Culm Grasslands Proof of Concept Phase 1

Developing an understanding of the hydrology, water quality and soil resources of unimproved grasslands

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Research project led by the University of Exeter and Devon Wildlife Trust. This project has been supported by the Environment Agency, the Higher Education Innovation Fund and the Northern Devon Nature Improvement Area programme, supported by Defra, DCLG, Environment Agency, Forestry Commission and Natural England. Cover picture: A typical Culm grassland landscape with grazing cattle © Devon Wildlife Trust.
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Executive summary

Overview

The lowlands of the UK's western regions were once characterised by florally-rich, unimproved grasslands known in Devon and Cornwall as Culm grasslands, and more widely as Rhôs pasture. As recently as the 1950s they covered 40,000 ha of the South West. Due to the intensification of agriculture only 10 per cent of these grasslands survive. They are the definition of a fragmented ecosystem. Yet, these landscapes have the potential to store significant amounts of water as they are not drained, unlike their intensively-managed counterparts; they yield high water quality as they are not exposed to fertilisers, pesticides or herbicides; they store soil carbon as they are not tilled or limed to improve productivity; they support one of the ten most endangered species in the EU – The Marsh Fritillary butterfly. Despite these multiple benefits, they were forgotten, too wet to farm for high yields and offering little financial incentive to manage. In part this was due to the lack of knowledge of what Culm grasslands could provide and how they could mitigate the effects of land use and climate change upon flooding, soil erosion and diffuse pollution. This study provides that understanding to establish a solid knowledge base, from which management of these critical landscapes can progress.

Key objectives

1) Characterise the physical and chemical properties of Culm grassland soils and whether these vary in relation to that of other land uses.

2) Quantify the water retention capacity of Culm grassland in relation to that of other land uses.

3) Quantify the hydrological functioning and water quality of a Culm grassland dominated catchment.

4) Extrapolate field based monitoring to quantify the water and soil resource storage potential of Culm grassland soils across the Culm National Character Area (NCA).

Results summary

Characterisation sampling was undertaken to quantify the spatial variability of physical and chemical soil characteristics, between and within the monitored sites (encompassing: Culm grassland on three key soil types, intensively managed grassland, invasive scrubland and wet woodland). Monitored Culm grasslands had higher mean carbon and nitrogen concentrations (13.3 ± 4.4 % and 0.9 ± 0.2 % respectively) than intensively managed grasslands (8.8 ± 2.1 % and 0.65 ± 0. 2%), but showed no significant difference with scrub or woodland soils. Total phosphate levels were found to be significantly higher (p<0.05) at the intensively managed grassland site (1277.63 ± 174.52 μg g^{-1}) than Culm, scrub or woodland sites. Physically, compared to intensively managed grassland soils, Culm soils were significantly ($p<0.05$) deeper, had a lower bulk density, higher soil moisture and higher organic matter content. Generally soils under Culm and invasive scrub showed only minor differences indicating a lagged response in soil characteristics to scrub encroachment. Wet woodland soils showed the greatest spatial heterogeneity within site, whilst intensively managed grassland IMG soils showed notably less variation than other land uses, suggesting agricultural improvement or intensification of grasslands results in homogenisation of soil properties. Carbon concentrations, combined with physical characteristics indicated that Culm soils, whilst less dense will store more carbon in topsoil than intensively managed grassland of the same soil type due to their greater depth (mean 1.8 ± 0.6 g cm^{-2} to topsoil depth in Culm and 1.5 ± 0.35 g cm^{-2} in intensively managed grassland). Extrapolating results across the Culm NCA allows an estimate of 715402 ± 167327 t of carbon, currently accumulated in Culm soils.

To increase understanding of hydrological function in Culm grassland relative to other land uses, the experimental framework allowed for near continuous measurement of soil water levels across the monitoring sites, via instrumented dipwells, connected to a telemetry network. Results are presented, monitoring water levels on a 15 minute time step from when the monitoring sites were instrumented in October 2012 to January 2014. Across all sites water table level showed notable variation over time, being lower in the dry season of the hydrological year (1st of April to 30th of September) and higher during the wet season (1st of October to 31st of March). However, on average water levels were consistently higher under Culm grassland (0.07 ± 0.01 m below surface) and lowest in intensively managed grassland (0.16 ± 0.08 m below surface). Combined with soil characteristics (i.e. depth and soil moisture), results suggested that Culm soils store more water than intensively managed grasslands, in addition to scrub and woodland. As with depth below surface, water stored in soils varied over time but mean estimates for Culm grassland (241.27 ± 75.46 l m^{-2} surface area) were, significantly higher than in intensively managed grassland (61.63 ± 45.27 l m^{-2} surface area). Extrapolating results across Devon Biodiversity Record Centre (DBRC) inventory Culm grassland sites in the Culm NCA gave an estimated water storage of 9429.8 ± 2807 Ml (10^6 litres) of water in Culm soils. Results showing the high water holding capacity of Culm grasslands have important implications for understanding the role they can play in the sustainable management of water resources, notably, reducing flooding risk and maintaining water supply.

This project also involved the monitoring of in-channel hydrological behaviour and water quality in a Culm dominated catchment. At Stowford Moor, an instrumented flume was used to quantify channel discharge throughout the monitoring period and collect samples for water quality analysis throughout storm events. Results from a total of 11 storm events are presented to provide baseline understanding. As may be expected, channel discharge at Stowford Moor showed a significant positive relationship ($p<0.05$), both with rainfall and antecedent soil water levels. However, the relatively weak nature of these relationships, suggests that Culm dominated catchments, due to their high water holding capacity, have low hydrological connectivity, showing a relatively attenuated channel response to rainfall. Water quality samples were analysed for dissolved organic carbon (mean 9.91 ± 3.18 mg l^{-1}); total oxidised nitrogen (mean 3.45 ± 2.64 mg l^{-1}); phosphorus (mean 66.84 ± 71.15 µg l^{-1}); suspended sediment (mean 51.55 ± 69.11 mg l^{-1}); potassium (mean 1.72 ± 0.50 mg l^{-1}); colour (mean 54.12 ± 11.26 mg l^{-1}) and pH (mean 6.28 ± 0.32). Comparisons with studies conducted in intensively managed, agriculturally dominated catchments, indicated that the Culm dominated catchment showed considerably less evidence of diffuse water pollution. Modelling work, undertaken indicates as well as storing more water, Culm grasslands release it more slowly. Modelling scenarios suggest that, compared to Culm grasslands, 11 times more water, rapidly leaves intensively managed grasslands, during storms, significantly increasing the risk of flooding downstream. As their water quality is significantly better in terms of nitrogen, phosphorus and sediment levels; the recreation of Culm also promises significant benefits for the water quality of south west rivers.

Conclusions

Research conducted in this study found a notable difference in hydrological functioning, soil and water resources relative to other land uses, particularly intensively managed grassland. Results overall indicated, that relative to intensively managed grassland, Culm grassland soils hold more water, store more carbon and water leaving a Culm dominated catchment was of a higher quality than intensively managed, agriculturally dominated catchments. Research presented within this report highlights the role played by Culm grasslands in the provision of key ecosystem services, including carbon storage, water quality and the sustainable use of water resources. Additionally, it is suggested that the restoration and reconnection of Culm grasslands to their previous spatial extent (or more) would enhance the provision of key ecosystem services. Combined characterisation sampling, hydrological monitoring and water quality analysis provide a strong empirical baseline, increasing understanding of Culm grasslands. However, further research is needed, to monitor the effectiveness of proposed restoration work, identify where in the Culm NCA restoration would be most effective and finally to quantify the value of ecosystem services provided in relation to existing or proposed payment and incentive frameworks.

Contents

1. Introduction

1.1. Project scope, aim and key objectives

Culm grasslands are an internationally important example of wet pasture that can provide multiple ecosystem services, but they have been impacted by land use change, resulting in a significant reduction in their coverage and face the additional pressure of climate change. It is believed the restoration of Culm grassland would lead to multiple benefits for water and soil resources in South West England. However, there is currently a lack of understanding of both ecosystem structure and function in Culm grasslands and an evidence base is required to address this knowledge gap and determine how restoring Culm grassland could mitigate the effects of land use and climate change upon water resources and ecosystems. Therefore, this study seeks to develop understanding of the hydrological functioning, soil and water quality of Culm grasslands. Specifically this study addresses the following objectives:

1) Characterise the physical and chemical properties of Culm grassland soils and whether these vary in relation to that of other land uses and covers (intensively managed grassland, invasive scrubland and wet woodland).

2) Quantify the water retention capacity of Culm grassland in relation to that of other land uses and land covers (wet woodland, invasive scrub and intensively managed/improved grassland).

3) Quantify the hydrological functioning and water quality of a Culm grassland dominated catchment

4) Extrapolate field based monitoring to quantify the water and soil resource storage potential of Culm grassland across the Culm NCA.

1.2. Overview and rationale

1.2.1. Culm and Culm National Character Area

The Culm National Character Area (NCA) covers 3,500 km^2 in South West England (Figure 1.1.). Culm grassland habitats occur within the Culm NCA and are of international conservation importance (Hughes 1997). They include wet, unimproved, species-rich pastures, typical of poorly-drained acid soils, supporting a suite of purple moor-grass and soft rush communities (Hughes 1997). The extent of the habitat in the Culm NCA represents more than 8% of the UK resource and 80% of that in England (Hughes 1997).

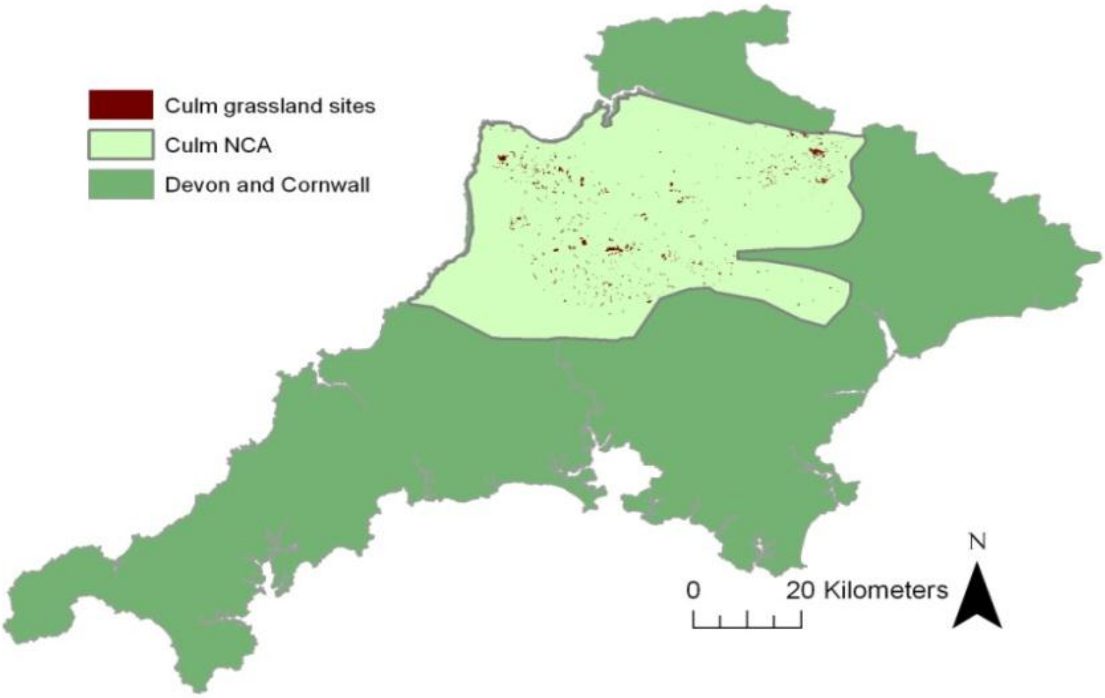

Figure 1.1. Location of designated Devon Biodiversity Records Centre (DBRC) inventory Culm grassland sites within the Culm NCA illustrating their fragmented distribution.

Since the 1960s, national policy changes have encouraged the drainage of vast areas of land for agricultural improvement; with 77% of available land in Devon now being used for agriculture (Van Soest, 2002). Consequently, Culm grassland sites have become highly fragmented (Figure 1.2.) and as classified by the Devon Biodiversity Records Centre Inventory, Culm grassland now covers 3926 ha, only ca. 2 % of the Devon section of the Culm NCA, from a former estimated extent of 29500 ha in 1900 (Hughes 1997). Many areas of Culm grassland still remain on floodplains and along river corridors; these sites are areas that would not be preferred for agricultural development. During the Second World War (WWII), much of the mature, deciduous wet woodland that inhabited the Culm measures was removed for timber (Van Soest, 2002). Lack of management since WWII has led to the re-colonisation of certain areas of Culm grasslands with secondary species, leading to an expansion of wet woodland and Culm scrub. The rate of Culm loss is believed to have been particularly rapid since the 1980s with 48 % of the loss occurring between 1984 and 1989; 87 % of this loss was due to agricultural improvement or intensification, 3 % due to afforestation and 1 % due to scrub invasion (Hughes 1997).

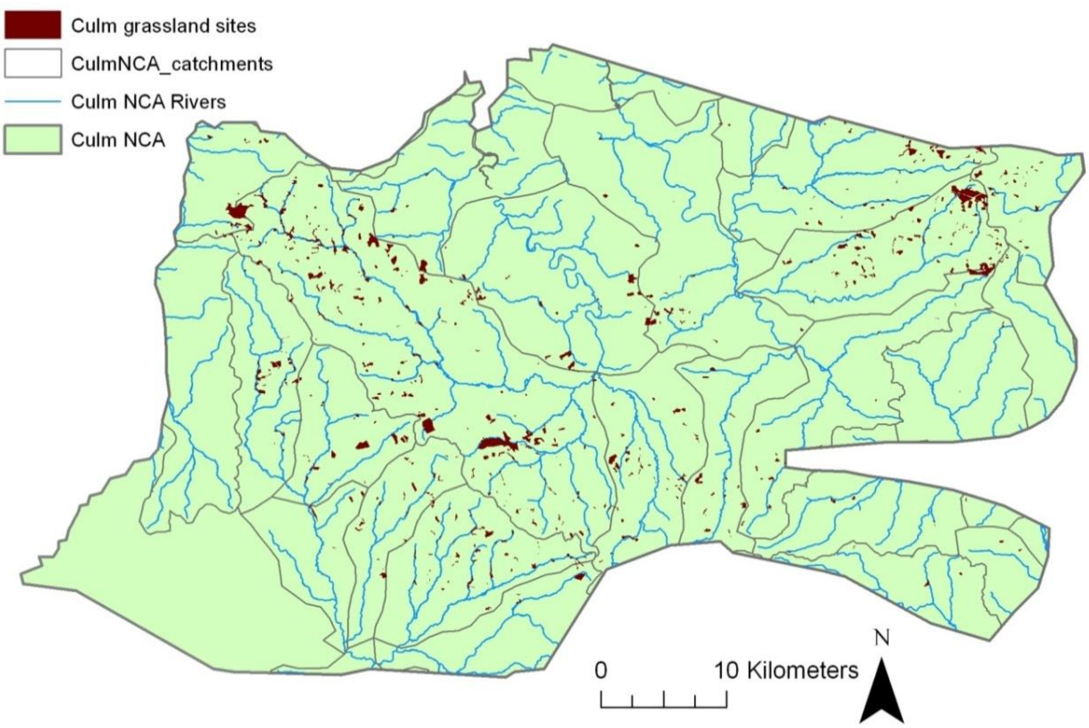

Figure 1.2. Location of DBRC inventory Culm grassland sites, river network and catchments within the Culm NCA.

Traditionally, Culm grasslands are managed by the light grazing of local cattle breeds, to promote re-growth (Van Soest, 2002). In many areas, woody species have colonised areas of previously open grassland, unless shrub removal management has been undertaken. Additionally, particularly riparian areas within Culm grasslands can be inhabited by wet woodland, including mature, deciduous species such as Oak, Beech, Alder, Willow and Birch, as well as secondary colonisation species.

Since 2008, Devon Wildlife Trust's Working Wetlands project has been working with farmers and landowners to manage, restore and recreate Culm grassland. It is part of South West Water's Upstream Thinking initiative and is now augmented by the Northern Devon Nature Improvement Area programme.

Figure 1.3. Visual comparison of aerial photographs of Stowford Moor. Black and White image (left) is taken in 1946; Colour Image (Right) is taken in 1990. Note expansion of mature deciduous woodland, as well as Culm Scrub, but also contraction in the area of Culm grassland around what is now the Nature Reserve/SSSI site.

1.2.2. Climate

The climate in the region is generally defined as 'oceanic', which can be described as a mild temperate rainy climate, with no distinct dry season (Van Soest, 2002). Rainfall in the area is mainly determined by topography: low-lying areas have generally lower amounts of rainfall than the more upland regions. GIS analysis indicates the Culm NCA has a mean, long-term (40 year) rainfall of ca. 1200 mm per annum.

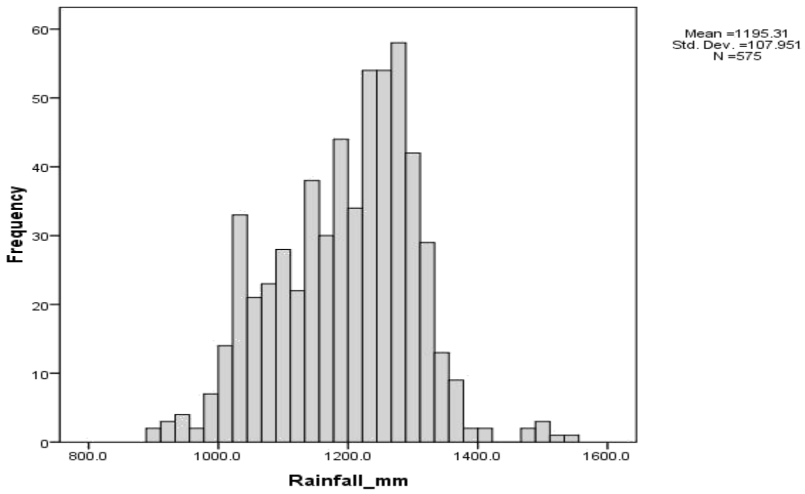

Figure 1.4. Histogram presenting the distribution and summary statistics for long term (40 year) rainfall records across the Culm NCA.

1.2.3. Geology

The Culm NCA is defined by the distinctive geology of Carboniferous Culm Measures deposits. The topography of the Culm NCA is characterised by an undulating plateau of folded Carboniferous shales and sandstones dissected by the large valleys of the Rivers Taw, Torridge and Tamar, as well as numerous smaller tributary valleys. The rocks, mainly sandstones and shales, were formed during the Carboniferous Period from about 360 to 290 million years ago (Hughes 1997). The entire area is blanketed by periglacial deposits (known as 'head') formed during the Quaternary Period" (Hughes, 1997).

Folding of the bedrock can affect the hydrology by constraining groundwater flow in the directions of folded sandstone aquifers. Furthermore, the relative permeability of layers throughout the formations causes difference in the saturated hydraulic conductivity of the bedrock throughout the area (Durrance and Laming, 1982, Findlay et al. 1984).

1.2.4. Soils and Topography

GIS analysis established that over 90 % of Culm grasslands are found on a combination of just three main soil types (according to the Hydrology of Soil Types, HOST, classification), dominated by Hallsworth soils (48 % coverage), Nercwys and Hallstow soils 32 % and Denbigh and Manod soils 12 % (Figure 1.5). Previous research supports this, finding Culm grasses to occur primarily on poorly draining soils and that 92 % of the Culm grassland sites were situated on soils with poorly drained HOST classes (Boorman, 1995; Van Soest, 2002). Analysis suggests soil type would be a key determination of the hydrological behaviour of Culm grasslands, as indicated by the strong relationship between runoff and baseflow for different soil types (Figure 1.7).

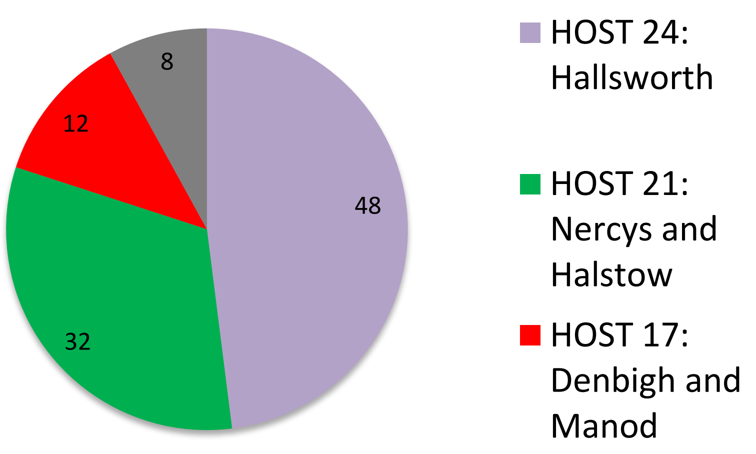

Figure 1.5. Percentage of Culm grassland per HOST soil class

Soil series	HOST	Description
Crediton	3	reddish loamy lithoskeletal sandstone
Denbigh	17	medium loamy material over lithoskeletal mudstone and sandstone or slate
Hallsworth	24	clayey drift with siliceous stones
Halstow	21	clayey material over lithoskeletal mudstone, shale or slate
Manod	17	medium loamy material over lithoskeletal mudstone and sandstone or slate
Nercwys	21	medium loamy drift with siliceous stones
Onecote	26	clayey material passing to clay or soft mudstone
Teme	8	medium silty river alluvium
Wickham	25	medium loamy or medium silty drift over clayey material passing to clay or soft mudstone

Table 1.1. HOST class and description for soil series found within the Culm NCA.

As found by Van Soest (2002) and Findlay et al. (1984), the distribution of soils in the Culm NCA is also closely related to topography. The relief in the area consists mainly of rolling hills with slope angles between 0 and 12 degrees and an altitude varying between 0 m at the coast to ca.500m above sea level on Dartmoor (Van Soest 2002). In addition GIS analysis found Culm grasses to occur predominantly on slopes with a gradient less than 4 degrees (Figure 1.6).

