twenty eight hydrological/hydrogeological monitoring sites were identified across Dartmoor National Park by a GIS screening tool (Figure. 12). The GIS screening tool used a number of digitized GIS layers, such as a digital terrain model, detailed river network and a map of restoration areas across Dartmoor. The GIS screening tool also provided an indication of;
    - Topography;
    - Intensity and extent of damage to the peat structure; and
    - Anthropogenic activity, such as GW/SW abstractions, GW/SW discharges, etc.
2. The twenty eight field sites were then assessed for suitability by Frances Cooper who is the Dartmoor National Park Mire Restoration Project Officer for access rights, site accessibility (i.e. proximity of roads, footpaths and bridleways), health & safety implications (i.e. military ranges), inaccessible terrain, restoration time-scales, etc. Approximately 20 sites were excluded during this assessment.
3. Site visits were undertaken to the remaining sites by staff from the Environment Agency, Dartmoor National Park Authority and the University of Exeter. Many potential monitoring sites were deemed unsuitable due to the limited peat damage, steep topography, etc. The most appropriate monitoring site was deemed Wildbanks. Further information relating to the Wildbanks monitoring site is presented below in Appendix 1 (Page. 32).

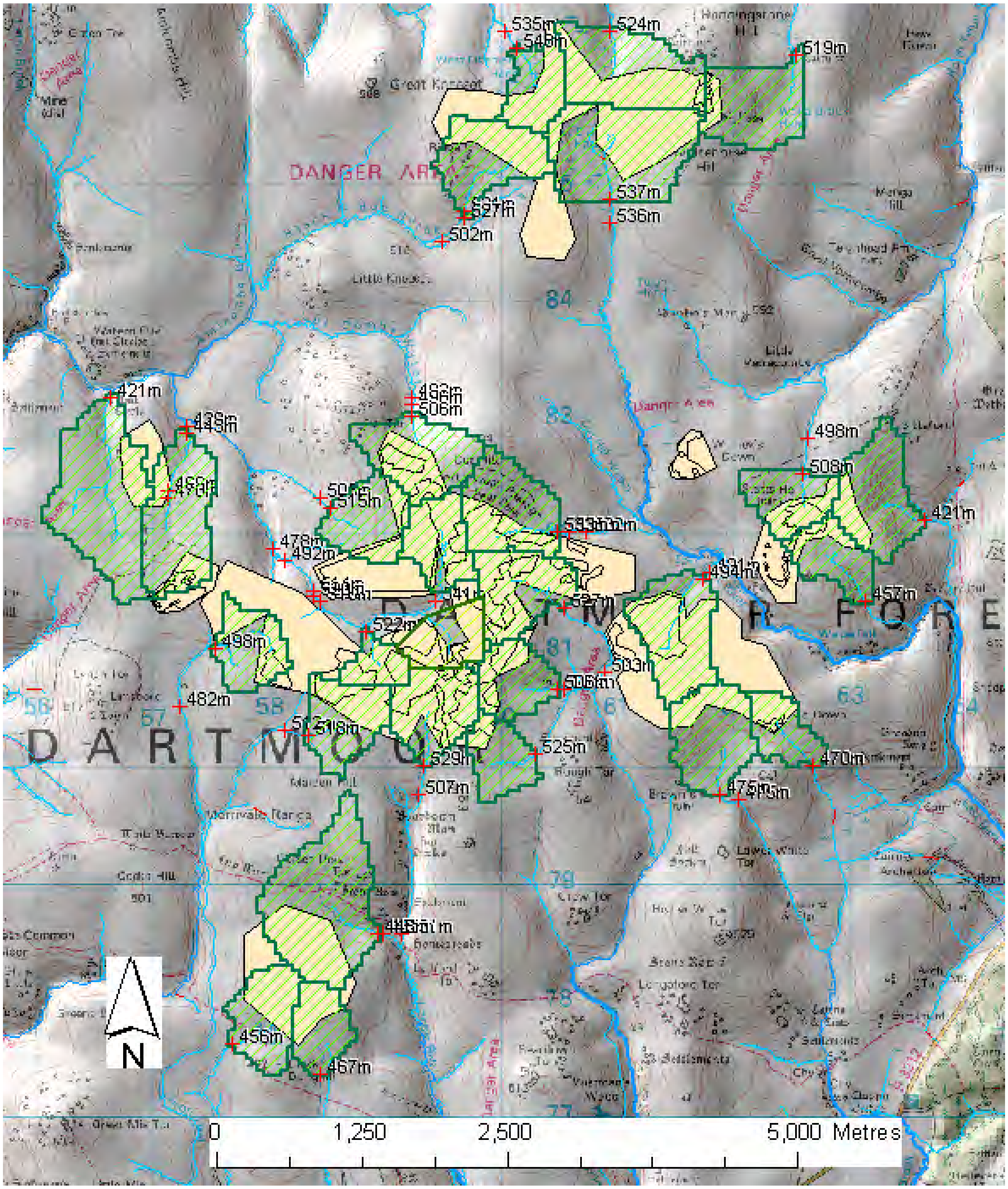

Figure 12. Outputs of the GIS screening tool for Dartmoor National Park (beige polygons display future restoration areas and potential monitoring sites are shown where the green hatched polygons overlap the beige polygons).

7. Overall Summary

This monitoring plan has been developed to accurately assess the impact of the gully blocking activities on the Mires-on-the-Moors hydrological and hydrogeological project objectives provided by the stakeholders (Section 3), produce a comparative dataset with the two Exmoor monitoring sites (i.e. Aclands and Spooners), provide a comprehensive baseline dataset for future collaborations/research opportunities, be modified for use across other peat restoration sites and contribute to the current understanding of peat groundwater and surface water processes.

8. Recommendations

