Understanding aquatic carbon loss from upland catchments in south west Scotland during land use change from commercial forest to wind farm

Melanie van Niekerk

2012

Submitted to the School of Natural Sciences
Biological and Environmental Science
University of Stirling
Scotland

For the degree of Doctor of Philosophy

Supervisor:
Prof David Gilvear

UNIVERSITY OF STIRLING

Acknowledgements

I would like to thank my supervisor, Professor Dave Gilvear for his expertise, support, advice and fieldwork assistance during the course of this PhD.

This research has been funded jointly by the University of Stirling and Scottish Power Renewables (SPR).

I am grateful to Stuart Bradley for his company during many field trips, his technical assistance and his impeccable taste in music.

Thanks also to Ronnie Balfour and James Weir for technical assistance, Helen Ewan and Lorna English for their patience and laboratory support, Jon McArthur for all matters concerning GIS and Scott Jackson and Bill Jamieson for IT and graphics support respectively.

I appreciate the practical assistance of SPR, especially Stephen Ward and Gerry Gibson as well as Adam Anderson of RPS, who all readily gave their time and provided data and records that have enriched this research.

My thanks also go to SEPA for providing the rainfall data used in this study

Jeff, thanks for your friendship and support, this will be you soon.

Abstract

High concentrations and fluxes of dissolved organic carbon (DOC) in fluvial systems are associated with the dark brown water colour familiar in many upland, peat-dominated areas and may indicate a depletion of the terrestrial carbon store. The removal of this colour can also be problematic and expensive for water companies as well as affecting the ecological functioning of the water body through factors such as reduced light penetration through the water column. Disturbance resulting from activities such as land use change can also enhance the loss of carbon and this may manifest itself in elevated concentrations and fluxes of DOC from aquatic systems.

This thesis describes and explains patterns of change in DOC quantity and quality from the Crosswater, Crosswater of Luce and Tig catchments draining Arecleoch Forest, a peatland in south Ayrshire, Scotland, from 2008 to 2010. This time period incorporates the installation of a 60-turbine wind farm built and operated by Scottish Power Renewables (SPR).

Water samples were collected from Arecleoch at different spatial scales ranging from catchments to soil pore water and temporal scales ranging from daily to seasonally. Concentrations of DOC were measured and fluxes estimated at the catchment scale. DOC concentrations from all three catchments exhibited the well-established seasonal pattern with maxima in late August/early September and minima seen in February/March. The Tig catchment experienced the greatest burden of disturbance from the wind farm development and returned the highest DOC concentrations and fluxes. The Crosswater catchment, used as a control site due to its isolation from wind farm activities, had higher DOC concentrations than the Crosswater of Luce throughout the monitoring period possibly due to a greater proportion of forest cover.

DOC flux ranged from 35.0 g C m^{-2} yr^{-1} from the Crosswater of Luce catchment in 2008 to 55.0 g C m^{-2} yr^{-1} from the Crosswater in 2009. The Tig catchment was not monitored for the whole period but returned the highest DOC fluxes of the three catchments between January and June 2010 (15.7 g C m^{-2}). These values are considered high for UK peatlands. It is possible to make a tentative estimate of an extra 12 g C m^{-2} being exported from the Crosswater of Luce in 2009 that may have been a result of wind farm and/or forestry activities in the catchment.

At the sub-catchment scale, "hot spots" of high DOC concentrations (up to 113.4 mg L^{-1}) were found during the final survey of headwater streams inside the development area of the wind farm site during construction in August 2010. Further surveys are recommended to assess whether DOC concentrations have decreased since completion of the wind farm. Daily water samples were collected upstream and downstream of turbine 33 during the excavation of the turbine base. DOC concentrations were higher downstream before work began on the turbine base and although the gap between upstream and downstream DOC concentrations increased over the monitoring period, statistical comparisons of these differences before and after the start of excavation work were not significant at the 95 % confidence level.

Challenges arose from the practicability of conducting robust research on a construction site and novel approaches to monitoring DOC were developed. Activity scores were used to quantify the effect of peatland disturbance on DOC concentrations at the catchment scale. The results suggest that this approach may have merit but requires comprehensive site records from the developer. The non-linear nature of the individual wind farm development and forestry activities made it impractical to disentangle the impact of each, particularly for forest harvesting.

Activity scores could, together with other information gathered from site records, be useful to developers as an indicator of the most likely periods for peat disturbance. Knowledge of the differing disturbance potential of the various activities could also provide useful information to feed into the carbon payback calculator.

DOC quality was explored using ultraviolet (UV) absorbance, specific UV absorbance (SUVA) and E4/E6 ratios. The latter metric identified changes in the composition of DOC related to disturbance with water samples from areas draining land subject to disturbance having lower E4/E6 ratios indicating a greater degree of humification of the DOC.

This research provides one of only three studies to investigate concentrations and fluxes of DOC in water courses draining land subject to disturbance relating to wind farm construction. It is the only study that incorporates a period of time prior to work beginning and takes in the whole of the development phase. In this respect it provides a valuable addition to our understanding of the way in which peatlands respond to land use change and may provide useful tools to assist developers in minimising the impact of their activities on these valuable carbon stores.

List of Contents

List of Figures

List of Tables

Introduction

This thesis tells the story of one piece of land, Arecleoch forest in south west Scotland, over a three year period (2008 – 2010), describing and deciphering patterns of change taking place across it during this time. It provides the only known study to date that quantifies dissolved organic carbon (DOC) exports at the catchment and sub-catchment scale, over a period that incorporates the construction of a wind farm, from start to finish. It also seeks to describe patterns of change in DOC quantity and quality at the sub-catchment scale and explores ways in which disturbance can be identified and quantified. Whilst the focus of the thesis is inevitably captured by the wind farm development, I have been mindful throughout of the need to place this in context as simply the most recent in a series of land use changes imposed upon this carbon-rich landscape.

Thesis structure

Land use changes taking place at Arecleoch forest have been investigated in terms of dissolved organic carbon losses to downstream aquatic systems. Concentrations and fluxes of DOC at different spatial scales (0.1 Km^2 sub-catchments to 20 km^2 catchments) will be described and quantified and explanations proposed for patterns and trends observed. The patterns of change are explored across three catchments draining Arecleoch forest within four broad themes.

Theme 1 is concerned with natural cycles of DOC concentration and the way that these interact with the relationship between DOC and discharge across the three catchments in the study area. Major anion concentrations are discussed in this theme.

In **theme 2** the focus shifts to DOC flux and a consideration the hydrology of the three catchments and practicalities of obtaining sufficient and robust information from which to estimate DOC flux are considered.

Theme 3 focuses specifically on the way in which decisions about how Arecleoch is managed have shaped the peatland and the extent to which it is possible to measure the impacts of the latest land use change in terms of aquatic carbon losses. Particulate organic carbon (POC) loss is also investigated and interpreted through the lens of the work being undertaken at Arecleoch. Theme 3 also introduces the Activity Score as a way of integrating site records from a wind farm developer with DOC concentration data to understand better the way in which specific construction aspects of such a development can affect DOC.

Theme 4 looks at the way in which carbon quality can be affected by peatland disturbance and starts to develop ideas for a way of recording carbon quality as a measure of disturbance in a way that is practicable and inexpensive.

Finally the discussion section attempts to distil and interweave the findings from themes 1-4 to produce a coherent storyline of Arecleoch between 2008 and 2010 as well as providing observations and recommendations that it is hoped will enrich the knowledge base on carbon loss from peatlands. Practical suggestions will be offered of ways in which enhanced DOC loss during peatland disturbance can be quantified and compared and used to inform tools such as the carbon payback calculator (Nayak *et al.* 2008).

Aims and objectives

General aims of the research

1. To describe the peatland on which first stood Arecleoch forest and latterly stands Arecleoch wind farm primarily through its hydrology, major anion concentrations and DOC concentrations and fluxes.

2. To describe the nature of DOC loss from a landscape during a period of transition, focussing on a wind farm development, and to understand the causes of change.

3. To appraise the significance of the impacts of wind farm construction on the peatland in terms of the quantity and quality of aquatic carbon loss and make recommendations to developers as to how to minimise such impacts.

4. To provide useful information to feed into the carbon calculator in terms of DOC losses.

5. To begin to develop practical tools for predicting and appraising negative effects of land use change on peatlands using information on DOC quality and POC concentrations.

Specific objectives

Theme 1, DOC concentration and patterns of change across three catchments at Arecleoch.

Seasonal and annual patterns in DOC concentrations are investigated across and between the three catchments. Data collected at Arecleoch is related to those from other studies, which establish distinct cycles of behaviour for DOC. The complex relationship between DOC concentration and discharge is also examined. Finally major anion concentrations across the catchments and through time are explored.

Theme 2, the hydrology of Arecleoch and DOC flux

In this theme DOC flux is estimated at the three catchments draining Arecleoch and catchment characteristics and land management regimes are used to explain the observations. The practicalities of gathering environmental data and comparing different options for accounting for data gaps are explored. Differences in runoff between the catchments are also investigated.

Theme 3, Land use change and anthropogenic sources of peatland disturbance at Arecleoch

The way in which DOC concentrations respond to land use change are described, using the Arecleoch wind farm development as the working example. This latest land use change is placed in historical context by describing previous land management practices there and making comparisons with other peatlands that have undergone similar and different fates. The aim is to make a quantitative assessment of the impact of this anthropogenic change on the peatland in terms of dissolved organic carbon concentrations in downstream aquatic systems. POC concentrations are compared at different spatial scales and a metric is proposed for distinguishing between sediment due to road runoff and that from the peat. The relationship between DOC concentration and the development activities taking place at Arecleoch is explored through the novel approach of an "Activity Score" system.

Theme 4, DOC quality as a measure disturbance

In the final theme the nature of DOC exported from Arecleoch is investigated using absorbance at different wavelengths of UV light and comparing the results at different spatial scales. Experiments are carried out to understand whether a combination of some of these metrics relating to changes in DOC quality can be developed into a disturbance index, giving practitioners on the ground a fast, simple and inexpensive means of monitoring the effects of their activities.

Concluding comments

Findings from themes one to four will be brought together and considered in the context of Arecleoch and more broadly in relation to the question of whether the siting of wind farms on peatlands can be judged in terms of being a positive or negative environmental decision from a carbon perspective. The potential for this research to contribute to the part of the Carbon Payback Calculator concerning attributing a cost to carbon losses in the form of DOC will also be discussed.

Hypotheses

This research will test six hypotheses set out below:

***Hypothesis* 1:**

DOC concentrations will be significantly higher at sample points subject to disturbance from the wind farm activity (Crosswater of Luce and Tig) and at times of greater construction activity (November 2008 to September 2010) than at the control sample point (Crosswater) and during the baseline period before construction began (January 2008 – October 2008).

***Hypothesis* 2:**

Annual DOC export from the Crosswater catchment will be significantly higher than DOC export from the Crosswater of Luce catchment when standardised for catchment area

***Hypothesis* 3:**

The export of DOC from the Crosswater of Luce as a proportion of that from the Crosswater per unit area will be higher after wind farm activity starts in the Crosswater of Luce catchment.

***Hypothesis* 4:**

DOC concentrations at the sub-catchment scale will be higher in areas of and at times of greater wind farm activity

***Hypothesis* 5:**

POC as a proportion of suspended sediment (ss) will be significantly higher where disturbance is from forestry and turbine installation activities. It will be significantly lower where the elevated concentrations of ss are due to road runoff.

***Hypothesis* 6:**

Streamwater draining areas subject to disturbance will contain DOC that has a higher degree of humification than DOC in streamwater draining undisturbed areas.

Site description

This is a general introduction to the study area but more detail concerning the wind farm development can be found in theme 3. Arecleoch forest is situated on a peatland in South Ayrshire, within the Forestry Commission's Galloway Forest district, which at 96 000 ha is the largest forest district in Great Britain (Figure 1) (Forestry Commission 2009). It is a peatland that has been heavily managed for generations and this research, covering the time period from January 2008 to the end of September 2010, captures the most recent anthropogenic effort to alter the form and function of the landscape. The Scottish Power Renewables' (SPR) Arecleoch wind farm is built mainly within Arecleoch forest, owned by Forestry Commission Scotland (FCS) and operated by the Forestry Commission, but also partly in the privately owned Eldridge Hill Estate (Figure 7). The replacement of 868 ha of commercial forest, 542 ha of which was felled specifically for the wind farm project, by 60 wind turbines and the associated infrastructure presents a powerful visual impact to anybody familiar with the area (SPR Environmental Statement Part 1). It can also provoke strong emotions both positive and negative as has been seen with other wind farm developments. Despite the evident visual changes to the landscape however, it must be remembered that most of the disruption associated with constructing an onshore wind farm takes place below ground.

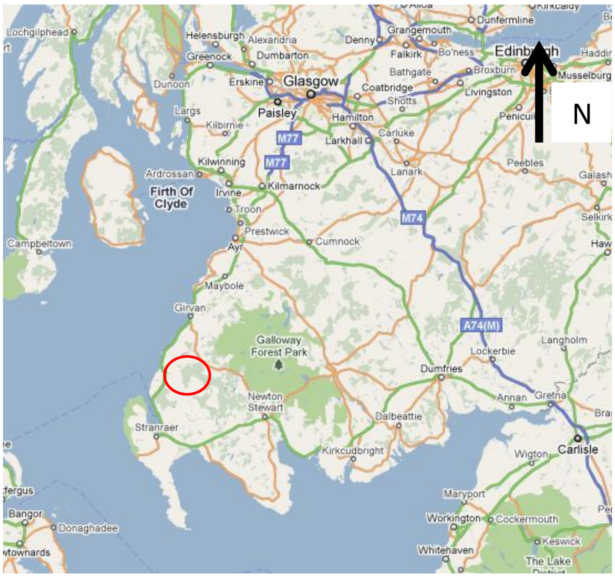


Figure 1. Location of Arecleoch forest within the Galloway forest district, SW Scotland (Crown Copyright/database right 2012. An Ordnance Survey/Edina Digimap supplied service)

Geology and vegetation cover

The solid geology of Arecleoch has been shaped by processes occurring during the last two ice ages. The area is underlain by Ordovician greywackes and siltstones with sub-ordinate sandstones and shales (SPR Environmental Statement Chapter 12). An Ordnance Survey map of the area indicates that it the superficial geology is entirely dominated by peat (Figure 2). Data from peat depth surveys presented in SPR's Environmental Statement provides greater resolution on the variability of the peat thickness (Figure 3) indicating that it has a range of 0.3 m to 5 m (SPR Environmental Statement part 8). In reality, the depths of peat encountered during the wind farm construction were considerably less than those expected from the survey work and depth modelling exercise (pers. Comm. SPR)

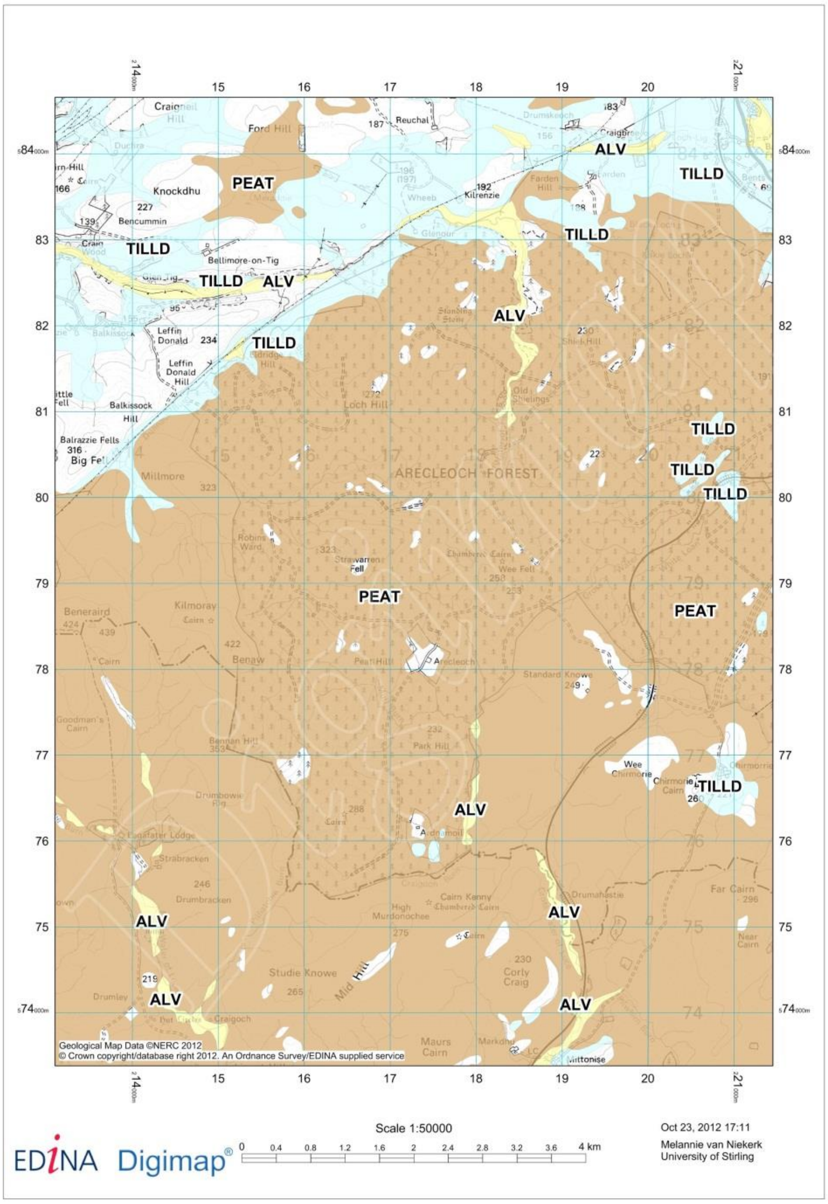


Figure 2. Extent of peat cover (brown) across Arecleoch (Crown Copyright/database right 2012. An Ordnance Survey/Edina Digimap supplied service). Key: ALV = alluvium (yellow), TILLD = Till, Devensian (blue).

Prior to the wind farm development vegetation cover on the site consisted mainly of commercial forest comprising a mix of sitka spruce (*Picea sitchensis)* and lodgepole pine (*Pinus contorta),* with trees planted along the riparian zone. Other vegetation was mainly degraded blanket bog and wet heath dominated by purple moor grass (*Molinia caerulea*).There were also less degraded areas, which were dominated by heather (*Calluna vulgaris*) (SPR Environmental Statement part 8).

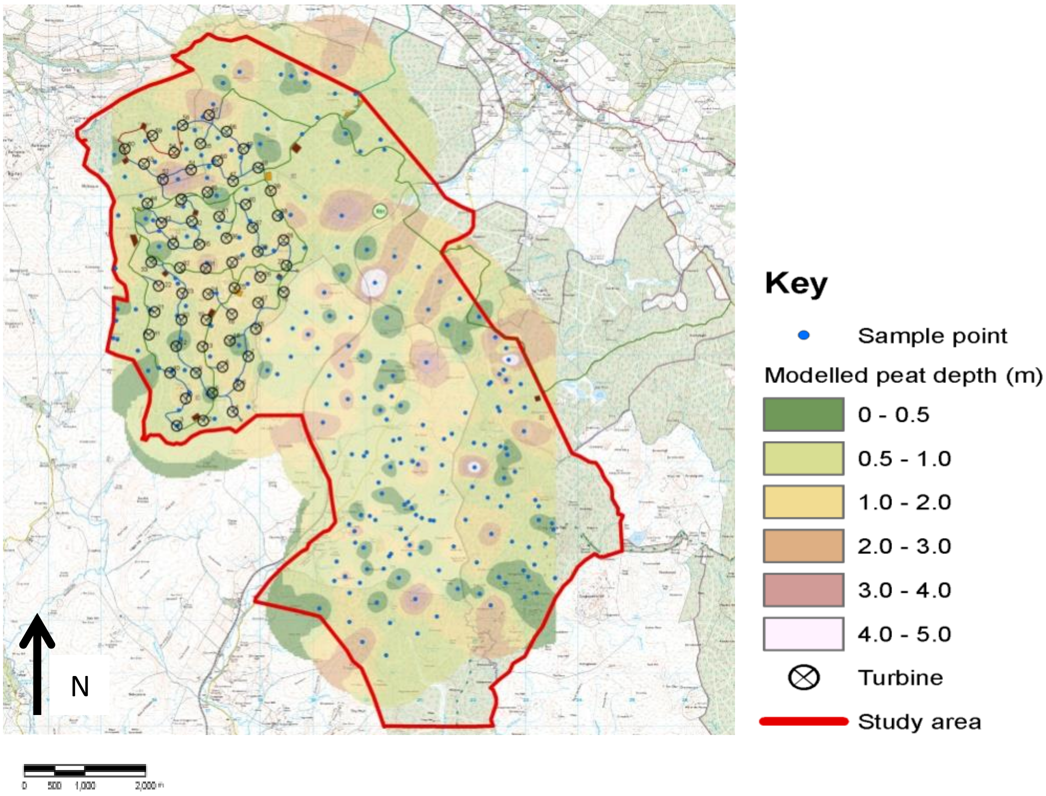


Figure 3. Modelled peat depths across the SPR wind farm development site at Arecleoch (SPR Environmental Statement part 8)

Land use at Arecleoch

The majority of the land now hosting the Arecleoch wind farm was acquired by the Forestry Commission as a block in 1955 with seven other acquisitions adding to the area between then and 1988 (Figure 4 and Table 1). At the time of acquisition by the Forestry Commission, each of the eight areas was covered by moorland. Commercial forest planting began in 1959 in the Arecleoch & Ardnamoil Farms block and continued until 1991.

Table 1. Acquisitions of land parcels by the Forestry Commission at Arecleoch with catchment area, purchase date, vegetation type at date of purchase, and planting information (Forestry Commission records). (key for tree types: ss=sitka spruce, lp = lodgepole pine, jl = Japanese larch, mb = mixed broadleaf, Qss = Queen Charlotte sitka spruce)

Acquisition	*Title*	*Area (ha)*	*Date purchased*	*What was there*	*Planting info (1985 stock map)*
1	Lagafater	102	23/06/1960	Moorland	Mostly ss with some lp – most in 1970
2	Arecleoch & Ardnamoil Farms	1257	07/10/1955	Moorland	1959-1970. Mostly ss with some lp
3	Glenour (Knockbrex)	57	15/08/1959	Moorland	1960-1961.Mostly ss with some lp
4	Dochroyle Farm II	856	15/01/1968	Moorland	1971-1984. Mostly ss with some Qss
5	Bardrochat Est Shiel & Loch Hill	696	27/03/1979	Moorland	1981-1991. Mostly ss with some qss
6	Bardrochat Est II	317	16/03/1984	Moorland	1988-1990. Mostly ss with other mixed woodland
7	Bents Farm	129	22/12/1988	Moorland	1991. Mostly ss with sp, JL,UP, MB, LP
8	Gowlands	236	28/03/1972	Moorland	1976-1983. Mostly qss with some ss

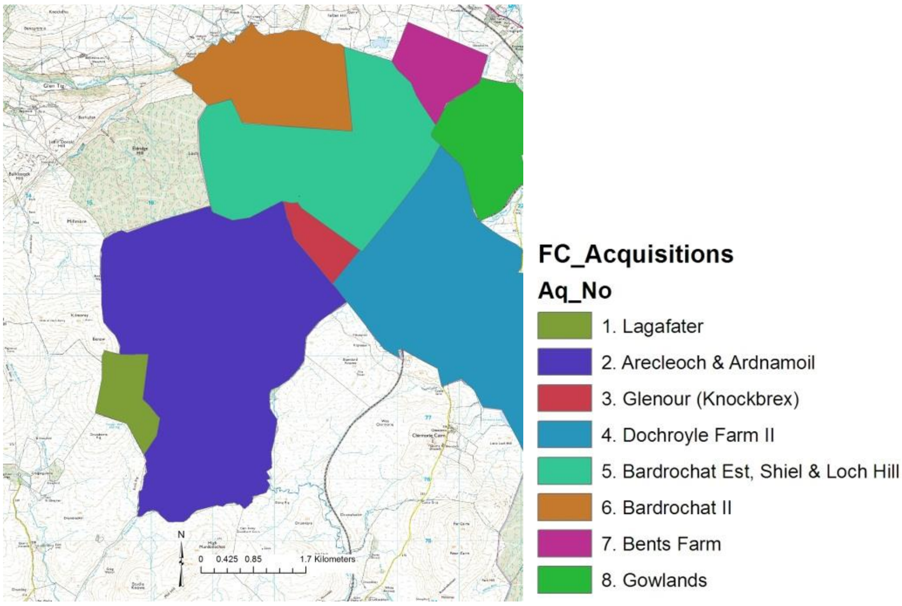
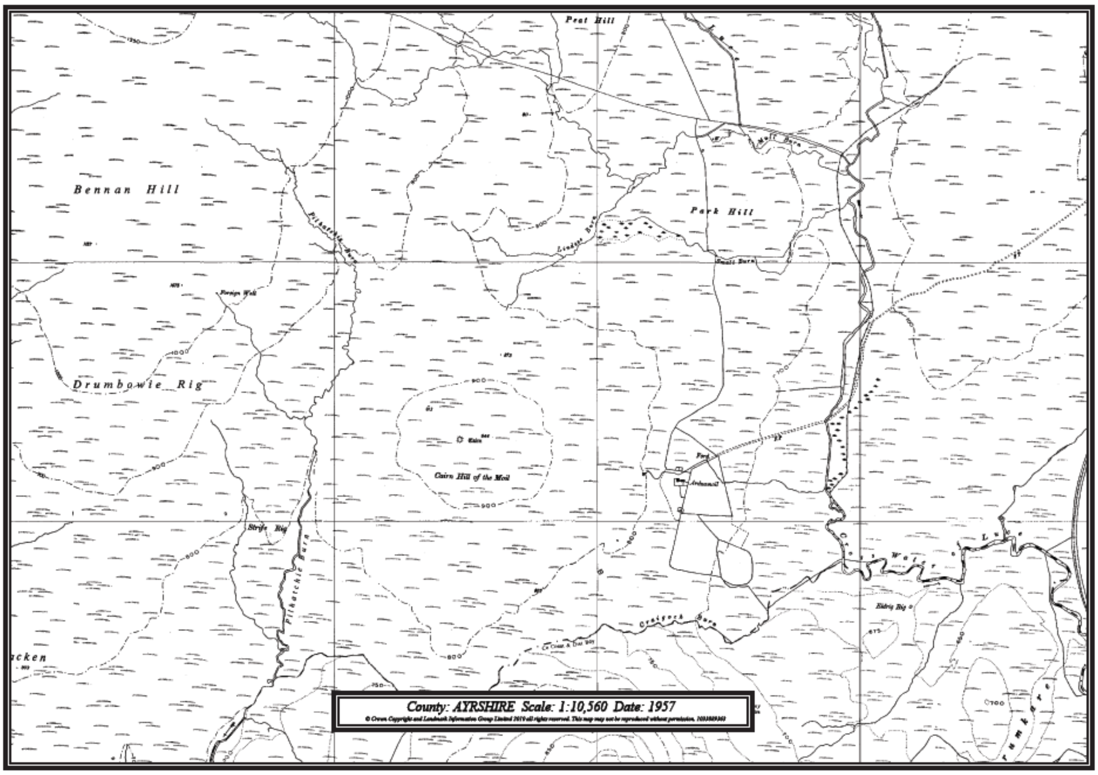


Figure 4. Schematic of Forestry Commission (FC) acquisitions at Arecleoch with data from (FC) acquisitions map.