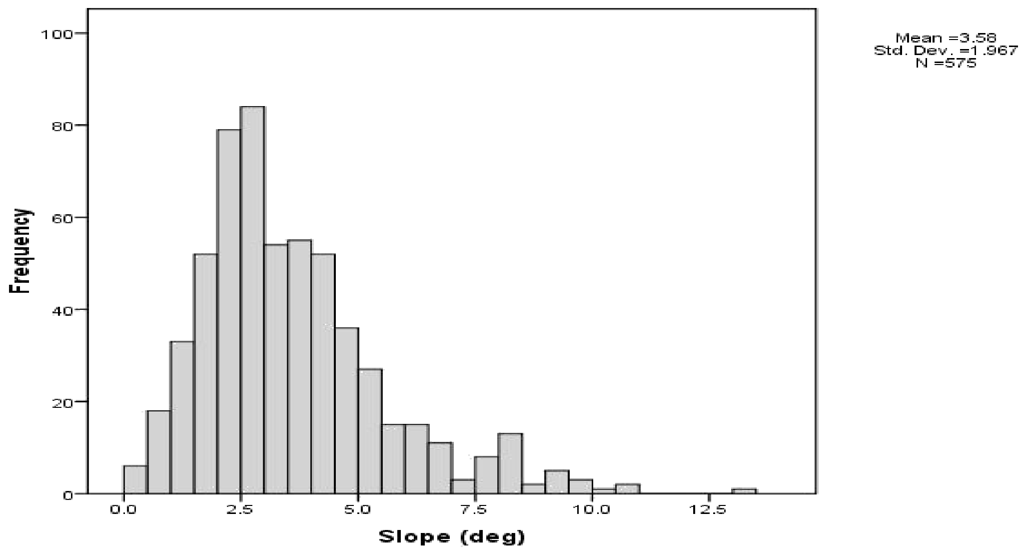

Figure 1.6. Histogram presenting the distribution and summary statistics for slope of DBRC inventory Culm grassland sites (calculated from 50 m DEM) across the Culm NCA.

Research has shown that soil type is a key control on hydrological function and that together soil type and topographical data can be a valuable tool, both for deciding areas of Culm suitable for restoration and modelling of hydrological function (Van Soest, 2002; Meredith, 2008). However, to perform hydrological modelling in enough detail to obtain reliable results, a high level of field information should be incorporated in the model and validation with field data is needed (Wainwright and Mulligan, 2005). This finding is a key point that supports the need for detailed field characterisation and monitoring of representative sites within the Culm grasslands.

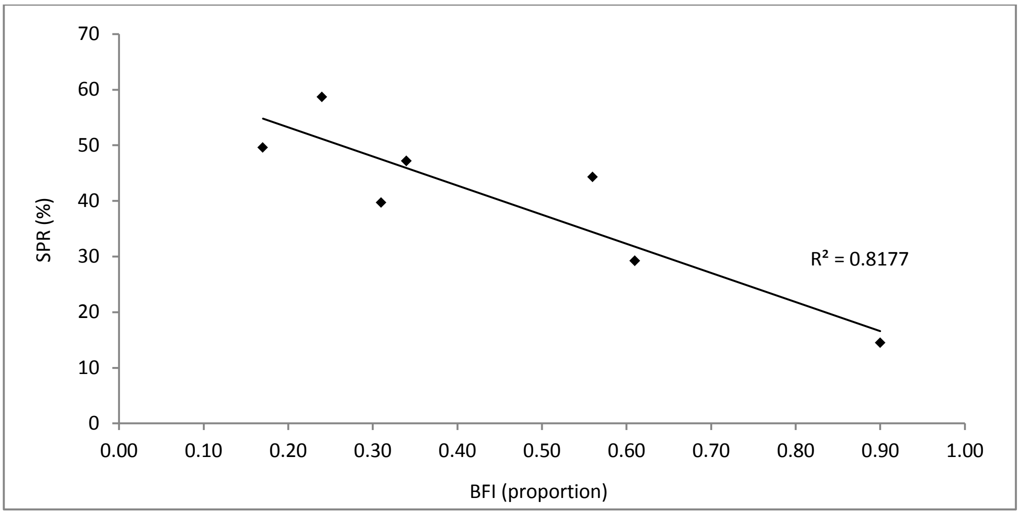

Figure 1.7. Relationship between base flow index (BFI) and standard percentage runoff (SPR) for Culm soils. Base flow index describes the proportion of rainfall that typically leaves a catchment as subsurface flow and standard percentage runoff, the converse, as the percentage of rainfall that typically leaves via faster, surface pathways. Individual points represent different HOST soil types found within the Culm NCA.

1.2.5. Hydrology

Hydrological functioning is mainly determined by the amount of precipitation, losses due to evaporation and evapo-transpiration by the vegetation and the permeability of geological formations and soil behaviour (Figure 1.7) in addition to anthropogenic land use (Findlay et al., 1984). Permeable soils and geology enable the water to infiltrate into the deeper groundwater and drain towards the stream. The impermeable soils and geology that are typical of the Culm measures cause the water to drain by shallow subsurface flow or overland flow. Research has found that the Culm grassland water balance was dominated by surface water, but ground water was important in wetland maintenance in the drier times of the year (Papatolios. 1994, Van Soest. 2002). Human activity has also been shown to have a noticeable impact upon hydrology, with draining to improve agricultural productivity being a common practice (Findlay *et al.,* 1984). This can lead to rivers responding quicker to a rainfall event, possibly resulting in increased flooding (Robinson and Beven, 1983).

Recent research has focused on the importance of managing wetland and grassland communities, not only for conservation value but also for their role in providing ecosystem services (Hogan *et al.*, 2000; Bullock and Acreman, 2003; Walker *et al.,* 2004; Bilotta *et al.,* 2008). Wetlands are significant in altering the water cycle and the majority of the available literature supports the notion that wetlands perform as a hydrological 'sponge' (Bucher *et al.*, 1993 in Bullock and Acreman, 2003). This involves both, peak attenuation during high flow (Blackwell 2011), thus reducing the risk of flooding and maintenance of low flow during dry periods. A review by Bullock and Acreman (2003) suggests that the location of the wetland habitats in relation to their placement within the catchment is key to hydrological function, with implications for flood control. However, there is little research relating directly to the hydrological functioning of Culm Grassland.

Limited information exists on the hydrological functioning of the Culm grasslands, Culm scrubland and the wet woodlands that inhabit the Culm Measures. For grasslands the Van Soest (2002) work is the best evidence to date, though it is not presented in enough detail to determine specific characteristics of the Culm hydrology across the dominant HOST classifications. For shrubland and woodland anecdotal evidence, as well as studies by authors such as Mitchell et al., (2007) which describe the invasion of woody species such as birch into analogous moorland ecosystems, suggests that the presence of woody plants in Culm grasslands will significantly alter the hydrology of these ecosystems. Alterations are likely to include the uptake of more soil water by extensive woody root systems, enhanced interception of precipitation by deciduous canopies, especially in drier parts of the year and modifications to the evapotranspiration regimes, when compared to pristine, Culm grassland. Empirical datasets describing the differing hydrological response of Culm grasslands in pristine condition versus those that have scrubbed-up and those that are dominated by older woodland are not currently available.

1.3. Experimental design and methods

Analysis of existing Culm grassland, showed there to be relatively little variation in slope, elevation or mean rainfall across all Culm sites; environmental properties that would be expected to affect hydrological functioning. However, analysis did reveal Culm sites to be located across a variety of soil types, which it was hypothesised could be a key control on hydrological functioning, particularly water retention and runoff. Soil type influences hydrology via its impact upon infiltration rates, water storage, subsurface drainage and surface runoff. The hydrology of soils type system (HOST) is used to classify soils according to their physical characteristics. As analysis revealed that over 90% of Culm grassland sites are located on three main HOST types (17, 21 and 24), these formed the basis of site selection. Sites were also selected so that the hydrological functioning of Culm could be compared to other key land uses within the Culm NCA - wet woodland, scrubland and intensively managed agricultural grassland (IMG). Prior to agricultural improvement the IMG site was Culm grassland. The location of study sites is illustrated in Figure 1.11.

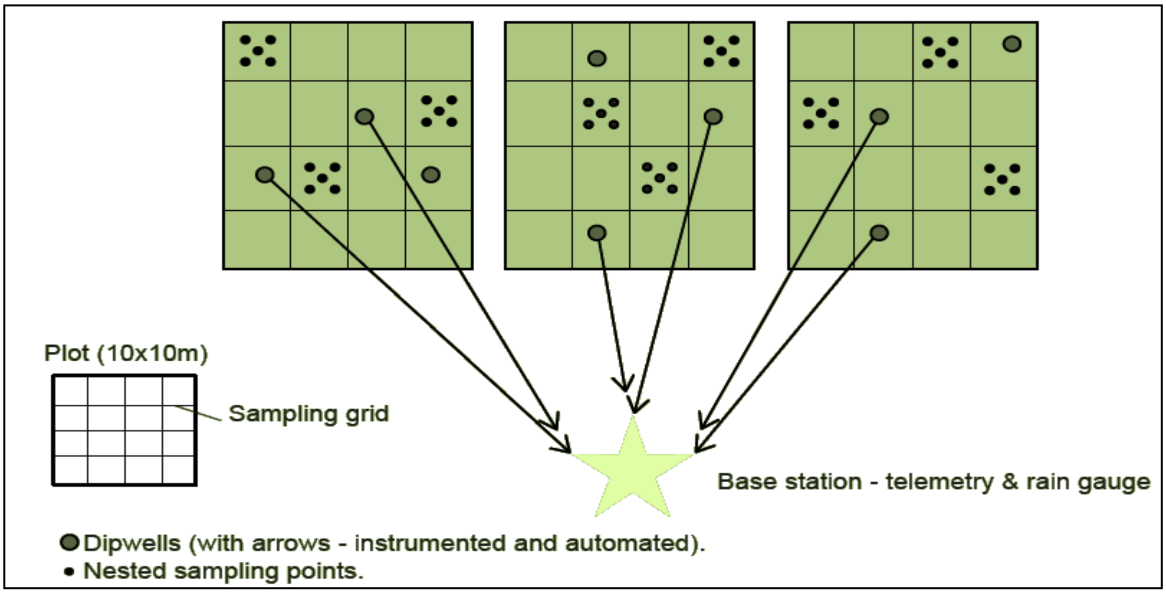

Figure 1.8. Schematic illustrating the experimental design used for soil sampling and instrumentation at each site.

Collection and analysis of soil samples

At each study site; 10x10m plots (3 replicates at each site) were constructed (Figure 1.8) and sampled for surface soil characteristics influencing water storage (topsoil depth (D), bulk density (BD), organic matter (SOM), soil moisture (SM) and particle size (PS)) in addition to quality and carbon resources (carbon (C), nitrogen (N) and total, organic and inorganic phosphorous (TP, OP, IP). All soil samples were collected with a sampling core 5 cm deep and 5 cm radius, the dimensions of which were used in the calculation of bulk density. Each plot, separated into a 2.5 m grid, with 3 randomly located nests of fine, sub 2.5m samples within each plot, allowing for nested geostatistical characterisation sampling, resulting in 40 samples per plot, 120 per site and 720 in total.

Soil characterisation samples were analysed by laboratory technicians at the University of Exeter. Wet samples were weighed, oven dried at 45°C until constant weight and re-weighed to determine wet and dry weight and soil moisture. Dried samples were passed through a 2 mm sieve to remove coarse stones and vegetation. A sub-sample of the 2 mm fraction was sieved to the proportion of sand (2-0.0625 mm), silt (0.0625-0.0039 mm) and clay (<0.0039 mm) in the sample. The sub 2 mm fraction was analysed for TC, TN, P (total/organic/inorganic) and SOM. SOM was determined via loss on ignition, percentage TC and TN was determined following fine grinding using an elemental analyser (Flash 2000, Thermo Scientific, UK) and P content was determined using sulphuric acid extraction (Glendell, 2013). BD was calculated by dividing the dry sample mass by cylinder volume.

Hydrological function

Each study site had six dipwells (two placed at random locations within each plot) inserted to topsoil depth and also protruding ca. 20 cm above ground allowing overland flow or surface ponding to be also captured. Each dipwell was instrumented with a submersible level sensor. Instrumented dipwells were used to monitor the water table level and how this changed in response and relation to rainfall events. To monitor rainfall, each site was equipped with a tipping bucket rain gauge with 0.2 mm accuracy. All monitoring equipment connected to a 3G telemetry network (Adcon Telemetry, Austria), providing a data feed on a 15 minute time step.

Figure 1.9. Left: RA440 telemetry base station at Stowford Moor, used to transmit data from field instrumentation on a 15 min time step over a 3G network. Right: Tipping bucket rain gauge at Halsdon; with junction boxes and cables leading to instrumented dipwells and an addIT radio unit to transmit data to the RA440 base station (© Alan Puttock).

At Stowford Moor, a Culm dominated catchment was equipped with a rated super-critical flume (Figure 1.10) with a stilling well and level sensor attached to the telemetry system which allowed the amount and rate of water leaving the catchment to be quantified (as with rainfall and water levels on a 15 minute time step). An autosampler was also connected to the flume allowing for samples to be collected for analysis of water quality. The telemetry network and in-flume level sensor allowed for the ability to remotely trigger the pump sampler, allowing sampling (24 x 1L samples through a range of flow conditions). Samples were collected with every 1 or 2 cm flume depth level change depending on antecedent base flow levels. All water quality samples were collected within 24 hours of sample triggering and transported to cold storage at Exeter University.

Figure 1.10. Instrumented Flume at Stowford Moor (© Alan Puttock)

Water quality analysis

Water samples were analysed for dissolved organic carbon, nitrogen, phosphorous, potassium, suspended sediment, colour and pH. All laboratory analysis was carried out at the University of Exeter.

Water quality samples were analysed for nitrogen, phosphorous, potassium, pH and DOC within 48 hours of sample collection and colour within 1 week of sample collection. Total oxidised nitrogen and dissolved ortho-phosphate concentration were measured colourimetrically via a continuous flow auto-analyser 3 (Bran+Luebbe, Norderstedt, Germany). Following filtration DOC concentration was analysed using a UV spectrometer (Trios Gmbh, Rastede, Germany) using a 10 or 20 mm path length at a spectral range of 190-360 nm. Potassium concentration was analysed via atomic absorption spectroscopy (Solar S Series, Thermo Scientific, UK). Colour was determined (relative to Hazen colour standards) via UV-Vis spectrometry (Unicam UV4-100 Thermo-Fisher scientific, UK). pH was measured relative to standards of pH 4 and 7 using a (AB15 pH meter (Fisher Scientific). Total suspended sediment concentration was determined by the mass of sediment per sample volume via evaporation. Following collection each water sample was allowed to settle for 1 week, without disturbing the sediment most of the water sample was then decanted and measured, the remaining water and sediment was agitated, measured, poured into a pre-dried and weighed evaporating dish and placed in an oven (80 °C) until dried (Glendell, 2013).

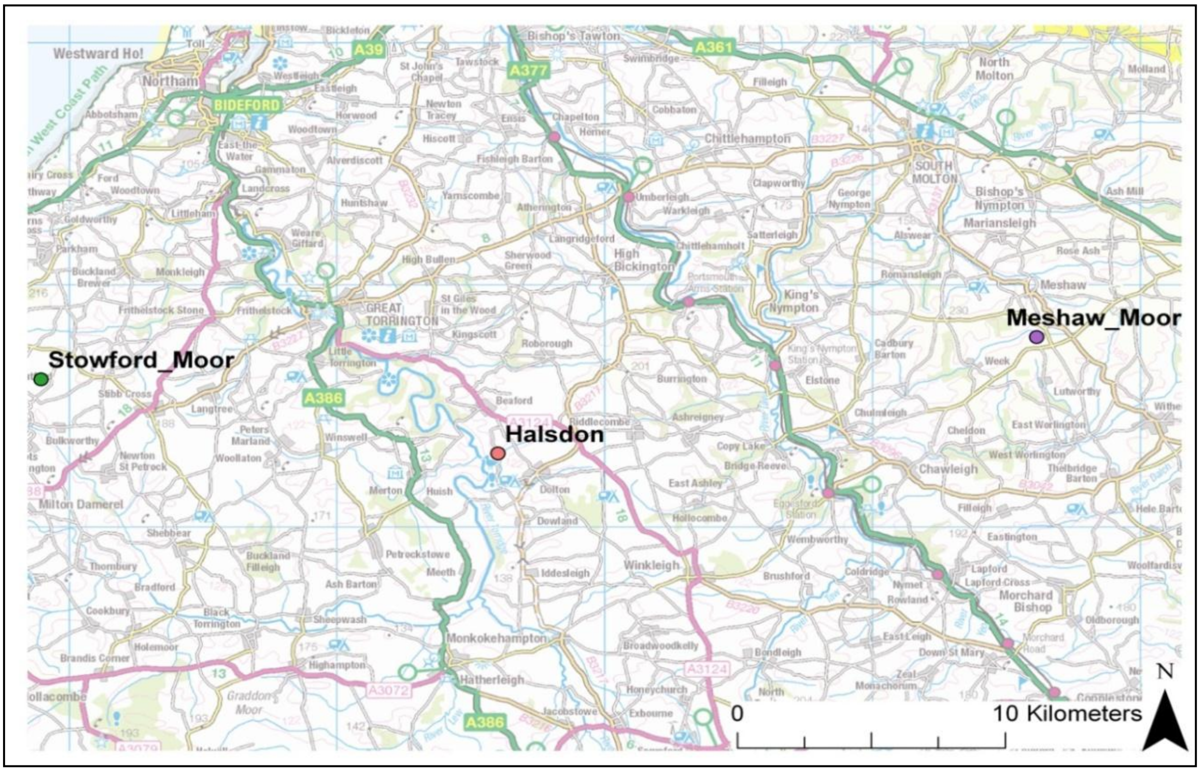

Figure 1.11. Location of monitoring sites in North Devon (base map source: Ordnance Survey)

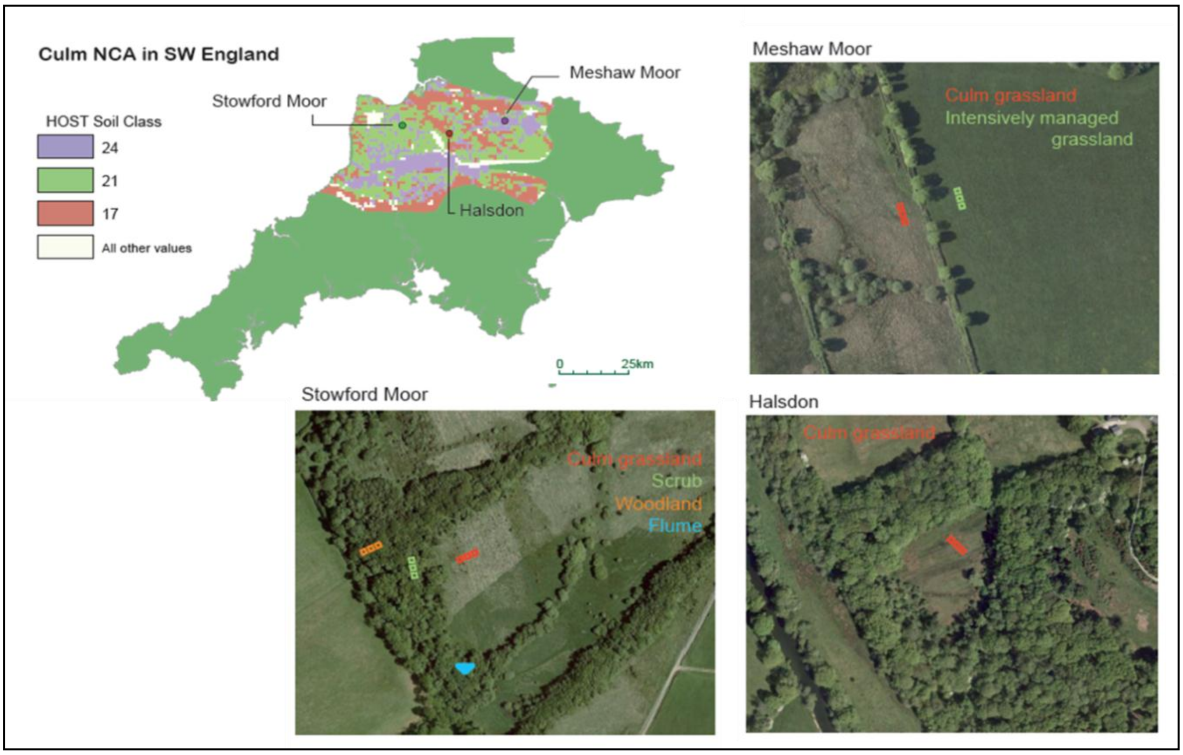

Figure 1.12. Location of sites within the Culm NCA (and In relation to HOST soil type) in addition to aerial photos and plot locations at each site.

Figure 1.13. Monitoring sites. Top left: Meshaw Culm grassland; top right: Meshaw intensively managed grassland; middle left: Halsdon Culm grassland; middle right: Stowford Moor Culm grassland; bottom left: Stowford Moor invasive scrubland; bottom right: Stowford Moor wet woodland. (© Alan Puttock)

2. Soil structure and resources

The following sections present results from characterisation sampling of surface soils across the monitored sites. Section 2.1. addresses soil resources, examining variation in carbon (C), nitrogen (N) and phosphorus (total: TP; inorganic: IP; organic: OP) between land use and Culm sites on different HOST types .Section 2.2. addresses soil depth (D), bulk density (BD), soil moisture (SM) and soil organic matter (SOM); key properties affecting hydrological functioning.

2.1. Soil resources

Results tables summarising laboratory analysis of key soil resources are presented (Tables 2.1. and 2.2.), before these results are interpreted in more detail, with a focus on the potential carbon storage of Culm grasslands, relative to other land uses and covers.

Site	SOM±SD (%)	N±SD (%)	C±SD (%)
Stowford Culm	32.19±10.18	0.90±0.24	16.42±5.31
Stowford Scrub	29.91±9.48	0.90±0.29	13.82±5.45
Stowford Wood	31.74±17.62	0.85±0.43	14.00±8.43
Meshaw Culm	29.84±5.90	1.02±2.29	13.38±2.68
Meshaw IMG	20.23±2.72	0.65±0.23	8.78±2.14
Halsdon Culm	20.94±6.40	0.72±0.11	10.08±1.94

Table 2.1. Mean values (±SD) for measured soil characterisation variables. SOM = soil organic matter; N =Nitrogen; C = carbon. For each variable at each site, n = 120.