It is recommended that the Mires-on-the Moors steering group should adopt this monitoring plan as it should supply all the necessary hydrological and hydrogeological information to assess the success/failure of the numerous Mires-on-the-Moors project objectives provided by the project partners (Section 3).

9. Acknowledgements

Thanks to David Smith, Frances Cooper, Martin Ross and Mary-Rose Lane for allowing me the opportunity to work on the Mires-on-Moors project. Thanks to Richard Brazier from the University of Exeter for providing me with technical advice. 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 and to Pauline Johnston for proof reading this report.

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Appendix 1

Wildbanks flow gauging station NGR - SX6142181240

Site description: The Wildbanks monitoring site is characterized by numerous hollows created by peat cutting for domestic purposes back in 16th and 17th centuries. Small gullies originating from these hollows have combined to form larger dendritic channel systems which over time have merged to create a large erosional gully feature (Figures 2 & 13). The main aim of the restoration effort at Wildbanks is to reduce these erosional processes by blocking the numerous peat cuttings and dendritic drainage channels with peat dams. The restoration area at Wildbanks straddles the higher interfluve regions of the monitoring site and is approximately 21.5 ha in size.

A small surface water pool is located to the north of the monitoring gully. The origin of this surface water pool is currently unknown.

Other factors: It is estimated that the depth of the peat underlying the Wildbanks monitoring site ranges between 4 - 5 metres in thickness. As a result, it may be challenging to install a flow gauging station at the Wildbanks monitoring site.

Access: The closest vehicle access point to the Wildbanks monitoring site is the Tourist Information Centre car park at Postbridge (SX6469478902) which is located along the B3212 that runs between Moretonhampstead (SX7536086175) and Two Bridges (SX6097274975). The distance to the monitoring site from this car park is approximately 5.0 Kms, which takes about 55 - 60 minutes to traverse on foot. The first 30 minutes of walking follows gravel footpaths and the latter 25 - 30 minutes traverses open peat land (Figure. 14).