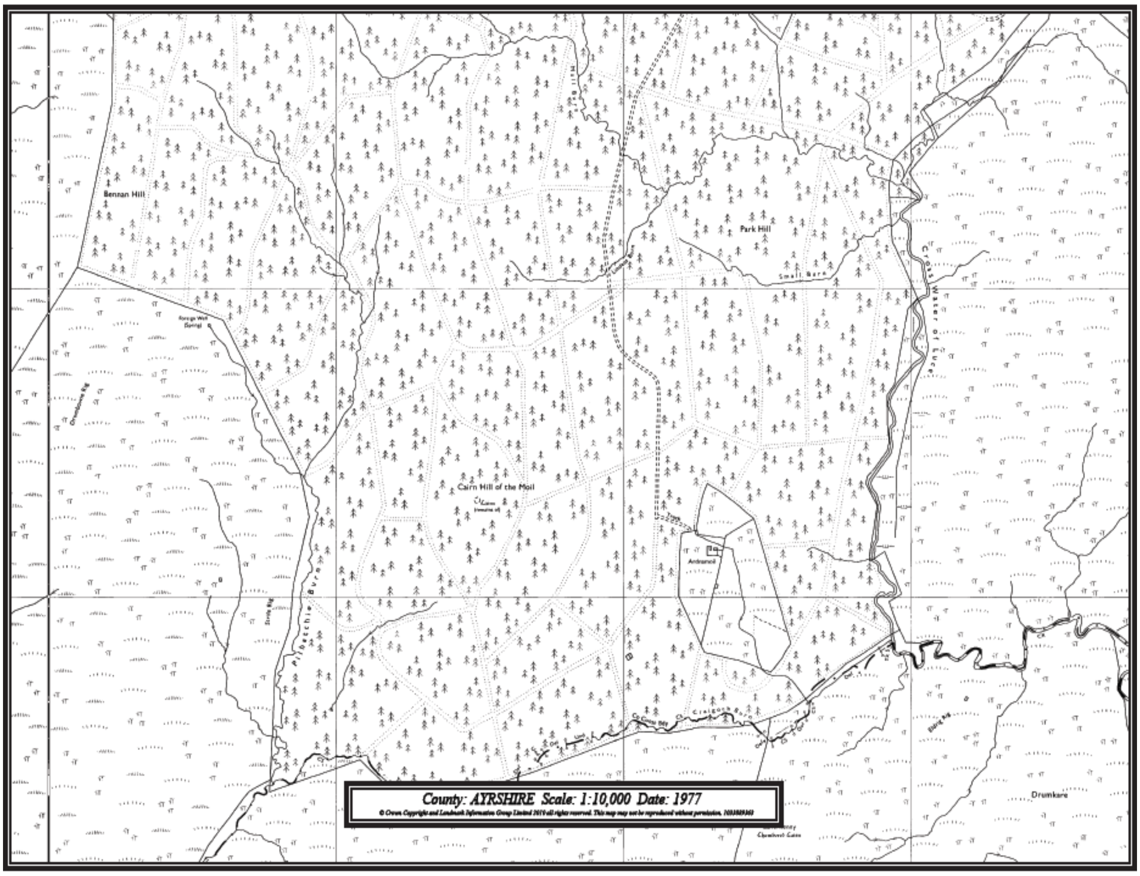


Figure 5. Maps showing differences in land cover over at Ardnamoil, south Arecleoch between 1957 (upper) and 1977 (lower).Crown copyright and Landmark Information Group Limited 2010

Some indication of the extent of this change of use can be gathered from maps of the Arecleoch acquisition block (Figure 5) showing the Park Hill area in the south of the now forest. In each case we can see the change from 1957, just before the start of land preparation for planting, to 1977 when the forest was well established.

More recently satellite imagery has allowed us vivid visualisations of the changing landscape. Two Google™ earth images taken over Arecleoch forest show the dynamic nature of what is often perceived to be a static environment (Figure 6). The date of capture of image a) is unknown but image b) was captured some years later in 2005. Within the dark green, mature forest of the Arecleoch block, some harvesting has taken place in the early map. By 2005 these areas have been replanted and other sections of forest have been felled. Each of these colour changes on the landscape seen from the air of course represents a great deal of activity and disturbance on the ground.

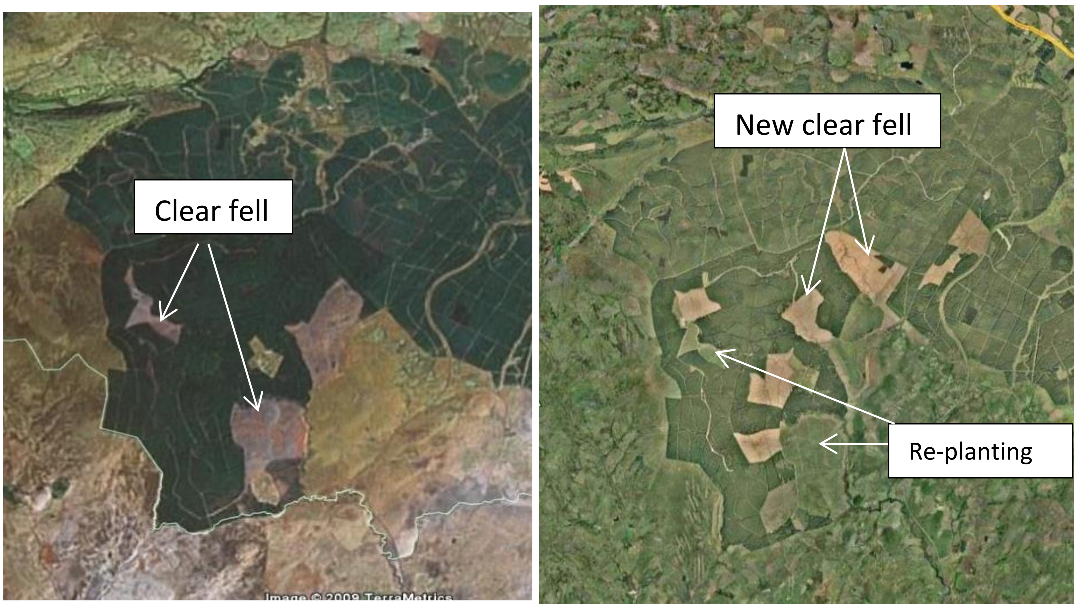


Figure 6. Satellite images of Arecleoch in (a) 2005 and (b) at a later, unspecified date indicating changes in forest cover (Images downloaded from Google™ earth)

Research rationale

The choice of location for this research came about due to SPR commissioning the University of Stirling to undertake a baseline survey of water quality as part of the planning application process for the wind farm. This ran from January to October 2008 and the joint funding of a PhD studentship was agreed by SPR and the University of Stirling to study the impact of the development on water quality for the next three years. My involvement began in October 2008 at the end of the baseline study. Consequently the selection of the three catchment sample points for this project was heavily informed by the work that had gone before. The intent was to develop a monitoring strategy that continued the intensive catchment scale water sampling while bringing in additional, extensive sampling across the wind farm site. As the wind farm construction proceeded it was possible to identify suitable locations for short term monitoring efforts that could be put in place to answer specific research questions that arose as a result of observations made while on site.

Theme 1. DOC concentrations, major anions and patterns of change across three catchments at Arecleoch

In this theme patterns of DOC and major anion concentrations across an annual time scale at Arecleoch will be described and the complex relationship between DOC and discharge will be disentangled. The specific aims of theme 1 are to:

- Describe three catchments at Arecleoch in terms of patterns of DOC concentration through time;
- Explore the relationship between discharge and DOC concentration for the three catchments and put forward explanations for differences that take into account land use changes taking place during the monitoring period; and
- Describe the differing patterns in major anion concentrations across the catchments.

The hypothesis that **DOC concentrations will be significantly higher at sample points subject to disturbance from the wind farm activity (Crosswater of Luce and Tig) and at times of greater construction activity (November 2008 to September 2010) than at the control sample point (Crosswater) and during the baseline period before construction began (January 2008 – October 2008),** will also be tested.

I will begin by reviewing the literature and drawing on the experience of previous researchers in this field to set a context in which to place the study at Arecleoch.

1.1 Dissolved organic carbon (DOC)

Dissolved organic matter, and therefore DOC, is defined as any organic component that passes through a 0.45 µm filter (Evans, Monteith & Cooper 2005). DOC is produced in peat and soils and comprises a mixture of animal and plant products, in various stages of decomposition that are dissolved in pore waters. Chemically DOC is a complex of organic compounds varying widely in molecular weight from small molecules such as organic acids and sugars to intermediate and large polymers (Bourbonniere 2009). The DOC concentration in soil pore water represents the balance between production (microbial decomposition, root exudation, litter leaching and desorption) and removal processes (eg flushing, microbial consumption and chemical adsorption) (Kalbitz *et al.* 2000). Once formed, DOC remains in soil pore water until it is flushed out by precipitation, consumed by microbes or adsorbed onto other particles and removed. DOC production roughly doubles with every 10^{o}C increase in temperature and DOC increases in concentration with increased primary production (Bourbonniere 2009; Wallage, Holden & McDonald 2006). Soils and their associated land-use are the primary influence on the spatial variation in DOC, which can vary markedly between different streams (Dawson & Smith 2007). Billet *et al.* (2004) found that total organic carbon (TOC) contributed 93 % of the mean annual downstream carbon flux in a lowland peatland catchment in central Scotland. The remaining 7 % was contributed by DIC and free CO_2. This study also demonstrated the importance of including fluvial fluxes in obtaining an accurate estimate of a complete carbon budget, and in this case it moved the peatland from being a carbon sink to a position of carbon neutrality. Soil type is a particularly important factor in upland areas where DOC is assumed to derive mainly from terrestrial organic matter (Brooks, McKnight & Bencala 1999; Hope, Billett & Cresser 1994). Specifically it has been found that carbon-rich headwater streams play an important role in the peatland stream continuum and are major point sources of DOC (Dawson *et al.* 2004). Work on the fluvial flux of carbon from peatlands has concentrated mainly on DOC, however this is only one of several release pathways, the others being particulate organic carbon (POC), dissolved inorganic carbon (DIC) and dissolved CO_2 (Worrall *et al.* 2007). Carbon from carbonate sources is referred to as DIC while dissolved CO_2 is the CO_2 dissolved in the stream water in excess of that which could be expected from equilibration with the atmosphere and comes from both organic and inorganic sources. The difference between DOC and POC is usually defined by the size of the filter used to separate the components (Worrall *et al.* 2003).

1.1.1 **Seasonal DOC trends**

The DOC-discharge relationship is discussed below and it will be seen that DOC concentrations often increase with high flows, but underlying this general trend is a complex set of relationships, reflecting seasonality and mobilisation that can also result in low flows having high DOC concentrations (Tetzlaff, Malcolm & Soulsby 2007). The powerful influence that the seasons exert over fluvial DOC concentrations is something worthy of particular attention. The rate of production of dissolved organic matter (DOM) is at its height in the warmth of the summer, but the flux of DOC will often only reach its maximum later on towards early autumn (September – October). This is because of the soil moisture deficit that exists in the summer months, usually with less frequent and smaller rain events, leading to a lack of soil water flow to water courses. The DOM that is generated in summer will therefore only make its way into streams and rivers following larger rain events, typical of early autumn, that flush the stored DOM through the system (Scott *et al.* 1998). DOC concentrations for a given discharge tend to decline in winter because catchments enter a dormant phase with less processing of soil carbon after the high flows of autumn and this reduces the available pool of DOC that can be exported from the catchment. Dawson *et al.* (2008)

found this dormant period generally begins by early November but at one catchment it was as late as the end of December.

Seasonal patterns have been observed by many workers. Grieve (1990) for example found that while storm events at Loch fleet in SW Scotland, produced small, discharge-related variations in DOC concentration of around 2 mg L^{-1}, seasonal variations were of a larger amplitude being in the order of 8 – 9 mg L^{-1}. Eimers *et al.* (2008) go as far as to suggest that seasonal runoff changes at eight headwater basins in south-central Ontario may affect annual DOC trends more than other variables that are measured annually. The work involved catchments with varying amounts of peat coverage and the authors found that the amount of peat and the influence of the spring melt affected the seasonal pattern of DOC concentration. Brooks *et al.* (1999) found that, contrary to the patterns described above, 70-80% of annual DOC export from a high elevation catchment in the USA occurred during the snowmelt period between April 15 and July 15. They suggest that the heterotrophic processing of labile soil carbon, rather than an autumnal flushing, is a primary control on the production of mobile DOC pools in the snow covered soils of their study catchments. They concluded that size of the actively cycling carbon pool is a major control on both the mass of DOC in leachate from organic soil horizons during snowmelt and overwinter CO_2 flux.

Scott *et al.* (1998) undertook a study of two peat drainage pools in northern England. In general, seasonal variations in DOC concentrations and fluxes were found to be consistent with an increased rate of production of potentially dissolvable organic compounds during summer when soil microbial activity is greatest. They also observed a different situation when rainfall was low and temperatures were high and following a protracted period of dryness in 1995, DOC concentrations measured were the lowest values recorded for that time of year. They concluded that the production of DOM in soils is sensitive to different temperature and soil moisture conditions. Under drought conditions the production rate was thought to be lower due possibly to reduced microbial activity or more complete mineralisation of carbon to CO_2.

Hence weather conditions, soil type and antecedent conditions can influence the typical seasonal patterns with which we are familiar and highlight the necessity of considering a broad range of inter-related, site-specific factors when interpreting DOC data. Also, inter-annual differences in DOC concentrations will be apparent due to differing weather conditions.

1.1.2 **The DOC - Discharge Relationship**

The relationship between DOC concentration and river discharge is not straightforward and in attempting to explain it one must employ many dependent clauses relating to sampling frequency, land use and soil type. To begin with the broadest brush, significant positive correlations between DOC concentration and flow have been reported (Grieve 1984; 1991; Hope, Billett & Cresser 1997) however other controls on DOC concentration may also be at play and can make interpretation of the effect of discharge between catchments difficult. For example Hope *et al.* (1997) also found that the percentage of the variance in DOC concentration explained by flow was only between 20 and 45% indicating that other controls on DOC concentration were present. In Grieve’s (1991) study of six upland Scottish catchments, it was observed that forested catchments (Sitka spruce *Picea sitchensis* and Lodgepole pine *Pinus contorta*) had higher mean DOC concentrations than moorland catchments but discharge weighted mean concentrations showed that absolute differences were small (10 – 15 % of mean DOC) thus land use was not a significant control on DOC. It was considered possible that differences were also related to soil type as well as the presence of forest. The effects of forestry on DOC concentrations and discharge are discussed in Theme 3.1.2.

In another study, Grieve (1990) found streams draining a forested catchment of Loch Fleet in southwest Scotland to have concentrations of DOC nearly double those of streams draining predominantly moorland catchments. Suggestions such as canopy leaching, differences in soil hydrology and the build-up of acid litter in the early stages of rotation were put forward as contributing factors but none was considered likely to provide the full explanation. When Grieve (1991) regressed DOC concentration on Log Discharge over the whole sampling period an R^2 of only 0.2 – 0.5 was obtained and an examination of the residuals revealed a strong seasonal variation (discussed above) that, when introduced into the regression model in the form of an annual sine wave with a maximum in late August, helped explain between 57 – 84% of the variance in DOC concentration over the six catchments, thus masking the DOC – discharge relationship. Dawson *et al.* (2002) reported that the relationship between discharge and DOC can be strengthened if the data are split seasonally. High DOC was assigned to summer through the first autumn storms and low DOC comprising the rest of autumn together with winter and spring. Elsewhere Dawson *et al.* (2008) observed a seasonal delineation of DOC concentration, but in this case the split between significantly high and low DOC concentrations was independent of discharge. They concluded that surface water DOC concentration was mainly controlled by temperature changes with the continuous export of available carbon from well-connected soils.

Soil type and flow pathways also interact with the DOC – discharge relationship. In mineral soils there is a large difference in soil water DOC concentration between the lower horizons (low DOC) and subsoil waters, which have higher DOC concentrations. The positive correlation between discharge and DOC in organo-mineral soils can therefore be explained by changes in flow paths. At times of low flow, water comes from deeper soil horizons so concentrations of DOC could be expected to be low. Conversely under high flow conditions one would expect the DOC to represent the higher concentrations found in upper soil horizons (Austnes *et al.* 2010; Cooper, Thoss & Watson 2007). In peaty soils the situation is different and while flow paths may still be important, there may be little difference between soil water DOC concentrations from the upper and lower soil horizons (Grieve 1991).

The main feature in peatland catchments is the hydrological connectivity between the peat and the underlying bedrock/mineral soil (Clark *et al.* 2007; Clark *et al.* 2008). Where there is hydrological connectivity, base flow will have low DOC concentrations representative of the groundwater. DOC concentration will increase with discharge as the water table rises because of inputs from DOC rich soil water flowing through the subsurface acrotelm (Austnes *et al.* 2010; Clark *et al.* 2007; Clark *et al.* 2008; Evans *et al.* 1999; Worrall *et al.* 2002; Worrall *et al.* 2002). As well as reporting DOC concentrations increasing during events in a Welsh peatland catchment, Austnes *et al.* (2010) also found soil water DOC concentrations to be higher than those of base flow indicating that this system was different to the one studied by Clark *et al.* (2007, 2008) where base flow was chemically similar to soil water. The findings of Austnes *et al.* (2010) suggest a significant input of drainage from the peat. This together with increased absorbance and lower pH values at high flow are typical of a system where the water table is rising within the acrotelm and where there is subsurface flow (Worrall *et al.* 2002).

Clark *et al.* (2007) investigated the discharge-DOC relationship for DOC concentrations and fluxes at different spatial scales and for different sampling intervals. Their findings for a weekly sampling programme at two upland peat catchments are summarised in Table 2 and illustrate the complexity of the DOC concentration – discharge relationship. It can be seen that for the small catchment the discharge-DOC relationship was poor except for autumn where the relationship was negative. However, for a larger catchment there was a positive Q-DOC relationship in all seasons. They ascribed the differences to varying proportions of peat drainage water to groundwater at the two sites illustrating the way in which an additional water source can alter the pattern of DOC concentrations. DOC flux conversely was found to increase with discharge (See theme 2).

Table 2. Relationship between DOC concentration and discharge at two differently sized upland catchments (After Clark *et al.* 2007)

	Catchment Size	
Season	Small (20 ha)	Larger (1150 ha)
Spring	Poor	Positive
Summer	Poor	Positive
Autumn	negative	Positive
Winter	Poor	Positive

Interpretations of storm sampling have greatly helped in the development of our understanding of the controls on peatland DOC concentration. DOC-discharge relationships can vary as a result factors such as the effect of storm flow hysteresis depending on whether the sample is collected on the rising or falling limb of a storm.

Samples collected on the falling limb following peak discharge or after exhaustion of supply may produce a lower DOC concentration of a given discharge (Dawson *et al.* 2008). DOC concentration can rise or fall during an event depending upon the composition of the system from which the DOC is released.

Worrall *et al.* (2002) described the release of DOC from peatland in the north Pennines as being partially decoupled from the hydrological behaviour of the peat and acting like a three end member system. Events were characterised initially by percolation-excess, new water from the acrotelm-catotelm interface, rich in DOC and then saturation-excess, new water depleted in DOC dominated. As events in this type of system progress DOC concentrations may fall due to supply exhaustion, saturated overland flow or macropore flow resulting in low DOC, rain-like water. Finally inter-event water comprised the third member, generated from catotelmic baseflow, and largely depleted of carbon (Worrall *et al.* 2002). In other peat catchments where there is no hydrological connectivity between the peat and mineral soil the release of carbon acts like a two end member system. Base flow is similar in composition to the DOC rich soil water of the catotelm and event stream water will exhibit a decrease in DOC as this base flow is replaced by rain-like water (Clark *et al.* 2007). A third type of system was reported by Austnes *et al.* (2010) investigating DOC concentrations in a peatland in north Wales. In contrast to Clark *et al.* (2007), base flow was more alkaline and had lower DOC concentrations than soil water.DOC concentrations increased at high flow but this was not considered to represent the same 3 end member mechanism described by Worrall *et al.* (2002) as there was no dilution at peak flow. Rather the authors suggested the two end member mixing model to describe their observations. Worrall *et al.* (2002) also reported that new water dominated all runoff events but the point was made that this is not always the case; for example in forested catchments it has been shown that old water stored from previous events may be forced out during a new event and can dominate runoff.

Thus we see that the interpretation of high resolution DOC concentration data from peatlands requires an intimate understanding of the system under study. The same caveat also applies to sampling at different spatial and temporal scales and using catchments that have undergone significant land use changes such as those at Arecleoch where hydrological pathways may have been altered through the management practices employed on the land through time.

1.1.3 **Controls on riverine carbon concentrations**

Many factors have been shown to influence the concentration (DOC flux is discussed in Theme 2 below) of DOC in streamwater both within and without the soil environment. Examples of the former include the rate of DOC production in organic soils and the rate of adsorption in mineral soils (McDowell & Likens 1988). Aitkenhead-Peterson *et al.* (2007) found the extent of peat cover for a set of 21 catchments in the Dee Valley in Scotland to be a good predictor of annual DOC concentration and export. They also found the correlations improved when annual data were broken down seasonally. Aitkenhead *et al.* (1999) investigated the extent to which slope, soil carbon content and peat cover are predictors of DOC concentrations in stream water draining catchments of the river Dee in north-east Scotland with areas from 0.5 to 150 km^2. Pooled data from all spatial scales indicated strongly significant positive linear relationships between DOC concentration and peat cover and two of the three measures of soil carbon content, but no relationship between catchment slope and DOC concentration. When the data was broken down according to catchment size it was revealed that the high proportion of variance in DOC concentration explained by

% peat cover (r^2 = 0.83, $p < 0.0001$) across all catchment scales was mainly due to the high degree of variance explained for small (< 5 km^2) catchments compared with larger catchments. This suggests that there is a decrease in the relative importance of peat soils as well as the introduction of other variables such as land use as catchment size increases.