Site	TP ±SD (μg g^{-1})	IP ±SD (μg g^{-1})	OP ±SD (μg g^{-1})
Stowford Culm	899.53±236.19	295.06±88.63	604.47±186.32
Stowford Scrub	731.48±149.12	234.26±85.90	497.23±113.96
Stowford Wood	719.51±204.77	239.22±92.55	480.30±131.13
Meshaw Culm	1118.11±179.70	390.37±129.35	727.74±113.88
Meshaw IMG	1277.63±174.52	531.36±140.53	746.26±124.25
Halsdon Culm	613.90±101.64	237.27±66.09	376.63±57.89

Table 2.2. Mean values (±SD) for measured soil characterisation variables. TP = total phosphate; IP = inorganic phosphate; OP = organic phosphate. For each variable at each site, n = 120.

2.1.1. Carbon in soil

2.1.1.1. Concentration and spatial distribution

Mean C concentrations across all Culm soils (132.92 ± 44.36 mg g^{-1}) were significantly higher ($p<0.05$) than in IMG (87.67 ± 21.41 mg g^{-1}). Mean C concentrations in Culm showed no significant variation ($p>0.05$) with either scrub (138.35 ± 54.30 mg g^{-1}) or woodland samples (141.26 ± 85.03mg g^{-1}). In addition to variation between land use there was also significant variation ($p<0.05$) between Culm soils located upon the different soil HOST types monitored with mean concentrations (mg g^{-1}) highest at Stowford Moor (HOST 21) and lowest at Halsdon (HOST 17).

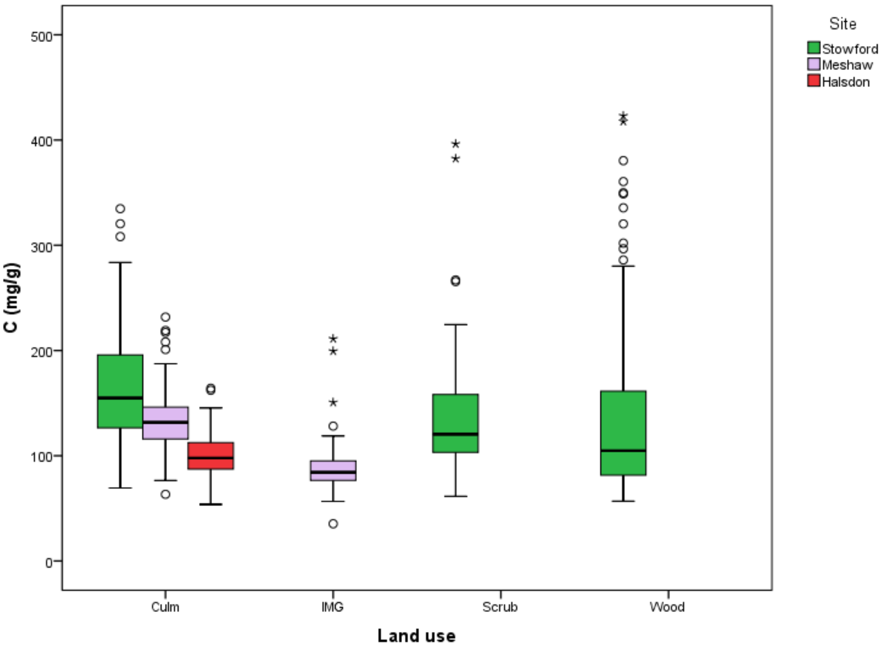

Figure 2.1. Box and whisker plot summarising variation in C levels across monitored sites. Centre line on bar =median; upper limit of bar = upper quartile; lower limit on bar = lower quartile; Whiskers = minimum and maximum values; circles and stars = data outliers.

In addition to variation in mean values between sites, the spatial distribution of soil C varied within sites as illustrated via spherical kriging in Figure 2.2. the greatest range in C was found at the woodland site and the lowest range at the IMG site. The low soil C concentration and low level of heterogeneity in IMG reflects the homogenous vegetation structure and low organic matter input in IMG's compared with the tussocky Culm grasslands and the woody vegetation present in woodland and invasive scrubland.

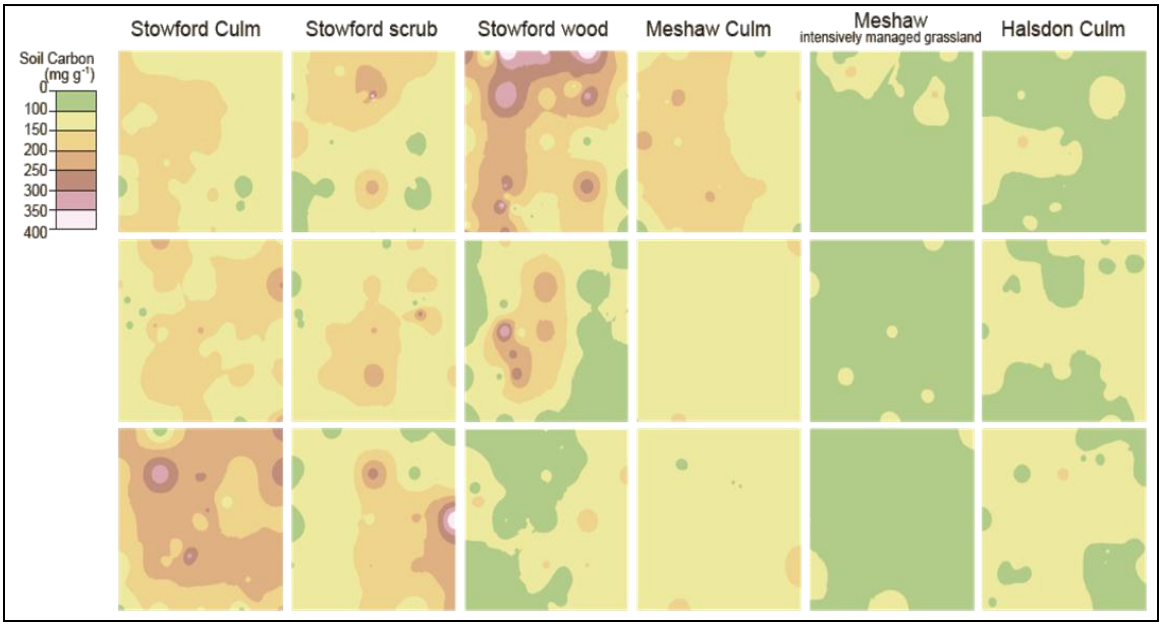

Figure 2.2. Soil C concentrations and spatial distribution at each plot, extrapolated from 40 sampling points per 10 x10m plot via spherical kriging.

2.1.1.2. Carbon storage estimates

To gain a greater understanding of C stored within soil at the monitored sites, laboratory analysis of C concentrations was combined with physical soil properties (depth and bulk density). Summary statistics for C per soil volume (mg cm^{-3}) and standardised by surface area (g cm^{-2} and t ha^{-1}) are presented in Table 2.3. As soil depth was shown to vary both within and between sites C per unit surface area, are presented for the sampled top 0.05 m of soil and also extrapolated to the measured topsoil depth at each point (assuming a uniform soil C concentration with depth).

Site	C (%)	C (mg cm^{-3})	C 0.05m (g cm^{-2})	C topsoil depth (g cm^{-2})	C 0.05m (t ha^{-1})	C topsoil depth (t ha^{-1})
Stowford Culm	16.42±5.31	45.95±9.63	0.23±0.05	1.25±0.42	22.98±4.81	125.01±41.77
Stowford Scrub	13.83±5.43	46.88±13.23	0.23±0.07	1.60±0.48	23.44±6.62	159.57±47.71
Stowford Wood	14.14±8.50	55.70±19.57	0.28±0.10	1.68±0.58	27.856±9.78	167.93±57.73
Meshaw Culm	13.38±2.68	48.15±7.58	0.24±0.04	2.27±0.45	24.07±3.79	227.35±45.10
Meshaw IMG	8.77±2.14	55.89±11.38	0.28±0.06	1.50±0.35	27.94±5.69	149.86±35.18
Halsdon Culm	10.08±1.94	42.44±8.71	0.21±0.04	1.93±0.41	21.22±4.36	192.89±40.65

Table 2.3. Summary statistics (mean ± SD) for soil carbon (C) characteristics and carbon storage calculations, both for the sampled top 0.05 m and extrapolated (assuming uniform soil carbon %) for measured topsoil depth at each sampling point. N=120 per site.

As shown in Table 2.3. whilst soil C concentrations were significantly higher ($p<0.05$) in Culm soils than their IMG counterparts, the significantly greater density of IMG soils (addressed in Section 2.2.2.) resulted in a greater ($p<0.05$) amount of carbon per unit volume in IMG soils. Similarly when normalised by surface area for the sampled top 5 cm of soil, mean values indicate a greater amount of carbon stored within IMG soils. However, presenting results per volume or for a standardised depth are misleading as analysis of the physical properties of Culm soils (Section 2.2.) showed them not only to be of a much lower density (mean 0.37 ± 0.10 g cm^{-3} in Culm and 0.64 ± 0.11 g cm^{-3} in IMG), but also a significantly greater ($p<0.05$) depth (mean 39.99 ± 10.87 cm in Culm and 26.82 ± 3.28 cm in IMG). When the measured depth of topsoil, where the majority of C is stored, is taken into account, results indicate Culm soils store significantly more carbon per unit surface area ($p<0.05$) with a mean of 1.8 ± 0.6 g cm^{-2} across all the Culm sites compared to 1.5 ± 0.4 g cm^{-2} at the IMG site.

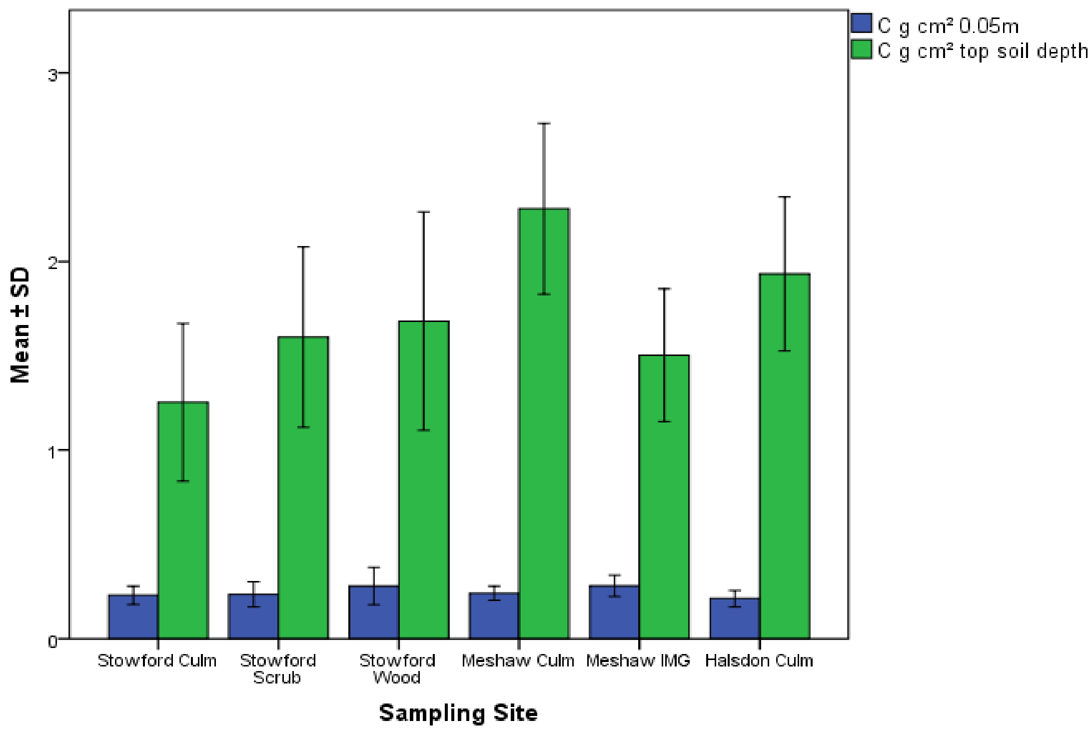

Figure 2.3. Mean (± SD) carbon storage statistics per sampling site, both for the sampled top 0.05 m and extrapolated (assuming uniform soil C for topsoil %) for measured topsoil depth at each sampling point. N=120 per site.

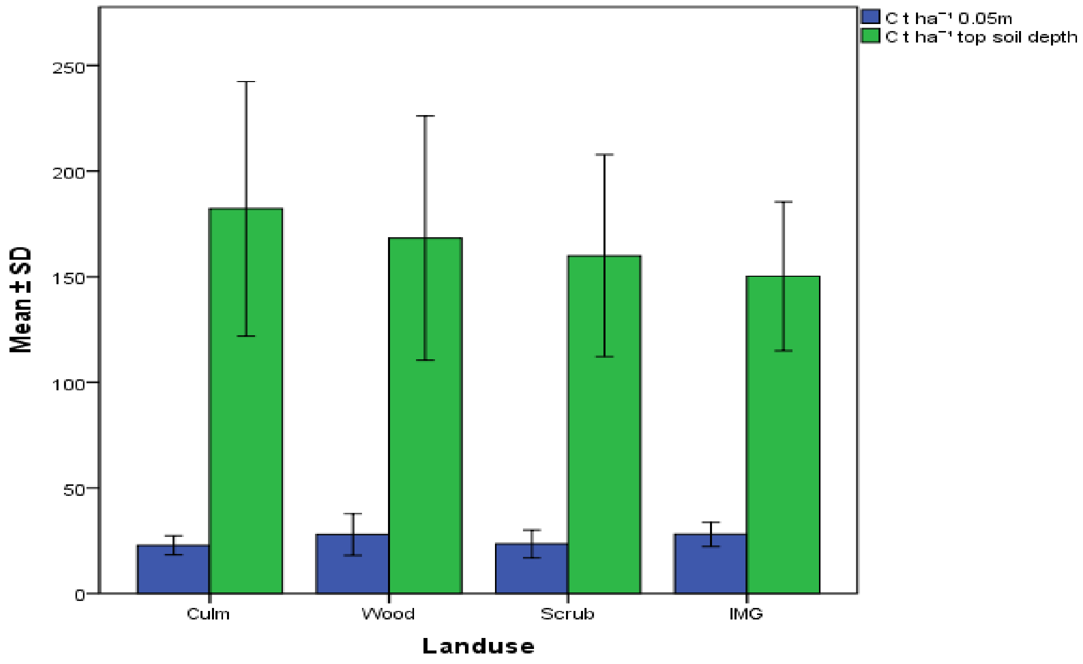

Figure 2.4. Mean (± SD) carbon storage and density statistics per land use type, both for the sampled top 0.05 m and extrapolated (assuming uniform soil carbon %) for measured topsoil depth at each sampling point. N=360 for Culm and 120 each for wood, scrub and IMG.

2.1.2. Nitrate and phosphorus concentrations in soil

Mean N levels in Culm soils (8.80 ± 2.36 mg g^{-1}) were significantly (p<0.05) higher overall than in IMG soil (6.53 ± 2.23 mg g^{-1}). There were no significant differences between N levels in Culm, compared to Scrub (9.04 ± 2.90 mg g^{-1}) and woodland (8.47 ± 4.33 mg g^{-1}), but between HOST soil types N levels were significantly different (p<0.05), being highest at Meshaw (10.18 ± 2.29 mg g^{-1}) and lowest at Halsdon (7.19 ± 1.10 mg g^{-1}). As illustrated in Figure 2.5. Culm grassland at Halsdon also exhibited the lowest variance in N levels, whilst this was highest at the Stowford woodland site.

Mean total P levels were found to be significantly higher (p<0.05) at the IMG site (1277.63 ± 174.52 µg g^{-1}) than all others, with this difference greatest for IP (531.36 ± 140.53 µg g^{-1}at Meshaw IMG). At Stowford mean TP levels were higher (p<0.05) under Culm (899.53 ± 236.19 µg g^{-1}) compared to scrub (733.26 ± 149.77 µg g^{-1}) or woodland (719.94 ± 203.95 µg g^{-1}), with high OP levels in Culm appearing to be responsible (Figure 2.5). Culm grasslands showed significant differences in TP, IP and OP levels between sites, all being lowest at Halsdon (HOST 17) and highest at Meshaw (HOST 24). These site differences possibly highlight, not only differences between soil types or previous/current land use, with the Meshaw Culm site having been most intensively grazed during the study period, resulting in greater manure inputs.

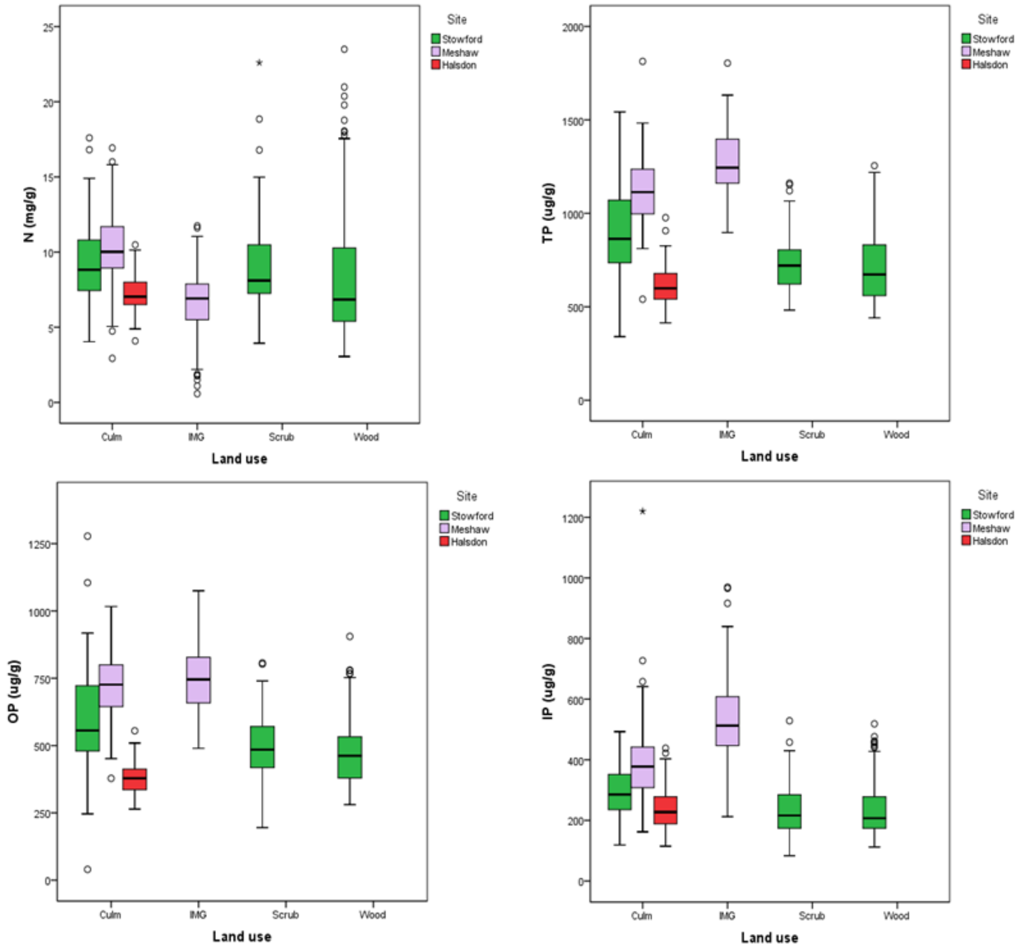

Figure 2.5. Box and whisker plot summarising variation in N (top let); TP (top right); OP (bottom left) and IP (bottom right) concentrations (mg g^{-1}) across monitored sites.

2.2. Soil properties influencing hydrology

Summary statistics are presented in Table 2.4. before the extent of variation between land uses and Culm of different HOST classes is analysed further in sections 2.2.1-2.2.5.

Site	BD±SD (g cm^{3-})	Moisture±SD (%)	Depth±SD (cm)	SOM±SD (%)
Stowford Culm	0.30±0.10	76.40±6.23	30.06±6.37	32.19±10.18
Stowford Scrub	0.35±0.10	69.43±5.39	34.17±5.43	29.91±9.48
Stowford Wood	0.48±0.18	60.26±11.11	30.16±7.06	31.74±17.62
Meshaw Culm	0.36±0.08	69.70±5.37	47.22±5.86	29.84±5.90
Meshaw IMG	0.64±0.11	51.85±3.78	26.82±3.28	20.23±2.72
Halsdon Culm	0.42±0.11	68.06±5.53	45.71±5.22	20.94±6.40

Table 2.4. Mean values (±SD) for measured soil characterisation variables. BD = bulk density; SM = soil moisture; D = top soil depth; SOM = soil organic matter. For each variable at each site, n = 120.

2.2.1. Soil depth

At each sampling point (n = 120 per site), topsoil depth was sampled using a peat probe. Mean soil depth was significantly lower (p<0.05) under IMG at Meshaw (26.82 ± 3.28 cm) than other land uses, including Culm grassland upon the same soil type (47.22 ± 5.86 cm). Thus, reflecting the compacting influence of intensive agriculture, including regular silage cuts upon soil structure. There was no significant difference (p>0.05) between mean Culm (39.99 ± 10.87 cm), scrub (34.17 ± 5.43 cm) and woodland (30.16 ± 7.06 cm) soil depths. However, Culm at Stowford (30.06 ± 6.37 cm) was significantly shallower (p<0.05) than at either Meshaw (47.22 ± 5.86 cm) or Halsdon (45.71 ± 5.22 cm). The shallower depth of soil at Stowford may reflect land use history, with their being a suggestion that the site was briefly intensively farmed during a period of agricultural intensification during between 1939-1947.Soils at the woodland site showed the greatest range in depth values (Figure 2.6.).

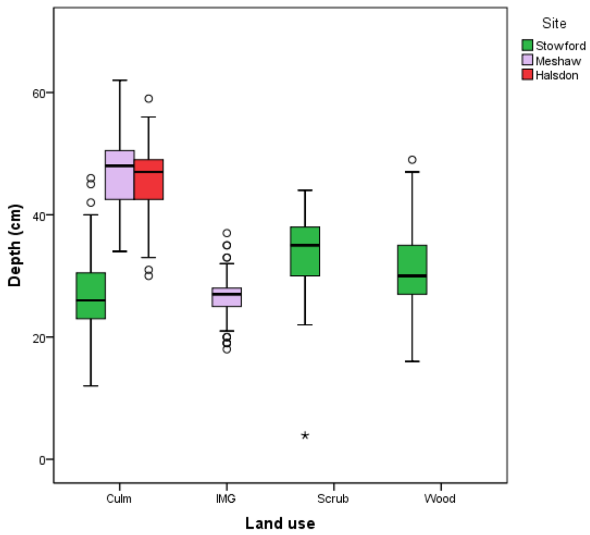

Figure 2.6. Box and whisker plot summarising variation in soil depth across monitored sites.

