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Variation in Wilting Point Among Functional Soil Classes for Hydrological Modelling of the Nant-y-Brwyn Catchment

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SUMMARY

The WADES project is assessing the impact of climate change on ecological services of moorlands, such as plant biodiversity and flood and drought regulation. o achieve this by producing a hydrological model based on the functional soil classes of the Nant-y-Brwyn catchment, North Wales. Using hypotheses suggesting how climate change may alter these soil classes, it is then possible to model the hydrological implications.

This report describes the collating of data that the hydrological model will require to run. The structure of the PDM model chosen to model the catchment area was analysed, and soil moisture capacity and field capacity were identified as key parameters. Potentially useful field measurements were identified, including taking soil core samples to calculate soil moisture capacities and the polythene sheet method for field capacity measurement. Fieldwork to obtain soil cores from four functional soil classes (deep peat with true blanket bog vegetation; organomineral soils with 10-40 cm or < 10 cm organic layers; and flushed soils dominated by groundwater efflux) was undertaken in the Nant-y-Brwyn catchment. Soil cores were then analysed in the laboratory. Soils were dried to water potentials near (above and below) the Wilting Point (–1.5 MPa), and measurements of actual water potential in the sample were taken using a WP4 Dewpoint PotentiaMeter machine. The samples were then weighed, dried and reweighed to calculate soil moisture content. A linear regression was fitted to the water potential vs. water content plot for each soil core, and used to calculate the expected water content at wilting point.

Results showed an as-expected general trend of higher soil moisture contents for less negative water potentials. This was less conclusive amongst the Flush soils however, where significant scatter was observed, along with the largest range of average soil moisture contents of all soil classes. Measurement errors are possible, but the Flush soil type was relatively heterogeneous and so uncertainty in the measurement is unsurprising. Bog soils had the smallest range of average soil moisture contents (0.08g H_2O g^{-1} dried soil), indicating more homogenous soil characteristics, despite having the greatest average soil moisture at wilting point, 0.98 g H_2O g^{-1} dried soil. Wet and dry soil classes were found to have smaller but similar average soil moisture values at wilting point, at 0.91 and 0.94 g H_2O g^{-1} dried soil, respectively.

Proposals have been made as to how the hydrological soil characteristics discovered would be represented in the PDM model, with focus on the proportional distribution of the soil classes in the catchment being incorporated into the PDM's Pareto distribution parameter.

CONTENTS

1 INTRODUCTION

The WADES project's overall aim is to assess the impact of climate change drivers, coupled with changes in land management, on moorland ecosystems and their resulting services such as plant and bird biodiversity, water purification and flood and drought regulation. Impacts to these services are attributed mainly to changes in vegetation type and soil structures that are expected as a result of the predicted hotter, drier climate. Reduced rainfall will lead to shifts to more drought tolerant vegetation such as shrubs. Changes in organic and nutrient contents in the soils are therefore also expected, which in turn would alter the soil structures which the hydrological pathways depend upon. Further detail on the WADES project hypotheses can be found in Rowe and Moore (2009).

In order to assess this, a hydrological model is to be set up for a catchment in the Nant-y-Brwyn catchment in the Migneint Moorlands, Snowdonia (Figure 1), to simulate the hydrological responses of four moorland soil properties to precipitation events. Future climate conditions could then be simulated using this set up to assess responses.

This report details the background research into the structure of the Probability Distributed Model (PDM), chosen as a potential model for use in the WADES project. The PDM is able to represent variance in soil capacities across the catchment using a Pareto distribution function, and thus is suited to the Nant-y-Brwyn catchment where four soil classes have been identified. The parameters required for the PDM are explained in this report, along with potential fieldwork that could be carried out to collect data for the parameters. Where fieldwork was carried out, the results and their analyses are presented.

Figure 1. Location of the Nant-y-Brwyn study site (red box) within the Migneint range in NW Wales.

2 THE PDM MODEL

2.1 Background to PDM Structure

The PDM model simulates flow outputs by determining the movement of rainfall inputs through three stores; *(i) soil moisture storage, (ii) surface storage and (iii) groundwater storage*, which make up the three main components of the model (Moore, 2007).

(i) The soil moisture storage component determines the separation of rainfall inputs into direct overland run-off and the slower subsurface run-off on account of the soil moisture storage capacity. For larger soil moisture storage capacities, a greater volume of rainfall input is utilised to recharge the soil before runoff is created. The PDM recognises that soil structures vary across a catchment, thus the soil moisture storage capacities are likely to vary too. This is accounted for using a Pareto distribution function to weight the spatial variability of soil moisture capacity towards larger or smaller capacities.
The model also accounts for water losses during soil recharge due to evaporation, and therefore recognises the volume of water required to recharge the soil from its maximum storage capacity to produce surface run-off is likely to be greater than the storage capacity itself.

(ii) Rainfall input partitioned off as direct run-off by model component *(i)* is routed through the surface storage component of the PDM. This component uses a transfer function to represent a cascade of two equal linear reservoirs, signifying the time taken for the routing of the overland pathways.

(iii) The third component of the PDM routes the subsurface run-off as a groundwater store, which eventually contributes to the total output. A routing function similar to the surface storage component is used here; however, it is a cubic, non-linear function to represent the slower nature of the routing.

The PDM can incorporate functions to represent extended surface storage times, such as in reservoirs, or for continuous abstractions of the input. However, these are unlikely to be required in this project.

2.2 PDM Parameters

	f_c	(no units)	Rainfall factor – used to compensate for errors in rainfall measurements e.g. from elevation aspects. Suggested formula for calculation in Calver *et al.* (2005) as shown in section 2.3.
	t_d	(hour)	Time delay factor –used to fine tune flow output in terms of routing times.
Component *(i)*	c_{min}	(mm)	Minimum storage capacity for the catchment soils. Can be found through fieldwork described in section 3.1.
Component *(i)*	c_{max}	(mm)	Maximum storage capacity for the catchment soils. Can be found through fieldwork described in section 3.1.
Component *(i)*	b	(no units)	Distribution of the soils storage capacities between c_{min} and c_{max}. Pareto distribution is used in the PDM.
Component *(i)*	b_e	(none)	Evaporation function
	k_g	(hour mm b_g -1)	Groundwater recharge time constant –Liu and Wang (1989) and Calver *et al.* (2005) suggest this may be inferred from the recessional limb of a hydrograph during a rainless period.

	b_g	(no units)	Exponent of recharge function – Moore (2007) suggests this is normally set to '1', however it does not state on what occasions it would not be '1'.
	S_t	(mm)	Soil tension storage capacity – inferred to be the field capacity of the soil. Can be found through fieldwork described in section 3.2.
Comp. (ii)	k_1,k_2	(hour)	Time constants of cascade of two linear reservoirs – Calver *et al.* (2005) suggest this can initially be taken as 'time to peak' on the hydrograph.
Comp. (iii)	k_b	(hour mm^{m-1})	Baseflow time constant – Formula for calculation suggested by Calver *et al.* (2005) as shown section 2.3.
	m	(no units)	Exponent of baseflow in non-linear storage.

2.3 Formula for Parameter Calculations from Calver *et al.* (2005)

Calver *et al*. (2005), as a part of a DEFRA research and development project, has suggested formulae to help set parameter values for the PDM model. The equations use other measurements and characteristics of the catchment area in their calculations.

$$f_c = -0.241 + 0.021\sqrt{DPSBAR} + 0.668\sqrt{(HOSTGMIN/100)} + 0.919\sqrt{(HOSTPEAT/100)} + 0.0093HOSTNG + 0.217\sqrt{(LANDA/100)}$$

$$k_b = 3.237 + 2.154BFIHOST + 0.015DPLBAR + 0.085\sqrt{DPSBAR} + 1.852\sqrt{URBEXT} + 0.986\sqrt{(HOSTPEAT/100)} - 0.845DRAIN2$$

When:

HOSTGMIN = % of catchment area covered by HOST classes 1-10, 13 and 14 (mineral soils with underlying groundwater).

HOSTPEAT = % of catchment area covered by HOST classes 11, 12 and 15 (peat soils with groundwater).

HOSTNG = % of catchment area covered by HOST classes 16-29 (essentially non-groundwater).

LANDA = % of catchment area covered by grassland based on CEH land cover data classes 5-8 and 19.

DRAIN2 = Drainage density (total length of river (km) divided by catchment area (km^2))

URBEXT = Extent of urban/suburban land cover (fraction of urban cover + (0.5*fraction of suburban cover)).

DPSBAR = Mean slope of drainage paths to site (m/km).

DPLBAR = Mean drainage path length

BFIHOST = Base Flow Index. Calculated from weighted average of HOST classes over catchment and gives a value in range of 0-1.

3 FIELDWORK METHODS FOR PARAMETER CALCULATIONS

Characteristics of the four soil types in the Migneint field site were quantified through field work. The aim was to measure soil water holding capacity for each of four soil types, and in particular to determine moisture content at Permanent Wilting Point (–1.5 MPa).

3.1 Soil Moisture Capacity

Soil types have differing water holding capacities due to their different pore structures. This quantity is involved in determining the separation of rainfall input into surface and sub-surface routing, as it enables an estimate to be made on when the soil will become saturated and 'spill'. This capacity is taken here to be the water content between soil saturation and the soils wilting point (not between field capacity and wilting point as is usually the definition of available water content), as this will allow the model to determine when, during a rainfall event, the soil will become saturated. The soils wilting point must therefore also be calculated. Wilting point can be found by undertaking fieldwork to collect soil cores, followed by lab analysis with the WP4 Dewpoint PotentiaMeter to detect when water potential of the soil cores is at the wilting point pressure of -1.5MPa.