Dawson *et al.* (2004) took a fresh look at the river continuum concept developed by Vannote *et al*. (1980), which seeks to explain longitudinal variation in carbon processes and invertebrate communities of rivers ecosystems in relation to controls on food resources. They explored it in the context of carbon flux along an acidic peatland stream continuum in NE Scotland and found a 15% reduction in the total carbon flux from the upper to the lower site. They suggested this to be associated with changes in intra-catchment soil type (for DOC), and increases in discharge and turbulence with gradient (for POC, CO_2-C), allowing re-suspension of particulate material and de-gassing of CO_2. Overall Dawson *et al.* (2004) found, in contrast to the model predictions of Vannote *et al.* (1980), no measurable annual net loss of DOC from the stream system although a decrease in DOC flux was seen over a 1.1 km reach of stream in one of the tributaries of their system. Dawson *et al.* (2004) propose that their findings do not suggest that there is no in-stream processing of DOC, rather they put forward that a dynamic equilibrium exists in that part of the system. They conclude that the peatland stream continuum functions in a different way to that put forward by Vannote *et al.* (1980) in that carbon transport is mainly dominated by abiotic, physical processes such as degassing, deposition and re-suspension of particulates and hydrological mixing.

Billett *et al.* (2006) also employed a longitudinal argument into their explanation of the variation in stream water DOC concentration for an upland peat catchment in NE Scotland. They determined that the relationship between stream water DOC concentrations and the soil carbon pool in the upper 1.5 km of the stream were probably driven by DOC production, which is temperature-related, in near-surface peats. Moving downstream, the relationship between organic carbon in the soil and stream becomes weaker as other processes increase in importance. These were said to include lower inputs from minerals soils and allochthonous within-stream processing of DOC.

1.1.4 **Rising DOC trends**

No discussion of DOC can be considered complete without some reference to the emerging story surrounding trends in concentrations discovered from the examination of long-term monitoring data sets. Increasing concentrations of DOC in surface water systems have been widely reported in Scandinavia (Hongve & Akesson 1996; Vuorenmaa, Forsius & Mannio 2006), Canada (Bouchard 1997), northern and eastern USA (Stoddard *et al.* 2003) and the UK (Evans, Monteith & Cooper 2005; Freeman *et al.* 2001). This represents cause for concern for several reasons. A direct effect is that it may represent a reduction in the terrestrial carbon store. Indirect effects are also seen in that fluvial DOC also mobilises metals and pollutants and the high proportion of humic substances in DOC can affect water quality in terms of colour, taste and aesthetic value (Wallage, Holden & McDonald 2006). Several hypotheses have been put forward to explain these trends but there has been much disagreement among the science community. The fact that the long-term trends in DOC concentrations can be orders of magnitude smaller than natural seasonal and spatial variation make it difficult to disentangle the weaker trends (Clark *et al.* 2010) or pinpoint the real significance.

There have been many explanations put forward to explain the rising trend in aqueous DOC concentrations, and what follows is a brief summary of the major contributors.

Reduced sulphate deposition

Over the course of the last 25 years there have been large reductions in anthropogenic atmospheric sulphur emissions and, consequently, a decline in sulphur deposition. Across a similar time period DOC concentrations have been found to have risen sharply, for example an average 91 % increase in DOC across the 22 lakes and streams in the UK's Acid Waters Monitoring Network (AWMN) sites since 1988 (Evans *et al.* 2006). Low pH and high ionic strength have been shown to decrease soil DOC concentrations (Kalbitz *et al.* 2000) and this observation has been linked with that regarding reduced sulphur deposition. It is now widely held that reductions in anthropogenic sulphur deposition and catchment acidity can go a long way towards explaining the rising trends in DOC concentrations (Evans *et al.* 2006; Evans & Monteith 2001; Monteith *et al.* 2007).

Higher temperatures

Freeman *et al.* (2001) found a 65% increase in DOC concentrations in range of upland UK catchments over a twelve year period. It was thought unlikely that theories such as decreasing acid deposition, land use change or discharge changes could explain the scale and nature of the increases across such a broad spectrum of sites. The authors favoured an explanation built on recorded temperature increases which could have affected all sites and they linked this to increases in the activity of the enzyme phenol oxidase. This increase in enzyme activity was also associated with a similar increase in DOC release (discussed below). An alternative view was expressed by Worrall *et al.* (2004) who studied DOC time series data from 198 surface water sites in the UK where 77 % had shown significant ($p= 0.095$) upward trends in DOC concentration across a range of time scales from 8 to 42 years. The remaining 23% showed no significant trends and none of the sites demonstrated a significant decrease in DOC concentration They considered that the 1 °C rise in temperature recorded over that period was insufficient to explain the 100 % rise in DOC concentrations exhibited by their data.

Changes in hydrology

Where increases in DOC concentration have been reported it is suggested that these may reflect changes in hydrology and in fact the measured concentrations and fluxes could be up to 34% greater than volume-weighted values (Eimers, Buttle & Watmough 2008). Tranvik and Jansson (2002) suggest that the focus of attention should shift towards the role of catchment hydrology in controlling the transport of DOC rather than putting forward factors such as temperature as the main driver of DOC increases. They commented that there have been large increases in DOC at some Swedish lakes in the 1970s and 1980 despite low annual temperatures and argued that this could be explained by an increase in precipitation and therefore runoff over that period. Clark *et al.* (2007) meanwhile point out the conflicting evidence over the relationship between stream flow and DOC concentrations in peatlands and are unconvinced that increasing rainfall could be the main driver of increasing DOC concentrations.

Disturbance and land management

While recovery from acid deposition correlates very well with increasing DOC trends in many regions, in the UK this does not explain the entire trend and, together with evidence of differences between neighbouring catchments, it appears that other factors must be involved. Among the possible range of local drivers, land management has been identified as a key cause. Clutterbuck & Yallop (2010) argued that burning peatlands to provide moorland habitat for grouse was a major driver of increased DOC release from UK upland peatlands while disturbance associated with the afforestation of peatland has also been implicated in the loss of carbon storage and this is discussed further in theme 3. While there is evidence that disturbance, and in particular the drainage of peatlands associated with some land management practices, can lead to increases in DOC export, this would only make land management an exacerbating factor (Worrall, Burt & Shedden 2003). Land use changes are not considered to be widespread enough to account for the overall upward trend in DOC concentrations observed (Worrall & Burt 2005; Worrall & Burt 2007).

Increasing levels of atmospheric CO_2

Freeman *et al.* (2004) used ^{13}C tracer experiments to find higher levels of ^{13}C assimilated into vegetation under enhanced CO_2 conditions than under ambient CO_2 conditions and suggested that increasing levels of atmospheric CO_2 could therefore be driving rising DOC concentrations. Alternatively, Worrall and Burt (2007) observe first that the rise in atmospheric CO_2 has been linear for over 100 years whereas DOC flux has not been shown to be linear. Secondly they note that atmospheric CO_2 has increased by around 16% over the period in question but DOC flux has risen by somewhere in the order of 100% requiring a non-linear multiplier effect to explain the difference.

Droughts and the Enzymic latch theory.

Increasing DOC concentrations recorded in the uplands of the UK may be driven by climate change and particularly by severe droughts (Worrall *et al.* 2004). In addition to DOC production caused by oxidation of peat in the acrotelm it is suggested that severe droughts lead to water table decline into the catotelm and further DOC production there. Raising water table levels may then be an essential part of stabilising or reversing DOC concentrations. Severe droughts also cause a drop in the long-term acrotelm-catotelm boundary and this may trigger what is known as the enzymic latch mechanism (Worrall *et al.* 2007). In peats anaerobic decomposition is not found to occur due to the inhibition of the enzyme phenol oxidase restricting decomposition and consequently, DOC production. The phenolic compounds that are responsible for inhibiting these enzymes have been shown to decrease in concentration under more aerobic conditions when water tables are lowered. Restrictions on decomposition are removed and are not reinstated upon rewetting of the peat leading to the idea of a "latch" mechanism (Freeman, Ostle & Kang 2001). In another study of long-term data series from an upland peat catchment in northern England to test the hypothesis that climate change could explain the observed increases in DOC flux from peatlands Worrall *et al.* (2004) examined temperature increase and water table fluctuations. The model that they produced predicted a 6% increase in DOC production over the period of study and not the observed 97%. They concluded that additional processes must be involved in causing the large DOC increase and they put forward the idea of a severe drought effect that would trigger the enzyme latch mechanism and lead to a step change in DOC production. The existence of a severe drought effect has since been examined further by Worrall and Burt (2008) who concluded that there was no widespread evidence for such a phenomena. They suggest instead that the observed DOC concentration and flux increases following a drought are a result of changes in flow and not an indication of increased DOC production. Freeman *et al.* (2004) had also run drought simulation experiments and found no evidence of DOC export rising above that of the control.

What the above examples point towards is that in arriving at a satisfactory explanation for the incontrovertible evidence of rising DOC concentrations, one must employ a flexible approach that seeks to be inclusive and encompassing rather than a dogged determination to unearth any single “Holy Grail”. For example In addition to the general increase in both summer and winter DOC concentrations observed by Harriman *et al.* (2003), an additional effect whereby a step change increase in DOC, lasting 3–4 years, was seen as soils were slowly re-wetted and extra carbon production was leached into streams following a series of long, dry summers. This was interpreted by Dawson *et al.* (2008) as an indication that alongside the general, upward trend in DOC concentrations due to the reduction in sulphate deposition, other factors such as disturbance may interact and serve to increase concentrations further. Roulet and Moore (2006) make the point that while there is clear evidence of changes in concentrations of DOC, it is very difficult to pinpoint accurately their origins. The interactions of DOC within a landscape are complex and nature they suggest is poor at providing robust controls on experiments. What we do know however is that there must be an increase in either net DOC production in terrestrial ecosystems or in the leaching of DOC from them. Evans *et al.* (2006) show that as there has been no increase in runoff from their study catchment, it must be a case of an increase in leaching. Roulet and Moore (2006) suggest that the hypothesis of Evans *et al.* (2006) could be tested in areas where SO_4 concentrations are increasing as DOC concentrations would be expected to show a decrease once changes in volume and pathways of water were taken into account.

Clark *et al.* (2010) recognised that opinion in this area of research may have drifted towards stalemate between advocates of some of the above hypotheses. They propose that confusion over the differing temporal and spatial scales of investigation have masked what may be fairly compatible data. For example catchments with different land management practices, soils and vegetation cover may not show the same response to regional drivers such as declining acid deposition. Remote areas with little history of acid deposition may show different trends to those in industrial areas - in polluted areas it might be difficult to detect a long term climate signal where it is masked by a stronger acid deposition signal. They conclude that rather than seeing the contrasting hypotheses as being in conflict, they should be taken together to elicit a wider understanding of the variability in DOC dynamics with respect to a number of drivers.

1.1.5 **Cautionary tales in interpreting DOC data**

Eimers *et al.* (2008) warn that caution must be exercised when interpreting DOC data indicating a rising trend, because elements such as the differences in record length and reporting methods can throw doubt on the reliability of comparisons between sites. Other factors that should be acknowledged when discussing DOC data are:

Sampling bias

Seven headwater catchments in Canada were studied, for which data was available over a 22 year period. Sampling bias was considered to be a significant problem with 35% of the annual sampling effort being carried out in spring, which did not match the proportion of flow (51 – 57%) (Eimers, Watmough & Buttle 2008). This could account for the observation that measured DOC concentrations were greater than volume weighted values as this pointed to a greater sampling intensity under low flow/ high concentration conditions.

Surface water or soil water?

Clark *et al.* (2008) carried out laboratory based experiments investigating changes in DOC concentrations in response to water table drawdown and temperature increases. Samples were taken from soil water extracted under tension. They found that DOC concentrations declined during water table drawdown but then increased significantly after water tables had recovered to the surface. They point out that the scenario painted by Eimers *et al.* (2008), using river water, of the role of hydrology in creating an apparent negative correlation between SO_4 and DOC concentrations could not explain their findings from soil water samples extracted under tension in a laboratory.

Clark *et al.* (2008) offered the following explanation for their findings:

1. Water table drawdown and aeration of the usually anaerobic peat causes an increase in biological activity, organic matter decomposition and net DOC production.
2. Water table drawdown also leads to more oxidation of reduced sulphur to SO_4 causing soil water acidification and less DOC solubility.

Combining points 1 and 2 they concluded that drying leads to more soluble DOC being produced but it being retained in the solid phase as secondary changes in soil water chemistry caused less of the organic carbon to be dissolved in the soil water. Also water table recovery following draw down causes a shift back to anaerobic conditions, decreasing the rate of biological activity, organic matter decomposition and net DOC production. SO_4 is reduced making DOC more soluble. Lofgren and Zetterberg (2011) investigated soil water DOC concentrations at 68 sites forested on glacial till. Data covered a range of time periods between 1987 and 2008 with at least ten years' data for each site. 72 % of the sites showed statistically significant ($p < 0.10$) decreasing SO_4 concentrations in the soil solution The main effect on soil DOC was either no (47%) or decreased (46%) concentrations. Five of the sites displayed significant ($p < 0.10$) increasing DOC trends.

Soil type/ location

Closely linked to the previous category, Clark *et al.* (2007) noted that most studies on DOC, showing that fluxes increase during storm events, had been carried out on areas with organo-mineral soils, and very few in peatlands. They suggested that peat soils differ from organo-mineral in terms of their profile, hydrologic behaviour and DOC dynamics as a consequence, may be different during storm events. It was seen as an important balance to redress as peatland drainage waters are known to have very high DOC concentrations and fluxes. The conclusions of Lofgren and Zetterberg (2011) discussed above add weight to the idea that it is the processes taking place in riparian zones and peat lands that control stream water DOC variations rather than what is happening in drier soils uphill. Consequently, drivers of surface water DOC trends should be sought in these organic rich soils with high connectivity to streams and lakes. A note to add with respect to Scottish soils is that high rainfall means that often they are wet form the catchment divide to the valley bottom.

The implication of the results in the light of climate change predictions are that increased water table draw down due to decreased summer rainfall and higher evapotranspiration increase the net production of DOC and also the temperature sensitivity of production. This amplifies the release of carbon from the peatland carbon store that would be caused by a temperature increase alone. However, in real life (ie not in a laboratory) the timing of DOC release is controlled by hydrology in terms of the transport of DOC from soil to stream, and the influence of water table draw down in controlling soil water chemistry that affects the solubility of the organic carbon produced.

Export, Flux or concentration?

Roulet & Moore (2006) make the point that it is important to distinguish between export and concentration when interpreting DOC data. An increase in export can result from more runoff with no change in concentration; an increase in concentration may occur with no change in hydrology but a change in production or retention in the landscape. Thus caution should be exercised in interpreting the rising trends in DOC concentration as an indication of changes in the carbon pool, especially where flow data does not exist. In a study by Eimers *et al.* (2008), higher DOC concentrations in the latter years were a result of lower spring flows and did not translate into greater DOC export and there would be a danger of over-estimating DOC loss from catchments if this is were taken into account. Conversely if changes in hydrology have increased discharge it could have important implications for the carbon budget of peatlands. If discharge were increasing then it could have the effect of buffering DOC concentrations so masking increases in carbon flux (Tranvik & Jansson 2002). Billett *et al.* (2004) warn that an increase in flow can lead to a greater mass of carbon being exported even if concentrations fall and even a small increase could switch a peatland from being a carbon sink to a carbon source.

Worrall & Burt (2007) observe that increases in DOC are generally measured in terms of DOC concentration but may be interpreted in terms of carbon flux. This may not always be appropriate as concentrations may change as a result of differing hydrological flow paths that may not represent changes in DOC flux. Indeed Worrall and Burt (2007) examined long term records from 208 sites and found that the large increases in DOC concentration observed across Great Britain for example by Freeman *et al.* (2001) could not be matched by similar increases in DOC flux for Great Britain as a whole, and two periods of increase that they did find supported the drought hypothesis. However, if DOC flux of each of the member nations of Great Britain were considered separately, then there were no major increases that could be associated with droughts and the small linear increases observed supported theories that increases in air temperature and atmospheric CO_2 can explain DOC increases.

The simple message to take away from the above is that if false or erroneous comparisons are made between studies, differences may be identified that, in reality, are not related to the claim being made or the hypothesis being tested.

1.1.6 **Why study DOC?**

Evidence that DOC concentrations have increased over the last thirty years has been presented above along with a discussion of the potential drivers of these changes. The implications of continuing rises in DOC concentrations in surface waters are serious on several counts and justify the research effort being focussed in this area. Firstly increasing DOC in water courses could signal major changes to the carbon budget of peatlands due either to a loss of carbon from the terrestrial carbon store (discussed further in Theme 2) or a higher rate of carbon cycling; secondly DOC is known to be highly correlated with water colour, the removal of which from potable water supplies constitutes a significant cost to Water Companies in some parts of the UK (Worrall *et al.* 2004). Incomplete removal of DOC can result in reactions with disinfectants used in the treatment process and lead to by-products such as trihalomethanes (THMs), which may have carcinogenic properties and whose concentrations are regulated by law (Ates, Kitis & Yetis 2007). A third reason to focus this research on DOC concerns the potential ecological impacts of rising concentrations. A direct negative effect is the reduction in light penetration through the water column associated with darker water colour (McCartney *et al.* 2003). But there is also evidence that increased DOC concentrations may have a role in complexing labile monomeric aluminium (AL-L) so reducing its ecological toxicity (Roy & Campbell 1997).

1.2 Major anion concentrations

Although the main focus of this research is on aquatic carbon concentrations and fluxes, concentrations of three important anions (nitrate (NO_3), sulphate (SO_4) and chloride (Cl)) were also measured throughout the study period. The interaction of carbon export with elements such as N and P is thought to be important in linking the terrestrial and atmospheric carbon cycles. At Whitelee wind farm a statistically significant positive relationship was found between phosphorus concentrations [P] and DOC concentrations [DOC] but an inverse relationship between nitrate concentration [NO_3^-] and [DOC]. The latter was attributed to inherent catchment characteristics and not a dilution process (Waldron *et al.* 2009). A further study at the same site found no evidence of wind farm related impacts on NO_3 concentrations in water courses draining the site (Murray 2012) unpublished PhD thesis). It was suggested though that this may in part be due to the fact that some of the sampling points were 4 km downstream of any disturbance.

Hydrological controls provide a continuous subtext informing the interpretation of seasonal variations in water chemistry. Alkalinity, pH, and base cation concentrations in stream water are often highest during summer baseflows and lowest in winter during storm events (Soulsby *et al.* 2002). Conversely minimum NO_3 concentrations have been shown to occur in summer and maxima in winter for rivers of the lower Humber in northern England and upland rivers of northern Scotland (Clark *et al.* 2004; Neal, Davies & Neal 2008). In Scotland for example this can be explained by the climate with wet summers being common and winter base flows occurring when freezing conditions result in streams being drained by groundwater sources. The result is that NO_3 concentrations, although still low, will tend to peak in winter reflecting the influence of low biotic uptake or elution from snowpacks (Soulsby *et al.* 2002). Land use has also been shown to affect anion concentrations. While the main findings of Helliwell *et al.* (2001) relate to differences in pH, it was also reported that NO_3 concentrations in two afforested catchments in the Galloway region of Scotland were consistently higher than in a nearby moorland peat catchment over a 15 year period. The lack of deposition and the retention of N by the peat at the moorland catchment were given as possible explanations for this. It was also found that the forest age had no discernible effect on NO_3 concentrations. In relation to Arecleoch, as well as using a general exploration of major anion data to characterise the area, it is also necessary for the land use change imposed on the forest to provide a backdrop against which to interpret the results. NO_3 release is associated with forest harvesting and can potentially lead to soil and stream acidification (Neal *et al.* 2001) . However, research into the association between NO_3 concentrations and forest harvesting in acidic catchments has produced varied results. In theory when felling is undertaken and biomass uptake is removed, rates of microbial mineralisation and nitrification increase and nitrate generation can occur.

Indeed forested catchments across Scotland over a 15 year study period demonstrated a clear response to felling with one site showing a 10-fold increase in NO_3 concentrations (Harriman *et al.* 2003). These values then declined over the next four years to levels below those pre-felling as the aggrading forest demanded more nitrogen. Other work suggests that increases in nitrate concentration, although seen mainly in the first three years after felling, were found mainly where replanting has not happened and where early autumn storm events had been sampled (Neal *et al.* 1998). Concentrations of Cl and SO_4 in the same study showed only small variations across sites having different felling histories. Cl represents a marine input from the atmosphere but in addition it can be used as a measure of water storage in the catchment from the extent to which the rainfall signal is damped as it passes through the catchment to the stream (Neal *et al.* 2001). Sulphate (SO_4) and non-marine-sulphate (nms) represent major atmospheric anion inputs from both marine and pollutant sources. The marine component is the difference between the total SO_4 and the nms component (determined as the product of the Cl concentration in the water and the ratio of SO_4 to Cl in seawater) (Neal *et al.* 2001). Elevated SO_4 concentrations in any year may be due to high marine SO_4 deposition but that is normally accompanied by similarly elevated Cl concentrations. Contrary to this other studies suggest that atmospheric contribution is not the major source of river loadings for either Cl or SO_4 (Smith *et al.* 2007) and individual high SO_4 values may represent flushing following a dry period.

1.3 The study area and methods

Arecleoch forest has been presented in the introduction above and this description will now be expanded to introduce the catchments at the centre of this part of the research. Most of Arecleoch forest is drained by three catchments (Table 3) radiating outwards from their headwaters in the heart of the forest: The Crosswater (abbreviated to X), and the Tig drain the north of the forest and both discharge into the river Stinchar. The Crosswater of Luce (Abbreviated to XL) drains the southern part of the forest and discharges into the river Luce system. A sample point was established on each of the three catchments and instrumented as described in below. The locations of the sample points are shown in Figure 7 .

These sample points were primarily set up to monitor DOC concentrations and fluxes before and during the development of Arecleoch wind farm. Water samples from the Crosswater of Luce (19.9 km^2 with 21 % subject to disturbance) and Tig (7.5 km^2 with 31 % subject to disturbance) catchments have generated time series data sets that communicate the impacts of disturbance to the peatland from this land use change while the Crosswater (8 km^2) was used as a control catchment as only 0.005 % was disturbed by wind farm construction activities. The exact choice of location for the sample points was however, largely informed by practicality and pragmatism; ease of access, secure attachment points for equipment and relative proximity. Consequently the water samples collected from each of the three catchments captures a different matrix of area, landscape characteristics and land use, as well as varying in features such as aspect and altitude (Table 2).

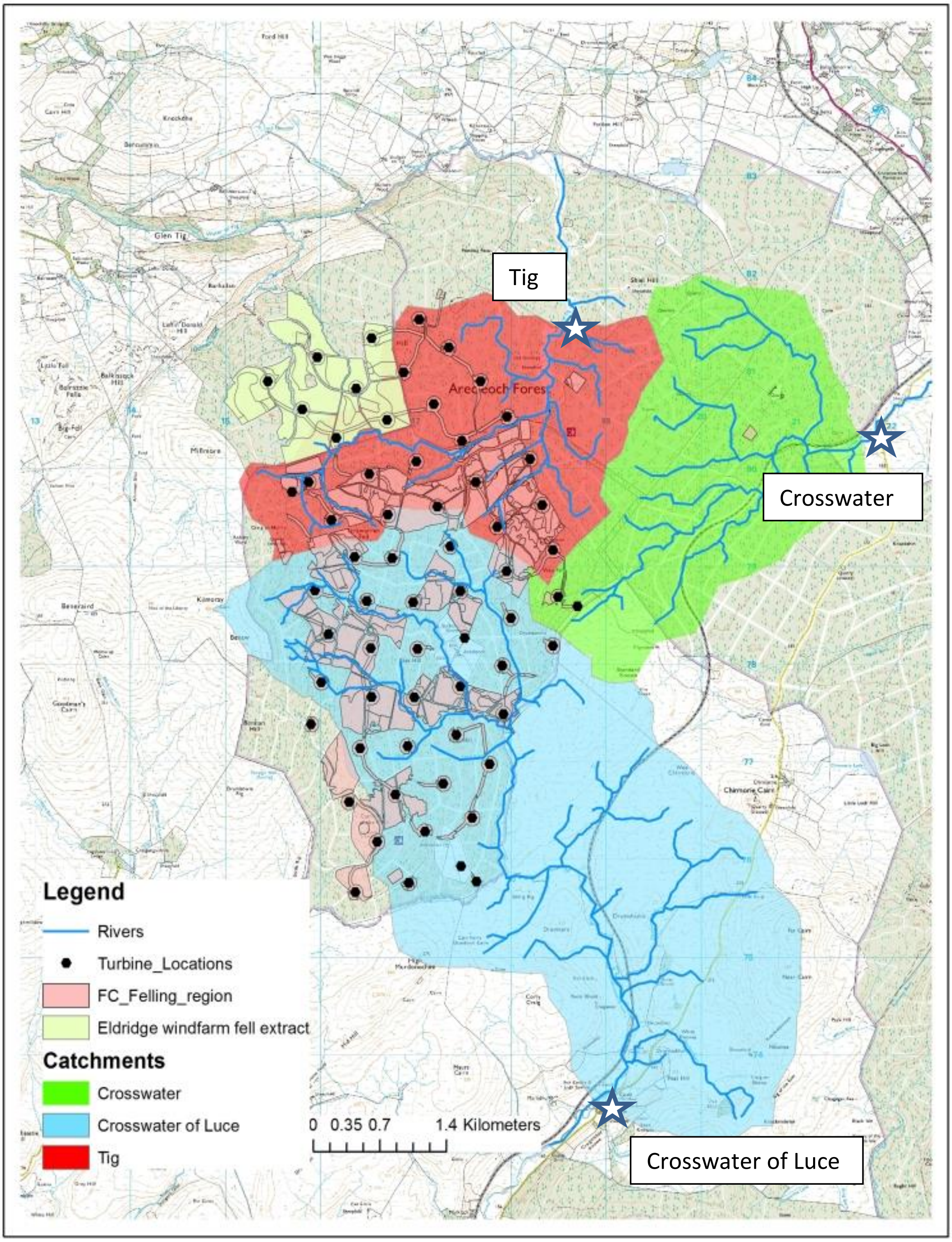


Figure 7. Arecleoch forest showing the catchment boundaries, sample points of Crosswater, Crosswater of Luce and Tig and extent of forest harvesting in the Forestry Commission (FC) and Eldridge Estate regions. (Map based on Ordnance Survey material ©Crown copyright 2001 and supplied by SPR and ArcGIS material). Stars represent catchment sample points.