2.2.2. Soil bulk density

Mean BD was found to be very low at the Culm (0.37 ±0 .10 g cm^{-3}) and scrub (0.36 ± 0.10 g cm^{-3}) sites, between which there was no significant difference (p>0.05) and highest at the IMG site (0.65 ± 0.08), which was significantly higher than Culm (p<0.05), whilst the woodland site was also significantly higher than Culm (0.48 ± 0.18 g cm^{-3}). Between Culm grasslands of different soil types, Stowford (HOST 21) had a significantly lower BD (0.31 ± 0.09 g cm^{-3}), than either Halsdon (HOST 17, 0.43 ± 0.10 g cm^{3}) or Meshaw (HOST 24, 0.37 ± 0.08 g cm^{-3}). As illustrated in Figure 2.7., the woodland site had by far the greatest variation in BD (range 0.87) whilst range was lowest at the IMG site (range 0.41) illustrating the greater compaction of intensively managed agricultural soils. Low BD values were to be expected in non-intensively managed Culm grasslands, however, whilst significantly higher

(p<0.05) BD values across the IMG site were consistently lower than other agriculturally dominated land in the SW which typically had higher values i.e. 0.8 g cm^{-3} in the Aller Vale (Glendell, et al, 2013) or 0.95 g cm^{-3} on the Great Field within the North Wyke Farm Platform (Peukert et al, 2013). The NSI database gives a value of 1.1 g cm^{-3} for HOST type 24 in topsoil, which is significantly higher than the values recorded here for the top 5 cm of the soils. In part these differences can be explained by the high organic matter contents of all surface soils sampled, but also because the NSI sampling was undertaken to greater depth, into the heavy clay soils of the B horizon.

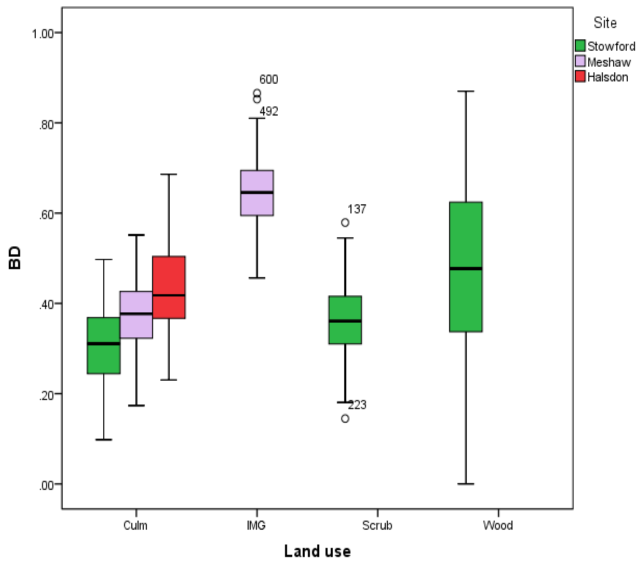

Figure 2.7. Box and whisker plot summarising measured bulk density (g cm^{-3}) across monitored sites.

2.2.3. Soil Moisture

Analysed percentage SM, determined from the difference between the mass of wet and dried characterisation samples was significantly greater (p<0.05) in Culm (71.37 ± 6.76 %) than under other land uses and lowest (p<0.05) under IMG (51.85 ± 3.78 %). SM was highest at the Stowford Culm site (76.40 ± 6.23 %), which was not only higher than the scrub (69.43 ± 5.39) and woodland sites (60.26 ± 11.11), but also Culm sites located upon different soil types. As illustrated in Figure 2.8. the variation in measured SM within sites was greatest under woodland cover.

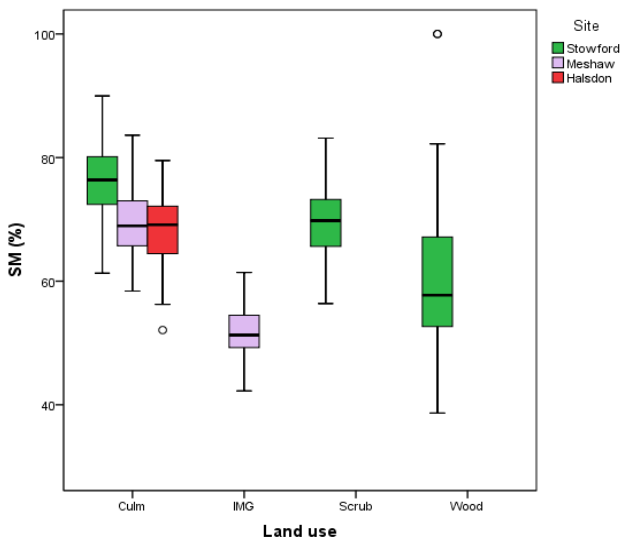

Figure 2.8. Box and whisker plot summarising measured soil moisture across monitored sites.

2.2.4. Soil organic matter

Mean SOM from characterisation sampling was highest under woodland (31.74 ± 17.62 %, $p<0.05$) and lowest under IMG (20.23 ± 2.72 %, $p<0.05$). However, the mean values separated by land use disguise notable variation between Culm grasslands situated upon different soil types. Stowford Culm (HOST 21) exhibited the highest ($p<0.05$) SOM (32.19±10.18) whilst at Halsdon (HOST 17) the mean SOM (20.94±6.40 %) was not significantly different ($p>0.05$) to that at the IMG site. As with the majority of other variables measured the range of SOM values within sites was greatest at the woodland site (Figure 2.9.), reflecting the high levels of spatial heterogeneity in vegetation cover and root structure and therefore organic matter input.

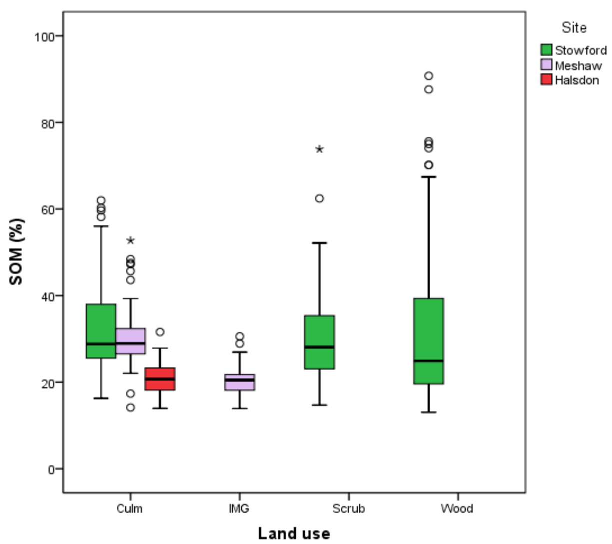

Figure 2.9. Box and whisker plot summarising measured soil organic matter (%) across monitored sites.

2.2.5. Particle size distribution

Figure 2.10 summarises particle size distribution of soil samples across all sites. All sites were dominated by Silt (Max 71 % under the Meshaw grass site; Min 60 % under Stowford Culm). The Meshaw sites (HOST 24) had the highest clay and lowest sand content (p<0.05), which would be expected to lead to a high water retention capacity, but also be prone to compaction. In Contrast, the Stowford sites (particularly Culm) had higher sand content and lower clay content, possibly leading to more rapid drainage.

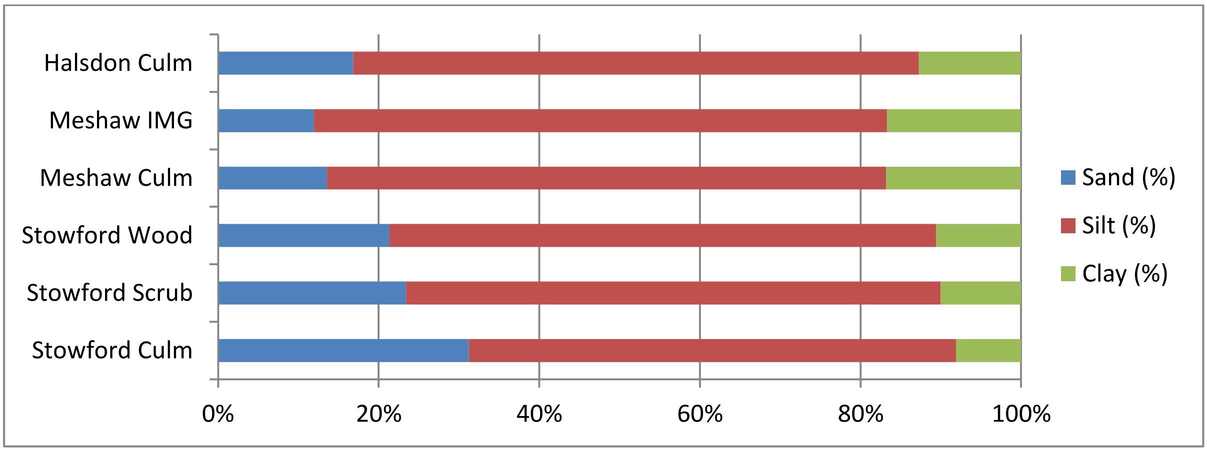

Figure 2.10. Percentage particle size distribution across monitored sites. For all sites n = 120.

3. Hydrological behaviour

Across all sites level sensors provided a near continuous record of water levels in soils across the monitored sites and in response to rainfall. Section 3.1. presents time series data for the monitored period between late October 2012 and early January 2014 across all the monitored sites. Recorded water level depths are combined with dipwell depths to present water level as depth below surface (DBS), whilst at each site results from the six dipwells are combined to give a mean value. Section 3.2. combines the monitored water level depth with physical soil characteristics across the sites to estimate water storage. To allow comparison between the sites and additionally extrapolation to the landscape scale, water storage estimates are normalised by surface area and presented as litres of water stored per square metre of surface area (l m^{-2}).

3.1. Soil water level

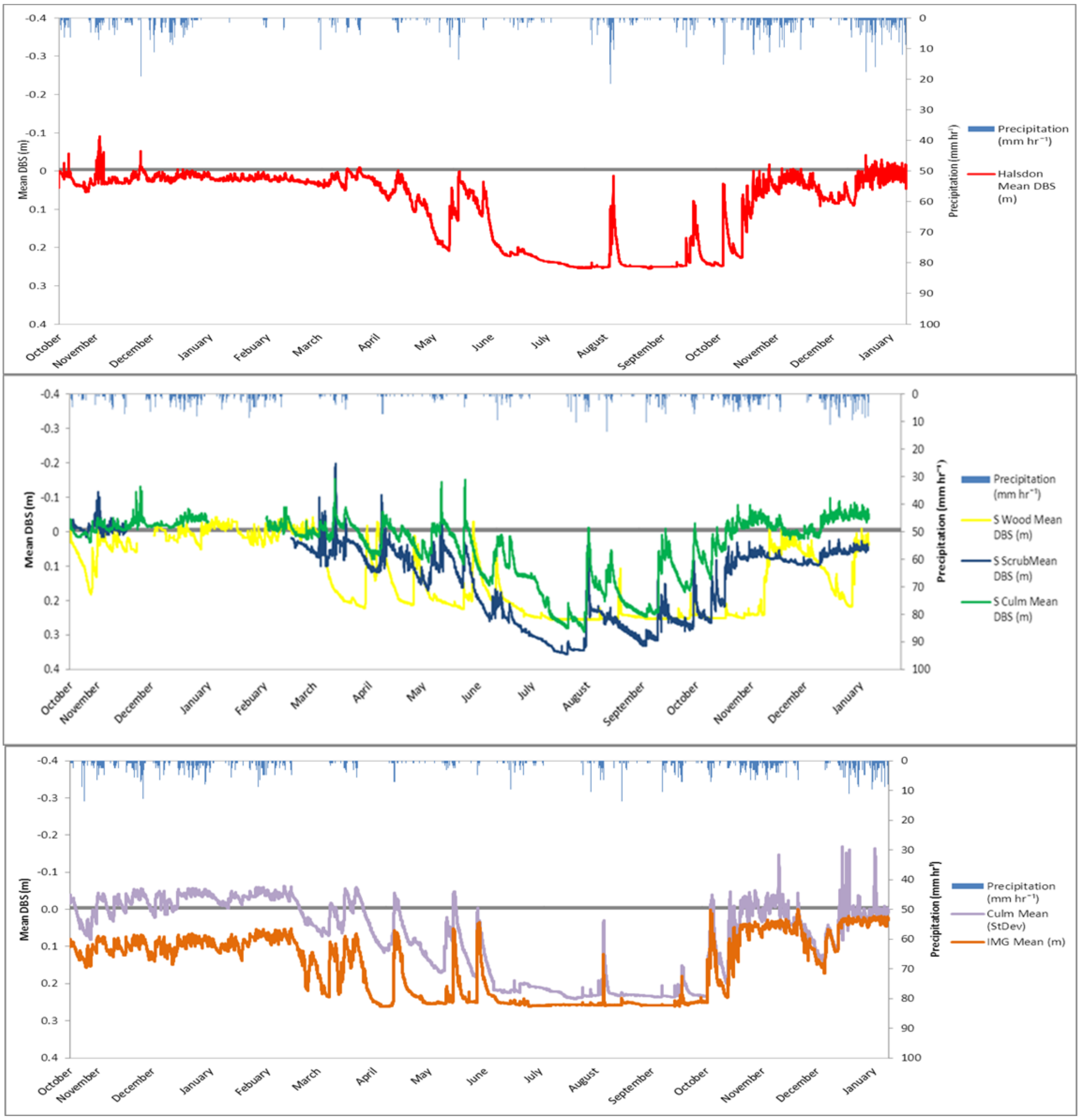

Figure 3.1. Mean water level depth below surface (DBS) across the monitored site between 16th October 2012 and 6th January 2014. Each time series represents the mean DBS from the six instrumented dipwells per site, rainfall intensity time series is also presented at each site (mm hr^{-1}). Top: mean DBS over time in Culm grassland at Halsdon (HOST 17). Middle: mean DBS over time in Culm grassland, invasive scrubland and wet woodland at Stowford Moor (HOST 21). Bottom: mean DBS over time in Culm grassland and IMG at Meshaw (HOST 24). The grey line in all plots represents the soil surface, as such any depths below this signify that the water table is drawn down beneath the soil surface and any depths above indicate that standing water is present above the soil surface.

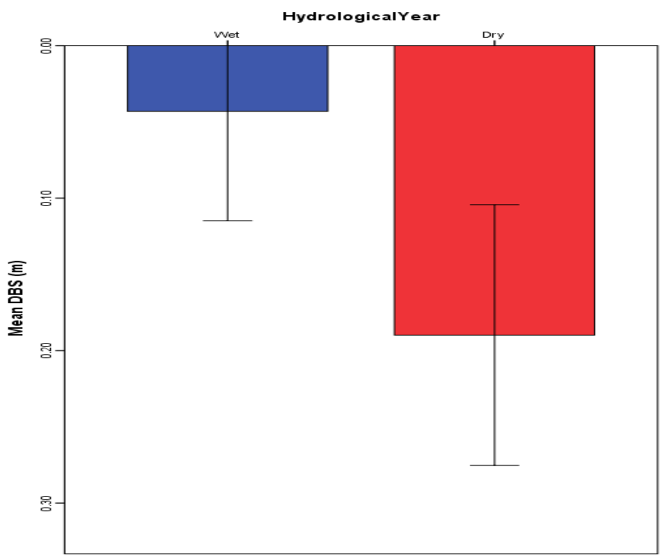

Figure 3.2. Mean water table depth below surface (DBS m± SD) for all level sensors, separated by Hydrological year (1st of October to 31st of March = Wet, 1st of April to 30th of September = Dry).

As illustrated in Figure 3.1. water level showed notable variation both between monitoring sites and over time. Over the entire time series mean DBS was least in the Culm grassland sites (0.07 ± 0.01m) and highest in IMG (0.16 ± 0.08 m). In addition to being significantly less than IMG ($p<0.05$), Culm grasslands also a significantly smaller mean DBS than either scrubland or wet woodland ($p<0.05$). From Figure 3.1. it also appears that Culm grassland sites showed a more attenuated soil water level response to rainfall and subsequent drainage, with the receding limbs of peaks being longer and of a lower angle than that for IMG, scrubland or woodland. Between the Culm sites situated upon different HOST soil types, Stowford Moor (HOST 21) had the lowest mean DBS (0.04 ± 0.09 m) being significantly less ($p<0.05$) than Culm grassland at either Halsdon (Host 17) or Meshaw (HOST 21).

None of the sites showed a significant positive correlation between water level DBS and rainfall over the time series. This reflects the multiple factors affecting water stored in soils (such as physical characteristics addressed in Section 2.2.) and also the attenuated response to rainfall. However, from Figure 3.1. it can be seen that DBS across all sites showed seasonal variation, appearing to have been general lower during the summer months. Seasonal variation in DBS is further illustrated in Figure 3.2., which taking the DBS from all monitored sites, shows that DBS was significantly less ($p<0.05$) during the dry season of the hydrological year (1st of April to 30th of September) than the wet season (1st of October to 31st of March).

3.2. Estimated water storage

DBS at each site was combined with physical characteristics from soil sampling to calculate estimates of water storage both spatially and temporally. Table 3.1. presents summary statistics for mean water storage and the variable used to calculate water storage for each study site.

As with DBS, estimations of water storage in soil varied both between the monitored sites (Figure 3.3.) and over time (Figure 3.4.). Mean water storage varied significantly (p<0.05) with land use over the monitored period, being overall highest under Culm (240.2 ± 71.5 l m^2) and lowest under IMG (61.63 ± 45.27 l m^{-2}). However, whilst the three Culm sites had the top mean water storage values, there was also a significant difference (p<0.05) between Culm sites, with results suggesting Meshaw stored the most water in soil (277.34 ± 71.97 l m^{-2}) and Stowford the least (193.20 ± 77.15 l m^{-2}). Across all monitored sites, mean estimated volume of water per m^2 was significantly less (p<0.05) during the dry season of the hydrological year (mean 115.6 ± 86.1 l m^{-2}) than during the wet season (mean 214 ± 90.7 l m^{-2}).

Site (HOST type)	Mean Soil Depth (m ±SD)	Mean DBS (m ±SD)	Mean SM (% ±SD)	Mean Water Storage* (l per m^{-2} surface area)
Meshaw IMG (24)	0.27±3.28	0.16±0.08	51.78±3.76	61.63±45.27
Meshaw Culm (24)	0.47±5.89	0.08±0.10	70.01±5.28	277.34±71.97
Stowford Culm (21)	0.30±6.37	0.04±0.09	76.44±6.44	193.20±77.15
Stowford Scrub (21)	0.34±5.43	0.14±0.11	69.02±5.04	144.18±79.25
Stowford Wood (21)	0.30±7.06	0.13±0.10	69.02±6.44	104.28±61.66
Halsdon Culm (17)	0.46±5.22	0.10±0.10	68.37±5.84	249.51±64.61

*Estimated from mean soil depth (D) and mean water table level below surface (DBS) and percentage soil moisture (% SM). Water storage capacity in litres per square meter =(D-DBS*1 m^2)*% SM).

Table 3.1. Summary statistics for mean water storage estimates over the monitored period, normalised by surface area (l m^{-2}) and summary statistics for topsoil soil depth (m), water table depth below surface (m) and soil moisture (%).

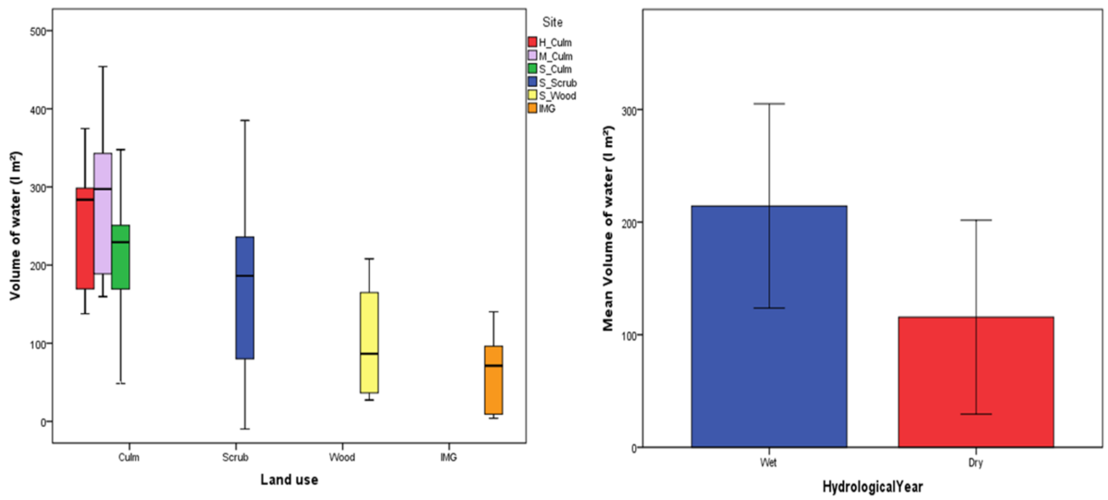

Figure 3.3. Water storage estimates. Left: Box and whisker plot summarising estimated volume of water stored, normalised by surface area (l m^{-2}) across monitored sites under different land uses/covers. Right: Bar graph showing mean water table depth below surface (DBS m ± SD) for all level sensors, separated by Hydrological year (1st of October to 31st of March = Wet; 1st of April to 30th of September = Dry).