Fieldwork

The catchment had previously been mapped, by Ed Rowe in August 2010, into four functional soil classes (

Figure 2):

"Bog": deep peat with true blanket bog vegetation;

"Wet": organomineral soils with a 10-40 cm organic horizon;

"Dry": organomineral soils with a < 10 cm organic horizon;

"Flush": mineral and organomineral soils dominated by groundwater efflux.

Soil cores were required for each of the 4 soil categories in the catchment. An area representative of each of these was identified with help from the pre-existing soil classification map and by using judgement on the expected characteristics of each soil type. A site within an area of a certain soil classification was picked at random by throwing a trowel over the shoulder. Before taking a soil core at this site, a bread knife was used to cut down into the soil to cut through any vegetation and roots. This would help to minimise compaction of the soil when inserting the corer. A square corer was used to obtain the samples, inserted to a depth of 45cm perpendicular to the ground surface. Upon removal, the extent of any compaction was noted and the core split into three equal sections to be placed in sealable, labelled polythene bags. Three core samples from each soil type were taken from different sites across the catchment to show any variability between them. Samples were kept in their sealed polythene bags in a cold store on their return to the lab.

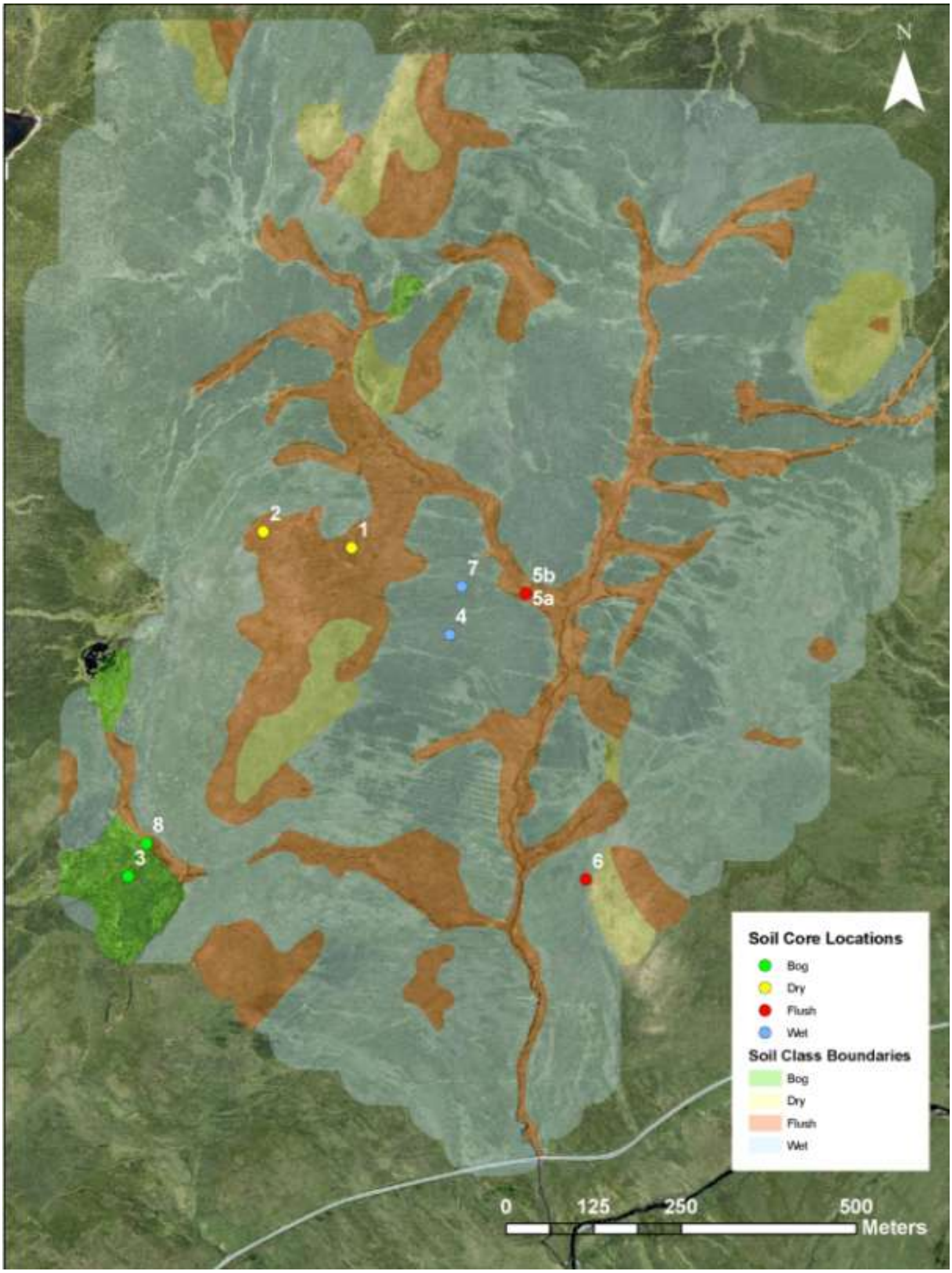


Figure 2. Areas of different soil classes in the Nant y Brwyn catchment, showing locations of sample cores.

Fieldwork Sources of Error

Often during this fieldwork, the 45cm depth was unreachable as the corer hit the mineral soil layer which it was not able to penetrate. When this occurred, the maximum obtainable to the bottom of the organic soil layer was used. Originally, a section of the mineral soil layer was sought to be included in the core, however as the corer was not able to penetrate this layer, it could not be sampled. In the wetter soils, the whole soil core would not be removed with the corer, but run out of the base instead. Repeat cores had to be taken in this case until an intact core was successfully removed. In contrast, other soil areas such as the bog, were found to have their top layers frozen due to the recent cold weather. In a similar method to that used to prevent compaction, the bread knife was used to cut through this top layer before coring.

The Bog soils had the deepest organic later at >40cm, whereas the organic layer in Dry soils is < 10cm thick. In the Wet soils, the organic layer was intermediate. In the Flush soils, organic layer depth appeared to be much more variable in its thickness and coarseness, depending on its location in the catchment.

Lab Analysis

The WP4 Dewpoint PotentiaMeter measures water potential in soils by determining the temperature at which condensation forms on a mirror inside the machine, after the vapour pressure in the air has equilibriated with the soil's water potential within a closed chamber. The machine is well suited to measuring water potentials around wilting point, -1.5Mpa.

Eight soil samples were prepared from each soil core, initially all from the top 15cm of the core. A bread knife was used to slice thin sections of the core that would fit into the disposable sample cups. It is advised that the sample cups should not be more than half full with soil so as not to dirty the mirror when measuring in the WP4. However due to these samples being prepared when wet, the volume of the soils reduced significantly as they were left to dry out before being tested. Thus the sample cups were filled completely, but with care being taken to leave the cup rim clean of soil. Sample cups were then labelled and placed in a 30°C oven with their lids removed to speed up the drying process. Depending on the soils initial wetness, samples required around 3-4 hours to dry out in the 30°C oven, although regular testing in the WP4 to show their drying progress is recommended as it was often easy to dry the soil samples beyond their wilting point. After drying, the soil samples were left to equilibrate in their cups with the lids on for a period of time, overnight if possible, before measuring water potential in the WP4. This is due to the surface of the soil sample drying quicker than the interior of the sample, especially when using the 30°C oven to accelerate drying, which could cause errors when measuring water potential.

When using the WP4 machine, it was switched on for half an hour before sampling. Calibration was carried out at intervals to ensure the machine is sampling accurately. A 0.5M solution of KCl is poured into a sample cup to carry this out. Readings should be within ±0.1MPa of -2.19MPa if sampling at 20°C or -2.22MPa at 25°C. Soil sample cups were left on the top of the machine with their lids on to equilibrate to the WP4's chamber temperature. After placing the sample cup in the machine drawer, the temperature difference between the soil sample and the chamber was checked to be within ±0.5°C by pressing the bottom right button on the WP4. The machine itself will not start readings unless the difference is below ±1°C, however to increase accuracy the samples in this investigation were left to equilibrate to below ±0.5°C. The WP4 was then set to continuous reading mode by pressing the top left button and connected to the laptop (see later section on setting up the laptop for continuous readings) before turning the drawer knob to read.

Continuous readings had to be taken for around 30-45 minutes before the readings settled down to give a steady water potential result. The time series of these continuous readings were plotted on a graph to show the settling of the readings taken by the WP4. Once readings began fluctuating around the same level, around 5 readings were taken to give the final water potential reading. Several samples were dried and analysed per core, to obtain results within around 0.5MPa either side of the 1.5MPa wilting point pressure. Samples were then removed from the chamber and placed in a porcelain crucible. The weight of the crucible and soil was then taken, from which the original weight of the crucible was subtracted to give the soil weight at wilting point. Soils were then placed in a 105°C oven for 16 hours before being weighed again to give their dry weight. Soil moisture volume is given by subtracting dried soil weight from weight of soil at wilting point.