Table 3. Sample point descriptions for the Crosswater, Crosswater of Luce and Tig catchments

	Crosswater	Crosswater of Luce	Tig
NGR	2168 8028	1887 7345	1855 8147
Catchment area (km^2)	8.0	19.9	7.5
Altitude of source (m)	220	360	310
River length from source to sample point (Km)	4.6	7.8	4.8
[1]Catchment slope (m/km)	104.3	75.3	73.5
Rainfall (mm)			
[2]Long term annual mean 1996 - 2010	1730		
[2]12 month total 2008, 2009, 2010	1875, 1984, 1522		
[3]Temperature (°C)			
Mean annual			
2008	8.31	8.31	8.31
2009	8.40	8.40	8.40
2010	7.19	7.19	7.19
Long term mean (1910 – 2010)	7.78	7.78	7.78
Discharge (m^{3}s^{-1})			
Mean			
2008	0.531	0.961	n/a
2009	0.445	1.103	n/a
2010 Jan – Sept	0.291	n/a	
Mean entire period	0.434	1.032	0.305
Max entire period	6.555	18.544	2.942
Min entire period	0.004	0.001	0.006
Forest (% catchment area)	88	40	100

[1] Catchment slopes calculated from OS 1:250 000 topographic maps. Mean difference in elevation between the upper part of the catchment and the sampling site was estimated and divided by the square root of the catchment area. (Hope *et al.* 1997). [2] Rainfall data from SEPA Lagarfater station (NGR 213933, 575968)

[3] Temperature data downloaded from Met Office website – regional values for the west of Scotland

(www.metoffice.gov.uk/climate/uk/averages/19712000/areal/scotland_w.html)

1.3.1 **Instrumentation of catchment sample points**

Each of the catchments was instrumented as described below at the sample point locations are shown in Figure 7:

- One ISCO 3700 automatic sampler equipped with 24 No 1 litre polypropylene bottles that were pre-washed and acid-rinsed. The samplers were programmed to collect a 750 ml water sample at 17:00 GMT at either 24 or 48 hour intervals so that fluxes and concentrations could be compared between the catchments under similar flow conditions and at the same point in the working day on the wind farm. In addition, the Crosswater and Tig sample points were equipped with rising stage samplers to collect samples at set water depths on the rising limb of a storm. These are described in detail in Theme 2.
- A solar panel was connected to each sampler serving to trickle charge the battery enabling continuity of sample collection over a longer period of time.
- A Level Troll pressure transducer was installed for recording stage every 15 minutes. River gauging was carried out at the time of sample collection over a range of flow conditions. The stage readings were then converted to discharge measurements using stage height – discharge ratings relationships as described in Theme 2.

Both the Crosswater and Crosswater of Luce were instrumented from the beginning of 2008 while data was not gathered from the Tig until July 2009. Monitoring continued at all three sample points until the end of September 2010. The instrument at the Crosswater remained operational throughout this period providing a semi-continuous stage record for the entire project. At the Crosswater of Luce the pressure transducer was damaged, possibly by debris or ice, in January 2010 and was not replaced until June 2010. A new pressure transducer and logger were installed on 18th June 2010 and one set of data from this was uploaded on July 18th 2010. Unfortunately thereafter the logger developed a fault and no further data could be recovered. The pressure transducer and data logger were installed at the Tig when that site was instrumented in July 2009. In January 2010 the pressure transducer here was also damaged, again the weather conditions at the time lead one to speculate that large debris or pieces of ice were responsible. The site was re-instrumented on 25th May 2010 and stage recording continued uninterrupted until the site was decommissioned at the end of September 2010. The period of monitoring encompassed one of the coldest winters on record and large floods events that severely tested the equipment.

1.3.2 **Sample collection and storage**

Water samples from the automatic samplers were collected approximately every three weeks. Bottles were returned to the laboratory as soon as possible and kept at 4°C in the dark pending filtration. Kalbitz *et al.* (2003) discovered a mineralisation of only 3 – 9 % of DOC from aqueous peat extracts over a period of 90 days thus the effects of storage on carbon loss were deemed to be negligible. Water samples for the spatial surveys in Theme 3 were collected manually every three months in acid-washed 500 ml plastic bottles, rinsed with stream water before collection.

1.3.3 **Laboratory analysis**

Filtration and suspended sediment

A summary of the number of samples collected for each experiment is provided in Appendix 1. Samples were filtered under vacuum, usually within 48 hours of collection, using pre-weighed (dried at 105 °C) nominal pore size 0.7 µm GF/C (Fisherbrand) filter papers, and suspended sediment estimated. Thereafter analysis for DOC, absorbance at 400 nm, and major anions was carried out on the filtrate using the methods described below.

DOC is defined as the fraction that passes through a 0.45 um filter thus the use of a nominal pore size larger than that means that an overestimate of DOC concentrations is possible. However, there was a practical advantage to using glass fibre filters as this eliminates the bleed into DOC that has been experienced with the use of polymeric filters (Strack *et al.* 2011) and the overestimate was considered to be negligible. It was also necessary to use a filter that would be unaffected by ashing at 350 °C for POC analysis

DOC

DOC concentrations were determined within 2 weeks of sampling using a Shimadzu TOC 5000 carbon analyser. Glass vials were washed in a 2 % Decon™ solution and rinsed with de-ionised water. Total carbon (TC) was measured directly and DOC was estimated by measuring dissolved inorganic carbon (DIC) and then subtracting it from TC. This method rather than the alternative NPOC was used as IC concentrations were less than 10 mg L^{-1}. Samples were analysed in triplicate to a coefficient of variation of 2%. TOC and TC Standards were diluted from 1000 mg C L^{-1} stock solutions to 100, 50, 10 and 5 mg C L^{-1}. All determinations were corrected against a system blank using deionised water.

Major anions

Nitrate, chloride and sulphate anion concentrations were determined using a Dionex DX 120 ion chromatograph. The samples were run against a three point calibration curve and de-ionised water was used as a blank. Blanks and standards were run after every tenth sample.

Absorbance

UV Absorbance was measured using a Helios Epsilon spectrophotometer with quartz cuvettes of either 1 cm or 4 cm optical path lengths. Distilled water was used as a blank and also as a reference, which was run every 15 samples. Measurements from a random selection of samples were duplicated to ensure the repeatability of the results.

1.3.4 **Data analysis**

The DOC data for the Crosswater and Crosswater of Luce were seasonally separated into high and low DOC periods. Various methods have to do this have included using DOC – discharge relationship and monthly mean temperatures (Dawson *et al.* 2002; Dawson *et al.* 2008). The lack of a clear DOC – discharge relationship at Arecleoch meant that the method used by Grieve & Marsden (2001) was considered to be more appropriate. A sine wave was fitted over the DOC concentration time series and is illustrated for the Crosswater in Figure 8 with the same sine wave fitted to the Crosswater of Luce time series. The high DOC period was defined as that corresponding to sine values from + 0.5 to + 1.0 and the low DOC period was considered to correspond to sine values from - 0.5 to - 1.0. Applying dates to these values gives a high DOC period between 14th July and 12th November and a low DOC period falling between January 13th and May 12th. High DOC values for the Crosswater and Crosswater of Luce were extracted and examined statistically by year. It should be noted that only a partial data set is available for 2010 as monitoring finished at the end of September. However this was the same for both catchments so a comparison can still be made.

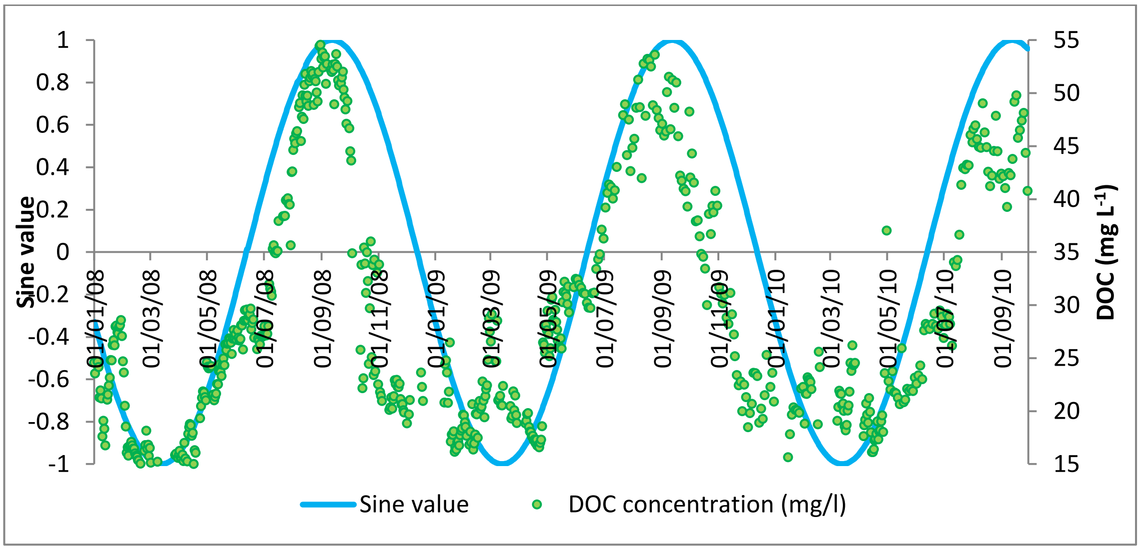


Figure 8. Time series of DOC concentrations at the Crosswater fitted with a seasonal sine wave N = 667.

Statistical analyses were performed using R v 2.11.1 (R Development Core Team) and Minitab v 16. All statistical analyses were performed to a 95 % level of confidence.

1.4 Results

1.4.1 DOC Concentrations at the Crosswater, Crosswater of Luce and Tig

Descriptive statistics for the three catchments are shown in Table 4. DOC concentrations observed at other Scottish peatland catchments range between 0.4 and 43.6 mg L^{-1} (Dawson *et al.* 2002; Grieve & Gilvear 2008; Waldron *et* *al.* 2009). DOC concentrations across the three catchments at Arecleoch between January 2008 and September 2010 exceeded this with a range from 2.38 t0 65.21 mgL^{-1}. The highest (65.21 mg L^{-1}) concentration was obtained from the Tig while the lowest (2.38 mg L^{-1}) was found at the Crosswater of Luce. Concentrations at the Crosswater lay between the other two sites except in terms of the minimum value, which was higher, at 12.39 mg L^{-1}.

Table 4 Descriptive statistics for DOC concentrations (mg L^{-1}) at the Crosswater, Crosswater of Luce and Tig catchments

Catchment	*n*	*Mean*	*SD*	*Median*	*Max*	*Min*
Crosswater	667	28.41	11.28	24.76	54.54	12.39
Crosswater of Luce	498	21.70	9.66	17.97	47.34	2.38
Tig	274	35.13	12.63	31.35	65.21	7.31

Differences in median DOC concentrations were analysed statistically using the Mann-Whitney test and found to be significantly higher at the Crosswater than the Crosswater of Luce across the whole monitoring period ($W = 48096$; $p < 0.05$). Tested in the same way median concentrations at the Tig were significantly higher than at the Crosswater ($W = 53934$; $p < 0.05$) using values corresponding to the sampling range of the Tig. These two catchments are fairly similar in many respects with the main difference being in the exposure of much of the Tig to the Arecleoch wind farm development, which was under way when monitoring began there in July 2009.

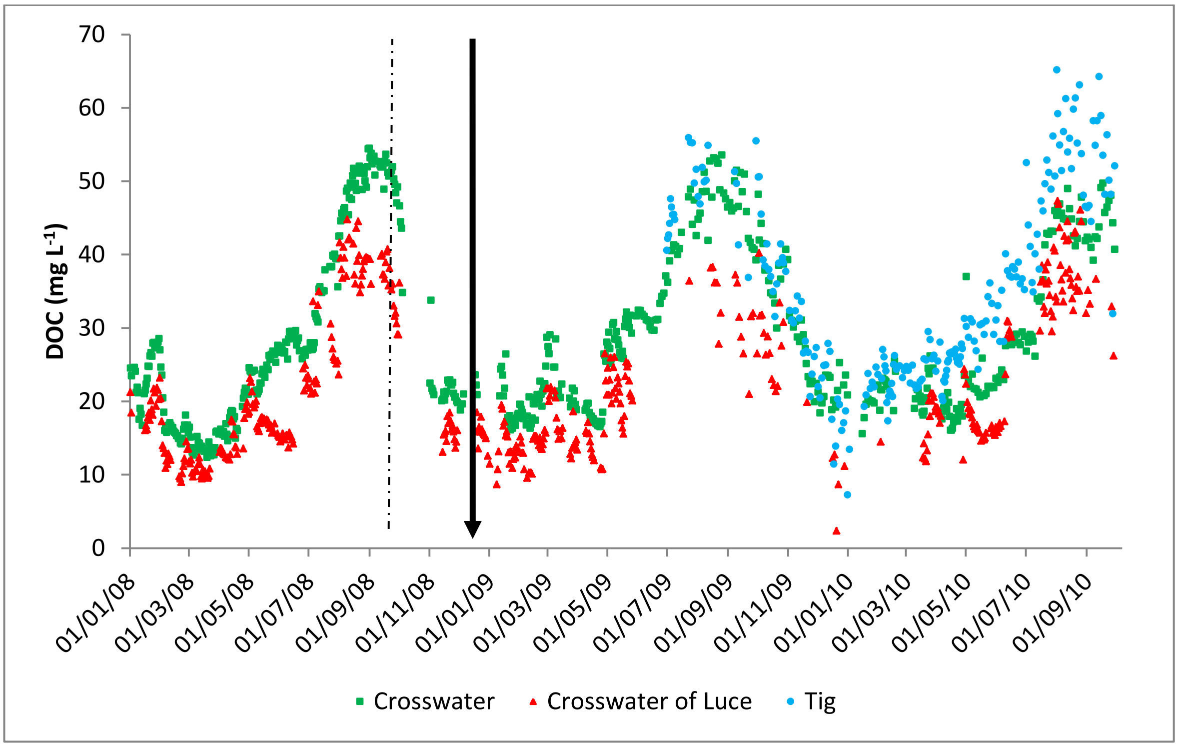


Figure 9 Concentrations of dissolved organic carbon (DOC) at the Crosswater, Crosswater of Luce and Tig between January 2008 and September 2010. The vertical arrow indicates the start of wind farm construction work on site by SPR on 1st November 2008. Dotted line represents start of PhD on 01/10/08

Concentrations of DOC at the three sample points exhibited the familiar seasonal pattern (Figure 9) with maxima in late summer/ early autumn and minimum values from the end of winter through to the beginning of spring. Gaps in the DOC record of the Crosswater of Luce in June and July 2009 and between November 2009 and April 2010 were due to equipment failure on site. Of the three winters included in the data set 2008 is different in that the low DOC period is fairly compact and concentrations show little variability about the sine wave pattern. Conversely the low DOC period of 2009 and 2010 is described by a flatter and less well-defined region covering a longer time frame. This is likely to mirror weather conditions over the three winters with 2008 being the last of a series of mild winters before two extremely cold winters, which resulted in long periods of below zero temperatures and frozen burns. The lowest value recorded was 2.38 mg L^{-1} at the Crosswater of Luce on 20th December

2009 and this was closely followed by 7.31 mg L^{-1} at the Tig on the 31st December 2009. Both of these data points occurred during a very cold period when the water temperature recoded by the pressure transducers in each stream read 0.5°C (Crosswater of Luce 20th December 2009) and 0.1 °C at the Tig on 31st December 2009. It is likely that both streams were covered with ice at the time as this was observed during fieldwork two weeks later. Under these conditions the movement of DOC from soil water to stream would be restricted and it is known from experiments relating to the freezing of samples that DOC precipitates out of solution when frozen, leading to lower concentrations being recorded (Fellman, D'Amore & Hood 2008; Spencer, Bolton & Baker 2007). Interestingly the low temperatures do not appear to have affected DOC concentrations at the Crosswater in the same way as the minimum of 15.62 mg L^{-1} is not as low as in the milder winter of 2008 (12.39 mg L^{-1} on 19th March 2008). Although the same annual DOC pattern is observed by the three catchments, concentrations at the Crosswater are significantly higher than those at the Crosswater of Luce. It is noticeable that there are patterns of successive falling DOC concentrations, particularly within the Crosswater of Luce data. These values were examined to identify where they arose in relation to a particular sample set. The concern was that there might be a pattern of falling DOC concentrations over a set of 24 samples that could suggest some deterioration in sample quality due to storage in the autosampler. However, it was established that these values, although sequential, did not comprise an entire sample set and concentrations rose again before the samples were retrieved. The cause of this pattern currently remains unexplained. From Figure 9 it can be seen that although DOC concentrations were higher at the Crosswater than the Crosswater of Luce the difference appears less during the peak of 2010 than in either 2009 or 2008. The difference in median DOC concentrations between the Crosswater and Crosswater of Luce during the "high" DOC period was 9.84 mg L^{-1} in 2008, this rose to 13.84 mg L^{-1} in 2009 and narrowed again in 2010 to 7.70 mg L^{-1} (Table 5). Using the Mann-Whitney test to compare "high" DOC concentration data at the two catchments for each year demonstrated that there remained a statistically significant difference in the median concentrations at the 95% confidence level (Table 5). The relationship between discharge and DOC concentration for the Crosswater, Crosswater of Luce and Tig is shown in Figure 10. For each catchment this is different with the Crosswater displaying no evidence of a correlation. At the Crosswater of Luce 31 data points were excluded from this part of the analysis due to problems with flow measurements that returned zero values. From the remaining data a slight positive relationship can be discerned and at the Tig there appears to be more than one relationship visible between the parameters with a positive correlation running through the centre of the data.

Table 5. Summary of Mann-Whitney statistical comparisons of median DOC concentrations (mg L^{-1}) in the "high" DOC range between the Crosswater (X) and Crosswater of Luce (XL) for 2008, 2009 and 2010

Year	*Median DOC (mg L^{-1})*		*Difference in median DOC concentration (XL – X) (mg L^{-1})*		
	X	XL		P value	Test statistic
2008	47.08	37.24	9.84	0.00	8842
2009	44.28	30.80	13.48	0.00	3354
2010	44.07	36.37	7.70	0.00	2529

1.4.2 **DOC - discharge relationship**

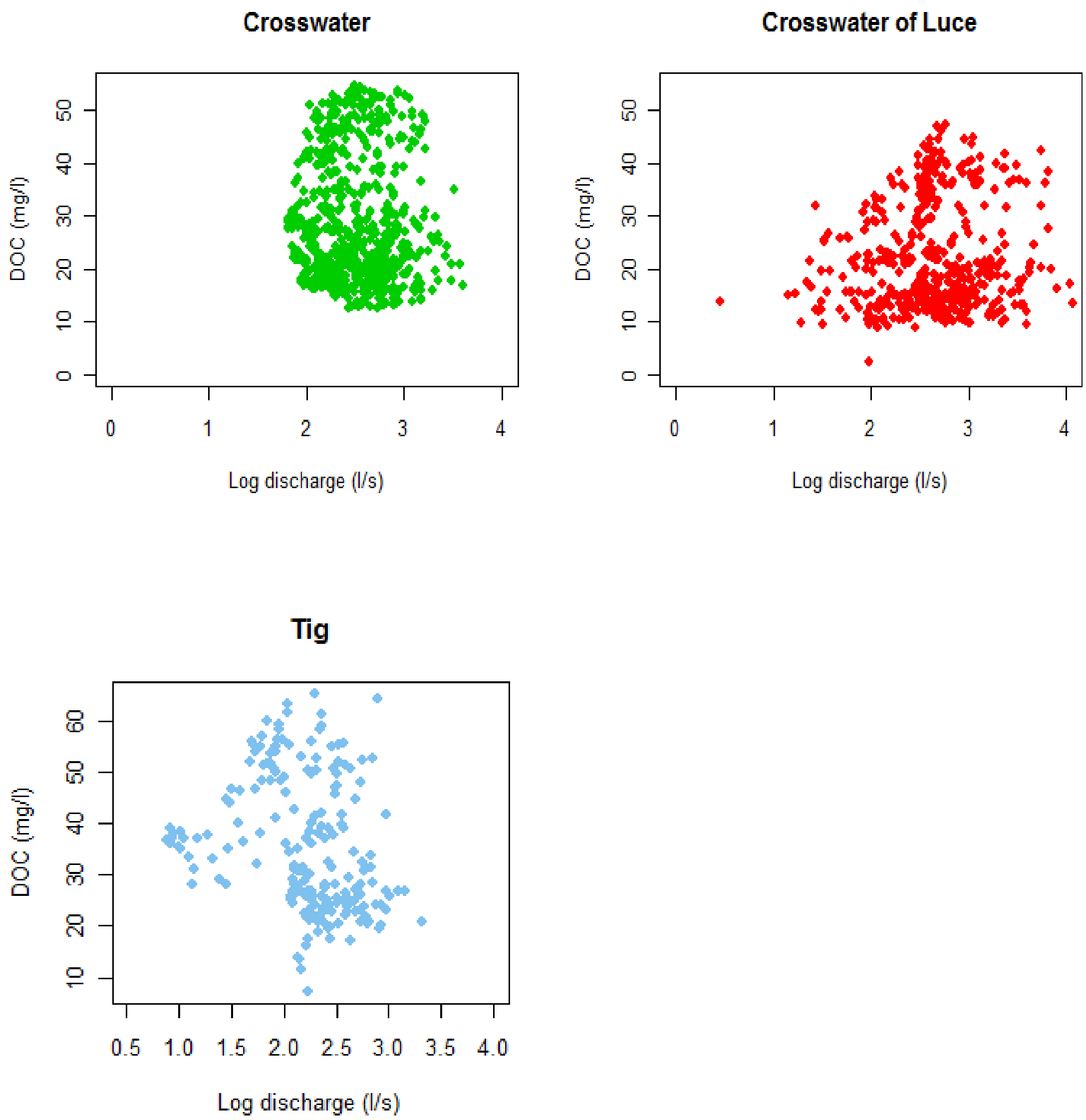


Figure 10. Association between DOC concentration (mg L^{-1}) and discharge ($Log_{10}Q$ (l/s)) at the Crosswater (N = 667), Crosswater of Luce (N = 498) and Tig (N = 274) catchments

Because of the strong seasonal patterns associated with DOC, the data were divided according to season and the correlations re-examined for each catchment. Here as for all subsequent data analysis the seasonal divisions follow the hydrological year:

Autumn = October, November, December
Winter = January, February, March
Spring – April, May, June
Summer = July, August, September

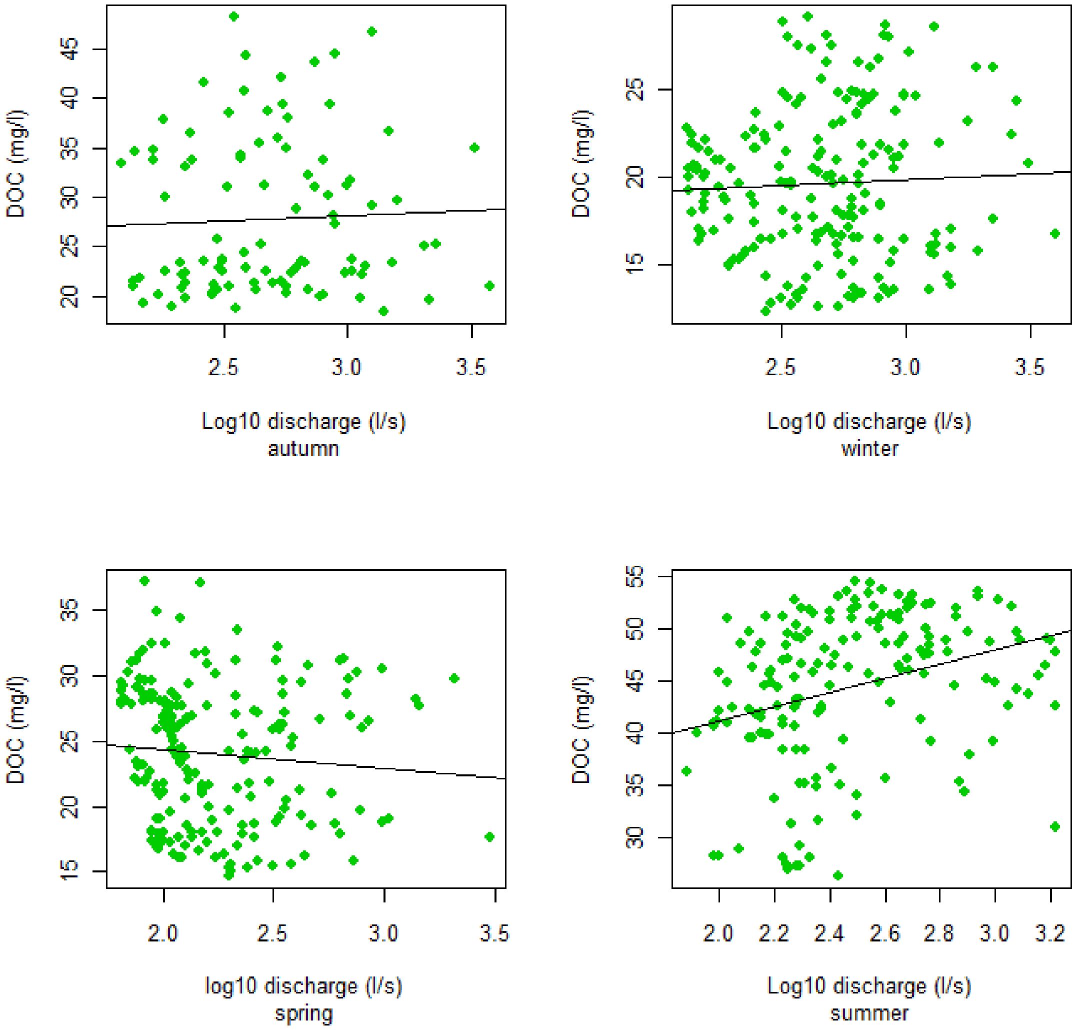


Figure 11. Association between DOC concentration and Log_{10} discharge at the Crosswater by season. N = 98 autumn, 194 winter, 201 spring, 174 summer.