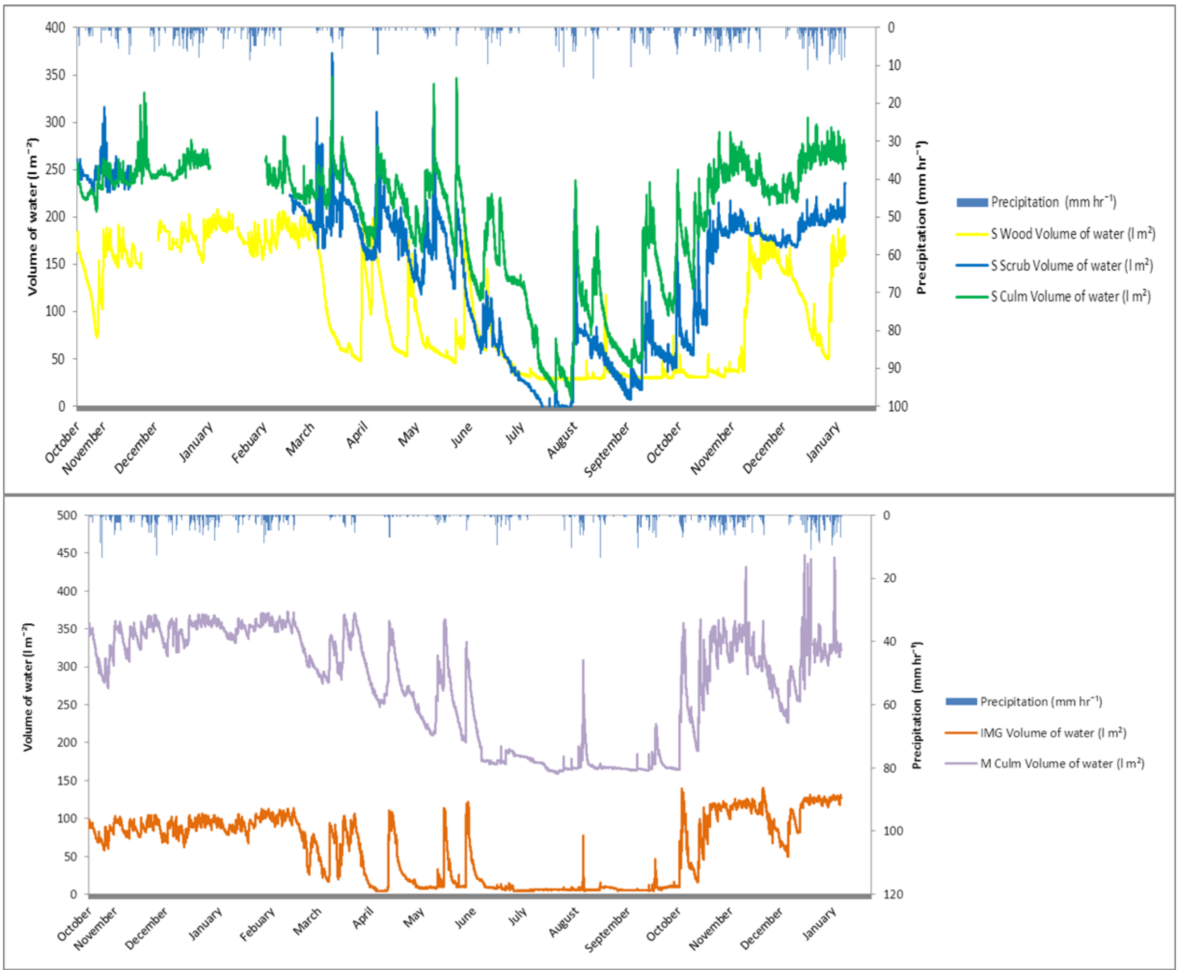

Figure 3.4. Times series of estimated volume of estimated water stored (l m^{-2}) illustrating differences between land covers. Top: difference between Culm grassland, scrubland and wet woodland at Stowford Moor. Bottom: difference between Culm grassland and IMG at Meshaw.

4. Catchment response to rainfall

Section 4.1. presents and summarise the entire time series record captured from the instrumented flume at Stowford Moor between 2nd November 2012 and 5th January 2014. Section 4.2. characterises the 11 events monitored for water quality during this period, whilst Section 4.3. presents results from water quality analysis and looks at potential mechanisms controlling the observed variation in water quality.

4.1. Summary of time series

Figure 4.1. presents the time series for discharge at the instrumented flume (cumecs: m^3 s^{-1}) in relation to rainfall (mm hr^{-1}) over the monitoring period (2nd November 2012 and 5th January 2014). During this period a total of 1029.8 mm of rain was recorded as falling at Stowford Moor. As would be expected, channel discharge was positively related to rainfall (p<0.05). However, as illustrated by results of linear regression between rainfall and discharge (Table 4.1.) the relationship, whilst statistically significant, was not very strong (r^2 0.14) indicating either that there were other mechanisms controlling discharge and additionally that the Culm dominated catchment, exhibited an attenuated response to rainfall.

Soil water levels throughout the catchment would be expected to influence channel discharge, with higher levels promoting saturation excess overland flow and consequently resulting in greater channel discharge. Figure 4.2. plots mean DBS (from all level sensors at Stowford Moor) against channel discharge. Mean DBS showed a positive correlation (p<0.05) with channel discharge, although like rainfall, was only shown to be a relatively weak independent variable influencing discharge (r^2 0.13). Combined via multivariate analysis rainfall and DBS showed a greater influence (r^2 0.27).

As with DBS and water storage (Section 3), channel discharge could also be separated by hydrological year. It must be recognised; that the monitoring period included a greater amount of time in the wet season of the hydrological year (249 days) than dry (183 days), however, that does not negate the seasonal disparity exhibited. For data recorded during the wet season of the hydrological year, channel discharge was significantly greater (p<0.05) with a mean discharge at the flume of 0.012 m^3 s^{-1}, relative to 0.0007 m^3 s^{-1} for discharge during the dry season. During the dry season of the hydrological year, Stowford Moor experienced both significantly less (p<0.05) rain (18.8 mm) and significantly lower (p<0.05) mean DBS across the catchment (0.18 ± 0.07 m) than during the wet seasons monitored (1011 mm and 0.03 ± 0.05 m respectively).

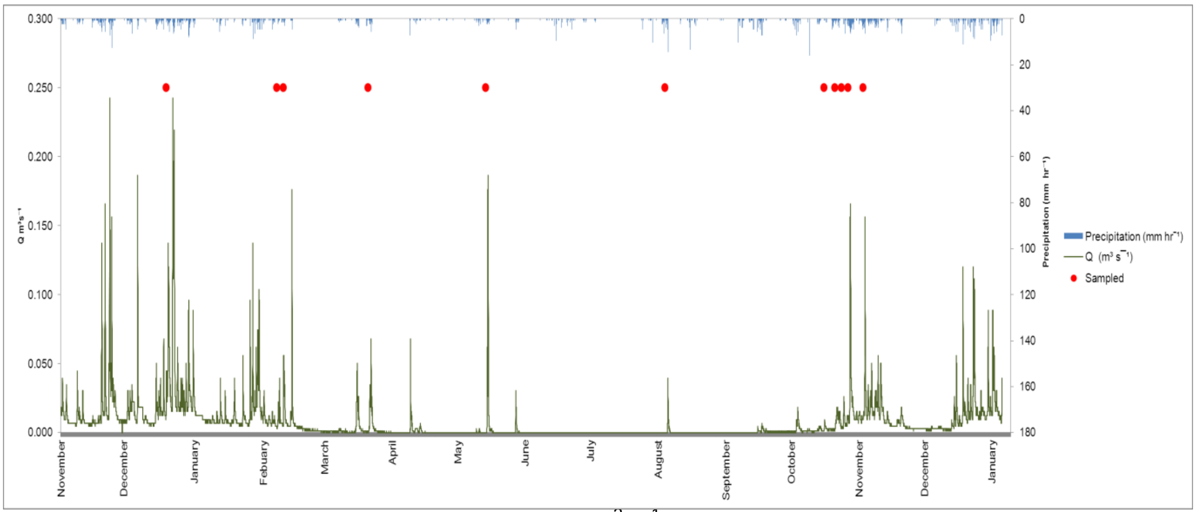

Figure 4.1. Times series for flume discharge (Q: m^{-3} s^{-1}) in relation to rainfall for monitored period at Stowford Flume. Red dots indicate date of sampled storm events addressed in Section 4.2.

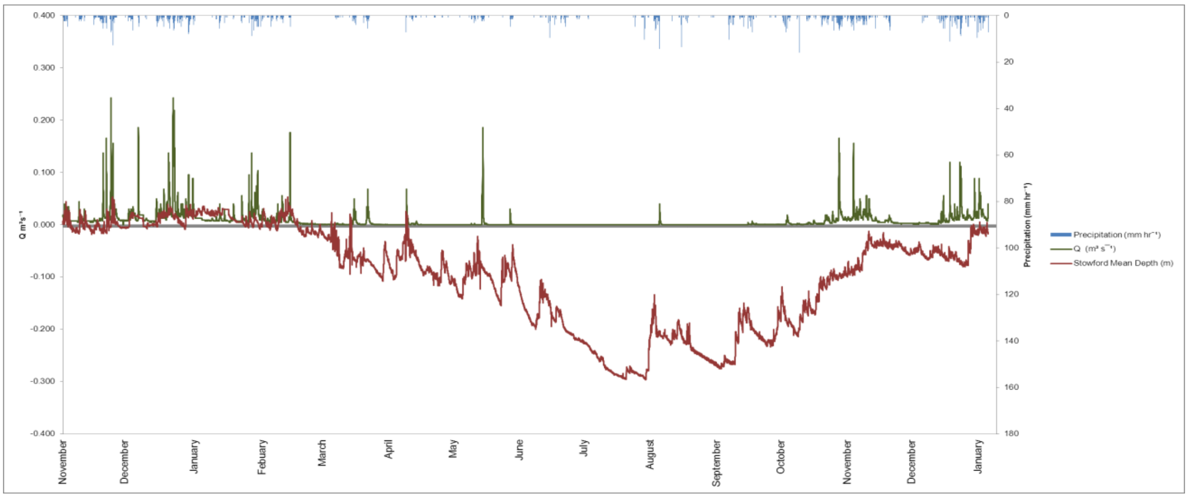

Figure 4.2. Time series for flume discharge (Q: m^{-3} s^{-1}) in relation to rainfall and dipwell levels (mean depth (m) compiled from Culm, scrub and wood sites) at Stowford Moor.

Variable	r^2	Sig.
Precipitation	0.14	0.000*
Stowford mean soil water DBS	0.13	0.000*
Precipitation and DBS	0.27	0.000*
Hydrological year	0.13	0.000*

Table 4.1. Regression relationships between flume discharge at Stowford Moor and precipitation, hydrological year (1st of October to 31st of March = Wet; 1st of April to 30th of September = Dry) and mean soil water depth below surface (from 18 dipwells compiled across Culm, scrub and wood sites) at Stowford Moor. Significance levels followed by an asterisk (*) are statistically significant (p<0.05).

4.2. Monitored event summary

Between December 2012 and November 2013, 11 events were monitored for water quality with automated collection of water samples throughout events. Water samples allow investigation into the overall water quality of a Culm dominated catchment. Monitoring a range of event sizes and throughout events at varying discharge (Figure 4.3.) allowed investigation into whether there was notable variation in water quality between or within monitored events. Table 4.2. presents summary statistics for the events monitored.

Section 4.1. found that although there was a positive correlation between instantaneous rainfall and discharge, this was relatively weak (r^2 0.14) suggesting an attenuated response. Figure 4.3. shows that when entire event rainfall is taken into account, this relationship is much stronger with an r^2 of 0.6 for total event rain and total event discharge for the events monitored. Mean DBS at the start of the event was also a statistically significant control over event discharge (p<0.05), but with a weaker r^2 value comparable to that for the entire time series (0.14).

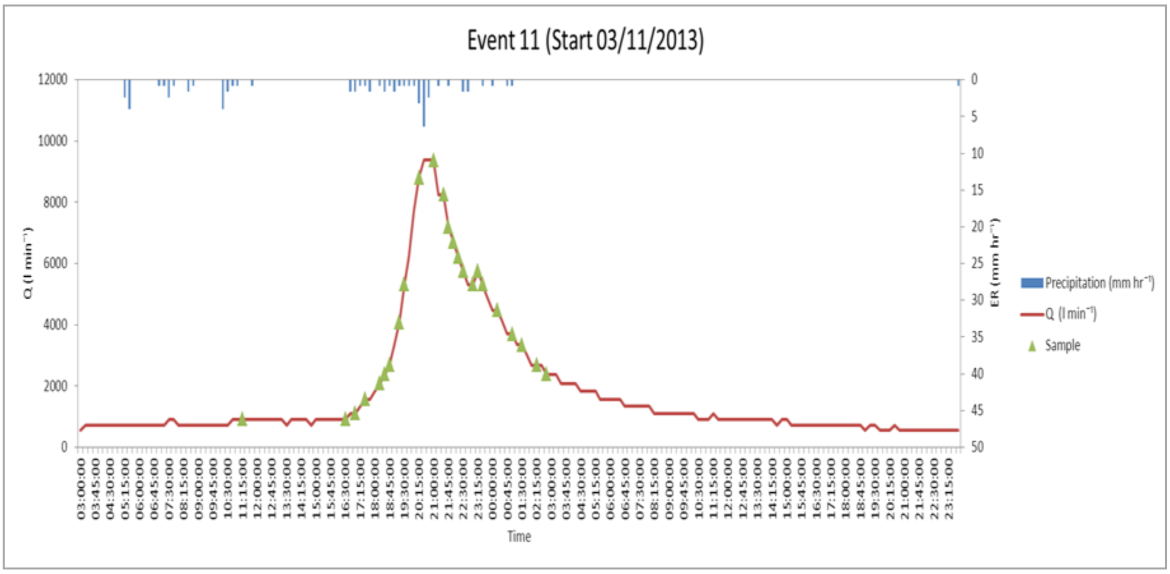

Figure 4.3. Sample event hydrograph. Hydrograph presents rainfall (mm hr^{-1}), discharge (Q L min^{-1}) and timing of sample collection (green triangles).

Event	Start Date	ER (mm)	Max *I* (mm hr^{-1})	DBS (m)	Max L (m)	Peak Q (m^3 s^{-1})
E1	19/12/2012	22	3.2	-0.020	0.27	0.14
E2	07/02/2013	5	2.4	0.007	0.13	0.04
E3	10/02/2013	10.4	2.4	-0.029	0.16	0.06
E4	21/03/2013	20	2.4	0.068	0.18	0.07
E5	14/05/2013	19.8	4.8	0.079	0.32	0.19
E6	04/08/2013	20.4	6.4	0.207	0.13	0.04
E7	16/10/2013	3.4	0.8	0.166	0.05	0.01
E8	21/10/2013	13	3.2	0.108	0.08	0.02
E9	24/10/2013	8	6.4	0.101	0.10	0.03
E10	27/10/2013	40.4	6.4	0.100	0.30	0.17
E11	03/11/2013	14.2	6.4	0.079	0.29	0.16

Table 4.2. Summary statistics for events monitored. ER = event rain; Max *I* = maximum rainfall intensity; Max L = maximum level in flume (m); Q = discharge. DBS = depth below surface (antecedent mean for all dipwell level sensors at Stowford Moor).

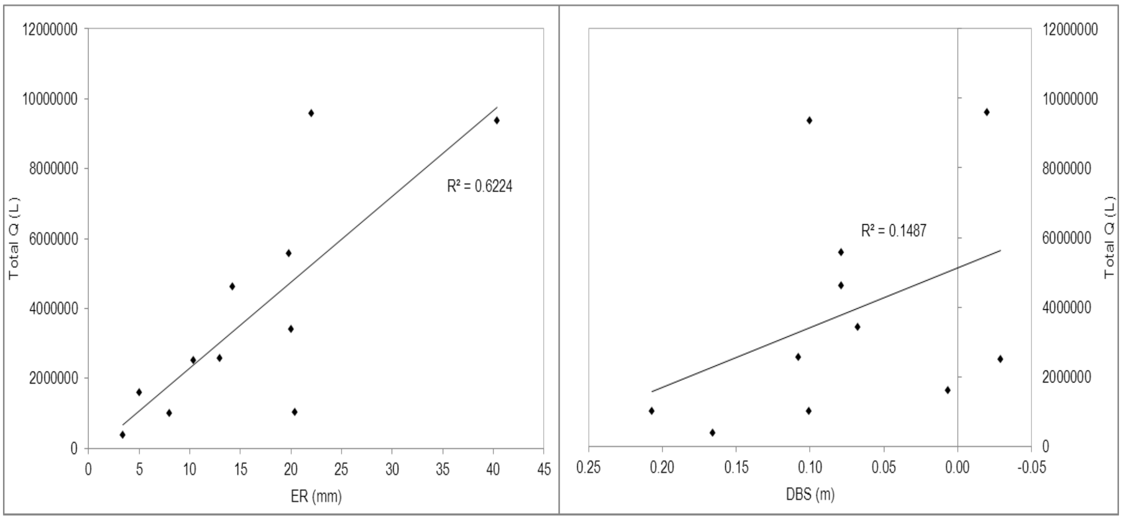

Figure 4.3. Left: Relationship between monitored event rainfall (ER) and total event discharge through the flume at Stowford moor (Total Q). Right: Relationship between antecedent soil water level (DBS = depth below surface, mean for all dipwell level sensors at Stowford Moor) and total event discharge through the flume at Stowford moor. Both relationships statistically significant (p<0.05).

4.3. Water quality

Section 4.3.1. presents summary statistics describing the concentrations and instantaneous loads of water quality variables analysed for. Section 4.3.2. extrapolates analysed results to calculate event yields for the period sampled. Section 4.3.3. investigates potential controls over water quality at Stowford Moor.

4.3.1. Water quality summary tables

Table 4.4. displays Summary statistics for all water quality samples analysed. Exploratory analysis for all variables showed there to be significant differences ($p<0.05$) between the sampling population as a whole and also between sampled events. Table 4.5. presents the mean values for each event.

	pH	DOC (mg l^{-1})	TON (mg l^{-1})	P (µg l^{-1})	SS (mg l^{-1})	K (mg l^{-1})	Colour (mg l^{-1})
Mean	6.28	9.91	3.45	66.84	51.55	1.72	54.12
SD	0.32	3.18	2.64	71.15	69.11	0.50	11.26
SE	0.02	0.24	0.20	5.27	5.12	0.04	0.83
Median	6.30	10.84	2.68	30.00	24.00	1.73	52.49
Max	6.93	17.47	19.59	398.00	410.00	2.82	86.94
Min	5.21	2.61	0.50	0.00	5.79	0.35	24.69

Table 4.4. Summary table for water quality concentrations; mean, standard deviation (SD), standard error (SE), median, max and min for each variable measured. DOC = dissolved organic carbon; TON = total oxidised nitrogen; P = phosphorus, SS = suspended sediment; K = potassium.

Event	pH	DOC (mg l^{-1})	TON (mg l^{-1})	P (µg l^{-1})	SS (mg l^{-1})	K (mg l^{-1})	Colour (mg l^{-1})
E1	6.32±0.06	NA	4.53±0.41	12.80±5.40	85.78±107.18	1.73±0.13	NA
E2	6.43±0.18	6.67±0.61	1.64±0.24	6.00±6.08	110.91±121.77	1.92±0.15	48.25±6.82
E3	6.57±0.06	6.74±0.88	1.79±0.45	55.15±13.77	63.08±25.62	1.77±0.23	48.15±4.73
E4	6.71±0.10	9.48±1.72	1.42±0.80	26.80±9.27	50.63±83.55	1.98±0.35	44.54±5.02
E5	6.52±0.16	13.92±2.38	6.79±5.02	181.08±32.56	41.93±50.80	1.81±0.33	59.37±12.01
E6	6.06±0.16	4.53±0.89	5.07±1.48	20.44±12.95	26.45±20.54	0.91±0.14	43.71±13.93
E7	5.79±0.04	8.08±1.41	4.28±0.05	113.33±21.94	21.67±3.06	1.20±0.11	50.00±1.91
E8	5.87±0.07	10.85±0.81	4.29±0.09	79.88±8.10	23.82±10.12	1.26±0.04	59.37±4.93
E9	5.97±0.41	10.83±1.66	2.73±0.11	112.44±27.75	21.89±3.30	1.34±0.05	54.71±6.25
E10	6.09±0.12	11.22±0.41	2.00±0.86	155.40±51.76	64.89±66.58	1.43±0.03	57.69±3.91
E11	6.11±0.20	11.96±0.55	2.06±0.17	28.17±4.30	39.36±42.26	2.56±0.13	66.52±6.57

Table 4.5. Summary table for water quality concentrations separated by monitored rainfall event (E); mean, standard deviation (SD), standard error (SE), median, max and min for each variable measured. DOC = dissolved organic carbon; TON = total oxidised nitrogen; P = phosphorus, SS = suspended sediment; K = potassium. Event characteristics are summarised in Table 4.2.

Combining measurement of water quality concentrations with flume discharge at time of collection allows for instantaneous loads to be calculated for each sample, as illustrated in Table 4.6., these loads varied significantly ($p<0.05$), both between and within events ($p<0.05$, Table 4.7.). DOC = dissolved organic carbon; TON = total oxidised nitrogen; P = phosphorus, SS = suspended sediment; K = potassium.

	DOC (g min^{-1})	TON (g min^{-1})	P (mg min^{-1})	SS (g min^{-1})	K (g min^{-1})
Mean	29.06	8.99	230.01	187.88	5.17
Std Dev	32.11	9.96	459.03	377.39	5.06
Std Error	2.38	0.74	34.03	27.97	0.37
Median	14.68	4.73	61.21	46.26	3.19
Max	132.31	67.69	2370.13	2071.70	21.54
Min	1.09	0.21	0.00	5.00	0.27

Table 4.6. Summary table for key monitored water quality instantaneous loads; mean, standard deviation (SD), standard error (SE), median, max and min for each variable measured.

Event	DOC (g min^{-1})	TON (g min^{-1})	P (mg min^{-1})	SS (g min^{-1})	K (g min^{-1})
E1		18.63±8.27	53.95±34.19	429.10±596.40	6.80±2.59
E2	7.15±3.61	1.67±0.67	7.04±6.68	97.38±79.93	1.98±2.83
E3	11.19±6.90	2.48±1.24	30.87±41.55	93.65±70.21	2.88±2.91
E4	18.58±10.47	2.40±1.28	47.56±21.89	123.44±256.88	3.98±2.76
E5	50.90±34.23	21.34±16.10	685.71±565.61	249.62±472.25	6.86±2.78
E6	5.42±3.19	6.28±4.15	21.33±10.51	24.92±15.30	0.99±2.84
E7	4.23±1.1.31	2.20±0.38	57.24±2.84	11.21±2.72	0.62±2.89
E8	8.65±2.91	3.38±1.01	62.25±17.66	19.89±12.38	0.99±2.92
E9	10.63±4.72	2.62±1.01	108.81±50.86	21.58±9.64	1.28±2.94
E10	71.55±42.23	10.01±4.30	119.05±819.51	452.55±588.51	9.19±2.86
E11	53.07±29.32	9.07±4.81	129.61±72.15	202.09±281.50	11.36±2.73

Table 4.7. Mean instantaneous loads for key monitored water quality variables (±SD) separated per event (E). Event characteristics are summarised in Table 4.2.