Using these data, gravimetric soil moisture content at water potentials around the wilting point can be calculated as volume of moisture in the sample per grams of dried soil. This was converted to volumetric soil moisture content by multiplying the gravimetric moisture content by an average bulk density measurement for that soil type calculated from a previous investigation (*appendix 3*). By fitting a linear regression to the plot of volumetric soil moisture contents against measured water potentials for each soil core, the moisture content at the -1.5MPa wilting point was calculated.

In terms of using this data for the parameters in the PDM model, the c_{max} value is taken to be where the largest soil moisture content exists at the wilting point after multiple soil cores have been tested for the same soil type. The smallest soil moisture content from these measurements is then used as c_{min}.

Lab Analysis Sources of Error

Often when taking readings with the WP4, it was difficult to obtain a stable measurement of the water potential for certain soil samples as it fluctuated greatly or continued to decline with every reading even after an hour of continuous sampling. This lead to difficulties when deciding when the water potential readings had reached their actual level, and which readings to include when calculating the average. As a rule to attempt to remove subjectivity, 4 or 5 readings were obtained that fluctuated around the same level, and not slowly, continuously decreased, before calculating the average. On occasion however, readings did appear to level out like this but then continue to fall with further readings.

There are several factors which could have contributed to these errors. The WP4 machine works most accurately when the whole base of the sample cup is covered with the soil sample. This was difficult to maintain due to the volume of the soil shrinking as it dried out in the sample cups. After oven drying, it is also possible that the soils had not fully equilibrated before testing, with the surfaces of the sample remaining drier than its centre. This could account for the continuous decrease in water potential whilst sampling as the soil is still equilibrating in the machine chamber.

These factors may have caused the variability seen in some of soil moisture content that meant trends between volumetric soil moisture content and water potential were hard to distinguish. It should also be noted however, that these fluctuations may be caused by variations within the soils themselves.

Setting up a Laptop to use with Continuous Readings

Connecting the WP4 to a laptop allows the machine to be left to record continuous measurements until it appears that the sample has equilibrated to a steady water potential. Water potential readings can then be plotted against time of reading to help show visually where readings become steadier and thus where to take average readings from.

The connection is made using the laptops ‘HyperTerminal’ software, accessible from Start>Programs>Accessories>Communications>HyperTerminal. For a new connection, a name must first be assigned, along with an icon to help identify the connection in the future. On the next ‘connect to’ screen, in the ‘connect using’ setting, select the port through which the USB cable connected to the laptop (all other settings on this ‘connect to’ screen can be ignored). This will usually be a COM# port, and can be found through Start>Settings>Control_Panel>System>Hardware>Device_Manager>Ports, and seeing which COM port appears when the USB cable from the WP4 is connected. On the ‘COM# Properties’ screen the port settings should be entered as follows - *Bits per second:* 9600, *Data bits:* 8, *Parity:* None, *Stop bits:* 1, *Flow control:* Hardware. Saving this connection when exiting HyperTerminal allows this connection to be quickly opened for future readings.

The readings from the WP4 will now appear in the white window in 4 columns representing time since sampling started, temp (°C), Water potential and pF. This text may be copied out into MS Excel and split into separate columns after pasting by clicking on the paste symbol that appears by the pasted text and selecting ‘text import wizard’.

3.2 Soil Tension Storage Capacity (Field Capacity)

Soil tension storage capacity is described by Moore (2007) as the ‘threshold storage below which there is no drainage,’ as all water is being ‘held under soil tension’ (p486). As field capacity is also defined as the water storage after all drainage due to gravity has occurred (usually after 2 days), methods to measure field capacity have been researched to provide a value for the S_t parameter.

Cassel and Nielsen (1986) explain both in-situ and approximation methods for field capacity measurements. Approximation methods, such as the artificial wetting of a soil core in a lab, are regarded less accurate as the sample has been disturbed and removed from its surroundings which help determine its field capacity. Even in-situ methods hold some uncertainty, however, as there is no established standard drainage rate which is considered negligible as to say when field capacity is reached (Cassel and Nielsen, 1986).

In-situ measurements have been used in this research, based on the polythene sheet method stated by Cassel and Nielsen (1986) and Rowell, (1994). A site of area at least $3m^2$ and representative of the selected soil type is identified. A small dyke is built around the site to contain water during the wetting up of the area. Enough water is then applied to the soil surface to infiltrate to at least 75cm soil depth. A polythene sheet is then used to cover the area for 2 days to prevent further rainfall input or losses to evaporation. After 2 days natural drainage, it is thought the soil will have reached its field capacity. Soil cores to the depth of the organic layer are then taken from the site where the soil moisture content is then determined in a lab. The equations for calculating field capacity are stated below.

$FC_w = M_w/M_s$

$FC_v = FC_w \times p_b/p_w = M_w/(V_a \times p_w)$

When:

FC_w = gravimetric field capacity (g water/g soil)

FC_v = volumetric field cap. (cm^3water/cm^3soil)

M_w = water mass

M_s = oven-dried soil mass

p_b = soil bulk density

p_w = water density

V_a = bulk soil volume

Alternatively, this method may be carried out using tensiometers installed at selected depths and monitored periodically during drainage. The readings of soil water pressure values can be compared to soil water characteristic curves (Cassel and Nielsen, 1986) so the reading after 48 hours gives field capacity. Such equipment is thought to perform badly in wet peatlands however; therefore the polythene sheet method is to be used in this investigation.

Fieldwork Sources of Error

Some uncertainty exists in whether 48 hours will be a sufficient period of time to allow the peatland sites to drain naturally to their field capacity, however, given their high water storage capacities and slow drainage rates. This should be kept in mind whilst analysing the peatland samples.

4 FIELD WORK RESULTS

The soil cores collected from the Migneint field site are described in *table 1* below. The results in this section refer to lab work carried out on these samples.

Sample	Grid Location	Section of Full Core	Soil Category	Total Depth (cm)	Overall Compaction (cm)	Section Depth (cm)	Description
1	SH78917 BNG456 95	Top	Dry	43	2	14.3	On slope at start of transect. Core hits hard mineral area, cannot core deeper.
		Middle	Dry	43	2	14.3	
		Bottom	Dry	43	2	14.3	
2	SH78791 BNG457 18	Top	Dry	23	1	23	On slope higher than sample 1
3	SH78598 BNG452 27	Top	Bog	44	1	21.6	Bog at end of hill. Top layer of Bog frozen.
		Bottom	Bog	44	1	14.6	
4	SH79057 BNG455 71	Top	Wet	50	10	20	Near AWS. Very wet heather. Requires numerous attempts.
		Bottom	Wet	50	10	20	
5a	SH79166 BNG456 30	Top	Flush	15	3	15	Up catchment from AWS, next to flush stream.
5b	SH79166 BNG456 30	Top	Flush	17	1	17	Opposite side of stream to 5a, higher up bank.
6	SH79252 BNG452 22	Top	Flush	45	4	13.7	Near fence on East side of catchment. Much higher and drier flush area than samples 5a/b.
		Middle	Flush	45	4	13.7	
		Bottom	Flush	45	4	13.7	
7	SH79074 BNG456 40	Top	Bog	45	0	15	Bog at end of hill.
		Middle	Bog	45	0	15	
		Bottom	Bog	45	0	15	
8	SH78624 BNG452 74	Top	Wet	45	4	13.7	Near AWS. Very wet heather. Requires numerous attempts.
		Middle	Wet	45	4	13.7	
		Bottom	Wet	45	4	13.7	

Table 1 **- Description of Soil Cores taken from the Migneint field site. Samples 5a and 5b were taken from the same section of flush soil.**