Separating the Crosswater data by season (Figure 11) improved the relationship between DOC concentration and discharge slightly and associations were explored statistically using the Spearman Rank correlation test. Significant relationships were found for summer (positive) and spring (negative) but associations for autumn and winter were weakly positive and non-significant. Correlations were run using raw and $llog_{10}$ values for DOC and discharge but the significance of association was unaltered.

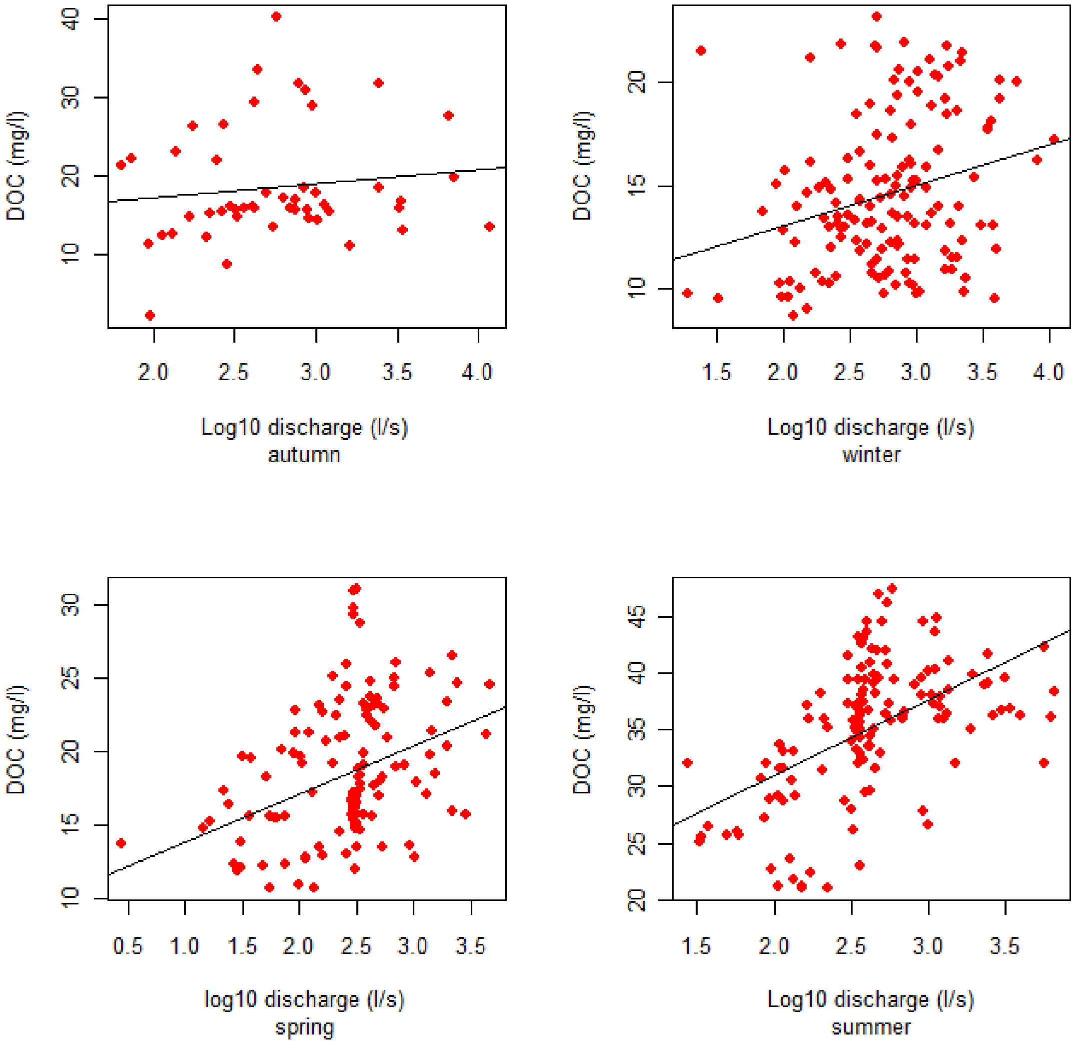


Figure 12. Association between DOC concentration and Log_{10} discharge at the Crosswater of Luce by season. N = 49 autumn, 151 winter, 152 spring, 146 summer.

DOC concentration and discharge were positively correlated for all seasons at the Crosswater of Luce (Figure 12). These were statistically significant for spring, summer and winter but not for autumn.

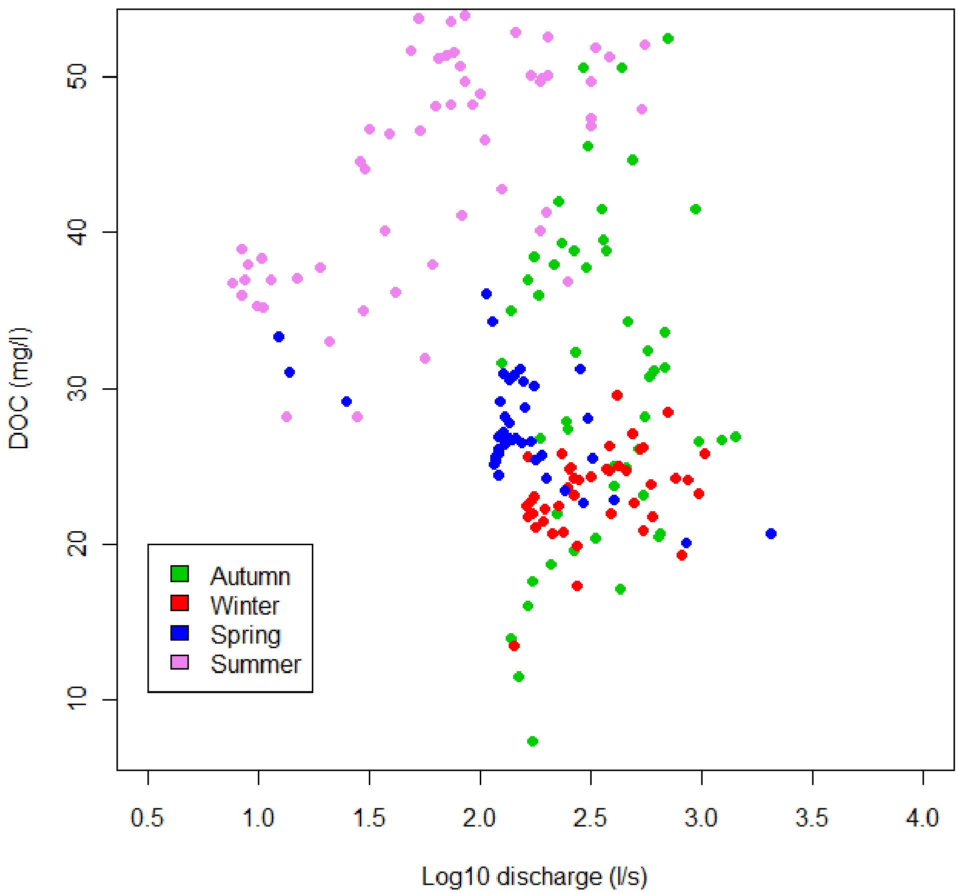


Figure 13. Association between DOC concentration and Log_{10} discharge at the Tig by season

The data are presented differently for the Tig (Figure 13) to enable a visual examination of the seasonal apportionment of the values. It can now be seen that the positive linear association in the centre of the plot plus the higher DOC concentrations belong to the summer sub-set of data. There are also six points in this group that come from spring ie having relatively high DOC concentrations for the given discharge. This is because the spring samples sub-set as a whole exhibits a negative correlation between DOC and discharge. Associations between the variables in autumn and winter are less distinct. Correlations for each season at the Tig were tested statistically using the Spearman Rank correlation test and a 95% significance level. From this we discover that positive correlations in summer and winter were significant while that of autumn was not. The negative association in spring was also significant. Table 6 summarises the seasonal correlations of DOC concentration and discharge at the three catchments.

Table 6. Summary of correlations between DOC concentration and Log_{10} discharge at the Crosswater, Crosswater of Luce and Tig catchments. Key: + = positive, - = negative, * = significant at 95%

	Crosswater	Crosswater of Luce	Tig
Spring	- *	+ *	- *
Summer	+ *	+ *	+ *
Autumn	+	+	+
Winter	+	+ *	+ *

Divided in this way summer is the only season where a significant positive association exists between DOC concentration and discharge for all catchments and the Crosswater of Luce is the only catchment which exhibits a positive correlation across all seasons. The negative correlations found in spring at the Crosswater and Tig may be a function of smaller catchment area and more intimate contact with the surrounding peaty soils. Thus they would be more likely to respond more quickly to rainfall with DOC being flushed out at relatively low flows and then reflecting either an exhaustion of supply or a dilution effect at higher flows. Conversely at the Crosswater of Luce it can be postulated that DOC may already have undergone some processing and the larger catchment size may offer a larger and more dispersed DOC pool from which to draw through the course of a storm event, resulting in positive correlations with discharge.

1.4.3 **Major anion concentrations**

Summary statistics for major anion concentrations at Arecleoch catchment sample points are shown in Table 7. At Arecleoch as observed elsewhere (Neal *et al.* 2001) Cl is the dominant anion, followed by SO_4 and NO_3. Pooled ion concentration data from all three catchment sample points were collated by year as illustrated in Figure14. The highest NO_3 concentration was 13.55 mg L^{-1} (Tig in 2010) and the median was 0.34 mg L^{-1}. The mean NO_3 concentration of 0.43 mg L^{-1} was higher than any of the monthly mean concentrations found by Clark *et al.* (2004) carried out across 13 upland catchments of northern Scotland and which ranged from 0.03 mg L^{-1} in August to 0.12 mg L^{-1} in December. At Arecleoch monthly mean NO_3 concentrations (not shown) did not exhibit the seasonal pattern reported by Clark *et al.* (2004) and each year several elevated concentrations appear as outliers (Figure 16) with this number being greatest in 2010, the year having the greatest overall variability in NO_3 concentrations. SO_4 concentrations ranged from 0.38 mg L^{-1} to 29.47 mg L^{-1} (Tig, 2010) and followed a similar pattern to NO_3 with the highest concentration of 29.47 mg L^{-1} at the Tig on July 7th 2010 and all values in excess of 12 mg L^{-1} coming from that year and from the Tig catchment (Figure 15). Median concentrations of NO_3 and SO_4 were significantly higher (Mann-Whitney, $p < 0.05$) in 2010 than in 2008 and 2009.

Table 7. Summary statistics for chloride, nitrate and sulphate concentrations (mg L^{-1}) pooled across all catchments at Arecleoch. N = number of samples

Variable	*N*	*Mean*	*StDev*	*Minimum*	*Median*	*Maximum*
Chloride	1325	11.59	3.92	0.19	10.66	24.85
Nitrate	1327	0.43	0.94	0.00	0.34	13.55
Sulphate	1326	3.96	2.90	0.38	2.98	29.47

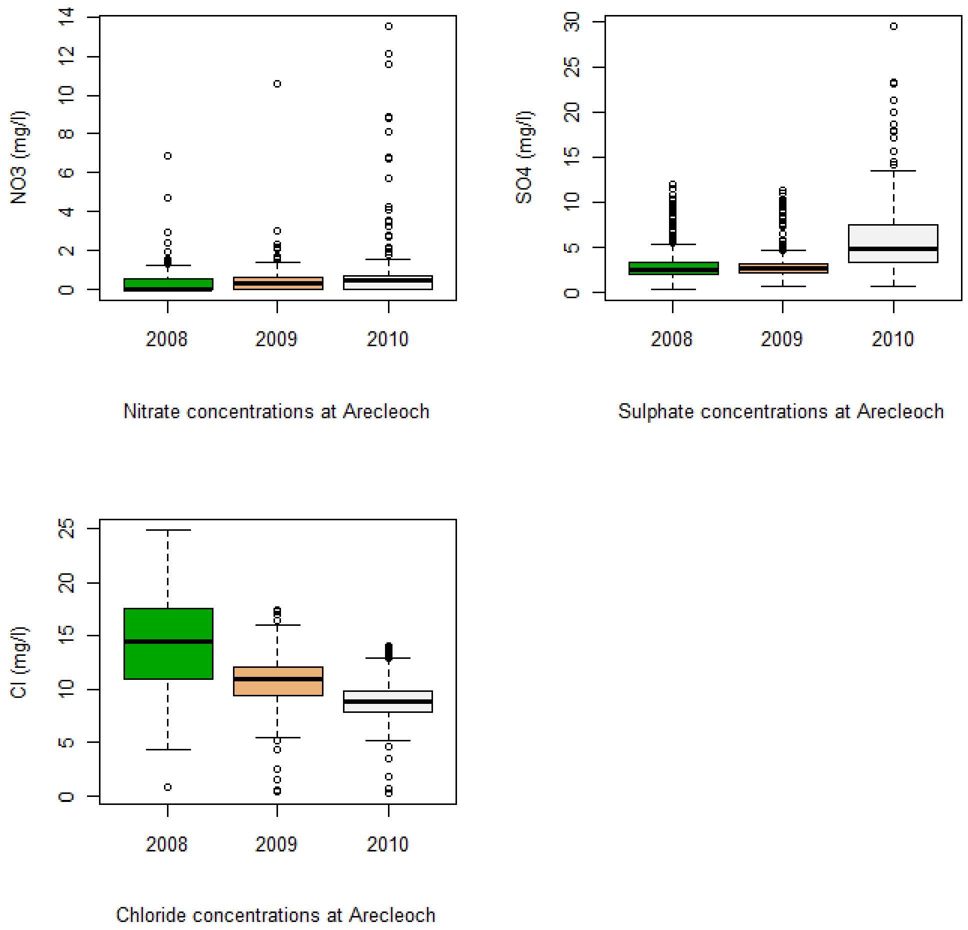


Figure 14. Ranges of major anion concentrations (mg L^{-1}) pooled across all catchments at Arecleoch and divided by year

Patterns in chloride concentration were different in that highest value of 24.85 mg L^{-1} was found at the Crosswater in 2008. In fact all concentrations above 21 mg L^{-1} were from 2008 and all but three of these (Crosswater of Luce) were found at the Crosswater (Figure 15). Differences were explored statistically using the Kruskal-Wallis test and median concentrations of SO_4, Cl and NO_3 were found to differ significantly ($P < 0.05$) between all of the three catchments. Using the pooled data for all there catchments, Cl concentrations showed a significant ($p < 0.05$) decrease from 2008 to 2009 and from 2009 to 2010.

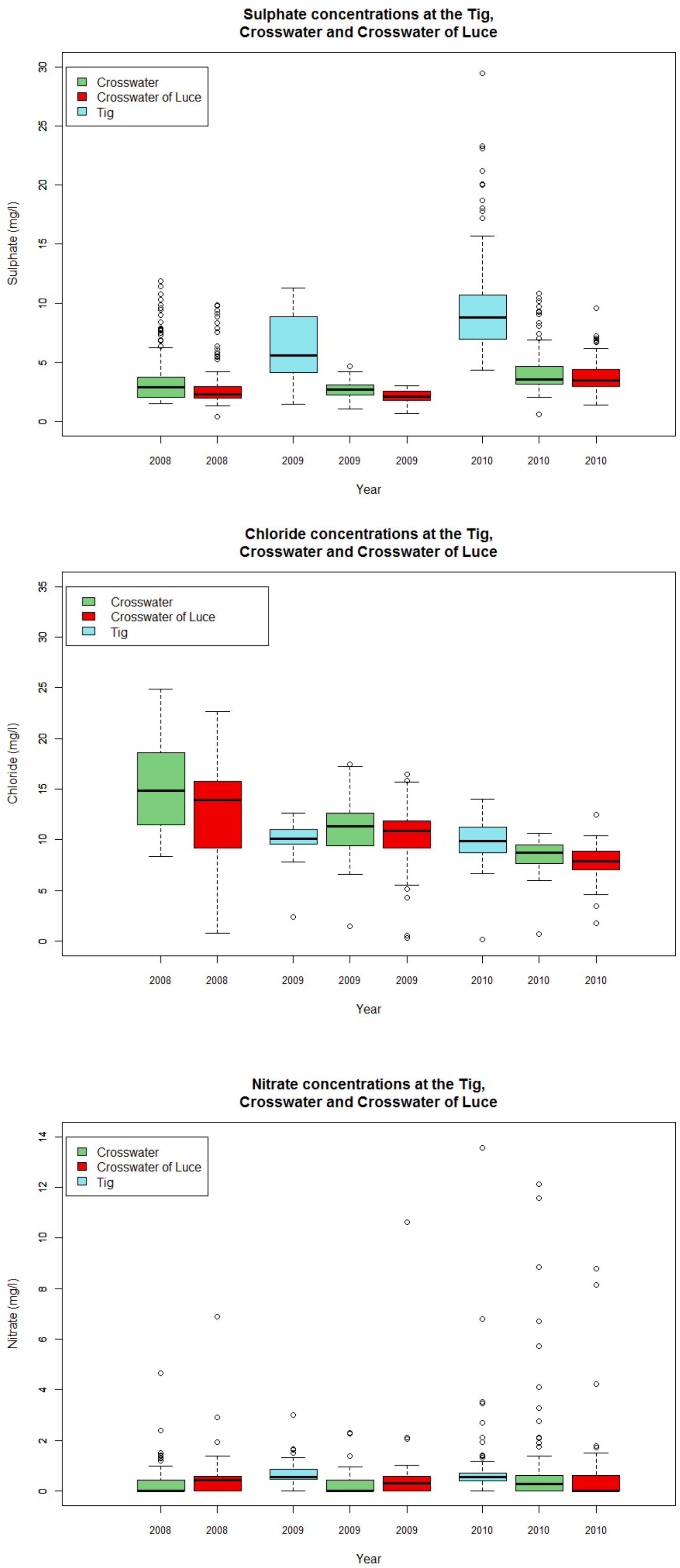
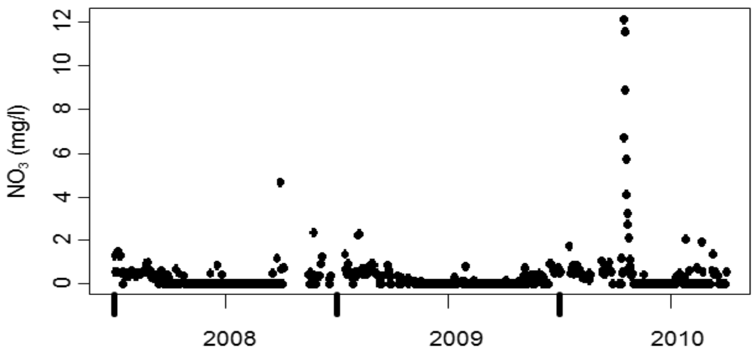


Figure 15. Ranges of major anion concentrations (mg L^{-1}) at Arecleoch divided by catchment and year

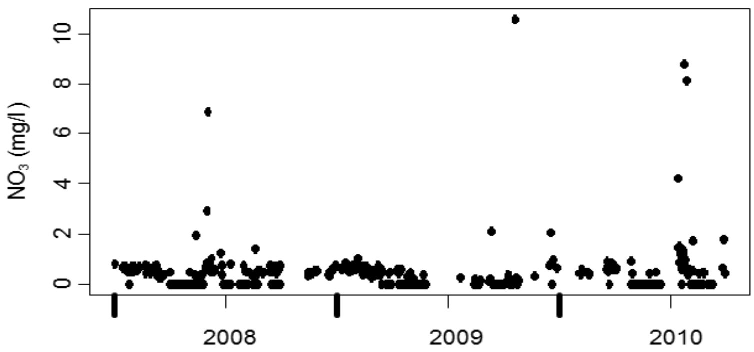
Table 8. Summary statistics for major anion concentrations (mg L^{-1}) at the Crosswater of Luce, Crosswater and Tig catchment sample points

	Crosswater of Luce			Crosswater			Tig		
Variable	*CL*	*NO_3*	*SO_4*	*Cl*	*NO_3*	*SO_4*	*Cl*	*NO_3*	*SO_4*
N	509	510	509	664	648	663	207	206	208
Mean	11.13	0.45	2.84	12.54	0.36	3.29	10.06	0.73	8.72
SE Mean	0.17	0.03	0.06	0.16	0.036	0.061	0.12	0.08	0.27
StDev	3.11	0.86	1.38	4.23	0.92	1.59	1.75	1.13	3.83
Minimum	0.35	0.00	0.38	0.13	0.00	0.63	0.19	0.00	1.43
Median	10.29	0.40	2.50	11.55	0.00	2.97	10.00	0.56	8.30
Maximum	22.64	10.61	9.85	24.85	12.11	11.90	14.02	13.55	29.47

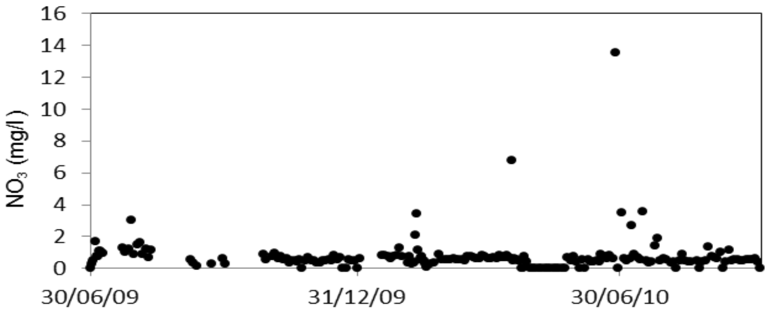
Nitrate concentrations in particular exhibited outliers at the high end of the range and the temporal distribution of these can be seen more clearly in a time series plot (Figure 16). At the Crosswater the highest NO_3 values all appeared sequentially over a short time period in April 2010. This being the control catchment for the wind farm catchment comparative study, there was very little disturbance in the catchment and SPR records indicate only cable laying at that time. However, forestry activity has not been comprehensively recorded and it was observed during field work that forest clearance for the grid connection was taking place in the Crosswater catchment. It is possible that the pulse of elevated NO_3 concentrations came from those felling activities. Harriman *et al.* (2003) found NO_3 concentrations in an upland forested peat catchment in Scotland varied between 0.62 and 1.24 mg L^{-1} before felling. They also found a tenfold increase in these concentrations after the forest was harvested, corresponding to a maximum of 12.4 mg L^{-1}. These concentrations are consistent with data from Arecleoch. High NO_3 concentrations from the Crosswater of Luce and Tig were more widely distributed through time with many being individual values rather than a more sustained pulse. In such instances speculation as to a cause is inadvisable.



a Crosswater



b Crosswater of Luce



C Tig

Figure 16. Time series plots of nitrate concentrations at the Crosswater, Crosswater of Luce and Tig catchment sample points

1.5 Discussion

The aim of Theme 1 was to interpret DOC and major anion concentrations from three catchment sample points draining Arecleoch forest monitored at a high frequency (24 or 48 hourly). For the purposes of investigating the impact of the Arecleoch wind farm development on DOC concentrations, the Crosswater catchment was used a control as it has very little wind farm activity within it. The Crosswater of Luce and Tig were the experimental catchments. DOC concentration data were available for the Crosswater and Crosswater of Luce from January 2008 to September 2010 whereas the Tig was only operational between July 2009 and September 2010. Median DOC concentrations followed the order:

Tig > Crosswater > Crosswater of Luce

The relatively high concentrations of the Tig and Crosswater compared to the Crosswater of Luce are thought to be a function of the catchment size and land use. The Crosswater and Tig are small and largely forested while the Crosswater of Luce is a much larger catchment with a lower proportion of forest cover and much of it has been under a less intrusive land management regime (rough grazing vs commercial forestry) until the arrival of Arecleoch wind farm (Table 2). Wind farm construction started on 1st November 2008 and was ongoing at the time sampling ended on 30th September 2010.