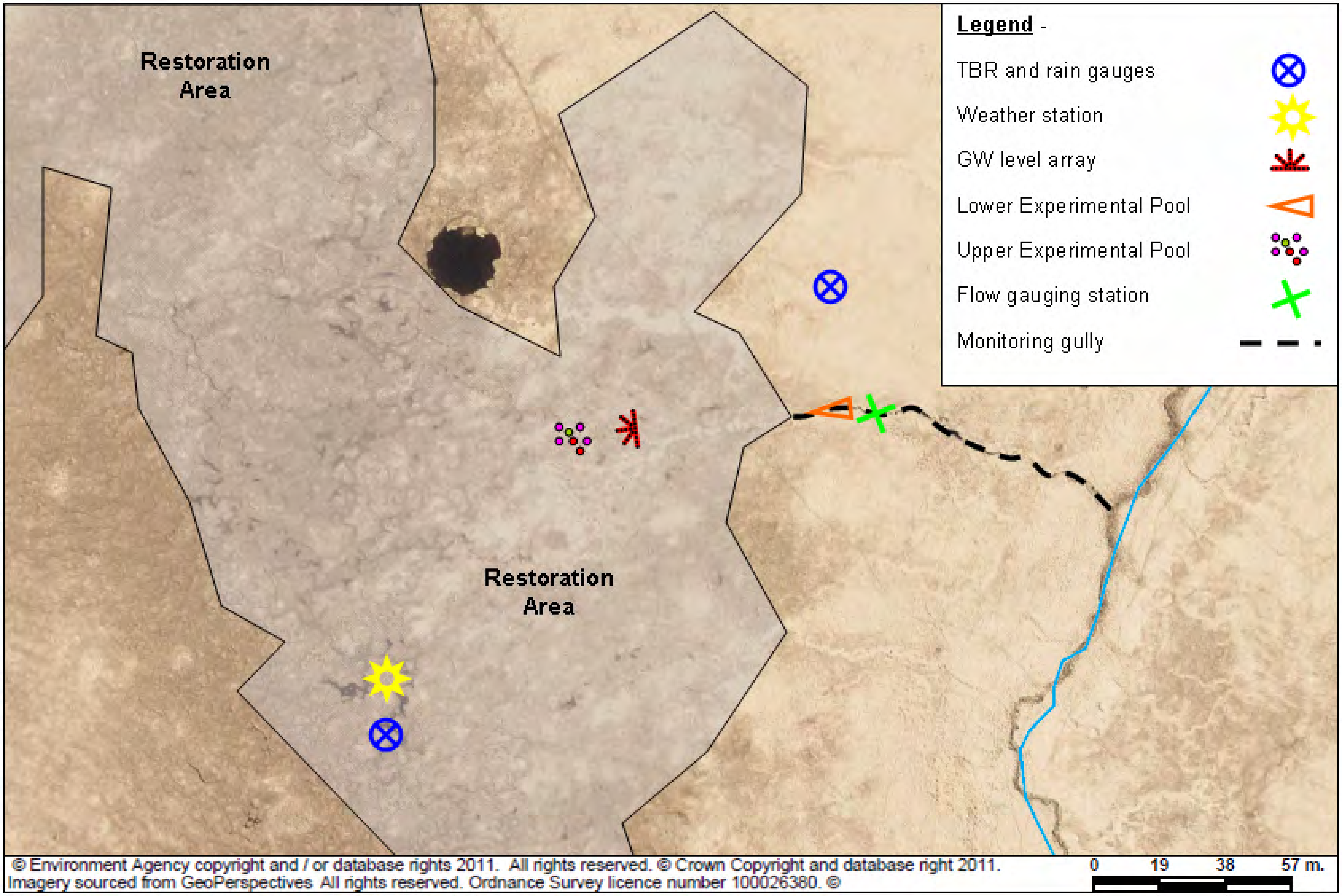

Figure 13. Aerial photograph (1:2,000) showing the proposed location of monitoring equipment at Wildbanks monitoring site.