4.1 Sample Locations

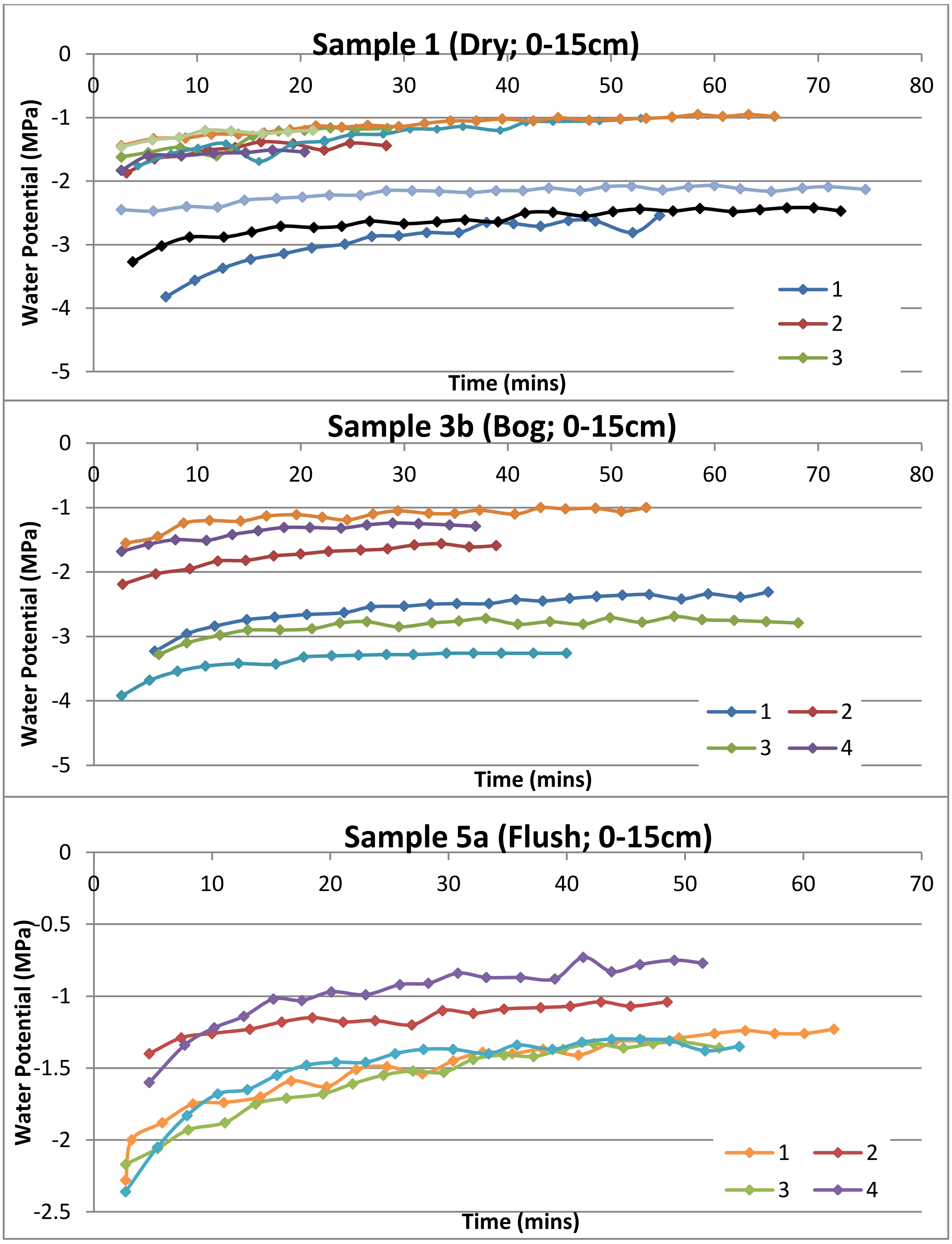
The GPS locations for each soil sample listed in table 1 were projected onto aerial photography of the Migneint area in ArcMap, and displayed in Figure 2.

It will be noted from Figure 2 that the soil core classification does not necessarily relate to the soil type classification from which it was taken from. Dry soil cores, for example, were taken from an area that has been mapped as flush, and sample 6 is within a wet soil boundary despite being classified as flush itself. Vegetation mapping is inevitably somewhat subjective, and spatial variation occurred at a smaller scale than could be mapped. Classification of soil cores was therefore carried out by characteristics and conditions of the soils at the exact sample location. Thus as no water was observed flushing from the high sloped areas of samples 1 and 2, but was from around sample 6, they have been classified as dry and flush respectively.

4.2 Soil Moisture Capacity

The top section of each soil core described in *table 1* underwent the testing for soil moisture capacity at wilting point, as described in section 3.1. The time series of continuous water potential measurements taken by the WP4 as the readings settled for the soil samples are presented in *figure 3*. Time series are not available for every soil core as the continuous sampling method of the WP4 was only set up midway through the lab work. The time series illustrated that even after one hour, many samples readings had not become completely steady. The fluctuations were, however, within the 0.1MPa accuracy range of the WP4 and thus an average of these readings is assumed to give the settled water potential result.

All the samples measured water potentials and their respective soil weights during this measurement are listed in *appendix 1*.



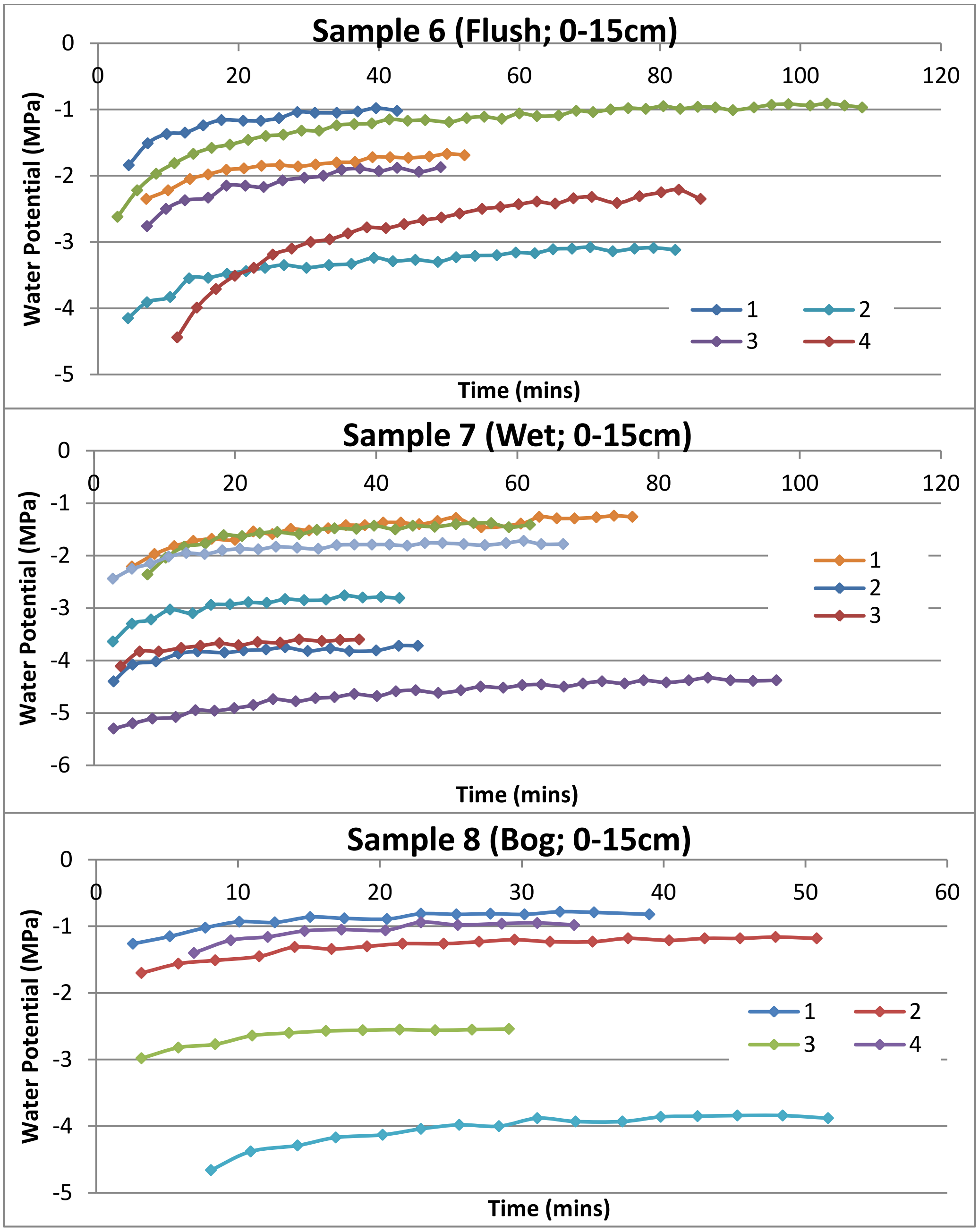
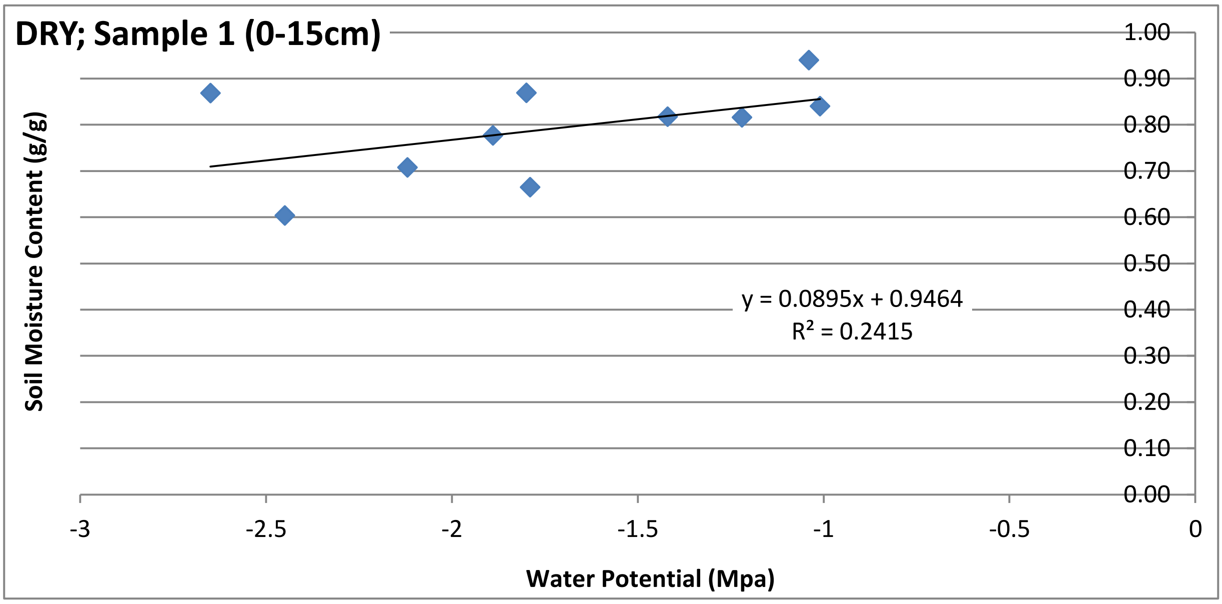


Figure 3. Time series of water potential measurements for soils taken from the top 15cm of Samples 1, 3b, 5a, 6, 7 and 8

Following the identification of the soils' water potentials, the samples were tested for gravimetric soil moisture content, as described in section 3.1. The results for this, plotted against the water potential are displayed in *figures 4-7*. Calculations were performed to produce volumetric soil moisture content data, however unrealistic values were turned out and thus it was assumed that the bulk densities from the previous investigation did not correspond well to the soil core samples taken during this investigation. Gravimetric soil moisture content has therefore been used for results in graphs and tables in this section, however both gravimetric and volumetric calculations are presented in *appendix 2*.