The hypothesis being tested in this theme was that **DOC concentrations will be significantly higher at sample points subject to disturbance from the wind farm activity (Crosswater of Luce and Tig) and at times of greater construction activity (November 2008 to September 2010) than at the control sample point (Crosswater)**

and during the baseline period before construction began (January 2008 – October 2008).

The evidence presented in this Theme partially supports the hypothesis in that the Tig catchment had significantly higher ($p < 0.05$) DOC concentrations than the Crosswater and Crosswater of Luce catchments. The significantly higher DOC concentrations at the Tig than the Crosswater cannot be explained in terms of catchment characteristics (they have similar forest cover and land use (Table 2)) and may therefore be due to differences in anthropogenic activity in the form of Arecleoch wind farm, which was greater in the Tig catchment. For the comparatively short monitoring period at the Tig, this site exhibited the highest DOC concentrations of the three catchments but there was no baseline data set for the Tig from before the wind farm construction started.

The hypothesis cannot be supported for the Crosswater of Luce. DOC concentrations were significantly higher ($p < 0.05$) at the Crosswater (control) catchment than the Crosswater of Luce (experimental) catchment for the whole monitoring period. Using the period of peak DOC concentrations (14th July and 12th November) to make a comparison between the Crosswater (control site but higher baseline DOC concentrations) and Crosswater of Luce (disturbed site but lower baseline DOC concentrations) the difference in median DOC concentrations increased from 9.84 mg L^{-1} in 2008, to 13.84 mg L^{-1} in 2009 and narrowed again in 2010 to 7.70 mg L^{-1} (Table 5). No significant ($p < 0.05$) decrease in the difference in median DOC concentrations between the two catchments was found for 2009 or 2010 when construction on the wind farm was taking place and thus this part of the hypothesis is not supported.

DOC concentrations at the Crosswater, Crosswater of Luce and Tig exhibited a strong, seasonal cycle. The cold winters of 2009 and 2010 may have caused a change in the shape of this sine wave to produce longer, flatter “low DOC” periods in those years than in 2008 at the Crosswater and Crosswater of Luce. The Tig was not instrumented in 2008 and so a comparison could not be made for this site.

Also in this Theme the complex relationship between DOC concentration and discharge was investigated. DOC concentrations were positively associated with discharge at the Crosswater of Luce and Tig sample points and the nature of the association became clearer when the data were divided seasonally. Correlations between DOC and discharge were positive for all seasons at the Crosswater and for all seasons except spring at the Crosswater of Luce and Tig. Here the correlations were significant and negative. Associations were weakest at all sample points for autumn. This was the only season where correlations were non-significant at the 95 % confidence level across all sites. The reason for the weaker autumnal association may be due to the time period over which the season is integrated. Autumn comprises October, November and December, which marks the falling limb of the annual DOC cycle. Peak DOC concentrations are found in September and values, as in the trough of winter achieve a plateau between August and October. From October however the rivers will be receiving variable exports from the soil representing the “post-first-flush” of DOC and this can be highly dependent upon antecedent conditions. Thus if September has been dry and less of the new DOC has been flushed out one would expect a different DOC-discharge relationship to a situation where late summer storms had already caused much of the DOC to be exported from the catchment. Thus autumn represents a particularly sensitive time frame and assessing the most appropriate division of this season is important. Indeed a case may be put forward for the use of a “DOC year” for data interpretation. This could comprise a simple “low” and “high” DOC division of January to June and July to December respectively.

Major anion concentrations were measured and NO_3 and SO_4 concentrations across the three catchments were higher in 2010 than in 2008 and 2009 while Cl concentrations were significantly lower each year. The interception by forests of marine salts such as Cl can lead to higher concentrations of these in runoff water (Harriman *et al.* 2003) and conversely it may be expected that removal of forest as was seen across substantial portions of Arecleoch in the latter years of the study may have led to the lower Cl concentrations being reported. While overall NO_3 concentrations were low with a median value of 0.34 mg L^{-1} significant outliers reaching a maximum of 13.55 mg L^{-1} at the Tig were also found and it is thought that these peaks may be caused by forest harvesting (Harriman *et al.* 2003). However high NO_3 concentrations at the Tig and Crosswater of Luce catchments were represented by individual values making the attribution of a cause difficult. The Tig catchment along with the Crosswater was almost entirely forested at the start of the study unlike the Crosswater of Luce. Also unlike the Crosswater, extensive forest harvesting took place within the Tig catchment that may have increased NO_3 concentrations further.

In a study of long-term water chemistry data across 37 acidified upland streams and lochs in Scotland annual median concentrations of SO_4 and Cl showed a significant decline with the greatest trend being seen in streams draining catchments in which commercial forest had been felled. This was due to the reduction in the interception of sea salt aerosols as a result of felling (Harriman *et al.* 2003). In the case of Arecleoch forest harvesting could account for falling Cl concentrations but not the increase in SO_4. It also seems unlikely that the increased SO_4 concentrations were caused by a flushing event following a dry periods because, as discussed above 2008 and 2009 were wet years relative to 2010.

Theme 2. Arecleoch hydrology and DOC flux

Theme two is centred on describing Arecleoch forest from a hydrological perspective and also exposing some of the practical difficulties encountered in attempting to gather a comprehensive data set from a 'real world' hydrological monitoring programme.

The specific aims of theme 2 are to:

- Investigate the relative merits of alternative choices for accounting for gaps in stage records at the Crosswater of Luce; and
- Characterise DOC flux for each of the three catchments over three years (2008 – 2010);

Two hypotheses will be tested in this theme:

Firstly that **annual DOC export from the Crosswater catchment will be significantly higher than DOC export from the Crosswater of Luce catchment when standardised for catchment area**.

Secondly that **the export of DOC from the Crosswater of Luce as a proportion of that from the Crosswater per unit area will be higher after wind farm activity starts in the Crosswater of Luce catchment.**

The catchments of the Crosswater, Tig and Crosswater of Luce have been introduced in theme 1.3 and the sample points are shown in Figure 17, Figure 18 and Figure 19. Some of their intrinsic differences are described in Table 3 and these differences will affect the hydrological responses of each catchment, for while precipitation falling in the heart of the forest will enter the surface water system via similar pathways, the journey thereafter to the sample points will differ. Along the way, sub-surface flow through the soil will flush DOC from soil pores into the aquatic system and the manner and rate at which this is achieved will be different for the three catchments. Within the soil there are slow and rapid hydrological pathways that are largely related to depth (surface, shallow, sub-surface and deep) and are dependent on features such as macropores (Holden & Burt 2003a). The turnover time of water may be measured in months in the soil profile and in hours or days along the streams and rivers and the turnover time of carbon will also vary. The qualitative composition of DOC is a result of biotic processes (bacterial activity), while the concentration and flux of DOC may be regulated more by abiotic-biotic linkages and by direct abiotic processes (adsorption, stream flow) (McDowell & Likens 1988). For example in the study by McDowell & Likens (1988), carried out at Hubbard brook Valley New Hampshire, increases in soil solution DOC concentrations were found at a forest floor following whole tree harvesting. However these were not matched by similar increases in stream water DOC concentrations due to adsorption of DOC by the mineral soils. The authors also put forward that similar abiotic – biotic linkages can occur in water courses where adsorption of DOC by stream sediment followed by metabolism by benthic microflora explained the relatively low and constant DOC concentrations found.

Figure 17. Crosswater sample point – a turbulent cobble/boulder bed stream - facing upstream (top) indicating the predominantly forested nature of the catchment and downstream with some moorland near the sample point (bottom). River under high flow conditions with rising stage sampler visible in the bottom image

Figure 18. Crosswater of Luce sample point – a gravel bed river -facing upstream (top) and at the sample point (bottom). The catchment has commercial forest in its upper reaches and rough grazing elsewhere and in the region of the sample point.

Figure 19. Tig sample point – a cobble/boulder bed stream in the heart of Arecleoch forest. The solar panel used to trickle charge the autosampler battery is visible in the foreground

2.1 Peatlands

Peatlands occur extensively across the northern temperate zone particularly in Canada, the USA, Fennoscandia, and the former USSR (Chapman *et al.* 2003). There are also smaller deposits in Iceland, Ireland, the UK, Germany and Poland (Joosten & Clarke 2002). These Northern peatlands are estimated to hold 455 billion metric tonnes of carbon, which is only slightly less than in all of the atmospheric CO_2 (Gorham 1991). Northern peatlands fix C at the rate of approximately 70 million tonnes per year but they also release about 50 million tonnes of methane per year (Gorham 1991). Because methane is far more powerful as a greenhouse gas than CO_2, it may be that peatlands are positive contributors to global warming (Chapman *et al.* 2003). UK peatlands contain a greater proportion of blanket bog than their Canadian and Siberian neighbours. This difference is a function of the variable maritime climate in the UK giving wetter and warmer weather than more northern boreal and sub-arctic regions (Billett *et al.* 2010). There have been various attempts to estimate the size of the UK terrestrial carbon store and the contribution that peatlands make to this store (Table 9). Part of the reason that estimates differ is that definitions of terms such as 'peatland' and 'blanket bog' have proven to inconsistent. In 1991 Gorham found a problem in reviewing the role of Northern peatlands in the carbon cycle when he noted that "*The databases for both stocks and fluxes are inadequate in almost every way…*" (Gorham 1991). There were major sources of uncertainty associated with measurements of area, depth and bulk density of the peatlands.

Table 9. Estimates of the UK carbon store

Area included	Carbon store (Mt C)	Reference
British peatlands excluding lowland fens	~ 3000	Cannell *et al.*, (1993)
Soils of Great Britain	9839 (+ - 2463)	(Milne & Brown 1997)
Scottish peatlands (upland blanket, lowland raised bogs and fen peats)	4523	(Milne & Brown 1997)
Great Britain	7513	Milne *et al.* (2001). Reported in (Dawson & Smith 2007)
Scotland	5434	Milne *et al.* (2001). Reported in Dawson and Smith (2007)
UK peatlands	2302	(Billett *et al.* 2010)

Cannell *et al.* (1993) put the value for carbon stocks in British peatlands, excluding lowland fens, at about 3000 Mt making this store nearly 30 times larger than the amount of carbon contained in all vegetation, both forest and non-forest, in Britain. Milne & Brown's (1997) estimate of 9839 Mt for the soils of Great Britain was notable for two things; firstly that Scottish peatlands contributed nearly half of this total, with 4523 Mt of carbon, and secondly the large standard error of ± 2463 Mt, reflecting uncertainties in assigning bulk density values to Scottish peats. More recent estimates reported in a review by Dawson and Smith (2007) suggest that soil carbon stores may be substantially less; 7513 Mt for Great Britain (5434 Mt in Scotland) or 3 times lower than the original figures (Garnett & Stevenson 2004). Finally, Billet et al (2010) now suggest that the best estimate of the amount of carbon stored in the peatlands covering 15 % of the UK stands at 2302 Mt. About 13 % of Scotland's land area (1 056 000 ha) is estimated to be covered by blanket mire, representing 10 % of the world's total (Coupar, Immirzi & Reid 1997). Most of this is found in the north and west of the country (Coupar, Immirzi & Reid 1997; Hamilton, Legg & Zhaohua 1997) and incorporates areas such as Arecleoch forest where the climate is cool and wet and where there are relatively few pressures from intensive agriculture, industry and other development. Upland blanket peatlands, such as the one now hosting Arecleoch forest and wind farm, are an important economic resource and have been exploited for a variety of purposes since their formation began around 9000-5000 BP (Chapman *et al.* 2003; Ramchunder, Brown & Holden 2009). For example, pre-historic hunter-gatherers used peatlands for seasonal hunting of wild animals; then trees were felled for low intensity grazing, which prevented forest re-growth and peat was extracted for fuel (Bragg & Tallis 2001). Extensive drainage for agricultural use in Europe began in the 17th century with year–round sheep grazing, game stocking and water catchment (Bragg & Tallis 2001; Chapman *et al.* 2003; Chapman *et al.* 2003). Since the middle of the 20th century large areas of peatland have been drained for forestry, military training, recreation and peat extraction (Bragg & Tallis 2001; Chapman *et al.* 2003). Thus peatlands represent highly managed ecosystems with a long history of disturbance and manipulation. The type of management undertaken has an impact on the vegetation communities present. Heavy grazing and/or a high frequency of burning is favourable to graminoids (*Eriphorum vaginatum, Molina caerulea,* *Trichophorum cespitosum)* while low frequency burning favours dwarf shrubs such as *Calluna Vulgaris* and *Empetrum* spp. The *Sphagnum*–rich bog cover holding the greatest conservation value is thought to be a product of low-intensity grazing and infrequent burning over a period of centuries (Bragg & Tallis 2001). Saturated, peat consists of about 90-95% water by weight and about 5-10 % solid matter. Of this solid fraction, often up to 95 % is made up of partially decayed vegetation, which has built up over hundreds or thousands of years in waterlogged conditions (Warburton, Holden & Mills 2004).

Many stream water quality variables, including DOC, are associated with the percentage of peat land cover in undisturbed catchments, indicating that peatlands may be important in controlling runoff and sediment export (Prepas *et al.* 2006). Runoff rates were found to be lower in relation to peatland cover when soils were dry, and suspended sediment export was related to % peatland cover over the catchment only when antecedent soil moisture conditions were wet. This suggests that antecedent moisture conditions may influence both the way in which water moves through catchments and the relationship between peatland, runoff and water quality (Prepas *et al.* 2006).

An ecosystem carbon balance is a measure of carbon flux in an out of a peatland taking into account all carbon species (Billett *et al.* 2004). This should include carbon in its dissolved (DOC, DIC), gaseous (CO_2, CH_4) and particulate (POC) forms. Net ecosystem exchange (NEE) is the balance between respiration and primary productivity and considers gaseous fluxes at the surface of the peatland (Worrall *et al.* 2009). NEE has been shown to be the largest and most variable flux term carrying with it potential errors of 30 to 100 % of the overall flux (Billett *et al.* 2010). The same study, carried out at Auchencorth Moss in SE Scotland reported that aqueous carbon loss was the second largest flux term. This reinforces the importance of using all carbon species in the calculation of a complete carbon balance and highlights the relative importance of aquatic carbon loss.

Various studies have been carried out into peatland carbon balances, investigating the extent to which peatlands represent a sink or source of carbon (Table 10). The carbon balances have been estimated either by measuring carbon fluxes between the ecosystem and the atmosphere or by dating the accumulation of peat (Worrall *et al.* 2009), and the results show a high degree of variability even within a single catchment.

Table 10 Estimates of the carbon sink and source capacity from four studies

Reference	Area covered	Source/sink
(Worrall *et al.* 2003)	Peat catchment in the north Pennines	sink of 14.9 g C $m^{-2}yr^{-1}$
(Worrall, Burt & Adamson 2006)	As above	net sink of about 7.4 g C $m^{-2}yr^{-1}$
(Worrall & Burt 2007)	As above	source of carbon of between -11.2 and -20.9 g C/m^2/yr
(Rowson *et al.* 2010)	2 drained peat catchments in northern England	both net sources of C in the 2 years of study (2003 and 2004)

Worrall *et al.* (2003) reported that an upland peat catchment in northern England represented a carbon sink of 14.9 g C m^{-2} yr^{-1}. They also found that while the catchment remained a carbon sink, a new, larger, estimate of DOC loss meant that the extent of the store was smaller than previously estimated comprising a net sink of about 7.4 g C m^{-2} yr^{-1}. In 2007, a further report on the same catchment considered it to be a source of carbon of 11.2 g C $m^{-2}yr^{-1}$but a sink of carbon gases of 15.91 g C m^{-2} yr^{-1}. It was predicted that the catchment would become an increasingly large carbon source over the next ten years as well as a decreasing sink of carbon gases (Worrall & Burt 2007).

More recently Rowson *et al.* (2010) calculated a complete carbon budget for two drained peat catchments close to the areas studied by Worrall *et al.* (2003, 2006, 2007) and found both to be net sources of C in the two years of study (2003 and 2004). In scaling up, Clymo *et al.* (1998) estimated that Northern peatlands are sequestering carbon at a rate of 21 g m^{-2} yr^{-1} or 0.21 t ha^{-1} yr^{-1}. Using an estimated area of 346 M ha this gives a total sink value of 0.07 Gt yr^{-1}. Taking fluvial carbon losses in isolation, Hope *et al.* (1997) estimate that the national annual loss of carbon in rivers is about 0.01% of the total soil organic carbon pool. This means that if there were no further carbon accumulation, the existing carbon stock would all but disappear in 10 000 years due to losses by this route alone. Attempts such as those outlined above, to calculate carbon balances draw attention to the importance of reducing uncertainty in flux measurements and applying the best measurements and approaches. In order to understand how carbon is exported from a peatland such as Arecleoch, it will be useful to consider the model that has been used to explain the structure of peatlands for many years and also to reflect upon recent studies highlighting its limitations in disturbed peatlands such as Arecleoch.

The acrotelm/catotelm model

In this model there are two hydrologically important horizons in peat soils: the acrotelm and catotelm. The acrotelm is the upper horizon consisting of loose, living vegetation, roots and decomposing plant material. It represents the surface layers down to the depth to which the water table sinks in a dry summer (Clymo, Turunen & Tolonen 1998). The acrotelm fixes carbon at the surface and loses it by aerobic decay below the surface until structural collapse causes the water table to rise and submerges the remaining plant material. In a steady state environment the acrotelm remains at a constant thickness rather than accumulating peat (Clymo, Turunen & Tolonen 1998). The peat structure changes with depth to the catotelm, which is a fully saturated layer consisting of older vegetation that is more decomposed (Ramchunder, Brown & Holden 2009). It is made of dense, darker peat and is anoxic for most of the year (Warburton, Holden & Mills 2004). It is the catotelm that takes on the role of peat accumulator (Clymo, Turunen & Tolonen 1998). In its original form the acrotelm/catotelm model has proved to be too rigid to represent our current understanding of the way in which a peatland functions. For example, a prerequisite of the model is for the water table to fluctuate consistently to the extent whereby it stays high enough to allow dead plant material enough room to accumulate in the catotelm, but also retreats low enough to allow for aeration and humification in the acrotelm (Haigh 2006). Charman (2002) considers the acrotelm/catotelm model to have practical limitations in this way as there is not always a clear progression from the loose, pale peat of the acrotelm to the saturated, dark, solid catotelmic peat. Instead it may be that a transitional layer is needed in order to recognise the changing boundary between the acrotelm and catotelm from dry years to wet years (Romanov, 1968 cited in (Haigh 2006)). Alternatively the acrotelm could be seen as representing a gradient from the surface to the catotelm boundary.

The acrotelm/catotelm model is also limited in that it does not include the influence of preferential pathways such as macropores and soil pipes in peatland hydrology. As such the model should be seen as a foundation upon which these other elements of complexity can build (Holden & Burt 2003a). Macropores are especially relevant features for disturbed peatlands where these structures are common and may explain some of the discordance between studies of runoff in different peatlands. Added to these factors complicating the acrotelm/catotelm model is the further layer of complexity delivered by commercial forestry. The cycle of drainage, ploughing, planting and harvesting that it involves has the capacity to mix the otherwise discrete layers of the acrotelm and catotelm, potentially altering them in form and function.

Hydrology

Encouraged by physical properties of peatlands such as having a water content of more than 90 % by volume and the ability to retain up to 25 times their own weight in water (Charman 2002), comparisons with a sponge were inevitable. The logical inference drawn from this association is that when they are not saturated, peatlands have a natural capacity for flood attenuation by means of absorbing rainwater. The reality is often somewhat different as saturation-excess overland flow and near-surface throughflow dominate runoff in many peatlands. It is possible that flow in these landscapes may be attenuated more than in those of steep, hard rock surfaces where Hortonian overland flow would occur following rainfall. However, up to 93 % of runoff can occur from the surface layer (within 1 cm of the surface) and very little rapid runoff is generated from the peat matrix itself (Holden & Burt 2003a; Warburton, Holden & Mills 2004). Lateral and vertical hydraulic conductivity values of peat are high in the surface peat layer (10^{1} – 10^{2}) but very low in the catotelmic layer (9×10^{-8} to 5×10^{-3}) (Warburton, Holden & Mills 2004) and this creates conditions ideal for surface flow and short lag times to peak flow. Some water does percolate downwards, with pipeflow providing the primary mechanism for this movement (Warburton, Holden & Mills 2004). Macropores also play a part and both may develop through peat desiccation and cracking of pipes particularly where drainage of the peatland has taken place (Warburton, Holden & Mills 2004) for example at Arecleoch.

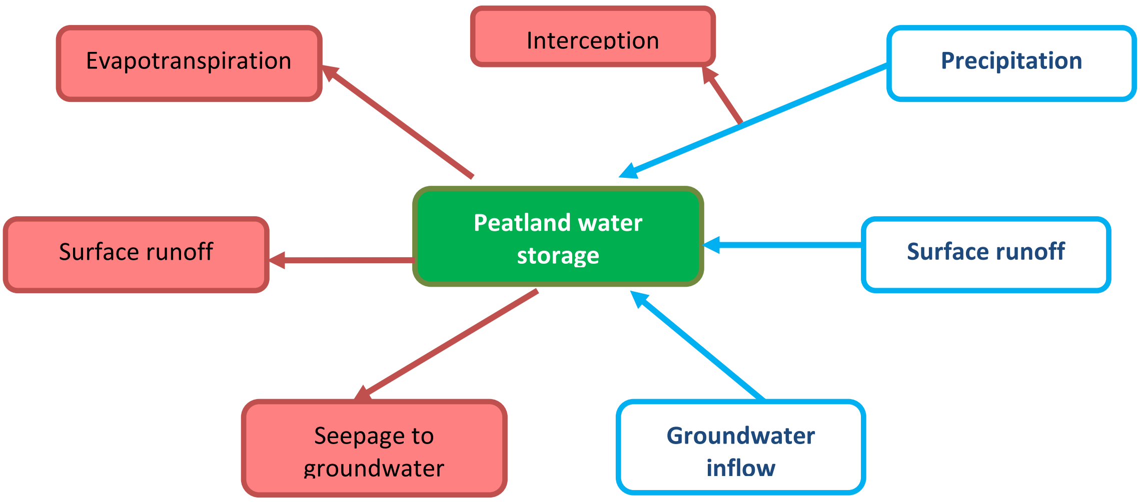


Figure 20. A peatland water balance. Labels in red indicate processes by which water leaves a peatland. Labels in blue indicate processes that add water to a peatland (from Charman 2002).

A dominant feature of the blanket peat moorland hydrograph is the rate at which discharge increases following the onset of precipitation. Labadz *et al.* (1991), studying a small (2.4 km^2) peat covered catchment in northern England, found a sharp response peak, a discharge peak often within 1 hour of maximum rain intensity and a return to levels just above base flow soon after rain stopped. This supports the idea that runoff production in wet periods on blanket peat moorland is dominated by overland flow processes (saturation and infiltration excess), and near surface flows through the acrotelm. These examples serve to illustrate the importance of understanding the hydrological functioning of peatlands when interpreting data relating to the hydrochemistry and export of carbon at a site such as Arecleoch. It may be useful therefore to summarise the main routes by which water enters and leaves a peatland.

A peatland water balance consists of an influx (recharge), efflux (discharge) and storage (the difference between the influx and efflux).

Figure 20 represents the peatland water balance showing some of the processes by which water enters and leaves the system. It can be seen that water can enter the peatland via precipitation, surface runoff and groundwater inflow while the main outputs are from surface runoff, seepage into groundwater, interception and evapotranspiration. Not all of these processes will operate in all peatlands. In ombrotrophic mires, the only input is from precipitation (as in the case of Arecleoch) whereas for fens the major inflows may be from groundwater or surface runoff (Charman 2002). Peat is highly deformable and may expand and contract under cycles of wetting and drying. Periods of drying can be associated with an increase in bulk density, while wetting has the opposite effect. However, once peat has shrunk under very dry conditions, it may not then return to its original condition on rewetting. The implication is that repeated cycles of wetting and drying may impose stress on a peatland that is more significant than, for example continual swelling resulting from prolonged rainfall and may contribute to the risk of peat slides and shears (Warburton, Holden & Mills 2004).