4.3.2. Estimated event yields and event catchment fluxes

Instantaneous loads of relevant water quality variables were extrapolated for the event period sampled, using the Webb and Walling method (Walling and Webb, 1985, Clark et al., 2007, Glendell, 2013) presented in Equation 1. Extrapolation of intra-event sampling allowed calculation of event yields (for sampled period) and also by dividing by catchment area (20 ha) as an event flux, normalised per m^2. Event yield and aerially weighted flux estiamtions for each water quality variable are presented in tables 4.8 and 4.9. As would be expected given the range of event characteristics and water quality concentrations recorded, event yields and fluxes showed significant variation ($p<0.05$) between monitored events.

$$F = K * Qr * (\sum_{i=1}^{n} Ci * \ Qi)/(\sum_{i=1}^{n} Qi)$$

Equation 1. Where: F = is the total solute load for sampling period (g); K = time period over which the load occurred (seconds); Qr = mean discharge from a continuous record (m^3); Qi = instantaneous discharge (m3 s-1); Ci = instantaneous concentration (mg l^{-1}); n = number of samples.

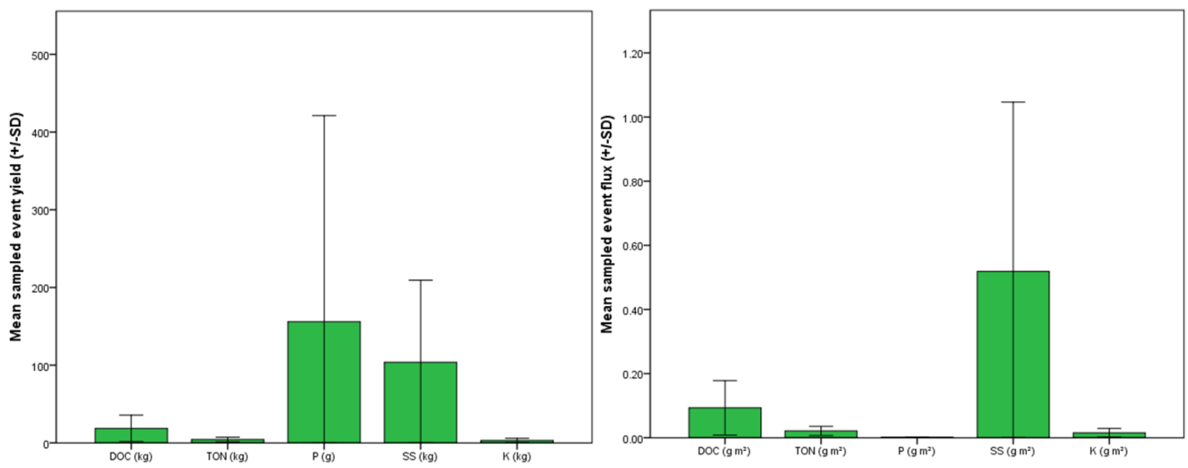

Figure 4.4. Left graph: Mean sampled event yields for key measured variables, all measured in kg (± SD) except P (g ± SD). Right graph: Mean sampled event fluxes for key measured variables (g m² ± SD).

Event	DOC (kg)	TON (kg)	P (g)	SS (kg)	K (kg)
E1	NA	27.06	78.41	623.20	9.90
E2	8.50	2.00	8.22	118.25	2.37
E3	17.89	2.82	39.39	105.72	3.22
E4	18.05	2.33	46.25	122.02	3.87
E5	22.05	9.30	296.01	110.40	2.96
E6	3.99	4.39	14.66	22.70	0.74
E7	0.46	0.24	6.57	1.22	0.07
E8	11.85	4.63	84.99	27.23	1.36
E9	9.46	2.40	100.91	19.23	1.17
E10	56.65	8.17	871.06	363.99	7.23
E11	37.51	6.42	92.17	147.11	8.04
Mean (±SD)	18.46±16.97	6.34±7.40	148.97±252.65	151.01±185.89	3.72±3.26

Table 4.8. Event sample period yield estimate for key measured variables, presented for individual events (E) and overall mean.

Event	DOC (g m²)	TON (g m²)	P (g m²)	SS (g m²)	K (g m²)
E1	NA	0.135	0.0004	3.116	0.049
E2	0.043	0.010	0.0000	0.591	0.012
E3	0.089	0.014	0.0002	0.529	0.016
E4	0.090	0.012	0.0002	0.610	0.019
E5	0.110	0.047	0.0015	0.552	0.015
E6	0.020	0.022	0.0001	0.113	0.004
E7	0.002	0.001	0.0000	0.006	0.000
E8	0.059	0.023	0.0004	0.136	0.007
E9	0.047	0.012	0.0005	0.096	0.006
E10	0.283	0.041	0.0044	1.820	0.036
E11	0.188	0.032	0.0005	0.736	0.040
Mean (±SD)	0.09±0.08	0.03±0.04	0.0007±0.0013	0.76±0.93	0.02±0.02

Table 4.9. Event sample period flux estimate for key measured variables, presented for individual events (E) and overall mean.

4.3.3. Factors influencing observed variation in water quality

Summary water quality results presented in Section 4.3.2 revealed that water quality and associated nutrient yields varied both between and within the 11 monitored events. The following sections examine whether channel discharge is a significant control over water quality. Additionally, rainfall event characteristics and antecedent soil water level conditions, -both of which were shown to influence discharge- are examined as controls upon water quality.

4.3.3.1. Channel discharge

Channel discharge is highly characteristic of event magnitude with higher peak and total discharges indicating bigger, more powerful events, which may be expected to lead to greater loss of nutrients from the catchment and consequently higher concentrations, loads and yields for monitored water quality variables. Table 4.10. presents summary statistics for linear regression analysis between instantaneous, total and peak channel discharge (controlling variables) and monitored water quality concentrations, instantaneous loads and calculated event yields. Channel discharge cannot be viewed as a fully independent variable to loads and yields as it is included in their calculation and as expected all showed a positive statistically significant relationship with discharge (p<0.05). The relationship with measured water variable concentrations was not as strong as indicated by lower R^2 values, with most water quality concentrations showing a weak but significant relationship (p<0.05) with instantaneous, but not total or peak discharge.

Figure 4.5. presents an example event hydrograph showing the close relationship between discharge and instantaneous DOC load throughout an event in contrast to the relationship with DOC concentration. Figure 4.5. also presents the strong linear relationship between discharge and DOC load for each event in contrast to the highly variable inter-event relationship between discharge and concentration. The lack of a consistent positive relationship between channel discharge and the concentration of water quality variables suggests other additional controls on channel water quality at Stowford Moor.

	Individual samples		Event means			
	Instantaneous Q		Total Q		Peak Q	
Variable	**R^2**	**Sig.**	**R^2**	**Sig.**	**R^2**	**Sig.**
pH	0.00	0.88	0.05	0.51	0.01	0.32
Colour conc (mg l^{-1})	0.06	0.00*	0.17	0.13	0.26	0.07
DOC conc (mg l^{-1})	0.13	0.00*	0.28	0.07	0.36	0.04*
TON conc (mg l^{-1})	0.01	0.16	0.00	0.85	0.08	0.63
P conc (µg l^{-1})	0.06	0.00*	0.03	0.61	0.01	0.37
SS conc (mg l^{-1})	0.06	0.00*	0.17	0.20	0.04	0.44
K conc (mg l^{-1})	0.07	0.00*	0.09	0.38	0.19	0.10
DOC load (g min^{-1})	0.97	0.00*				
TON load (g min^{-1})	0.32	0.00*				
P load (µg min^{-1})	0.55	0.00*				
SS load (g min^{-1})	0.35	0.00*				
K load (g min^{-1})	0.88	0.00*				
DOC event yield (kg)			0.90	0.00*	0.66	0.00*
TON event yield (kg)			0.64	0.00*	0.26	0.06
P event yield (kg)			0.44	0.03*	0.37	0.05*
SS event yield (kg)			0.81	0.00*	0.30	0.05*
K event yield(kg)			0.77	0.00*	0.53	0.01*

Table 4.10. Summary relationship statistics between discharge (Q L min^{-1}) and water quality concentrations, instantaneous loads and sampled event yields. DOC = dissolved organic carbon; TON = total oxidised nitrogen; P = phosphorus, SS = suspended sediment; K = potassium. Significance levels followed by an asterisk (*) are statistically significant (p<0.05).

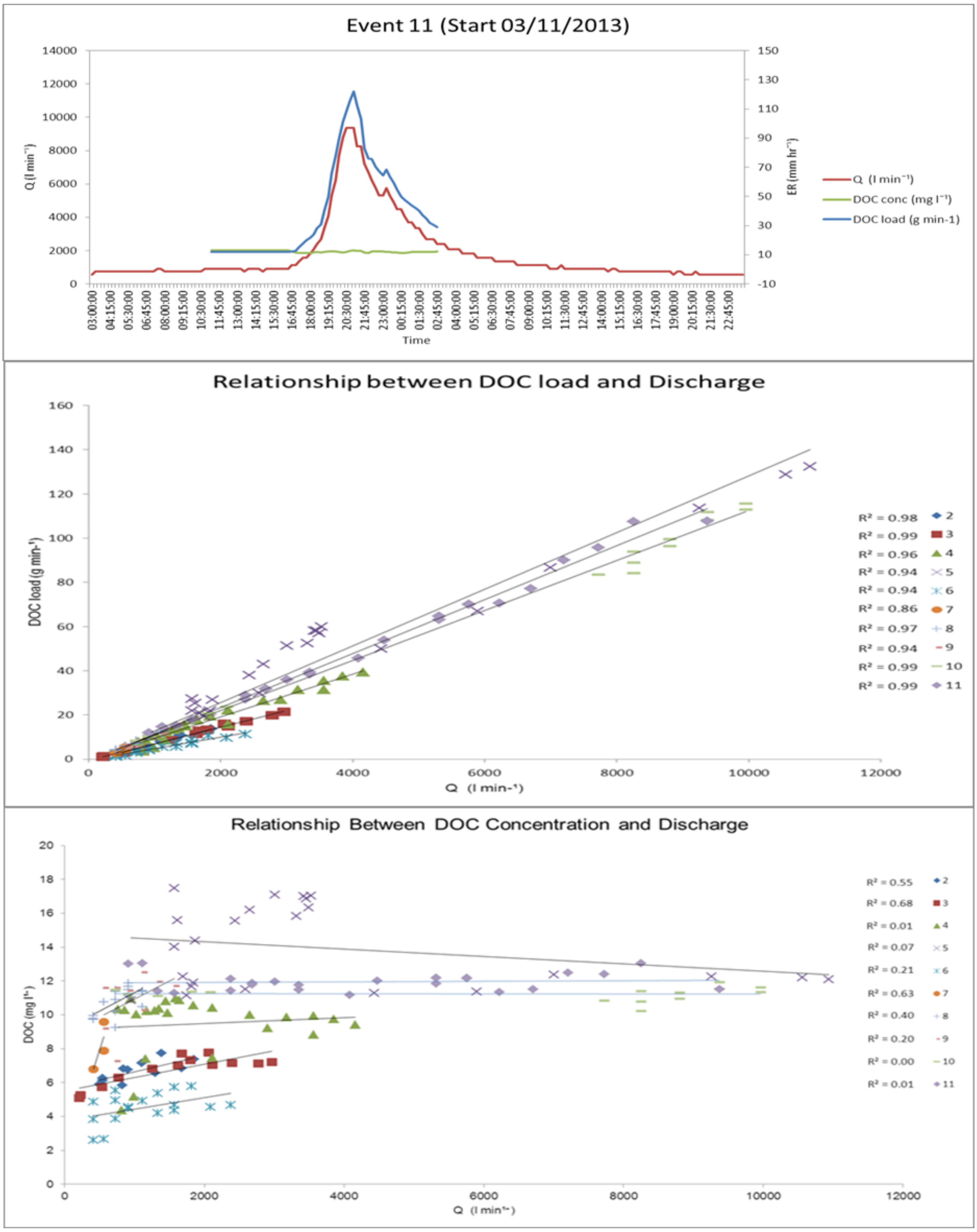

Figure 4.5. Exploration of the relationship between discharge and water quality (concentrations and instantaneous loads). Top: example hydrograph (monitored event 11) showing relationship between discharge (Q), extrapolated DOC sample concentration and extrapolated DOC sample load. Middle: Relationship between DOC instantaneous load and discharge for all events (except E1). Trend lines and presented R^2 values represent linear relationship between variables. Bottom: relationship between DOC concentration and discharge for all events (except E1). Trend lines and presented R^2 values represent linear relationship between variables.

4.3.3.2. Additional influences on water quality

Rainfall and antecedent water levels

Rainfall event characteristics and antecedent soil water levels were shown to influence discharge (Section 4.2). Rainfall influences the volume of water within the catchment and also characteristics affecting runoff to the channel via the infiltration capacity of soils and the increased hydrological connectivity. Overland flow may be expected to occur when the saturation or infiltration capacity of soils is exceeded. However, as demonstrated in Table 4.11. there was only a limited influence of rainfall or DBS upon water quality. Total event rain was significantly related to DOC and P yields (*p*<0.05) and showed a notable positive relationship with all monitored yields. DBS was positively related to SS concentration (but not yield) possibly indicating the occurrence of greater overland flow and thus, greater erosion with high water table levels. However, overall the lack of high r^2 and significance levels indicates a fairly attenuated catchment response.

	ER		Max *I*		DBS	
Variable	r^2	Sig.	r^2	Sig.	r^2	Sig.
pH	0.09	0.70	0.00	0.94	0.42	0.03*
Colour conc (mg l^{-1})	0.09	0.63	0.08	0.44	0.00	0.91
DOC conc (mg l^{-1})	0.03	0.41	0.01	0.36	0.01	0.82
TON conc (mg l^{-1})	0.00	0.90	0.01	0.74	0.14	0.25
P conc (µg l^{-1})	0.08	0.42	0.01	0.77	0.08	0.39
SS conc (mg l^{-1})	0.09	0.71	0.09	0.38	0.57	0.01*
K conc (mg l^{-1})	0.00	0.90	0.01	0.80	0.36	0.05
DOC event yield (kg)	0.56	0.01*	0.26	0.13	0.05	0.55
TON event yield (kg)	0.10	0.18	0.00	0.99	0.17	0.21
P event yield (kg)	0.63	0.00*	0.16	0.23	0.01	0.84
SS event yield (kg)	0.34	0.06	0.00	0.99	0.27	0.10
K event yield(kg)	0.25	0.07	0.05	0.50	0.26	0.11

Table 4.11. Summary relationship statistics between event rainfall (ER mm); max rainfall intensity (Max *I* mm hr^{-1}); soil water depth below surface (DBS (m) compiled from all level sensors at Stowford) and water quality concentrations, instantaneous loads and sampled event yields. DOC = dissolved organic carbon; TON = total oxidised nitrogen; P = phosphorus, SS = suspended sediment; K = potassium. Significance levels followed by an asterisk (*) are statistically significant (*p*<0.05).

Hydrological year

Table 4.12. presents summary statistics for water quality concentrations separated by season in the hydrological year and whether the difference between the two is significant. Season may be expected to affected water quality both as a consequence of increased magnitude and frequency of rainfall events during the wet season and also due to other factors such as temperature, and biological activity possibly affecting nutrient availability (Koehler et al, 2009), and consequently water quality characteristics. However, only K, P and

TON showed significant differences between seasons, with K being higher during the wet season and TON and P being higher during the dry season, possibly as a consequence of a dilution or exhaustion effect during the wet season.

	Hydrological Year		
Variable	Wet (±SD)	Dry (±SD)	Sig.
pH	6.27±1.32	6.33±0.28	0.19
Colour conc (mg l^{-1})	54.90±9.26	52.03±15.33	0.25
DOC conc (mg l^{-1})	9.96±2.11	9.77±5.07	0.81
TON conc (mg l^{-1})	2.68±1.32	5.94±3.99	0.00*
P conc (µg l^{-1})	53.49±60.78	109.98±84.78	0.00*
SS conc (mg l^{-1})	56.76±75.12	34.69±40.72	0.07
K conc (mg l^{-1})	1.81±0.46	1.41±0.52	0.00*

Table 4.12. Mean water quality concentrations, separated by hydrological year (1st of October to 31st of March = Wet; 1st of April to 30th of September = Dry). Significance levels followed by an asterisk (*) are statistically significant (*p*<0.05). For dry season N=43 for wet season N=139 (except DOC and colour where N=115).

Supply limitation effect

For suspended sediment, many of the monitored events showed a statistically significant decrease in suspended sediment concentration over the course of the event (Figure 4.6.). This suggests that although as indicated in (Figure 4.6.) by the relationship with Q, there is a transport limitation effect influencing suspended sediment, there is also a supply limitation effect. A supply limitation effect in suspended sediment would be expected in environments such as Culm grassland which are not thought to have low vulnerability to erosion. A supply limitation or exhaustion effect was not found to be significant for the other water quality concentration variables monitored (*p*>0.05).

Event	R2	Sig.
E1	0.41	0.00*
E2	0.66	0.00*
E3	0.14	0.00*
E4	0.03	0.17
E5	0.51	0.00*
E6	0.48	0.00*
E7	0.01	0.87
E8	0.05	0.02*
E9	0.02	0.36
E10	0.10	0.02*
E11	0.17	0.00*

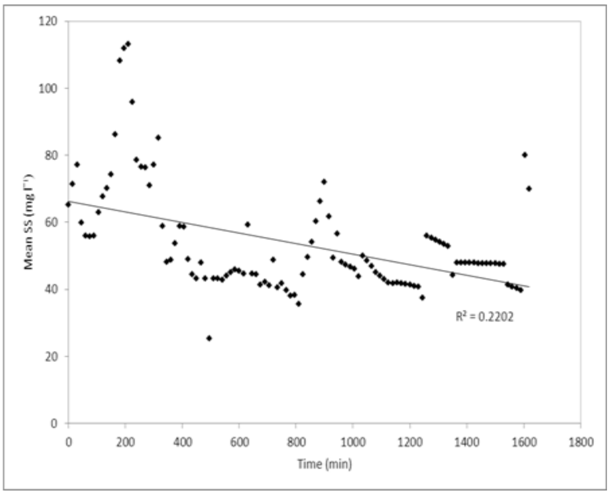

Figure 4.6. Left: regression relationship between time (from start of sampling) and suspended sediment concentration. Significance levels followed by an asterisk (*) are statistically significant (p<0.05).Right: relationship between mean suspended sediment concentration and time (in minutes from start of sampling).

5. Extrapolation of results

It is proposed that Culm grasslands can play an important role in the sustainable management of water resources, the improvement or maintenance of water quality to meet environmental objectives and carbon storage. This is supported by the collection of baseline and characterisation data collected and presented within this study and addressed under objectives 1-3. Extrapolating field based understanding to the landscape scale, whilst involving a high degree of uncertainty; helps get an understanding of the value of the existing water and soil resources provided by Culm grasslands; in addition to how this could be increased under hypothetical Culm restoration scenarios.

The following sub-sections extrapolate results to examine: (1) water and carbon stored in Culm soils; (2) influence of Culm grassland upon water quantity entering rivers and (3) influence of Culm grassland upon river water quality. Broad scale extrapolations for the entire Culm NCA will be presented, in addition to catchment or sub-catchment case study examples focused upon the Exe and Tamar.

5.1. Water and carbon stored within Culm grassland soils

To make an estimation of the volume of water and carbon stored in Culm grassland soils within the Culm NCA, mean areally normalised water (l m^{-2}) and topsoil carbon (t ha^{-1}) storage estimates from field monitoring were combined with the current total area of DBRC inventory Culm grassland sites. Extrapolations give an estimate 9430 ± 2807 megalitres (ML = one million litres) of water and 715402 ± 167327 t of carbon for the existing Culm resource.

Within each catchment, situated within the Culm NCA, the total area of Culm grassland has been calculated (Figure 3) allowing water and carbon storage estimates per catchment to be calculated. Estimations at a catchment scale have particular relevance for water storage and the sustainable management of water resources within South West England. Full water and carbon storage and associated standard deviation values for all catchments are provided in Table 5.3. Extrapolations give an estimated mean 299 ML of water being stored within DBRC inventory Culm grassland sites in the Exe catchment (Yeo Devon; Creedy; Middle; lower and Tidal) and mean 1620 Ml of Water within the Tamar (Upper; Middle; Lower; Deer and Claw; Carey; Thrushel and Wolf; Lyd).

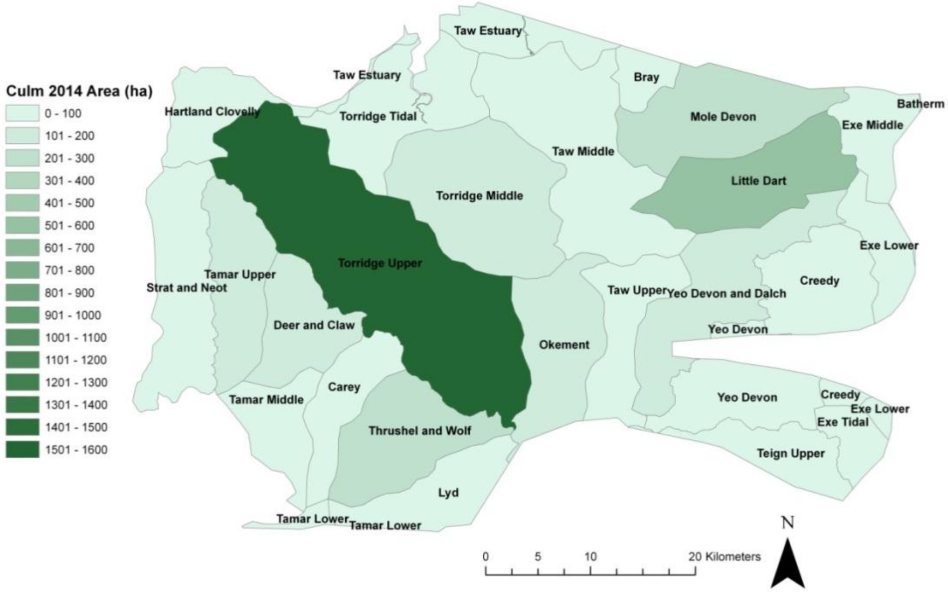

Figure 5.1. Area of Culm grassland (ha) separated by catchment within the Culm NCA.