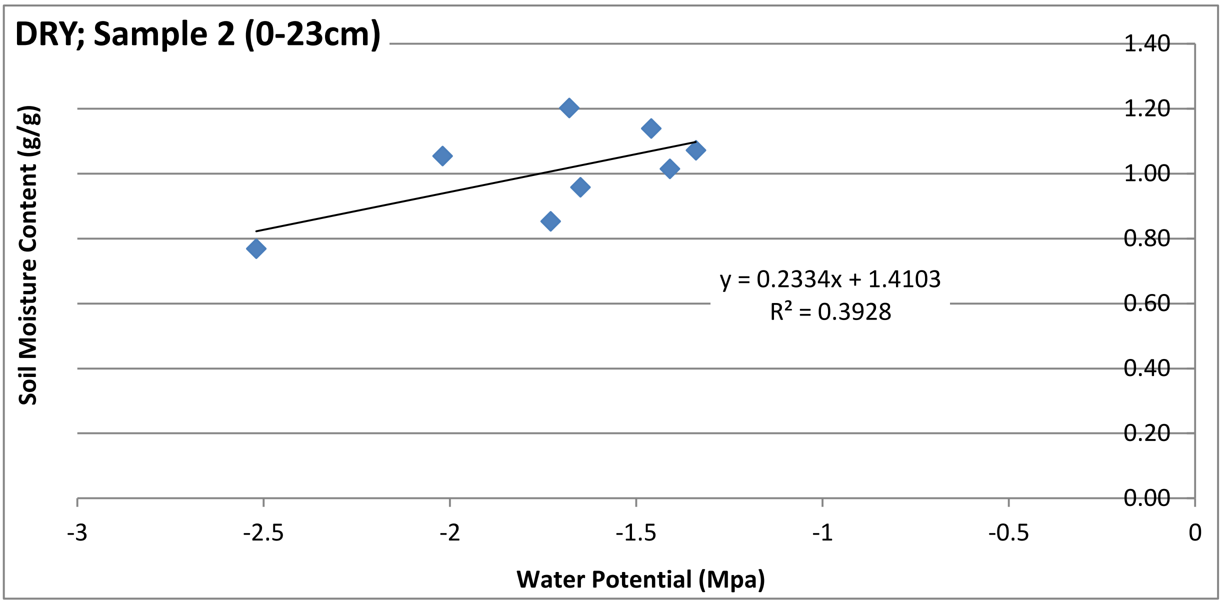


Figure 4 – **Water potential and corresponding gravimetric soil moisture contents (g H_20/g dried soil) for soil samples from dry soil types.**

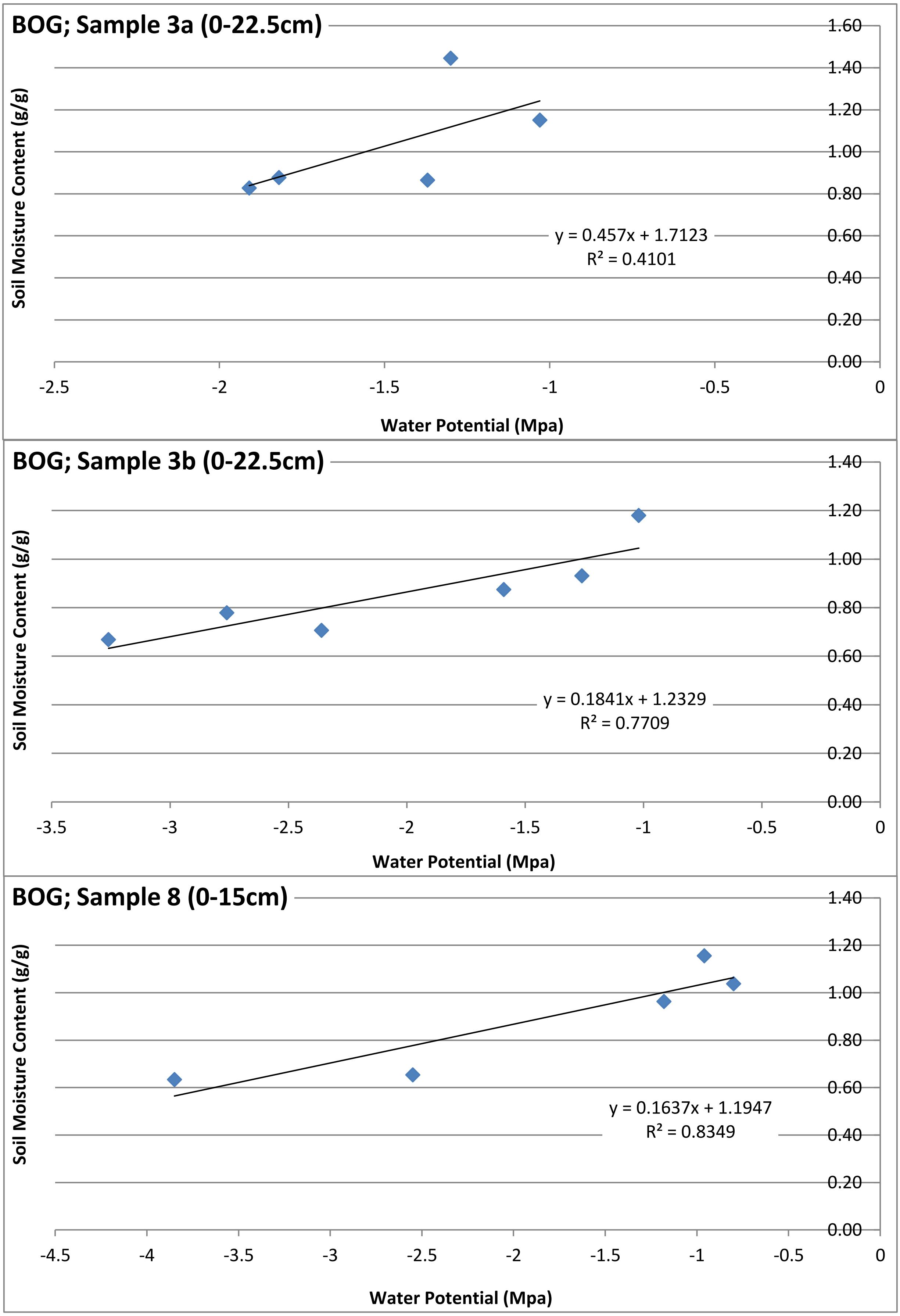
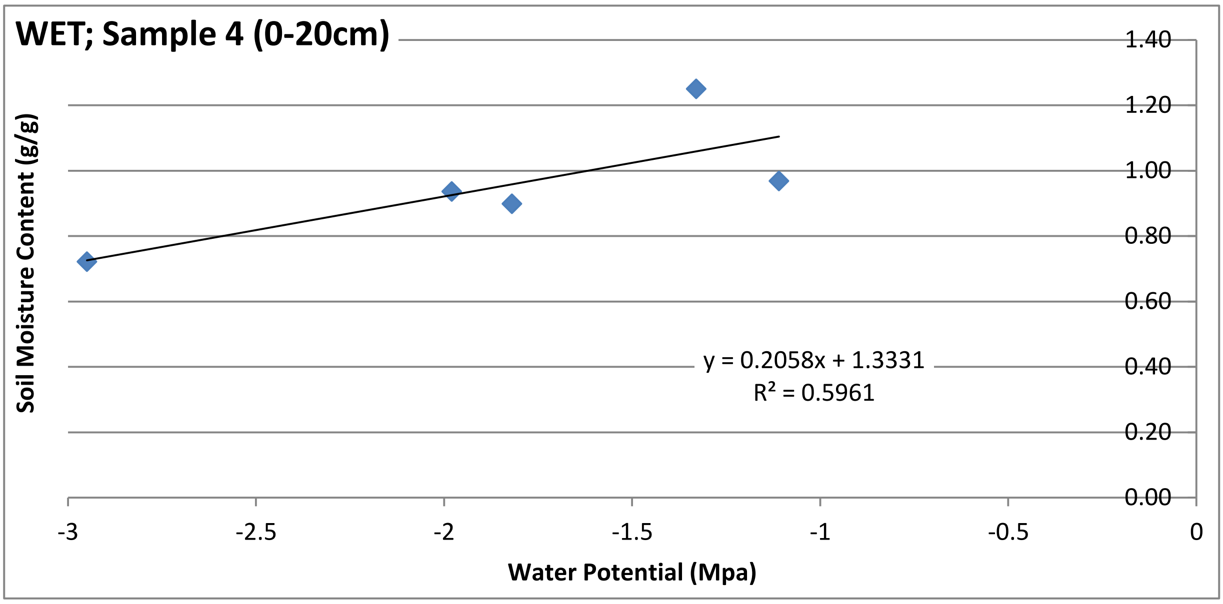