Holden and Burt (2003b) set out to challenge the hypothesis that flow in deeper peat layers may make an important contribution to runoff. They used data selected from nested monitoring programmes at catchment, hillslope and plot scales over a period of five years. From this they discovered the peats to have a limited storage capacity with rain being rapidly transported to the river and stream channels, producing flashy hydrographs. Flow was largely confined to the surface and top 5 cm of peat, this being a consequence of the saturated peat below having very low hydraulic conductivity and so generating very little runoff. They examined this pattern in more detail and found that overland flow is dominant during times of high flow while the major pathway during periods of low flow is between 1 cm and 10 cm deep in the peat profile. The one significant contribution from greater depths was by means of soil pipes, which provided about 10 % of the overall discharge to the catchment. The study was carried out on intact peatlands and it was recognised that the situation may be different in disturbed peats with more through flow at greater depths and more bypassing flow via macropore and soil pipe networks. In catchments hosting commercial forests there the influence of increased drainage density must also be considered.

The classical conceptual model of UK upland hydrology presented catchments as having a limited contribution from groundwater but rather being dominated by rapid responses to storm events. However this picture has been refined as new evidence has demonstrated that groundwater can have a far greater input to streamflow and there is a wide range of residence times (Soulsby *et al.* 2002). Considerations of hydrology are particularly important when carrying out paired catchment studies. Rowson *et al.* (2010) found water yield (m^3/m^2) was higher in one catchment than the other. They also found rainfall patterns differed between the 2 years in that a very dry summer in 2003 led to a large drop in the water table but 2004 had several big storms in August and October. One may have expected export to be greater in 2004 due to the delayed effects of the previous drought year, and to a small number of intense storms. However, water yield per unit catchment area was higher across one catchment in both years implying that there must be an intrinsic difference between the two catchments.

Fluvial Flux of DOC

The fluvial flux of DOC from stream to ocean makes an important contribution to the carbon cycle and organic carbon has an important function in several streamwater processes (Hope, Billett & Cresser 1994). Figure 21 illustrates how the small but significant contribution of aquatic carbon flux fits in with other inputs and outputs of the carbon budget of a peatland. Inputs are from rainwater and primary production that sequesters CO_2 from the atmosphere. Outputs are through fluvial release of DOC, POC, DIC and dissolved gases, and CO_2 and CH_4 to the atmosphere from the decomposition of soil organisms. Weathering of underlying rocks can also add directly to the dissolved pool (Worrall, Burt & Adamson 2003). As with concentration discussed above, studies on the factors controlling DOC flux have put forward a variety of influences such as precipitation, the size of the carbon pool and in-stream processing (Clair, Pollock & Ehrman 1994; Dawson, Bakewell & Billett 2001; Hope *et al.* 1997).

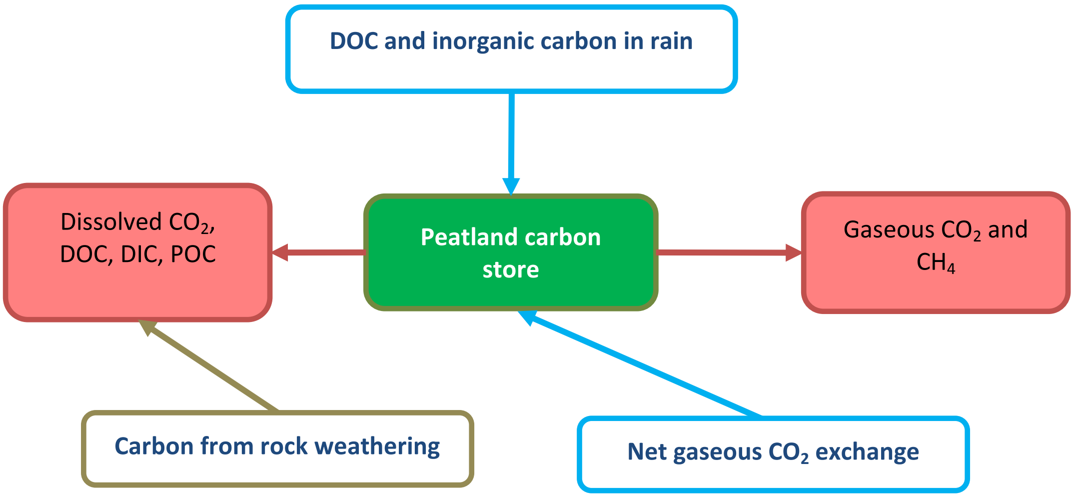


Figure 21. Elements of a peatland carbon store (from Worrall *et al.* 2003 SoTE) Inputs (in blue) are from rainwater and primary production. Outputs are through fluvial release of DOC, POC, DIC and dissolved gases, and CO_2 and CH_4 to the atmosphere from the decomposition of soil organisms. Shown in brown is the input of carbon to the aqueous system from weathering of underlying rocks

Estimates of DOC flux from some UK peat catchments similar in scale to Arecleoch are shown in Table 11. It has been said that aquatic carbon flux estimates may carry smaller levels of uncertainty than net ecosystem exchange (NEE) (Billett *et al.* 2010) but caution must still be exercised when interpreting annual flux data of carbon from a peatland. Estimates can demonstrate a high degree of variability according to the way in which the data is collected. For example a group of five peatland study sites in the UK with catchments ranging from 0.2 to 3.35 km^2 had DOC fluxes varying between 18.5 to 26.9 g C m^{-2} yr^{-1} and showing a high degree of consistency (Billett *et al.* 2010).

Table 11 Estimates of DOC fluxes found in some small catchments in upland Britain

Site	Period	Catchment area (km2)	Mean flux (g C m^{-2} yr^{-1})	Reference
Cottage Hill Sike (N Pennines)	2003 – 2007	0.2	29.2	(Billett *et al.* 2010)
River Etherow (S Pennines)	2003 – 2007	Not known	10.5	(Billett *et al.* 2010)
Beaghs Burn (N Ireland)	2003 – 2007	Not known	18.8	(Billett *et al.* 2010)
Water of Charr (NE Scotland)	1992 - 1993	14.2	11.3	(Hope, Billett & Cresser 1997)
Stag Burn (NE Scotland)	1992 - 1993	4.2	11.5	(Hope, Billett & Cresser 1997)
Ochil (C Scotland)	1982 - 1983	0.51	8.4	(Grieve 1984)
Trout Beck (N Pennines)	1999 - 2000	11.4	9.4 – 15.0	(Worrall *et al.* 2003)

Conversely Worrall *et al.* (2003) found annual DOC flux calculations at an 11.4 km^2 catchment on the Moor House and Upper Teesdale National Nature Reserve in northern England to differ greatly according to the sampling methodology. Values from one catchment varied from 9.4 g C m^{-2} yr^{-1} to 32.6 g C m^{-2} yr^{-1}. The latter value was obtained from a series of rainfall events during the autumn flush while the former represented measurements taken from weekly samples across the year and was considered to be the more representative, although the sampling bias inherent in this method must be recognised. Worrall *et al.* (2009) more recently set out a new method for calculating the carbon budget of the same peatland over a 13 year period, and found that within the overall carbon budget DOC flux at the catchment outlet varied between 10.3 and 25.2 g C m^{-2} yr^{-1}

As well as the temporal variability described above DOC flux can exhibit extensive spatial variation. Hope *et al.* (1997) found that the annual flux of organic carbon increased cumulatively downstream in the rivers Dee and Don. However, the DOC and POC load at any time was not solely a function of the area of catchment drained. Some upper reaches of the river Dee had disproportionately high loadings in relation to catchment size. There were significant ($p < 0.01$) positive correlations between peat cover and annual carbon export to streams as well as significant ($p < 0.05$) negative correlations between carbon flux and altitude. When the relationships between DOC and POC and % peat cover were explored using linear regression models the regressions for all DOC flux estimates and for non-storm POC flux estimates were significant at the $p < 0.01$ level (r^2 = 0.59-0.72). Catchment size and altitude, while significantly correlated with flux did not improve the amount of variance explained when included in the model. Along the river continuum, DOC has been found to be the dominant component of the C flux and observed to decrease downstream (19.4 – 16.7 g C m^{-2} y^{-1}). This was in contrast to POC fluxes, which increased along the river (1.48 – 1.69 g C m^{-2} y^{-1}) (Dawson *et al.* 2004). In one part of the study no overall annual net loss of DOC from the system was able to be measured. This suggests a dynamic equilibrium operating in the continuum rather than a lack of DOC processing. Elsewhere in the study DOC losses were found and it was also considered to be a possibility that there were other, unmeasured DOC inputs from diffuse sources that could increase estimates of within stream DOC loss. Thus we see the temporal and spatial variability exhibited by DOC in catchments similar to those being studied at Arecleoch and the importance of integrating these factors into any interpretation of DOC flux estimates and the concomitant effects of anthropogenic influences.

2.2 Stage – discharge relationships at Arecleoch

The Crosswater and Crosswater of Luce catchments will be used as the main descriptors of Arecleoch's hydrology and for estimates of DOC flux between 2008 and 2010. Additional DOC flux information from July 2009 to September 2010 will provided by a more limited data set from the Tig catchment. The Crosswater catchment has been relatively undisturbed by activities relating to the wind farm development whereas the Crosswater of Luce and Tig catchments have undergone a significant land use change. The Crosswater and Crosswater of Luce catchments have a full discharge record for the 2008 – 2009 period but between January and September 2010, the Crosswater alone will be used as there is no stage data for the Crosswater of Luce (See 1.3.1 for details of catchment instrumentation). DOC export from the catchments will be examined from January 2008 to September 2010. Daily precipitation values have been taken from the SEPA station at Lagarfater Lodge, less than 2 km west of the southern part of the Arecleoch forest boundary. Data from this station was taken from 1996 to 2010 and has been integrated annually and monthly.

In order to establish a rating relationship between stage and flow to allow discharge to be estimated, each of the rivers needed to be gauged across a range of flow conditions. For each of the three rivers the process of gauging was the same. For more permanent gauging stations this can be assisted, and the reliability of the stage-discharge relationship improved, by having in place a weir or flume across the river channel. However this increases both the cost of the project and raises considerations associated with having in place a permanent, artificial structure on a section of river. For the three channels here the gauging was carried out manually using the non-structural velocity-area method. When discharge estimates are plotted against the instantaneous stage measurements, the group of points usually lies on a curve which is approximately parabolic (Shaw, 1994).

2.3 Rising stage samplers

Having the autosamplers deployed for routine monitoring and the lack of telemetry meant that a more creative solution was needed if information relating to DOC under storm conditions was to be collected. To this end rising stage samplers (RSS) were installed at the Crosswater and Tig sites. This is a passive-style apparatus used to collect water samples at designated points in the rising stage of a storm. Five polythene 500 ml prewashed bottles were attached to Dexion™ posts fixed to the stream bed (Figure 22). The height of the inlet of each bottle relative to the nearest stage recording was noted for each set of equipment. As the water level rises it enters the first bottle via the inlet tube and fills it until the river water level reaches the end of the vent outlet. Thereafter water neither enters nor leaves the sample bottles during the remainder of the rising limb and the falling limb of the storm. This system has the advantage of being low-cost and simple to operate but it also has its disadvantages. If a middle order event occurs and fills the first two bottles any subsequent storms will only be sampled from bottle three onwards. If the event only partially fills a bottle before receding, there is also the possibility that a subsequent event may add more water to that bottle until the outlet vent is covered, thereby leading to mixing of event water. The inlet tubes were set to receive water at approximately 20 cm intervals (Table 12) but it was not feasible to match the stage height of the bottles between the two rivers.

Table 12 Stage height associated with rising stage sample bottles at the Crosswater and Tig

Level	*Crosswater (m)*	*Tig (m)*
1	0.42	0.37
2	0.62	0.57
3	0.82	0.71
4	1.02	0.84
5	1.23	0.98

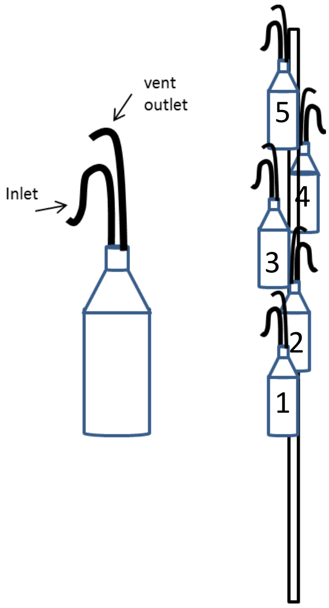


Figure 22. Illustration of a rising stage sampler (left) and image of actual equipment (right) in situ at the Crosswater sample point

Rees (1989) employed an even simpler version of this equipment whereby a series of cups were attached to metal posts. The topmost cup filled would indicate the peak stage and the cups below would be left containing storm water as the stage subsided; in effect a falling stage sampler.

2.4 Estimating DOC Flux at Arecleoch

2.4.1 **Flux estimation using interpolation**

DOC flux estimates were determined for the three catchment data sets. There are several ways of doing this based on either extrapolation or interpolation procedures (Walling & Webb 1985; Webb, Phillips & Walling 2000). Walling and Webb (1985) set out five methods of estimating river loads and in general, extrapolation works best where a good rating curve between concentration and flow can be found. However this is not the case where determinants have a strong seasonal component, for example DOC (Worrall & Burt 2007). Although extrapolation has been used in calculating DOC fluxes (McDowell & Likens 1988), it has been suggested that interpolation may be more reliable and less prone to errors than more complex extrapolation methods (Webb, Phillips & Walling 2000)). Of the five methods proposed by Walling & Webb, method 5 has been recommended where the parameter in question has a strong seasonal or annual periodicity and continuous discharge data are available (Littlewood 1992) and it has been used in previous studies to calculate carbon fluxes (Cooper & Watts 2002; Dawson *et al.* 2002; Hope, Billett & Cresser 1997; Worrall & Burt 2007; Worrall & Burt 2008).

$$\boldsymbol{Flux = K.\frac{\sum_{i=1}^{n}[CiQi]}{\sum_{i=1}^{n}Qi}.Qr}$$ **Equation 1**

Where K = conversion factor allowing for period of sampling; Ci = concentration of determinand in sample i; Qi = instantaneous discharge at sampling time i; Qr = mean river discharge over the period; and n = number of samples.

Because the method 5 calculation uses an estimate of annual mean flow that is derived from a continuous flow record the potential for underestimation, as a consequence of under-representing high flow samples, is reduced (Littlewood 1992). Consequently method 5, described by equation 1, was chosen for this study. Estimates were expressed as the total amount of carbon exported at the sample point and standardized per unit of catchment area.

2.4.2 **Errors associated with flux estimates**

As the carbon fluxes are only estimates, it is important to include a measurement of precision in presenting the data. The error of any load estimation is a function of the sampling regime used and the load estimation method applied to the data if we ignore variation in concentration values due to sampling and laboratory techniques. The sampling regime can affect flux estimates and it is generally thought that less frequent sampling will capture fewer high flow samples. This means that flux estimates would be expected to be biased towards low flow conditions and to represent underestimates. Clark *et al.* (2007) compared DOC flux estimates using four-hourly storm sampling to weekly or monthly monitoring and observed that, contrary to expectation, sampling at a frequency low enough to exclude storm events resulted in fluxes being over-estimated because concentration decreased with flow during their autumn study period. Low frequency sampling would only under-estimate flux if concentrations increased with flow, as the observed flow-weighted mean concentration would be lower than the actual flow-weighted mean concentration.

The effect of sampling bias on flux estimates was investigated by systematically leaving in and removing samples collected under storm flow from a data set used for DOC flux estimates (Hope, Billett & Cresser 1997). They found that flux estimates and their associated errors were reduced when they excluded from flux calculations samples taken during storm flow. In small catchments greater differences in flux have been observed with POC and particulate material has been identified as the main source of error (Littlewood 1992). Using the most appropriate flux estimation method is also important, as discussed above, and method 5 can help to reduce the size of errors by integrating continuous flow records. In this study, flux estimates were derived from samples collected at 24 or 48 hour intervals and stage was recorded every 15 minutes and will have captured a wide range of hydrological conditions. It would be expected that this would reduce the errors associated with flux estimates Standard errors and 95% confidence intervals were calculated following the procedure described in Hope *et al.* (1997) and subsequently used by others including Dawson *et al.* (2002) and Dinsmore *et al.* (2010) and This is represented by equation 2 where the total annual discharge (F) is multiplied by the square root of the variance of the flow weighted mean concentration (C_f). The variance of C_f is estimated from equation 3 where Q_n is the sum of all individual Q_i values. The 95 % confidence limits for the flux estimates were then assumed to equal ± 1.96*SE

$$\mathbf{SE = F \times \sqrt{var(C_f)}}$$ **Equation 2**

$$\mathbf{VAR(C_f) = [\sum(C_i - C_f)^2 \,.\, Q_i/Q_n] \times \sum Q_i^2/Q_n^2}$$ **Equation 3**

Where F = total annual discharge, (C_f) = flow weighted mean concentration, VAR(C_f) = variance of flow weighted mean concentrations, C_i = instantaneous DOC concentration, Q_i = instantaneous discharge at the time of sampling and Q_n = annual sum of Q_i.

With interpolation methods of flux calculation, the main sources of error are those inherent in the method and those arising from the sampling frequency (Worrall *et al.* 2009). Method 5 was found to have an inherent error of ± 3 % (Harrison *et al.* 1990 reported in Worrall *et al.* (2009)) and a weekly sampling frequency incurred a standard error of ± 8 % compared to a sub-daily frequency (Worrall & Burt 2007).

2.5 Results

2.5.1 **Total number of samples collected**

Table 13 gives a record of the number of instantaneous water samples collected, analysed and resulting DOC data used in this section.

Table 13. Number and type of water samples collected from the Crosswater, Crosswater of Luce and Tig catchment sample points between January 2008 and October 2010.

Sample type	*Dates*	*Catchment*	*Number of samples*	*Description*
Routine	01/01/08 – 30/09/10	Crosswater	667	Daily/ 48 hourly
Routine	01/01/08 – 30/09/10	Crosswater of Luce	498	Daily/ 48 hourly
Routine	22/07/09 – 30/09/10	Tig	274	Daily/ 48 hourly
High flow	Eight flood events	Crosswater	21	Rising stage sampler
	Five flood events	Tig	17	Rising stage sampler

2.5.2 **Precipitation and temperature**

The annual mean temperature of the region is 7.8 °C (www.metoffice.gov.uk website) and the long-term mean rainfall from Lagarfater Lodge for the period from 1996 to 2010 is 1730 mm per year (Table 3). This is similar to the most recent Met Office 30 year average (1971 – 2000) for western Scotland of 1730 mm. Set against this figure, the three years comprising the Arecleoch monitoring programme represent one relatively dry year (2010) with 1522 mm of rain (88 % of the long - term mean) and two wet years (2008 and 2009) with 1875 mm (108 %) and 1984 mm (115 %)

respectively. The long term annual mean temperature for the west of Scotland (1910 – 2010) is 7.8 °C (Table 3). Of the three study years, 2008 and 2009 were warmer than average (8.3 °C and 8.4 °C respectively) while 2010 was colder with a mean temperature for the year of 7.2 °C. Thus relative to the long term mean values, 2008 and 2009 were wet and warm while 2010 was colder and drier.

2.5.3 **Discharge**

2.5.3.1 River regimes.

Monthly mean discharges for the Crosswater exhibit a seasonal pattern with the highest values being found in in the winter (Jan – March) and autumn (Oct – Dec) (Figure 24). Noteworthy exceptions to this are February 2009 and 2010, which had lower mean discharges. This may be due to low temperatures and frozen conditions, including a long period of snow cover in 2010. Furthermore August and September 2008 and August 2009 exhibited higher discharges, which correspond to unusually high peaks in the precipitation record (Figure 23).

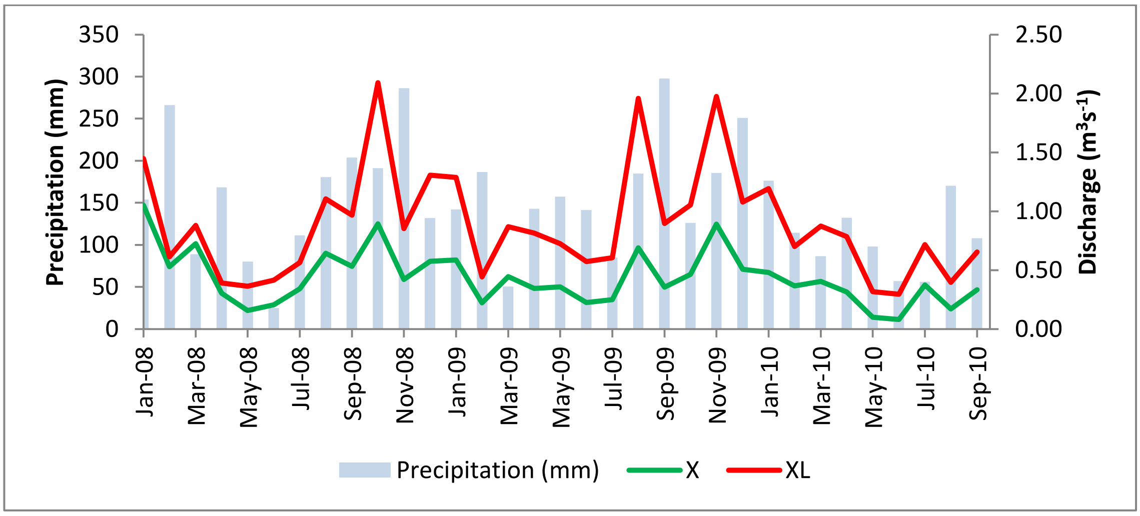


Figure 23.Time series plot of mean monthly discharge at the Crosswater (X) and Crosswater of Luce (XL) with mean monthly precipitation from the SEPA station at Lagarfater. Synthesised values used for XL in 2010.

Month	Jan-08	Oct-08	Nov-09	Mar-08	Aug-09	Aug-08	Jan-09	Dec-08	Sep-08	Feb-08	Dec-09	Jan-10	Oct-09	Mar-09	Nov-08
X Q	1.051	0.894	0.891	0.723	0.688	0.644	0.585	0.575	0.532	0.528	0.514	0.479	0.462	0.444	0.419

Month	Mar-10	Jul-10	Feb-10	May-09	Sep-09	Apr-09	Jul-08	Sep-10	Apr-10	Apr-08	Jul-09	Jun-09	Feb-09	Jun-08	Aug-10
X Q	0.405	0.373	0.364	0.358	0.354	0.343	0.342	0.333	0.313	0.304	0.249	0.225	0.223	0.206	0.171

Month	Oct-08	Nov-09	Aug-09	Jan-08	Dec-08	Jan-09	Aug-08	Dec-09	Oct-09	Sep-08	Sep-09	Mar-08
XL Q	2.092	1.975	1.959	1.448	1.307	1.287	1.105	1.077	1.053	0.966	0.896	0.880

Month	Mar-09	Nov-08	Apr-09	May-09	Feb-08	Jul-09	Jun-09	Jul-08	Feb-09	Jun-08	Apr-08	May-08
XL Q	0.869	0.852	0.813	0.726	0.612	0.605	0.573	0.563	0.443	0.415	0.390	0.364

Season	Wi	Sp	Su	Au

Figure 24. Mean monthly discharge (Q) at the Crosswater (X) and Crosswater of Luce (XL) arranged in order of magnitude and colour coded according to season. Units = $m^3 s^{-1}$.

As is usual for river regimes, discharge from the two catchments is closely related to precipitation and highest monthly discharges correspond to peaks in the monthly mean rainfall record for January 2008, October 2008, August 2009 and November 2009 (Figure 23).

2.5.3.2 Specific discharge

The Crosswater and Crosswater of Luce catchments are very different in surface area and it is unsurprising that the larger Crosswater of Luce catchment (19.9 km^2) has a higher monthly mean discharge than the Crosswater (8 km^2). To compensate for this difference the discharge data were converted into relative values per unit catchment area for 2008 and 2009 (Figure 25) and this is termed specific discharge.