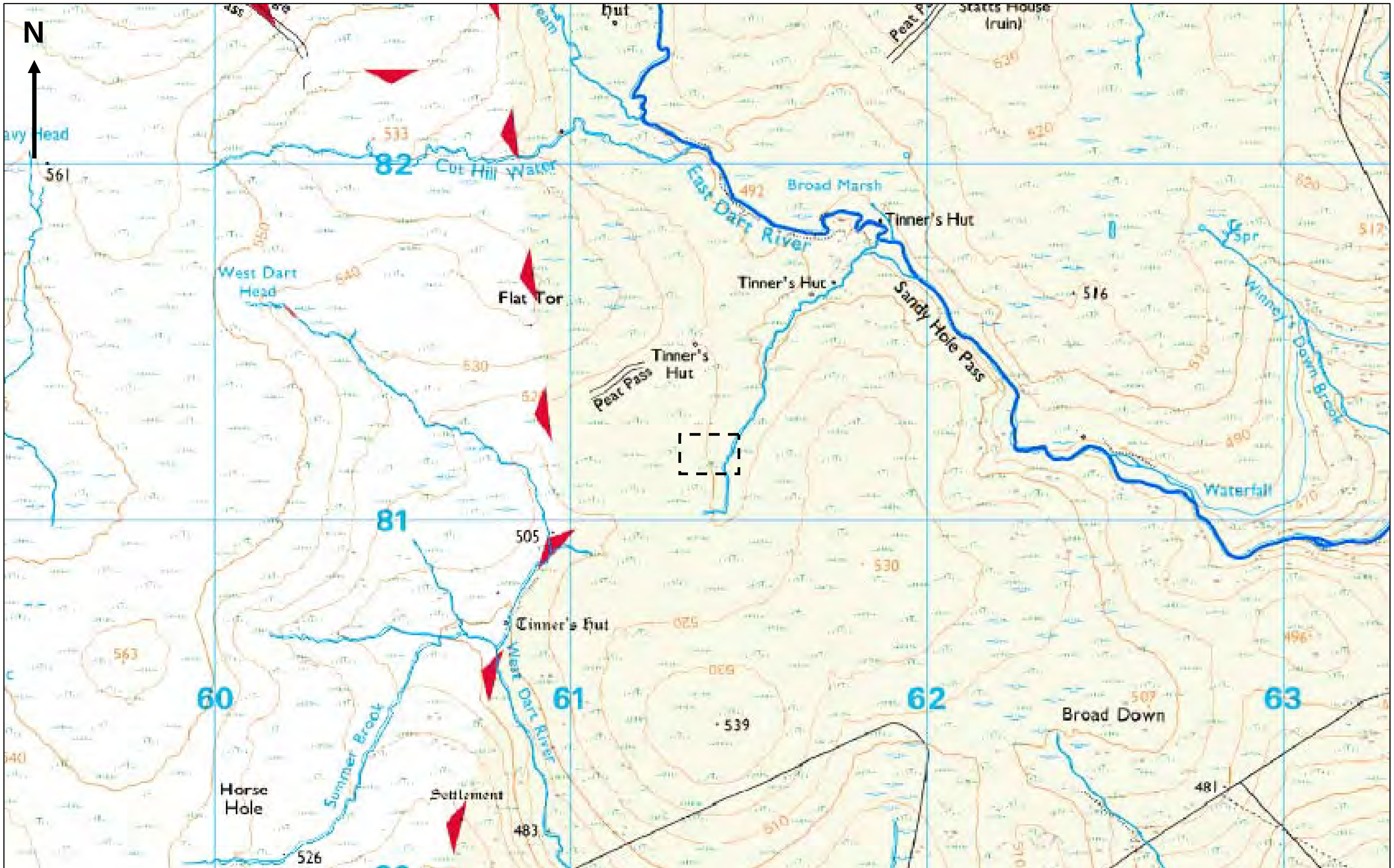

Figure 14. A map (1:20,000) showing the location of the Wildbanks monitoring site. The hatched box depicts the full extent of Figure 13.