Figure 5 – **Water potential and corresponding gravimetric soil moisture contents (g H_2O/g dried soil) for soil samples from bog soil types.**



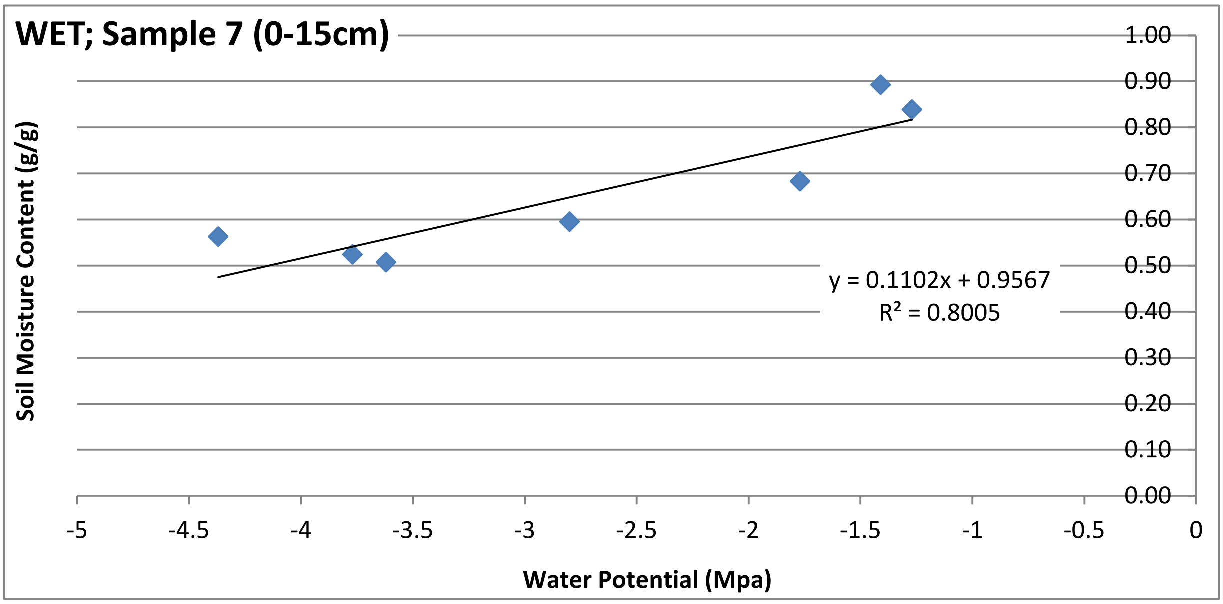


Figure 6 – **Water potential and corresponding gravimetric soil moisture contents (g H_20/g dried soil) for soil samples from wet soil types.**

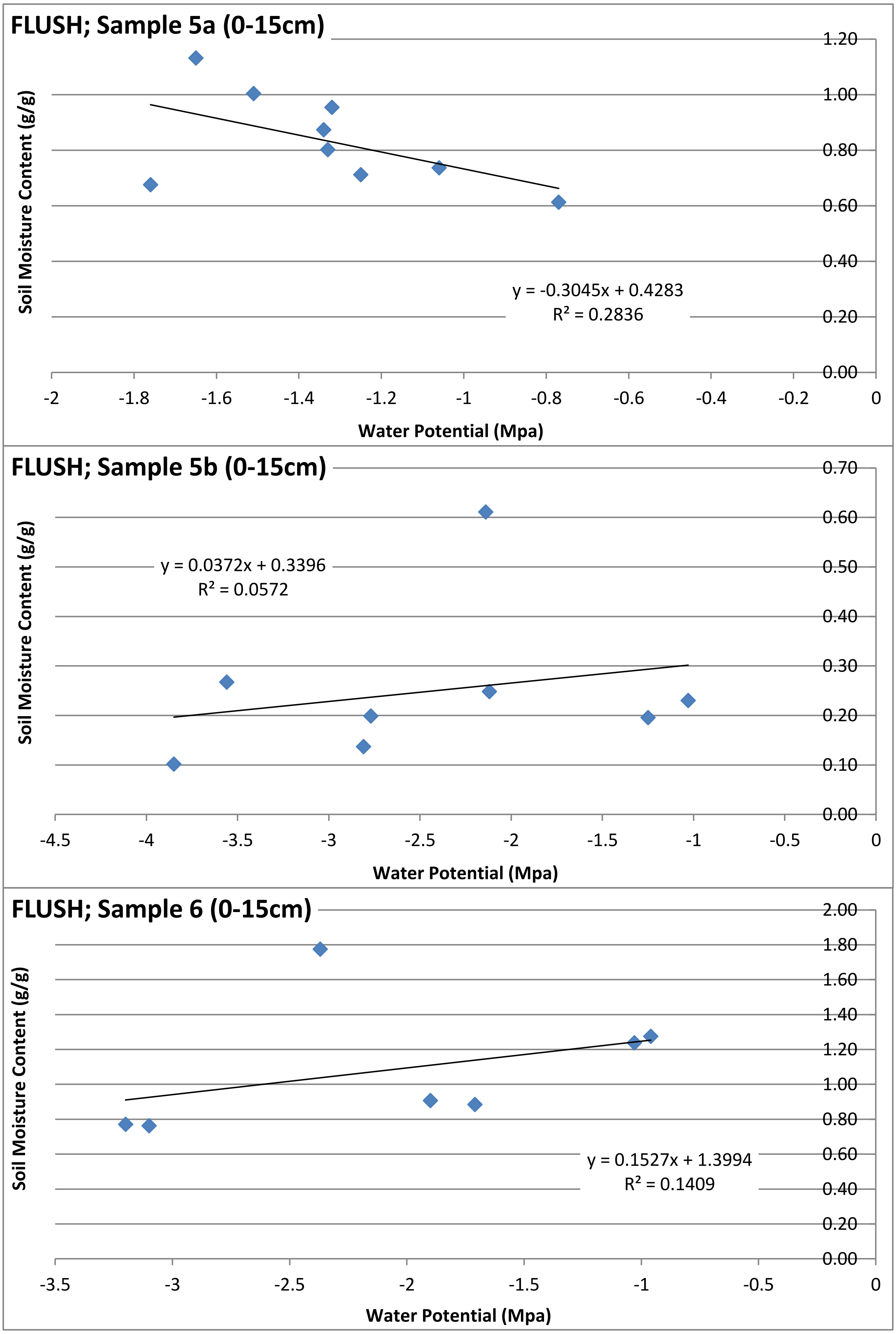


Figure 7 – Water potential and corresponding gravimetric soil moisture contents (g H_20/g dried soil) for soil samples from flush soil types.

The equations for the trendlines in *figures 4-7* were then used to calculate the soil moisture content values when the water potential equalled -1.5MPa, that wilting point pressure. *Table 2* lists these wilting point soil moisture contents for each sample.

Soil Type	Sample	Gravimetric Soil Moisture Content at -1.5MPa (g H_20/g dried soil)	Average Gravimetric Soil Moisture Content (g H_20/g dried soil)	Gravimetric Soil Moisture Content Range (g H_20/g dried soil)
Dry	1	**0.81**	0.94	0.25
Dry	2	**1.06**		
Bog	3a	**1.03**	0.98	0.08
Bog	3b	**0.96**		
Bog	8	**0.95**		
Wet	4	**1.02**	0.91	0.23
Wet	7	**0.79**		
Flush	5a	**0.87**	0.78	0.88
Flush	5b	**0.29**		
Flush	6	**1.17**		

Table 2 – Gravimetric soil moisture contents at wilting point, calculated from trend line equations. Average gravimetric soil moisture contents and range of gravimetric soil moisture contents for each soil type at wilting point are also listed.

The plotted results in *figures 4-7* generally show a trend of lower gravimetric soil moisture contents for more negative water potentials. Uncertainty is noted in several of the figures however, as measured points are seen to deviate away from best fit lines. This is most apparent in flush soils, where points are seen to fall furthest away from the trend line, such as for the readings at -2.14Mpa and -2.37Mpa in soil cores 5b and 6 respectively (*fig.7*). For soil sample 5a (*fig.7*), the trend is even seen to be reverse of all other soil samples. This uncertainty is reflected by flush soils having the largest range of gravimetric soil moisture contents at the wilting point of all soil types at 0.88ml/cm^3, larger than their actual average value of 0.78g H_20/g (*table 2*) dried soil.

Scatter within the points of sample 3a (*fig.5*) is also noted, however the gravimetric soil moisture value at -1.5Mpa calculated from the trend line equation corresponds closely with other values for bog soils, as can be seen from *table 2*, giving confidence to this trend. The range of soil moisture content for bog soils is in fact smallest of all soil types, at just 0.08g H_20/g dried soil; the average soil moisture content value for bog soils is highest, however, at 0.98g H_20/g dried soil.

Wet soil and dry soil types range is similar at 0.23 and 0.25g H_20/g dried soil respectively, although the dry soil type has an average soil moisture content that is 0.03g H_20/g dried soil higher than wet soil, at 0.94g H_20/g dried soil (*table 2*).