It has been identified that the coverage of Culm grassland resources in SW England have become highly fragmented (Figure 5.1) and drastically reduced, compared to their previous extent. Analysis showed Culm grassland sites in the Culm NCA now cover approximately 3926 ha, compared to a former estimated extent of 29500 ha in 1900. This loss is predominantly believed to due to agricultural improvement, afforestation and scrub invasion. Thus, it can be hypothesised that if the area of Culm grassland was increased the provision of associated ecosystem services would also increase. Consequently, there is interest in restoring Culm grassland, whether by the removal of invasive scrub, or reverting IMG back to Culm.

Previous extents of Culm grassland, within the Culm NCA (1990 and 1900) were combined with mean water and carbon storage estimations to create hypothetical extrapolation scenarios. The 1900 scenario is based upon the 29,500 ha value of Culm grassland given by Hughes (1997). The 1990 scenario is based upon sites that were Culm grassland when surveyed between 1989 and 1991, but where repeated surveys (carried out mid-to-late 2000s) have since shown Culm to be lost, mainly to agricultural improvement or scrub invasion. For the 281 ha lost since the 1990s detailed survey information exists, as such accurate calculations of loss per catchment can be made. Spatial information for Culm loss since 1900 was not available, therefore a uniform spatial rate of loss per catchment has been assumed.

Results from linear extrapolations (Figure 5.2.) suggested that if Culm within the Culm NCA, was restored to 1990 levels (an increase of 281 ha) extrapolations indicate there would be potential for storage of 10106 ± 3008 ML of water and 766677 ± 179320 t of carbon (107 % increase). If Culm was increased to the 1900 scenario (an increase of 25574 ha) extrapolations indicate there would be potential for storage of 70852 ± 21092 ML of water and 5375264 ± 125723 t of carbon (751 % increase).

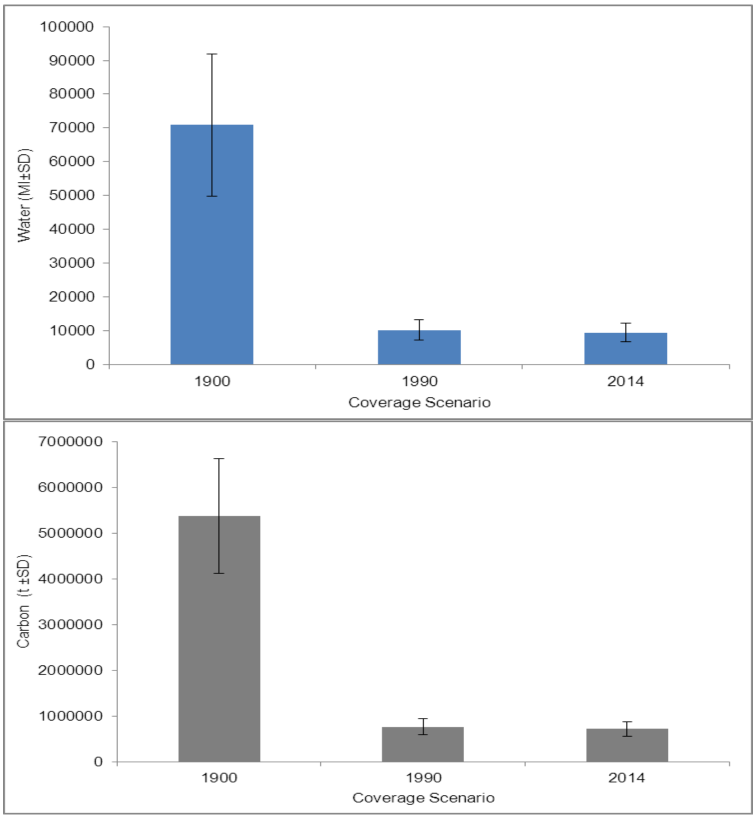

Figure 5.2. Extrapolated estimates for water (top) and carbon (bottom) storage in the Culm NCA under different Culm grassland coverage scenarios.

Previous extents of Culm can also be used to estimate storage at the catchment level. Full water and carbon storage values and area covered by Culm at a catchment level are provided in Table 5.3 for current, 1990 and 1900 Culm extent scenarios. For the Exe catchment lying within the Culm NCA (Figure 5.3.) encompassing parts of Yeo Devon; Creedy; Middle Exe; lower Exe and Tidal Exe it is estimated that a total of 340 Ml of water would be stored if Culm was restored to 1990 levels (an increase of 41 ML or 114 %); whilst restoration to a 1900 scenario level would lead to a storage of 2245 ML (an increase of 1946 ML). As illustrated in Figure 5.3, the current extent of the Culm NCA only covers a relatively small area of the Exe catchment. Estimations of the volume of water storage under current and hypothetical past extents and restoration scenarios would undoubtedly increase if analysis was extended to consider Culm or similar unimproved wet grasslands throughout the entire Exe catchment. Under a hypothetical scenario if the 1900 coverage of Culm within the Exe component of the Culm NCA (1.2 %) was extended across the entire Exe catchment (153000 ha), there would be estimated water storage of 4552 Ml of water in Culm soils.

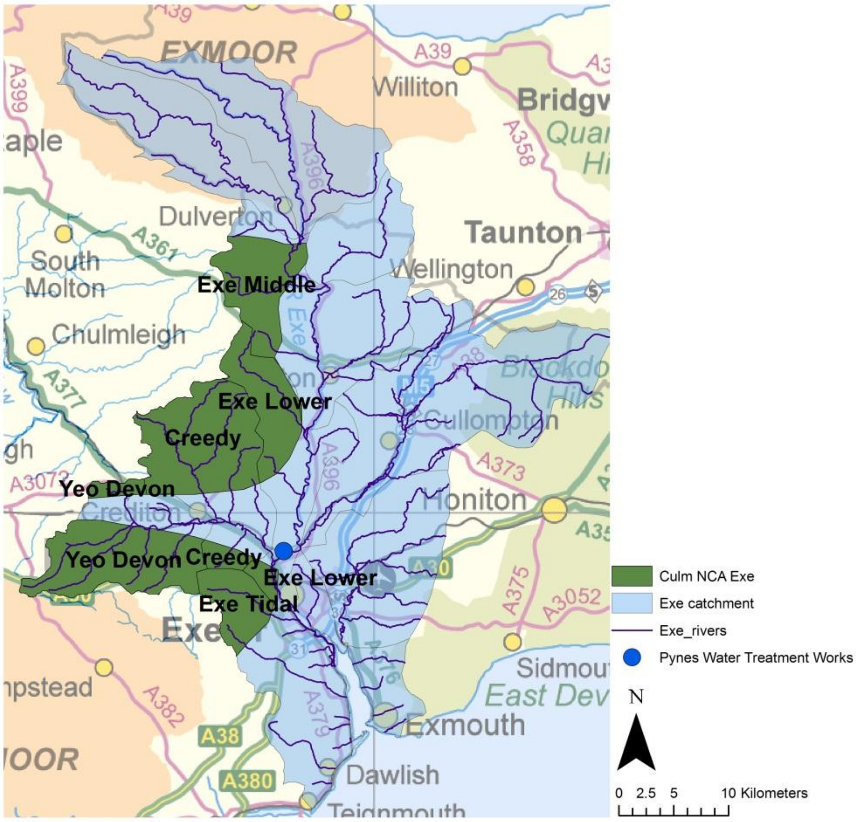

Figure 5.3. Exe catchment within Devon and area covered by the Culm NCA.

In the Tamar (Figure 5.4.) encompassing Devon sections of the Upper Tamar; Middle Tamar; Lower Tamar; Deer and Claw; Carey; Thrushel and Wolf; Lyd; it is estimated that a total of 1776 ML of water would be stored if Culm was restored to 1990 levels (an increase of 156 Ml or 110 %); whilst restoration to a 1900 scenario level would lead to a storage of 12171 ML (an increase of 10551 ML). Values presented herein only cover Devon sections of the Tamar for which DWT and DBRC Culm records are available. Water storage in Culm grasslands, within the Tamar catchment would undoubtedly increase, if information for Culm or wet unimproved grasslands was available for Cornwall; this is particularly the case in the Upper and Middle Tamar where the river running through the centre of the catchment forms the boundary between Devon and Cornwall. It is believed water storage estimations for these catchments (both current and under potential restoration scenarios) could be approximately double that reported, if Culm in Cornwall was also accounted for.

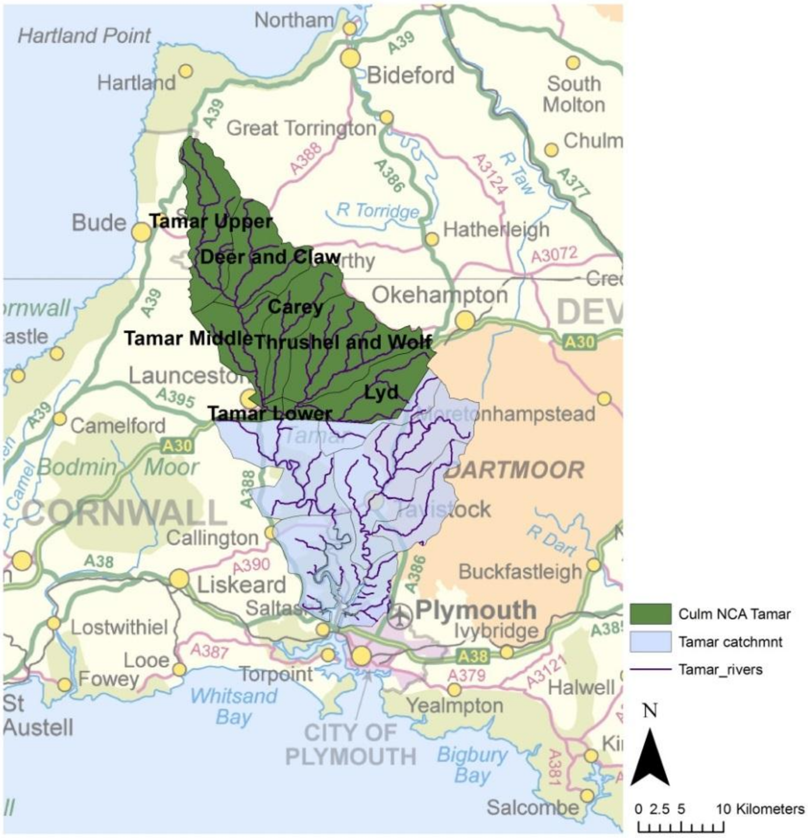

Figure 5.4. Tamar catchment within Devon and area covered by the Culm NCA.

For certain sections of the Tamar catchment situated within the Culm NCA, detailed land use surveys carried out, or commissioned by Devon Wildlife Trust allow for a much more detailed understanding of the previous extent of Culm.

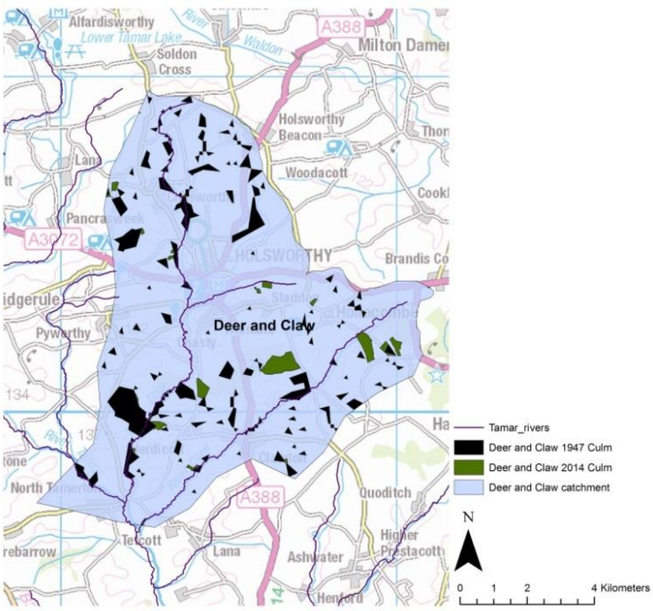

Figure 5.5. 2014 and 1947 coverage of Culm grassland within the Deer and claw sub-catchment of the Tamar.

In the Deer and Claw, a sub-catchment of the Tamar, analysis of aerial photography shows the extent of Culm grasslands in 1947 and that still remaining today (Figure 5.5.). The loss of Culm grassland, in this case to IMG since 1947, reflects the influence of post-war policy land use policy changes favouring drainage and agricultural intensification. In the Deer and Claw, the coverage of Culm grassland has reduced from 622 hectares or 7.8 % of the catchment in 1947 to 148 ha or 1.9 % in 2014; equating to a 418 % reduction. In the Deer and Claw if Culm grassland was restored to 1947 levels this would result in an estimated 1493 ± 444 Ml of water, up from a current 356 ± 106 Ml stored within Culm grasslands.

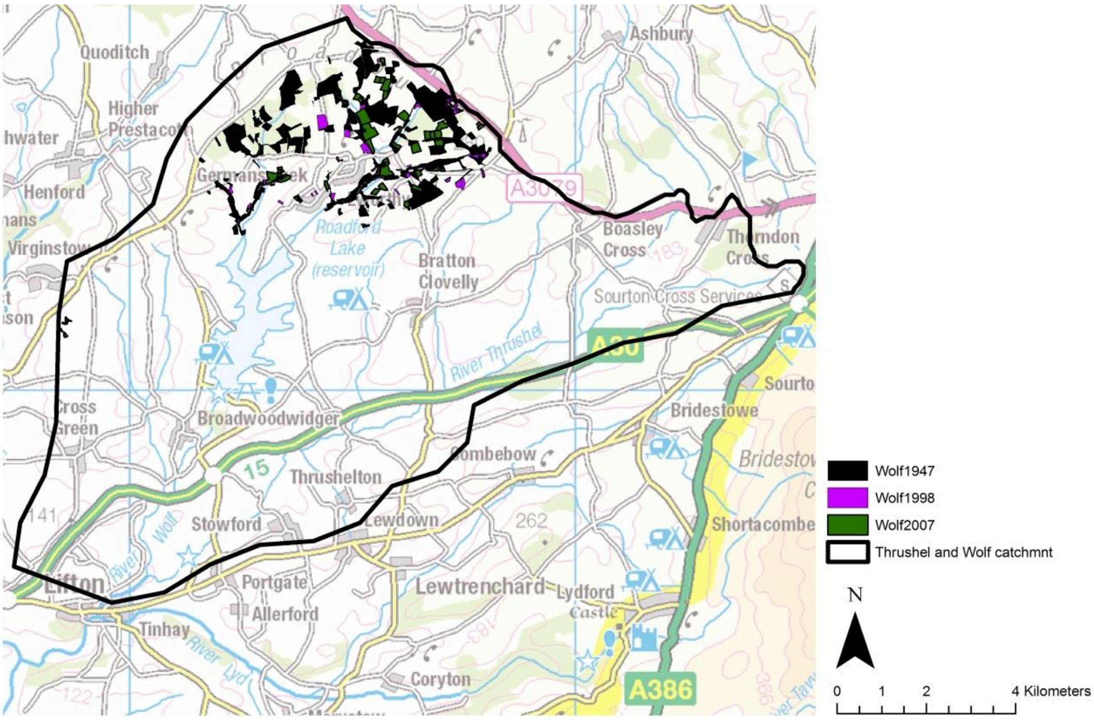

Figure 5.6. 2007,1998 and 1947 coverage of Culm grassland within the Wolf catchment, upstream of Roadford reservoir.

The upper Wolf sub-catchment, within the Tamar, drains directly into Roadford reservoir (Figure 5.6.), a South West Water managed reservoir which supplies North Devon, via treatment works near Okehampton and also releases into the river Tamar, for abstraction at Gunnislake to supply Plymouth and parts of South Devon. As such, any land use in this area and the concomitant change in hydrological functioning have the potential to directly influence water resource management. Analysis of aerial photos, commissioned by the Devon Wildlife Trust, surveyed land use/cover between 1947, 1998 and most recently 2007. As illustrated in Figure 8, there has been a notable reduction in the area of land classified by the survey as unimproved Culm grassland since 1947. In 1947, 455 ha of land were Culm, compared to 132 ha in the 2007 survey, a reduction of 323 ha. However, interestingly, between 1998 (124 ha of Culm) and 2007, some areas of the upper Wolf, showed an increase in unimproved Culm, with an overall increase of ca. 8 ha, indicating that some areas of IMG, had either been actively restored or abandoned and reverted to Culm. Whilst more detailed surveying and ground truthing would be required to verify these findings, they point to the potential for more widespread reversal to Culm grassland if deemed advantageous. In the area of the Wolf, above Roadford reservoir, if the level of Culm was restored to 1947 levels (an increase of 345%) estimated mean water storage in Culm soils would increase from 316.5 ± 94 Ml, to 1093 ± 325 Ml.

An increase in Culm grassland, in the upper Wolf and other scenarios considered above will not only impact upon the quantity of water being stored in these landscapes, but also the quantity and rate at which it is entering the river network, in addition to the quality of this water. Using data from the monitoring of water volumes in Culm and IMG, as well as the hydrological functioning and water quality of a Culm dominated catchment, the implications of the current and increased Culm grassland will be considered.

5.2. Influence of Culm grasslands upon stormflow

Results from storm event monitoring showed that the channel leaving the Culm dominated, Stowford Moor sub-catchment (20 ha) showed a relatively weak relationship with rainfall and antecedent soil water levels. Additionally, event monitoring at Stowford Moor showed low runoff coefficients (the amount of runoff, monitored at the catchment outlet, relative to rainfall received). Stowford Moor had an average runoff coefficient of only ca. 1 % (mean 0.96; median 0.90; standard deviation 0.45) from events monitored with a range of 0.25 – 1.88 %. Clearly, values recorded at Stowford Moor only represent a snapshot, as hydrological response will vary across Culm sites, depending on site characteristics such as topography, size soil and vegetation; in addition to antecedent conditions. However, the low runoff coefficients presented, further reinforce the conclusion that Culm grasslands have a high water holding capacity and low hydrological connectivity, therefore showing an attenuated response to rainfall and a slow release of water, with important implications for downstream flood risk.

The runoff coefficients observed at Stowford are notably lower than those recorded in studies of IMG within SW England. From the high temporal monitoring of an intensely managed grassland catchment (Denbrook a first order, catchment in Devon situated on HOST 24 soil), during a summer storm, Granger et al (2010), observed a catchment runoff coefficient of 17 %; whilst from the monitoring of 18 events in the Aller catchment (an agriculturally dominated catchment, located on the north-east edge of the Exmoor National Park) observed a median runoff coefficient of 12 % (Glendell *et al*, 2014) and for intensively managed grassland fields at the North Wyke farm platform (an instrumented farm scale experiment, comprising 68.4 ha in total on which the dominant land use is currently IMG) observed mean runoff coefficients of between 9 and 14 % (Eludoyin, 2014).

Together, the quoted studies in IMG in SW England give a mean runoff coefficient of 11 %. As with water storage results, showing Culm can store 4 times as much water as IMG, these runoff coefficient values can be used to make extrapolations to speculate on the value of the current Culm resource and hypothesise about the potential impact of restoration scenarios. At the most basic level the rainfall-runoff relationships observed during monitoring in this study; with reference to other studies indicate that following rainfall, in-channel storm flow will be 11 times less than that from an intensively managed grassland catchment.

Taking the mean runoff coefficients, if a 20 mm rainfall event was to occur at Stowford Moor (assuming an even spatial distribution of rainfall across the catchment), this would be expected to result in a total stormflow discharge in the region of 0.04 ML or 40 m^3. By contrast, hypothetically, if such an event was to occur on an intensively managed grassland catchment of the same size, the mean runoff coefficient would suggest a stormflow discharge of around 440 m^3.

Rainfall is highly variable, both spatially and temporally, and as already noted, whether or not rainfall results in runoff and consequently, both runoff and in-channel stormflow will be dependent on a range of site specific and antecedent conditions. However, to illustrate the potential implications of Culm restoration, upon in-channel stormflow response, scenarios from the Exe and the Tamar are considered assuming a uniform spatial distribution of rainfall and a uniform runoff response (i.e. a Culm runoff coefficient of 1 % and IMG runoff coefficient of 11 %).

In the areas of the Exe lying within the Culm NCA, DBRC Culm grassland currently covers 124 ha, down from 142 ha in 1990 and an estimated 935 ha in 1900. Assuming the mean runoff coefficient recorded from Stowford, an evenly distributed rainfall event across the Culm sites is estimated to result in a stormflow discharge in the region of 2480 m^3 into the Exe. Whilst an increase in Culm grassland coverage under any restoration scenarios would result in an increase in discharge from Culm, assuming this is a change from IMG, the net catchment scale response will be a major reduction in water rapidly leaving the land and entering channels, predominately upstream of the city of Exeter immediately following rainfall. Again assuming a 20 mm rainfall-runoff event, it is estimated that the restoration of intensively managed grassland to 1990 levels of Culm could result in a 560 m^3 less water entering the channel, whilst restoration to 1900 levels would result in a 20230 m^3 reduction.

In the Upper Wolf a sub-catchment of the Tamar, Culm currently covers approximately 132 ha, which upon receipt of a 20 mm rainfall-runoff event would be expected to result in a stormflow discharge of 264 m^3 of water into the Wolf River, above Roadford reservoir. However, as in the Exe, there has been a significant reduction in Culm, as a result of agricultural intensification. The restoration of Culm to 1947 levels (455 ha) could result in a net catchment reduction of around 7325 m^3 to the total amount of water entering the channel as stormflow (from a 20 mm event). The Upper Wolf catchment, supplies Roadford reservoir with an estimated 3000 Ml (million litres) of water per year. If the area of Culm grassland were restored to 1947 levels, (from 132 ha currently to 453 ha) then the annual amount of water leaving the catchment would be significantly reduced, to 2600 Ml (i.e. a 15 % reduction). Critically, all of this storage increase would occur in the wet winter months, reducing the risk of flooding, with a predicted decrease in storage during drought periods as more water would be released to the reservoir maintain water levels when they are most needed.