5 ANALYSIS

The large range of gravimetric soil moisture contents for flush soils could be attributed to both uncertainties in the sampling and laboratory methods, as described in sections 3.1 and 3.2, and to the natural variability of the soils characteristics. However as the range seen is considerably bigger than other soil classes ranges, ten times larger than that for bog soils, the natural characteristics of the soil is thought to have overwhelmingly influenced its range of soil moisture contents. Observations of the flush cores noted that gravel bands were present within the core, deposited by previous surface water flows which can occur regularly in these areas of the catchment. Thus soils even within the same sample core are heterogeneous, causing the variability and scatter in the flush soil results. As the range for flush soils is larger than its average gravimetric soil moisture content, much uncertainty surrounds the reliability of this average value. It is likely that the average value would be lower for flush soils however if coarser gravel soils are present, as this would reduce the soils water retention potential and thus give lower soil moisture contents (Leeper and Uren, 1993).

Bog soils having the highest average gravimetric soil moisture content concurs with findings by Hudson (1994), that greater volumes of water were held in soils at the wilting point when organic matter content was higher. Whilst taking sample cores, it was noted the bog soils had by far the deepest organic soil horizon, extending well beyond the sampled 45cm depth, suggesting the organic content was high in these soils. The small range in values of soil moisture content at wilting point also suggests the bog soils are very homogenous.

Less variation is seen between the wet and dry soil classes with similar values for both average and range of soil moisture content. Values are closer to those of the bog soils than flush soils however, suggesting soils are still largely homogenous. Care should be taken when distinguishing between these soils however as the classification of soils during sampling was subjective, and thus the lack of distinction between soil moisture content of certain soil classes may result from cores taken from areas that were on the boundary of soil classes.

6 REPRESENTING SOIL CLASSIFICATIONS IN THE PDM

The different soil types and their distribution in the Migneint catchment must be represented in the PDM to produce an outflow that reflects the real-life situation. The PDM accounts for soil moisture storage capacity variance by incorporating a Pareto distribution parameter (*b*) to represent the proportion of larger capacities to smaller ones. The different soil types may therefore be represented in the model by finding the average soil moisture storage capacities for each of the four soil types through fieldwork described in the previous section, then weighting this for the proportion of the catchment that is classified as each soil type. By summing the area of all the polygons for each soil type in ArcMap (*figure 2*), the proportion of the catchment each soil type covers can be estimated. The results of this are listed in *table 3*.

Soil Class	Area (km2)	Proportion of Catchment (%)
Bog	0.028	1.77
Dry	0.076	4.79
Flush	0.283	17.94
Wet	1.191	75.50
Total	**1.578**	**100**

Table 3 – *A*rea covered by each soil class in the catchment. The proportion of each soil class in respect to the total catchment area is also shown.

Errors and uncertainties are still expected to exist in the model, however, as the PDM does not appear to account for differences in other parameter values that may occur between different soil types. For example, the baseflow time constant (k_b) is likely to vary significantly between soil types as the bog areas are relatively disconnected in terms of its flow pathways, although the flush areas very well connected. However, the equation for k_b suggested by Calver *et al.* (2005) (section 2.3) goes someway to correct this, incorporating the base flow index which should be calculated using a weighted average of the HOST classified soils in the catchment.

Alternatively, to account for variations in parameters other than the soil moisture storage capacity, the PDM could be set up and run for each soil type. Parameters would then be more representative of the specific soil characteristics and thus produce a more realistic outflow for that soil type. Should the model be set up in this way, the outputs could be compared to the dip well data for that soil type. After this had been done for the four soil types, a way of integrating the outputs or combining the parameter values would need to be looked into to produce an output for the whole catchment.

7 CONCLUSIONS

The PDM model uses a Pareto distribution function to incorporate the variance in soils and their hydrological properties across catchments. This is therefore suited to the Nant-y-Brwyn catchment where 4 soil classes have been determined. The main parameters required to represent the variance across the catchment relate to the groundwater storage component of the model and include the max and min soil storage capacities and the soil tension storage capacity (field capacity). The most accurate methods of obtaining values for these parameters which are most representative of real life was decided to be through fieldwork where samples were taken in-situ.

Fieldwork and laboratory tests showed bog soils to hold the most moisture at wilting point, which has been attributed to the higher organic material content. Dry and wet soils' average moisture capacities were lower, but not excessively so. It should be noted that due to the small differences in these values between soil classes, any errors that may have occurred during the sampling and testing methods would have had a greater impact on one soils value relative to another. More significant differences were seen between the ranges of soil moisture contents, in particular for flush soils, which, due to the conditions in which its layers are created, is more heterogeneous than other soil types.

Therefore in general, with the exception of flush soils, only small variance across the catchment was seen. Such conclusions have implications for the representation of the catchment soils within models like the PDM, as soil characteristics across the catchment may be more homogenous than previously thought, affecting the value of the PDM's Pareto distribution. To confirm this finding, further core samples would be needed across wider areas of the catchment however, particularly in areas where soil classification is less subjective as this would help reduce uncertainty on the values stated in this report. Once these soil capacity values have been better supported, the PDM model can then be run based on these findings and simulate the hydrological output of the soils, and then adjusted to account for expected future changes in the environment to model the impact of climate change.

8 REFERENCES

Liu, X.R. and Wang, J.Q (1989) A conceptual model simulating the hydrological processes on a drainage basin in a plain area, *New Directions for Surface Water Modelling* **181,** pp.195-202

Moore, R.J. (2007) The PDM rainfall-runoff model, *Hydrology and Earth System Sciences* **11**(1), pp.483-499

Cassel, D.K. and Nielsen, D.R. (1986) Field capacity and available water capacity. In: Klute, A. (Ed.) *Methods of Soil Analysis, Part 1: Physical and mineralogical methods*, pp.901-926

Leeper, G.W. and Uren, N.C. (1993) *Soil Science: An Introduction*, Melbourne University Press, 300pp.

Rowell, D.L. (1994) *Soil Science: Methods and Applications*, Longman: Essex

Rowe, E. and Moore, R. (2009) WADES Document Series: Programme of Work, *Centre for Ecology and Hydrology; Bangor*, [online] Avaliable at: http://www.ceh.ac.uk/sci_programmes/Water/Wades_Project/index.html [last accessed 15/02/2011]

Calver, A., Crooks, S., Jones, D., Kay, A., Kjeldsen, T. and Reynard, N. (2005) National river catchment flood frequency method using continuous simulation, *DEFRA/EA R&D Technical Report FD2106/TR*, Centre for Ecology and Hydrology; Wallingford

Hudson, B.D. (1994) Soil organic matter and available water capacity, *Journal of Soil and Water Conservation* **49**(2), pp.189-194

9 APPENDIX

site	test #	crucible #	cup weight (g)	cup/soil weight (g)	crucible weight (g)	crucible/soil weight (g)	SOIL WEIGHT (g)	MPa
Sample 1 DRY (top section)	1	164	2.95	5.23	16.14	18.42	2.28	**-2.65**
	2	154	2.90	5.24	16.81	19.16	2.35	**-1.42**
	3	180	2.95	5.46	16.29	18.79	2.51	**-1.80**
	4	177	3.17	6.25	16.14	19.23	3.09	**-1.04**
	5	132	2.94	5.49	16.34	18.87	2.54	**-1.01**
	6	132	2.92	4.88	16.33	18.28	1.96	**-1.89**
	7	178	3.17	5.13	15.68	17.65	1.97	**-1.79**
	8	177	2.95	5.08	16.16	18.30	2.14	**-2.12**
	9	164	2.96	4.96	16.13	18.14	2.01	**-2.45**
	10	132	2.96	4.74	16.33	18.11	1.78	**-1.22**
Sample 2 DRY (top section)	1	164	2.95	5.47	16.13	18.63	2.51	**-1.68**
	2	182	2.95	5.11	15.64	17.80	2.16	**-1.46**
	3	154	3.20	5.31	16.82	18.94	2.12	**-1.41**
	4	178	2.97	6.03	15.73	18.79	3.06	**-2.02**
	5	33	2.97	4.73	17.27	19.03	1.76	**-1.73**
	6	132	2.92	4.98	16.33	18.42	2.08	**-1.65**
	7	148	3.14	4.60	16.14	17.58	1.45	**-2.52**
	8	180	2.98	4.72	16.29	18.03	1.74	**-1.34**
Sample 3a BOG (top section)	1	154	3.17	4.15	16.82	17.83	0.99	**-1.82**
	3	177	2.95	4.29	16.15	17.50	1.35	**-1.30**
	4	180	2.93	3.98	16.29	17.36	1.06	**-1.91**
	5	178	3.19	4.33	15.73	16.87	1.14	**-1.03**
	6	40	2.92	4.10	16.14	17.31	1.18	**-1.37**
Sample 3b BOG (top section)	1	164	2.95	3.94	16.14	17.13	0.99	**-2.36**
	2	180	2.98	4.25	16.30	17.58	1.28	**-1.59**
	3	177	3.19	4.56	16.16	17.53	1.37	**-2.76**
	4	132	2.90	4.31	16.33	17.74	1.41	**-1.26**
	5	182	2.93	4.22	15.64	16.92	1.29	**-3.26**
	6	148	3.17	4.82	16.14	17.76	1.64	**-1.02**
Sample 4 WET (top section)	1	164	2.95	4.28	16.13	17.28	1.24	**-1.11**
	2	33	2.95	4.77	17.27	19.09	1.82	**-1.98**
	3	182	3.19	4.51	15.63	16.93	1.31	**-1.82**
	5	132	2.98	4.34	16.34	17.70	1.36	**-2.95**
	6	148	2.92	4.63	16.13	17.84	1.71	**-1.33**
Sample 5a FLUSH (top section)	1	33	2.95	4.90	17.29	19.21	1.94	**-1.32**
	2	148	2.90	5.31	16.15	18.55	2.41	**-1.51**
	3	177	2.95	5.62	16.15	18.81	2.67	**-1.76**
	5	132	2.92	5.18	16.33	18.59	2.26	**-1.65**

Sample 5b FLUSH (top section)	1	33	2.95	11.39	17.27	25.71	8.44	**-3.85**
	2	40	2.93	8.56	16.15	21.76	5.62	**-1.25**
	3	164	2.95	9.75	16.15	22.95	6.80	**-2.81**
	4	154	2.95	6.22	16.82	20.09	3.27	**-3.56**
	5	180	2.93	9.18	16.29	22.54	6.25	**-1.03**
	6	154	2.96	8.58	16.80	22.45	5.64	**-2.77**
	7	177	2.94	4.66	16.14	17.90	1.74	**-2.14**
	8	180	2.95	8.47	16.29	21.83	5.53	**-2.12**
Sample 6 FLUSH (top section)	1	33	2.95	5.39	17.27	19.71	2.44	**-1.03**
	2	177	2.98	4.99	16.15	18.16	2.01	**-3.10**
	3	148	2.95	5.01	16.15	18.21	2.06	**-1.90**
	4	164	2.93	4.86	16.40	18.30	1.92	**-2.37**
	5	164	3.19	5.08	16.14	18.02	1.89	**-1.71**
	6	178	2.92	4.60	15.73	17.38	1.67	**-3.20**
	7	40	2.95	5.39	16.13	18.56	2.44	**-0.96**
Sample 7 WET (top section)	1	132	2.95	4.15	16.35	17.54	1.20	**-1.27**
	2	164	2.98	3.95	16.15	17.1	0.96	**-3.77**
	3	180	2.95	4.04	16.31	17.39	1.09	**-3.62**
	4	182	3.18	4.67	15.64	17.14	1.50	**-1.41**
	5	154	3.14	4.4	16.83	18.07	1.25	**-4.37**
	6	112	2.93	4.53	16.96	18.55	1.60	**-2.8**
	7	135	2.93	4.5	16.24	17.8	1.57	**-1.77**
Sample 8 BOG (top section)	1	177	2.94	4.54	16.14	17.76	1.61	**-0.8**
	2	40	3.16	5.02	16.14	18.01	1.87	**-1.18**
	3	148	2.95	4.24	16.15	17.44	1.29	**-2.55**
	4	33	3.18	4.84	17.28	18.94	1.66	**-0.96**
	5	178	2.95	4.55	15.72	17.29	1.59	**-3.85**

Appendix 1 - Water potential measurements carried out on soil cores when close to wilting point. Weights of soil samples at the time of measurement are also listed and are necessary for soil moisture content calculations later. Soil weight was calculated by subtracting sample cup weight from weight of sample cup containing the soil sample. This was then verified against a calculation of crucible weight subtracted from weight of crucible containing the soil sample. Where results differed slightly, an average between the two gave the final soil weight result.

site	test #	cruicble/soil dry weight (g)	DRY SOIL WEIGHT (g)	MOISTURE CONTENT (g)	% Water	grav. moisture content (g H2O/g drysoil)	vol. moisture content (ml H2O/cm3 drysoil)
Sample 1 DRY (top section)	1	17.36	1.22	1.06	46.49	**0.87**	**0.56**
	2	18.10	1.29	1.06	44.99	**0.82**	**0.52**
	3	17.63	1.34	1.17	46.51	**0.87**	**0.56**
	4	17.73	1.59	1.50	48.46	**0.94**	**0.60**
	5	17.72	1.38	1.16	45.67	**0.84**	**0.54**
	6	17.43	1.10	0.86	43.73	**0.78**	**0.50**
	7	16.86	1.18	0.79	39.95	**0.67**	**0.43**
	8	17.41	1.25	0.89	41.45	**0.71**	**0.45**
	9	17.38	1.25	0.76	37.66	**0.60**	**0.39**
	10	17.31	0.98	0.80	44.94	**0.82**	**0.52**
Sample 2 DRY (top section)	1	17.27	1.14	1.37	54.58	**1.20**	**0.77**
	2	16.65	1.01	1.15	53.24	**1.14**	**0.73**
	3	17.87	1.05	1.07	50.35	**1.01**	**0.65**
	4	17.22	1.49	1.57	51.31	**1.05**	**0.67**
	5	18.22	0.95	0.81	46.02	**0.85**	**0.55**
	6	17.39	1.06	1.02	48.92	**0.96**	**0.61**
	7	16.96	0.82	0.63	43.45	**0.77**	**0.49**
	8	17.13	0.84	0.90	51.72	**1.07**	**0.69**
Sample 3a BOG (top section)	1	17.35	0.53	0.46	46.73	**0.88**	**0.76**
	3	16.70	0.55	0.80	59.11	**1.45**	**1.25**
	4	16.87	0.58	0.48	45.28	**0.83**	**0.72**
	5	16.26	0.53	0.61	53.51	**1.15**	**1.00**
	6	16.77	0.63	0.55	46.38	**0.87**	**0.75**
Sample 3b BOG (top section)	1	16.72	0.58	0.41	41.41	**0.71**	**0.61**
	2	16.98	0.68	0.59	46.67	**0.87**	**0.76**
	3	16.93	0.77	0.60	43.80	**0.78**	**0.67**
	4	17.06	0.73	0.68	48.23	**0.93**	**0.81**
	5	16.41	0.77	0.52	40.08	**0.67**	**0.58**
	6	16.89	0.75	0.89	54.13	**1.18**	**1.02**
Sample 4 WET (top section)	1	16.76	0.63	0.61	49.19	**0.97**	**0.91**
	2	18.21	0.94	0.88	48.35	**0.94**	**0.88**
	3	16.32	0.69	0.62	47.33	**0.90**	**0.84**
	5	17.13	0.79	0.57	41.91	**0.72**	**0.68**
	6	16.89	0.76	0.95	55.56	**1.25**	**1.17**
Sample 5a FLUSH (top section)	1	18.28	0.99	0.94	48.84	**0.95**	**0.94**
	2	17.35	1.20	1.21	50.10	**1.00**	**0.98**
	3	17.74	1.59	1.08	40.34	**0.68**	**0.66**
	5	17.39	1.06	1.20	53.10	**1.13**	**1.11**

Sample 5b FLUSH (top section)	1	24.93	7.66	0.78	9.24	**0.10**	**0.10**
	2	20.85	4.70	0.92	16.37	**0.20**	**0.19**
	3	22.13	5.98	0.82	12.06	**0.14**	**0.13**
	4	19.40	2.58	0.69	21.10	**0.27**	**0.26**
	5	21.37	5.08	1.17	18.72	**0.23**	**0.23**
	6	21.50	4.70	0.94	16.59	**0.20**	**0.19**
	7	17.22	1.08	0.66	37.93	**0.61**	**0.60**
	8	20.72	4.43	1.10	19.89	**0.25**	**0.24**
Sample 6 FLUSH (top section)	1	18.36	1.09	1.35	55.33	**1.24**	**1.21**
	2	17.29	1.14	0.87	43.28	**0.76**	**0.75**
	3	17.23	1.08	0.98	47.57	**0.91**	**0.89**
	4	17.09	0.69	1.23	63.97	**1.78**	**1.74**
	5	17.14	1.00	0.89	46.95	**0.89**	**0.87**
	6	16.67	0.94	0.72	43.54	**0.77**	**0.76**
	7	17.20	1.07	1.37	56.06	**1.28**	**1.25**
Sample 7 WET	1	17.00	0.65	0.55	45.61	**0.84**	**0.82**
	2	16.78	0.63	0.33	34.38	**0.52**	**0.51**
	3	17.03	0.72	0.37	33.64	**0.51**	**0.50**
	4	16.43	0.79	0.71	47.16	**0.89**	**0.87**
	5	17.63	0.80	0.45	36.00	**0.56**	**0.55**
	6	17.96	1.00	0.60	37.30	**0.60**	**0.58**
	7	17.17	0.93	0.64	40.58	**0.68**	**0.67**
Sample 8 BOG	1	16.93	0.79	0.82	50.93	**1.04**	**1.02**
	2	17.09	0.95	0.92	49.06	**0.96**	**0.94**
	3	16.93	0.78	0.51	39.53	**0.65**	**0.64**
	4	18.05	0.77	0.89	53.61	**1.16**	**1.13**
	5	16.69	0.97	0.62	38.80	**0.63**	**0.62**

Appendix 2 - Weights of soil samples after drying in 105°C oven. Dry soil weight has been calculated by subtracting crucible weights listed in *appendix 1* by the weight of the crucible containing the dried soil sample. Volumetric soil moisture content has then been calculated by multiplying the gravimetric measurements by the bulk density values in *appendix 3*.

	Average Bulk Density (g/cm3)	Standard Deviation
BOG	0.8658	0.1662
DRY	0.6399	0.3435
FLUSH	0.9797	0.424
WET	0.9396	0.3594

Appendix 3 - Bulk densities of the four soil types averaged from a previous study. These values are used for volumetric soil moisture content calculation in *appendix 2*. Standard deviation of the values also listed.