The Culm NCA, receive a long term (40 year) average of 1200 mm per year. Whether this results in stormflow is highly dependent on event and antecedent conditions. However, the hypothetical scenarios presented here, indicate that the amount of this rainfall entering river networks as stormflow is significantly reduced in Culm grassland relative to IMG. Thus, the careful management and restoration of the Culm grassland resource could play an important role in mitigating the negative effects of storm events that have caused significant socio-economic damage in South West England in recent years.

5.3. Influence of Culm grasslands upon water quality

Water quality was monitored for water leaving a Culm dominated catchment. As with water quantity, comparisons will be made with studies conducted in IMG in Devon (the Aller and Denbrook catchments). Median water quality concentrations for the Aller agriculturally dominated catchment and Stowford Moor Culm dominated catchment are presented in Table 5.1. The Aller revealed higher concentrations of nitrogen, phosphorus and suspended sediment compared to Stowford Moor suggesting greater diffuse water pollution from agricultural inputs. These results illustrate that the interaction between hydrology and land use exerts a key control over water quality. Median values suggest the Culm dominated catchment showed a more moderate response when compared with the Aller, which has a lower response threshold to hydrological drivers (Glendell et al, 2014). In contrast to the other water quality concentrations examined, dissolved organic carbon was notably higher at Stowford Moor, with median concentrations over twice as high for the storm events monitored, perhaps indicating the greater availability of organic material and higher decomposition rates, compared to intensively managed grasslands.

	Water quality concentration median values			
Site	DOC (mg l^{-1})	TON (mg l^{-1})	P (µg l^{-1})	SS (mg l^{-1})
Stowford Moor Catchment	10.8	2.7	30.0	24.0
Aller Agriculture Catchment*	5.0	9.5	45.0	77.9

*Summary values taken for all storm flow samples collected between July 2010 and January 2013 at the Aller catchment outlet (Glendell, 2013).

Table 5.1. Water quality concentration median values (DOC = dissolved organic carbon; TON = total oxidised nitrogen; P = phosphorus and SS = suspended sediment) for the Aller and Stowford Moor catchments.

Results from storm flow concentration ranges for monitored events at Stowford Moor are compared with ranges from the monitoring of a storm event at Den Brook are presented in Table 5.2. For all water quality variables presented, both the maximum and minimum concentrations recorded were greater for Den Brook. In another study (Bilotta et al, 2010), concentrations of SS recorded in the first-order channel at Den Brook, had a peak of 1140 mg l^{-1} and a mean concentration of 65 ± 12 mg l^{-1}. In contrast events monitored at Stowford, showed a mean SS concentration of 51.55 ± 69.11 mg l^{-1} with a maximum recorded concentration of 410 mg l^{-1}.

	Storm Flow Concentration Ranges		
Site	DOC (mg l^{-1})	P (µg l^{-1})	SS (mg l^{-1})
Stowford Moor Catchment	4-26	0-398	6-410
Den Brook Agricultural Catchment*	9-248	90-5870	20-925

*Granger et al (2010) Water, Air and Soil Pollution

Table 5.2. Comparison of water quality storm flow concentration ranges (DOC = dissolved organic carbon; P = phosphorous and SS = suspended sediment) from all events monitored at Stowford moor and high resolution temporal monitoring of a storm event at Den Brook.

Comparisons with examples from the Aller and Denbrook intensively managed agricultural catchments demonstrate that in terms of concentrations of nitrogen, phosphorus and suspended sediment, water leaving a Culm catchment was cleaner than that leaving intensively managed grassland. However, monitored concentrations of sediment and nutrients are only part of the story. As noted, Culm grasslands also lose less water than their intensively managed counterparts during storms, resulting in lower event and annual loads, entering river networks. Nutrient concentrations and loads are known to alter within and between events, being influenced by rainfall-runoff event characteristics, antecedent and seasonal conditions, in addition to land management practices (i.e. grazing patterns). However, even summary mean values can be used to illustrate the potential differences between land uses and consequences of restoration strategies.

It has been estimated that intensively managed grasslands lose around 11 times more water as storm flow than Culm grasslands, which will multiply with water quality variable concentrations to determine the amount of sediment and nutrients entering channels. If comparing median values to the Aller intensively managed agricultural catchment (Table 1), total oxidised nitrogen concentrations are approximately 4 times those from Culm, phosphorus concentrations 2 times and suspended sediment 3 times greater than Culm, although DOC concentrations are half. Therefore, for example it could be hypothesised that a rainfall event of the same size would result in a suspended sediment event yield 33 times greater from an IMG, than a Culm-dominated catchment.

For example, if Culm was restored to 1947 levels, simple extrapolations indicate it is estimated that soil erosion annually results in 230 tonnes of sediment entering Roadford Lake reservoir. If Culm was restored to 1947 levels we predict an average reduction of sediment entering the reservoir of ca. 30 tonnes (i.e. a 16 % reduction) over the year. Over time such a reduction in sediment levels would have a valuable impact, reducing sedimentation risk to the reservoir and minimising costs of dredging, whilst similar reductions in nitrogen and phosphorus loss would reduce the risk of eutrophication and the necessary cost of water treatment.

As has been discussed previously (Brazier et al, 2007), results from agriculturally dominated catchments, such as Den Brook and the Aller demonstrate that intensively managed lowland grasslands, may be contributing significantly to sediment and nutrient budgets in rivers. In contrast, results from Stowford Moor indicate that unimproved, semi-natural, wet grasslands such as Culm, not only exhibit an attenuated hydrological response to rainfall, but also lower levels of erosion and nutrient loss. Consequently, event and annual sediment and nutrient losses to connected channels will be significantly greater from intensively managed grassland than Culm, with potentially important environmental and economic implications.

Catchment	Area of Catchment (ha)	Area Culm (ha)			Culm % Catchment Coverage			Mean Water Storage (Ml)						Carbon Storage (t)					
		2014	1990	1900	2014	1990	1900	2014	±SD	1990	±SD	1900	±SD	2014	±SD	1990	±SD	1900	±SD
Batherm	6550.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bray	11076.8	4.9	4.9	36.8	0.0	0.0	0.3	11.8	3.5	11.8	3.5	88.4	26.3	892.8	208.8	892.8	208.8	6708.8	1569.1
Carey	6602.9	82.0	108.3	616.1	1.2	1.6	9.3	196.9	58.6	260.1	77.4	1479.8	440.5	14941.4	3494.7	19733.6	4615.5	112269.9	26259.1
Creedy	13900.0	7.6	8.7	57.1	0.1	0.1	0.4	18.3	5.4	20.9	6.2	137.2	40.8	1384.8	323.9	1585.2	370.8	10405.5	2433.8
Deer and Claw	7920.5	148.4	159.5	1115.1	1.9	2.0	14.1	356.4	106.1	383.1	114.0	2678.2	797.2	27040.3	6324.5	29062.9	6797.6	203181.1	47522.6
Exe Lower	11521.4	8.2	8.2	61.6	0.1	0.1	0.5	19.7	5.9	19.7	5.9	148.0	44.1	1494.1	349.5	1494.1	349.5	11227.0	2625.9
Exe Middle	18410.0	84.3	100.4	633.4	0.5	0.5	3.4	202.5	60.3	241.1	71.8	1521.4	452.9	15360.5	3592.7	18294.1	4278.9	115418.9	26995.7
Exe Tidal	19449.2	7.8	7.8	58.6	0.0	0.0	0.3	18.7	5.6	18.7	5.6	140.8	41.9	1421.3	332.4	1421.3	332.4	10679.3	2497.8
Hartland Clovelly	6996.6	44.3	44.3	332.9	0.6	0.6	4.8	106.4	31.7	106.4	31.7	799.5	238.0	8072.0	1888.0	8072.0	1888.0	60653.1	14186.3
Little Dart	12690.3	521.9	538.5	3921.6	4.1	4.2	30.9	1253.5	373.1	1293.4	385.0	9418.7	2803.8	95096.6	22242.4	98121.3	22949.9	714556.9	167129.8
Lyd	11066.5	38.0	38.0	285.5	0.3	0.3	2.6	91.3	27.2	91.3	27.2	685.8	204.1	6924.1	1619.5	6924.1	1619.5	52027.5	12168.9
Mole Devon	24345.8	248.0	255.6	1863.5	1.0	1.0	7.7	595.6	177.3	613.9	182.7	4475.6	1332.3	45188.7	10569.3	46573.5	10893.2	339548.0	79417.9
Okement	14603.3	176.3	205.6	1324.7	1.2	1.4	9.1	423.4	126.0	493.8	147.0	3181.7	947.1	32124.0	7513.6	37462.9	8762.3	241380.3	56457.1
Strat and Neot	13643.4	5.1	5.1	38.3	0.0	0.0	0.3	12.2	3.6	12.2	3.6	92.0	27.4	929.3	217.4	929.3	217.4	6982.6	1633.2
Tamar Lower	12151.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tamar Middle	6199.1	32.7	49.5	245.7	0.5	0.8	4.0	78.5	23.4	118.9	35.4	590.1	175.7	5958.3	1393.6	9019.5	2109.6	44771.0	10471.6
Tamar Upper	9383.8	139.5	139.9	1048.2	1.5	1.5	11.2	335.0	99.7	336.0	100.0	2517.5	749.4	25418.6	5945.2	25491.5	5962.3	190995.7	44672.6
Taw Middle	20835.0	84.2	89.9	632.7	0.4	0.4	3.0	202.2	60.2	215.9	64.3	1519.5	452.3	15342.3	3588.5	16380.9	3831.4	115282.0	26963.6
Taw Upper	9941.5	87.0	112.0	653.7	0.9	1.1	6.6	209.0	62.2	269.0	80.1	1570.1	467.4	15852.5	3707.8	20407.8	4773.2	119115.6	27860.3
Taw Estuary	24465.4	0.7	0.7	5.3	0.0	0.0	0.0	1.7	0.5	1.7	0.5	12.6	3.8	127.5	29.8	127.5	29.8	958.4	224.2
Teign Upper	24785.1	15.7	15.7	118.0	0.1	0.1	0.5	37.7	11.2	37.7	11.2	283.3	84.3	2860.7	669.1	2860.7	669.1	21495.6	5027.7
Thrushel and Wolf	11500.6	233.8	244.1	1756.8	2.0	2.1	15.3	561.5	167.2	586.3	174.5	4219.4	1256.0	42601.2	9964.1	44478.0	10403.1	320106.1	74870.6
Torridge Middle	18372.8	159.4	162.4	1197.7	0.9	0.9	6.5	382.8	114.0	390.0	116.1	2876.7	856.3	29044.6	6793.3	29591.3	6921.2	218241.7	51045.2
Torridge Tidal	12777.9	18.4	21.8	138.3	0.1	0.2	1.1	44.2	13.2	52.4	15.6	332.1	98.8	3352.7	784.2	3972.2	929.1	25192.3	5892.3
Torridge Upper	37438.8	1594.3	1694.5	11979.1	4.3	4.5	32.0	3829.1	1139.9	4069.8	1211.5	28771.0	8564.6	290501.1	67946.2	308758.8	72216.5	2182737.0	510526.7
Yeo Devon	12183.4	16.5	16.5	124.0	0.1	0.1	1.0	39.6	11.8	39.6	11.8	297.8	88.6	3006.5	703.2	3006.5	703.2	22590.9	5283.9
Yeo Devon and Dalch	14279.3	167.2	175.7	1255.3	1.2	1.2	8.8	401.6	119.5	422.0	125.6	3015.0	897.5	30465.9	7125.8	32014.7	7488.0	228738.9	53500.4
Total		3926.2	4207.6	29500.0				9429.8	2807.1	10105.7	3008.3	70852.1	21091.5	715402.1	167327.5	766676.6	179320.2	5375264.4	1257236.2

Table 5.3. Extrapolation calculations (for Culm NCA and per catchment) showing current culm coverage (% of catchment), area of Culm grassland (ha) under each scenario in addition to water and carbon storage estimates and associated standard deviation values.

6. Summary and conclusion

Sections 2-5 of this report presented results from field, laboratory and extrapolation modelling analysis aimed at developing understanding of the hydrological functioning, soil and water resource characteristics of Culm grasslands and how these relate to other monitored land uses and covers (intensively managed grassland, invasive scrubland and wet woodland). Section 6.1. summarises and discusses presented results in relation to the key objectives identified in section 1.1. whilst section 6.2. provides a brief conclusion to the report.

6.1. Summary

Objective 1: Characterise the physical and chemical properties of Culm grassland soils and whether these vary in relation to that of other land uses and covers.

It is recognised that soils play a central role in the provision of ecosystem services (Haygarth and Ritz, 2009, Horrocks et al, 2014). To gain a baseline understanding of Culm soils, characterisation sampling was undertaken to quantify the spatial variability of physical and chemical soil characteristics, between and within the monitored sites (encompassing: Culm grassland on three key soil types, intensively managed grassland, invasive scrubland and wet woodland). Monitored Culm grasslands had higher mean carbon and nitrogen concentrations (13.3 ± 4.4 % and 0.9 ± 0.2% respectively) than intensively managed grasslands (8.8 ± 2.1 % and 0.65 ± 0. 2%), but showed no significant difference with scrub or woodland soils. Phosphorus levels were found to be significantly higher ($p<0.05$) at the intensively managed grassland site (1277.63 ± 174.52 µg g^{-1}) than Culm, scrub or woodland sites. Physically, compared to intensively managed grassland soils, Culm soils were significantly ($p<0.05$) deeper, had a lower bulk density, higher soil moisture and higher organic matter content. Generally soils under Culm and invasive scrub showed only minor differences indicating a lagged response in soil characteristics to woody encroachment. Wet woodland soils showed the greatest spatial heterogeneity within site, whilst IMG soils showed notably less variation than other land uses suggesting agricultural improvement or intensification of grasslands results in homogenisation. Carbon concentrations, combined with physical characteristics indicate that Culm soils, whilst less dense will store more carbon in topsoil than intensively managed grassland of the same soil type due to their greater depth (mean 1.8 ± 0.6 g cm^{-2} to topsoil depth in Culm and 1.5 g ± 0.35 cm^{-2} in intensively managed grassland).

Objective 2: Quantify the water retention capacity of Culm grassland in relation to that of other land uses and land covers.

To increase understanding of hydrological function in Culm grassland relative to other land uses, the experimental framework allowed for near continuous measurement of soil water levels across the monitoring sites, via instrumented dipwells, connected to a telemetry network. Results are presented, monitoring water levels from when the monitoring sites were instrumented in October 2012, to January 2014. Across all sites water level showed notable variation over time, being lower in the dry season of the hydrological year (1st of April to 30th of September) and higher during the wet season (1st of October to 31st of March). However, on average water levels were consistently higher under Culm grassland (0.07 ± 0.01 m below surface) and lowest in intensively managed grassland (0.16 ± 0.08 m below surface). Combined with soil characteristics (depth and soil moisture), results suggested that Culm soils store more water than intensively managed grasslands, in addition to scrub and woodland. As with depth below surface, water stored in soils varied over time but mean estimates for Culm grassland (241.27 ± 75.46 l m^2 surface area) were, significantly higher than in intensively managed grassland (61.63 ± 45.27 l m^2 surface area). Results showing the high water holding capacity of Culm grasslands have important implications for understanding the role they can play in the sustainable management of water resources, notably, reducing flooding risk and maintaining supply.

Objective 3: Quantify the hydrological functioning and water quality of a Culm dominated catchment.

This project also involved the monitoring of in channel hydrological behaviour and water quality in a Culm dominated catchment. At Stowford Moor, an instrumented flume was used to quantify channel discharge throughout the monitoring period and collect samples for water quality analysis throughout storm events. Results from a total of 11 storm events were presented to provide baseline understanding. As may be expected channel discharge at Stowford Moor, showed a significant positive relationship (p<0.05), both to rainfall and antecedent soil water levels. However, the relatively weak nature of these relationships, suggests that Culm dominated catchments, due to their high water holding capacity have low hydrological connectivity, consequently showing a relatively attenuated channel response. Water quality samples were analysed for dissolved organic carbon (mean 9.91 ± 3.18 mg l^{-1}); total oxidised nitrogen (mean 3.45 ± 2.64 mg l^{-1}); phosphorous (mean 66.84 ± 71.15 µg l^{-1}); suspended sediment (mean 51.55 ± 69.11 mg l^{-1}); potassium (mean 1.72 ± 0.50 mg l^{-1}); colour (mean 54.12 ± 11.26 mg l^{-1}) and pH (mean 6.28 ± 0.32). Comparisons with studies conducted in intensively managed, agriculturally dominated catchments, indicated that the Culm dominated catchment showed considerably less evidence of diffuse water pollution.

Objective 4: Extrapolate field based monitoring to quantify the water and soil resource storage potential of Culm across the Culm NCA.

It was proposed that Culm grasslands can play an important role in the sustainable management of water resources, the improvement or maintenance of water quality to meet environmental objectives and carbon storage. This is supported by the collection of baseline and characterisation data collected and presented within this study and addressed under objective 1-3. Extrapolating field based understanding to the entire Culm NCA, whilst involving a high degree of uncertainty; helps get an understanding of the magnitude and value of the existing water and soil resources provided by Culm grasslands. Calculations based upon mean water storage and carbon per surface area based on field monitoring, were combined with the existing area of Culm grassland gave mean estimations of 9429.8 ± 2807 Ml of water and 715402.1 ± 167327.4 t of carbon in Culm soils within the Culm NCA. GIS analysis showed that ca. 40 % of the current coverage of Culm grassland is located within the Upper Torridge catchment and accordingly this is where extrapolation figures show the majority of water and soil resources to be with values of 3829 ± 1140 Ml of water and 290501 ± 67946 t of carbon.

It has been identified that the coverage of Culm grassland resources in SW England have become highly fragmented and drastically reduced, compared to their previous extent. GIS analysis showed DBRC inventory Culm grassland sites in the Culm NCA now cover ca 3926 ha, compared to a former estimated extent of 29,500 ha in 1900 (Hughes 1997). This loss is predominantly believed to be due to agricultural improvement, but also as a result of afforestation and scrub invasion (van Soest, 2002, Hughes 1997). Thus, it can be hypothesised that if the area of Culm grassland was increased the provision of associated ecosystem services would also increase. Consequently, as with other landscape restoration in that may increase water holding capacity (Grand-Clement et al, 2013) there is a high degree of interest in restoring Culm grassland, whether by the removal of invasive scrub, or reverting intensively managed grassland back to Culm (Tinch et al, 2012). Previous extents of Culm grassland, within the Culm NCA (1990 and 1900) were combined with mean water and carbon storage estimations to create hypothetical extrapolation scenarios. Results suggested that if Culm within the Culm NCA was restored to 1990 levels (an increase of 281 ha) extrapolations indicate there would be potential for storage of 10106.0 ± 3008.3 Ml of water and 766677.0 ± 179320.2 t of carbon (107 %). If Culm was increased to the 1900 scenario (an increase of 25,574 ha) extrapolations indicate there would be potential for storage of 70852.0 ± 21091.5 Ml of water and 5375264.0 ± 125723.2 t of carbon (751 %). As well as storing more water, Culm grasslands release it more slowly. Modelling scenarios suggest that, compared to Culm grasslands, 11 times more water, rapidly leaves intensively managed grasslands, during storms, significantly increasing the risk of flooding downstream. The recreation of Culm also promises significant benefits for the water quality of south west rivers. Monitoring of Culm showed there not only to be a reduction in storm flow, but also a reduction in suspended sediment (3 times greater in IMG comparison), oxidised nitrogen (4 times greater in IMG comparison) and phosphorus concentrations (2 times greater in IMG comparison). Combined, flow and nutrient concentrations and modelling scenarios indicate that event and annual sediment and nutrient yields could be much reduced, if the coverage of Culm was increased.

6.2. Conclusions and need for further research

Research undertaken for the Culm Proof of Concept study has demonstrated a notable difference in the hydrological functioning, soil resources and water quality of unimproved Culm grasslands, relative to other land uses, in particular intensively managed, agricultural grasslands. Results from the monitoring work, indicate that unimproved Culm grassland soils can store up to five times more water than intensively managed grasslands and up to twice as much carbon compared to intensively managed grassland soils. Culm grasslands also exhibit much lower runoff coefficients than intensively managed grasslands, resulting in a much more attenuated response to rainfall and a notable reduction in water rapidly entering channels immediately following storm events.

In addition to changes in the quantity of water stored and entering channels, water leaving Culm grasslands yield high water quality, which is significantly better than intensively managed grasslands in terms of nitrogen, phosphorus and suspended sediment levels. It is already known that Culm grasslands provide significant value in areas such as biodiversity, with for example, Culm supporting one of the ten most endangered species in the EU (The Marsh Fritillary butterfly). This study highlights the previously overlooked role that Culm grasslands can play in the provision of key ecosystem services; storing and slowly releasing water, reducing the risk of downstream flooding and maintaining a sustainable water supply; storing high levels of carbon and providing clean water downstream.

This document extrapolates field monitoring to the landscape scale. Whilst there is a high degree of uncertainty in such studies, the hypothetical scenarios presented herein highlight both the current and the potential value of the Culm resource. Furthermore, due to policy and land use changes, the current Culm grassland resource is highly fragmented, with approximately only 10 % of the 1900 resource remaining. It is suggested that the restoration and reconnection of Culm grasslands to their previous spatial extent (or more) would significantly enhance the provision of key ecosystem services. Results from research presented in this study offer farmers, landowners and policy makers a way forward to manage land for multiple benefits to society.

Whilst results from field monitoring provide a strong baseline understanding of the soil properties, resources and hydrological functioning of Culm grasslands and extrapolation scenarios indicate their current and potential value. Recreation of Culm grasslands on catchment scales could be beneficial as a strategic, soft-engineering management strategy, reducing the risk of flooding whilst simultaneously increasing the sustainability of our water supply. further research is required to: (1) identify where in the Culm NCA and wider SW England, restoration to Culm grassland (from intensively managed grassland or invasive scrubland) would be most effective (2) monitor the effectiveness of proposed and currently occurring restoration work (3) quantify and monetise the value of ecosystem services provide by Culm, to inform policy and land/water management decisions and in relation to existing or proposed payment and incentive frameworks.

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