Figure 25. Monthly mean specific discharge at the Crosswater (X) and Crosswater of Luce (XL)

When represented in this way it can be seen that the Crosswater has a higher specific discharge than the Crosswater of Luce particularly in the early part of the time series. Mean specific discharge vales for 2008 are 0.066 m^3 s^{-1} km^{-2} at the Crosswater and 0.046 m^3 s^{-1} km^{-2} at the Crosswater of Luce. In 2009 the mean values are 0.056 m^3 s^{-1} km^{-2} and 0.051 m^3 s^{-1} km^{-2} respectively. The values observed in this study are similar to those reported elsewhere. For example Tetzlaff, Malcolm and Soulsby (2007) found mean annual specific discharges of 0.04 to 0.06 m^3 s^{-1} km^{-2} at two forested catchments in central Scotland between 1988 and 2005. These two small (0.9 km^2 and 1.4 km^2) catchments, mainly on peat and peaty gley soils, underwent sequential forest harvesting and replanting during the study period and it was thought that the piecemeal nature of the forestry limited any effects on annual stream flows. The Crosswater has a higher proportion of forest cover than the Crosswater of Luce (88 % and 40 % respectively) which may reduce runoff due to interception thus producing lower discharge. The higher elevation of the Crosswater provides the possibility of more precipitation at that site although this was not recorded for each of the sample points individually and the fact that the two catchments are adjacent reduces the likelihood of climatic differences.

The Mann-Whitney test was used to explore differences in specific discharge between the two catchments. No significant difference at the 95 % confidence level was found between the Crosswater and Crosswater of Luce over the whole period (Table 14).

Table 14. Mann-Whitney test statistic (W) and p values for testing differences in specific discharge between the Crosswater and Crosswater of Luce

Period	*W*	*P*
2008-2009	662.0	0.1296
2008	177.0	0.1260
2009	159.0	0.6236

Performing the same test on the 2008 and 2009 data separately also reveals no significant differences between the catchments in either of the years. The magnitude of the difference in specific discharge was investigated next using the Mann-Whitney test, the outcome of which demonstrated a significantly ($W = 106.0$, $p = 0.006$) smaller difference in 2009 than 2008. This change in the relationship between the two catchments in terms of the difference in mean discharge per unit area may in part be due to climatic influences given the aforementioned altitude differences; however the proximity of the catchments means that variables such as rainfall and temperature are likely to affect both similarly. In seeking an explanation for the observation one is drawn towards the physical changes taking place within the Crosswater of Luce from October 2008 onwards, such as forest harvesting (See Theme 3) that could lead to increased runoff and a higher discharge in this catchment. It would have been interesting to pursue this line of evidence into 2010 where wind farm construction activity peaked, had there been stage data available for the Crosswater of Luce.

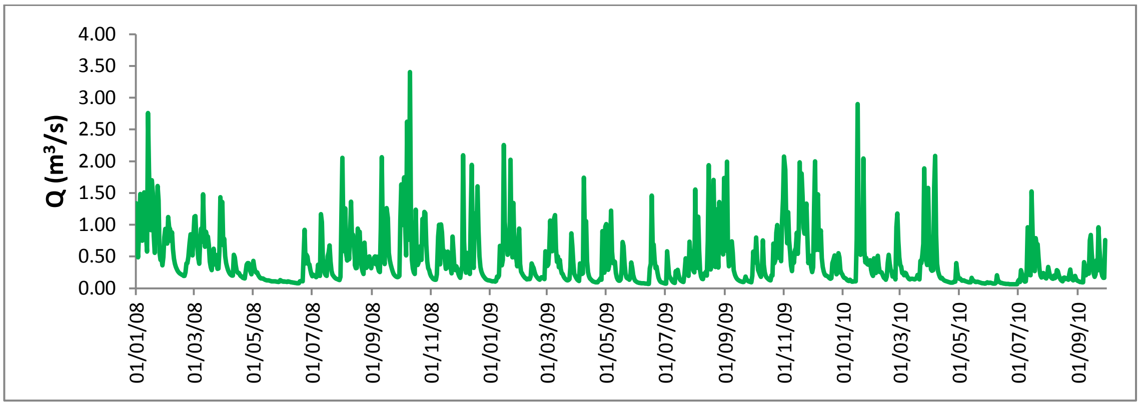


Figure 26. Daily discharge values (m^3s^{-1}) at the Crosswater catchment sample point

Daily discharge for the Crosswater, where a full record is available, is shown in Figure 26 for the period between January 2008 and September 2010. The flashy nature of the stream is more apparent here than using discharges integrated monthly. Discharges below 0.5 m^3/s occurred 71 % of the time but accounted for only 36% of the total runoff. This is in line with other similar sized catchments, for example at the Moor House nature reserve in the northern Pennine hills in England discharge from an 11.4 km^2 peatland catchment was above 0.4 m^3/s for 75 % of the time but accounted for 21 % of the discharge volume (Holden and Burt 2003).

2.5.3.3 Significant storms and rising stage sampler

A total of eight storm events were captured by the rising stage sampler at the Crosswater and five at the Tig (Table 15). An indication of the magnitude of the event is given by the peak stage and 24 hour precipitation record. Stage at the Tig during storm events followed a similar pattern to that at the Crosswater. For events 3,4,5,6 and 8 the stage record indicates that more than one period of high flow may have contributed to the sample series. Bottles one and two would have been filled during the first period of rainfall with a subsequent, larger event adding further to the sample set. This would make detailed analysis of individual events difficult and any conclusions must be drawn with this in mind. However as the aim here was to determine the influence of high flow on overall DOC concentrations at the catchment scale the mixing of samples is of less concern.

Table 15. Summary of samples collected from the rising stage samplers at the Crosswater and Tig catchment sample points and total precipitation for the day of sample

Event	*Date*	*Peak stage (m) at Crosswater*	*Samples collected*		[1]*Precipitation (mm)*
			Crosswater	Tig	
1	08/04/09	0.91	1,2,3		10.4
2	17/06/09	0.91	1,2,3		12.4
3	26/07/09	0.62	1,2,3		19.6
	01/08/09	0.88			44.6
4	14/08/09	0.77	1,2,3	1,2,3	53.0
	15/08/09	0.85			1.4
5	16/11/09	1.04	2,4,5	1,2,3,4,5	28.0
	17/11/09				
6	06/04/10	0.89	1,2	1,2,3,4,5	13.6
7	15/07/10	0.87	1,2	1,2	15.0
8	13/09/10	0.63	1,2	1,2	26.4
	29/09/10	0.73			14.2

1. **Total precipitation at Lagarfater station for the 24 hour period**

At the Crosswater eight events were captured by the rising stage samplers (Table 16). For the first four events sample bottels 1 – 3 were filled but with the probability of these being split between two storms for events 3 and 4. Event 5 was a larger storm with a maximum stage height of 1.04 m, which was sufficient to fill bottle 5. However only sample bottles 2, 4 and 5 were able to be collected. Events 6, 7 and 8 each resulted in the lowest two sample bottles being filled.

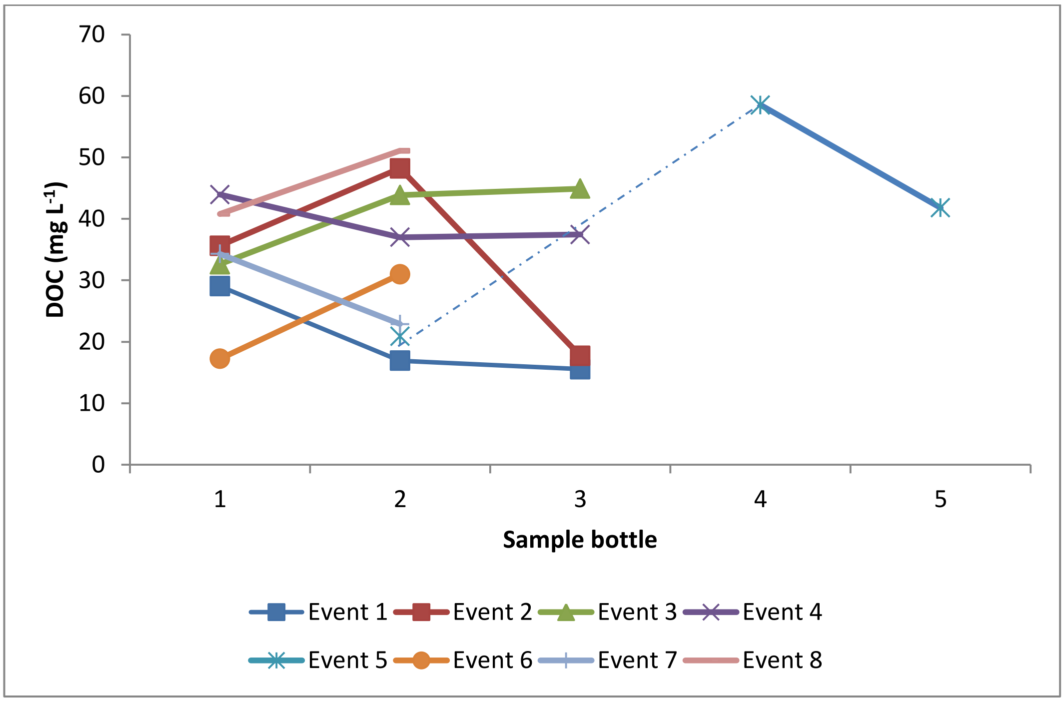


Figure 27. DOC concentrations at the Crosswater rising stage sampler for eight storm events

The pattern of DOC concentrations across the eight events was variable (Figure 27) with the second sample having the highest DOC concentration twice (events 2 and 5) where three samples were collected and for events 6 and 8 where only two samples were collected. The DOC concentration at the autosampler for the same day as the storm event is shown in Table 16 and Figure 28 and compared with the mean DOC concentration from the rising stage sampler for each storm. Using the Mann-Whitney test no significant difference at the 95 % confidence level as found between the two sets of samples ($W = 67$, $p > 0.05$). This indicates that DOC concentrations measured at 1700 GMT were representative of values at different times of day during high flow events.

Table 16. Distribution of samples collected from rising stage samplers at the Tig and Crosswater (X) sample points. SS = sample site; Event = rain event captured; Sample = sample bottel filled (1 = lowest); DOC RSS = DOC concentration at the rising stage sampler (mg L^{-1}); DOC auto = DOC concentration rom the autosampler at 17:00 h on the same day (mg L^{-1}).

SS	Date	Event	Sample	DOC RSS	DOC auto
X	08/04/09	1	1	29.04	18.82
X		1	2	16.92	
X		1	3	15.54	
X	17/06/09	2	1	35.62	29.71
X		2	2	48.23	
X		2	3	17.70	
X	26/07/09	3	1	32.62	44.14
X	01/08/09	3	2	43.88	44.83
X		3	3	44.92	
X	14/08/09	4	1	43.96	50.30
X	15/08/09	4	2	37.02	47.83
X		4	3	37.44	
X	17/11/09	5	2	20.91	28.15
X		5	4	58.51	
X		5	5	41.79	
X	06/04/10	6	1	17.25	17.25
X		6	2	30.96	
X	15/07/10	7	1	34.29	33.90
X		7	2	22.89	
X	13/09/10	8	1	40.81	43.78
X	29/09/10	8	2	51.08	40.76
Tig	14/08/10	4	1	45.89	54.91
Tig	15/08/10	4	2	42.78	
Tig		4	3	51.43	
Tig	17/11/09	5	1	19.35	27.90
Tig		5	2	18.91	
Tig		5	3	25.37	
Tig		5	4	19.39	
Tig		5	5	19.80	
Tig	06/04/10	6	4	23.20	20.66
Tig		6	5	23.98	
Tig		6	1	20.74	
Tig		6	2	15.54	
Tig		6	3	27.40	
Tig	15/07/10	7	1	45.69	42.10
Tig		7	2	49.96	
Tig	13/09/10	8	1	67.94	64.29
Tig	22/09/10	8	2	66.06	52.14

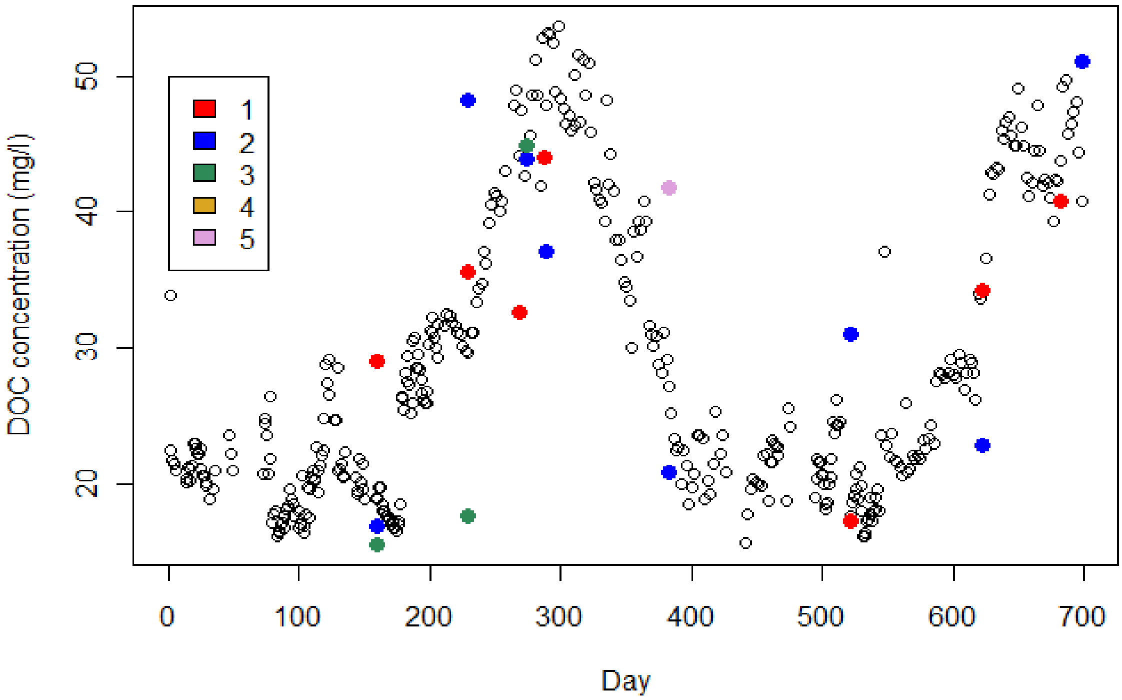


Figure 28. DOC concentrations at the Crosswater catchment sample point with rising stage samples for events 1 - 8. Day 1 = 01/11/08. Colours represent bottles 1 -5.

The rising stage sampler on the river Tig was installed later than that at the Crosswater and captured five storm events corresponding to events 4 – 8 at the crosswater. For events 5 and 6, all five sample bottles were filled and on both occasions DOC concentrations peaked at sample 3 and then reduced, possibly due to exhaustion of supply. In event 4 DOC was also highest in sample 3 but the storm was not sufficient to fill the last two bottles and thus it was not possible to see if the pattern described above applied here. In events 7 and 8, only the first two sample bottles were filled and DOC rose from 1 to 2 in event 7 but fell in event 8. DOC concentrations from the automatic sampler were also found not to be significantly different from the mean values collected during each storm ($W = 28$, $p > 0.05$).

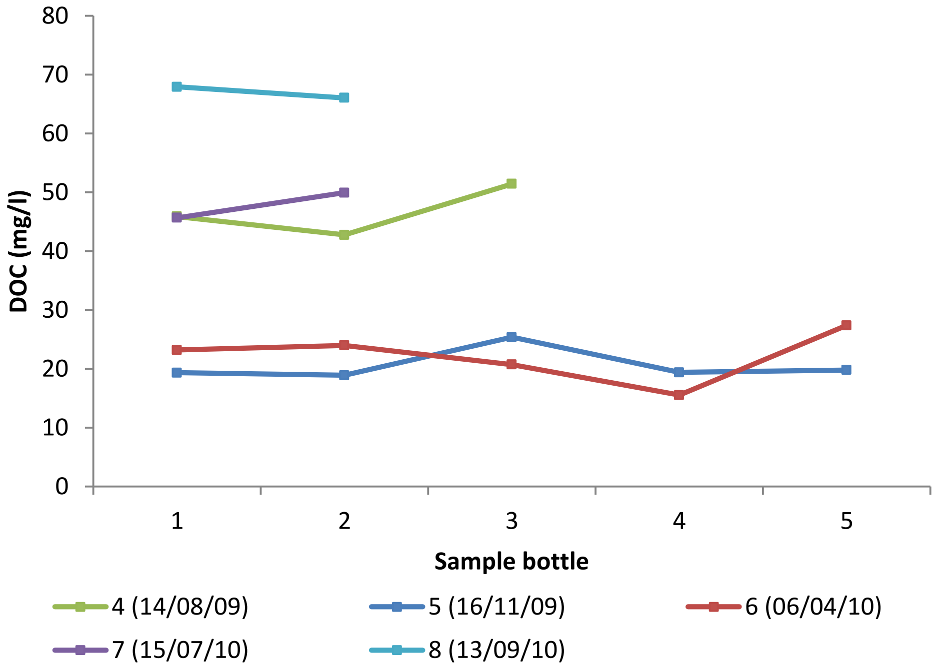


Figure 29. DOC concentrations at the Tig rising stage sampler for storm events 4 to 8. Legend gives event number followed by the date.

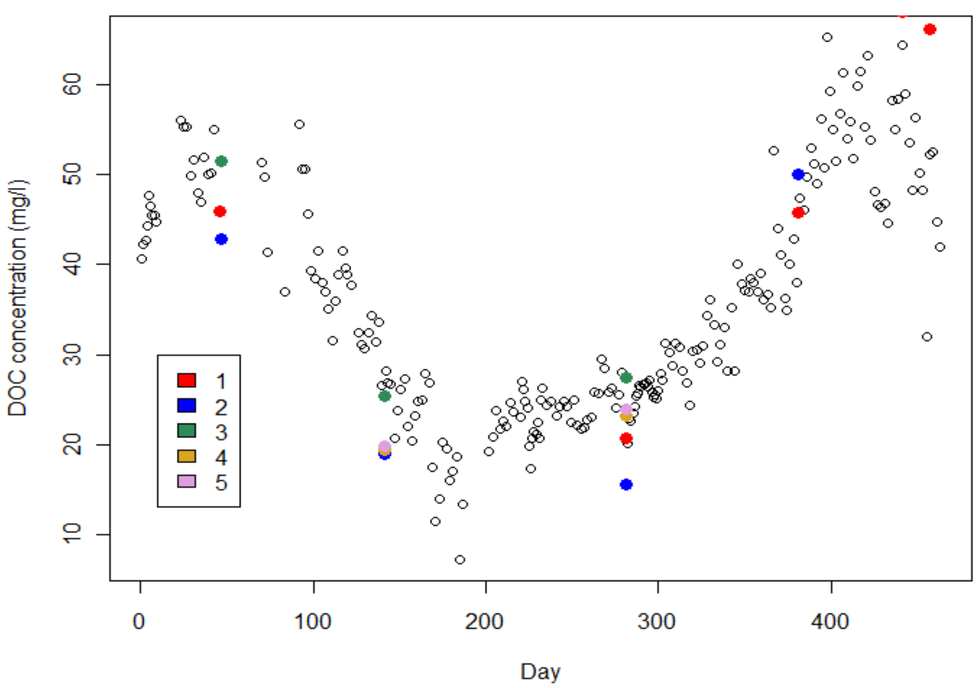


Figure 30. DOC concentrations at the Tig catchment sample point with rising stage samples for events 4 - 8.Tig. Day 1 = 30/06/09

2.5.4 **Stage discharge rating curves**

Obtaining robust ratings relationships for the three rivers proved challenging because of the infrequent nature of the site visits and the fact that many of them were carried out by a lone worker. The methods employed to account for these challenges are explained below. Also in the case of the Crosswater of Luce and the Tig, where the stage record is interrupted, a new rating relationship would be required each time the pressure transducer was replaced (exact repositioning proved impossible). Insufficient gaugings were obtained from each of the discrete stage periods to achieve this goal fully. Only in the case of the Crosswater was there an uninterrupted stage record and associated gauging for a robust rating to be established. Various methods will be explored to account for the resulting data gaps shown in Figure 31.

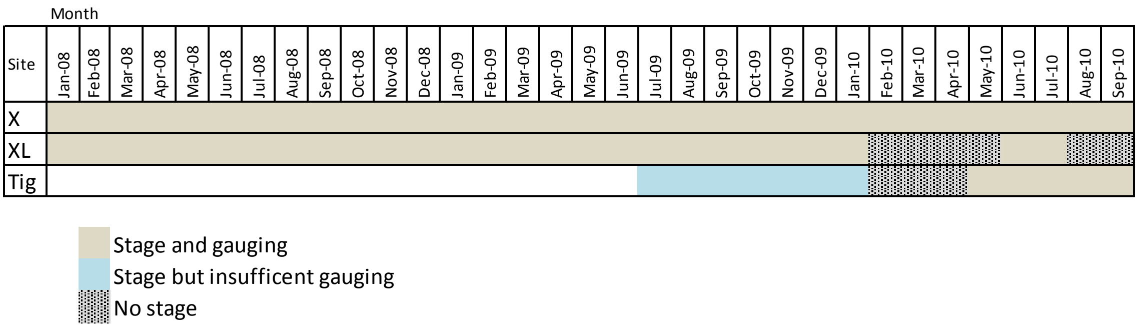


Figure 31. Stage and gauging records for the Crosswater, Crosswater of Luce and Tig

Crosswater stage – discharge relationship

The river Crosswater was gauged at the monitoring point on 13 occasions and the rating relationship is illustrated in Figure 32. The best fit relationship, ie giving the largest R^2 value, was quadratic and this relationship was used in all DOC flux estimations for the Crosswater catchment. Semi-continuous stage measurements at the Crosswater record a maximum of 1.25 m and a minimum of 0.14 m over the entire monitoring period, which indicates that while the gauging exercises captured low flow conditions there were no instances of high flow in the rating relationship. This is due to the impracticality of entering the river under such extreme conditions and this also occurs at the other two monitoring sites.

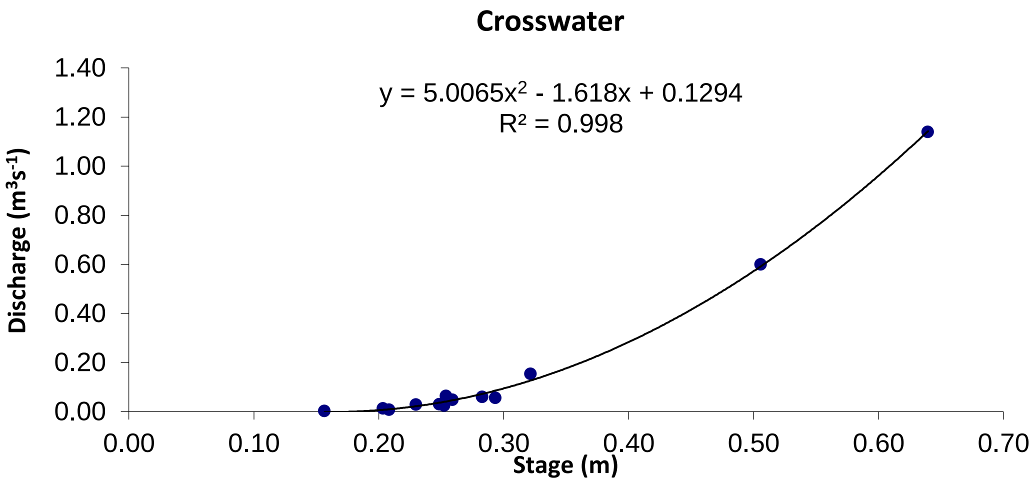


Figure 32. Rating equation for the Crosswater showing the relationship between discharge (m^3s^{-1}) and stage (m) and giving the resulting rating equation

Crosswater of Luce stage – discharge relationship

In contrast to the remarkably consistent performance of the equipment in the Crosswater catchment, the Crosswater of Luce suffered several data gaps due in part to extremes in flow experienced by the river (Figure 33 and Figure 34). The most extensive of these was in the stage record as shown in Figure 31 above. The first two years of the project between January 2008 and December 2009, though eventful in terms of damage to other equipment, did not give rise to any incidents affecting the collection of stage data. However no data relating to stage exists for 2010 except for a few weeks over June and July. The two year period prior to 2010 provides a robust baseline for the catchment but the Crosswater of Luce was designated as the experimental catchment to measure the impact of disturbance from the wind farm. As the greatest intensity of wind farm-related activity in the catchment took place during 2010 the gap in this part of the record is particularly challenging.

Figure 33. Crosswater of Luce sample point during a prolonged dry period showing exposed instrumentation within the red circle. Water flowed only in a channel on the far side of the gravel bar (indicated by the arrow)

Figure 34 Crosswater of Luce sample point during high flow conditions showing the automatic sampler dislodged and separated from its green and yellow stand.

Period one – 01 January 2008 to 14 January 2010

Five river gaugings were available for the period of time when stage data existed and these are plotted in Figure 35. The apparently high correlation between stage and discharge (R^2 = 0.9994) masks a problem in the spread of the discharge measurements. The number and range of gaugings were limited by the practicalities outlined above and by the flow and weather conditions, which conspired to create a gap in the mid-discharge region. This is a frequently identified problem in stream gauging but meant that the DOC flux estimates calculated using the discharge values generated from this equation needed to be treated with an extra element of caution.

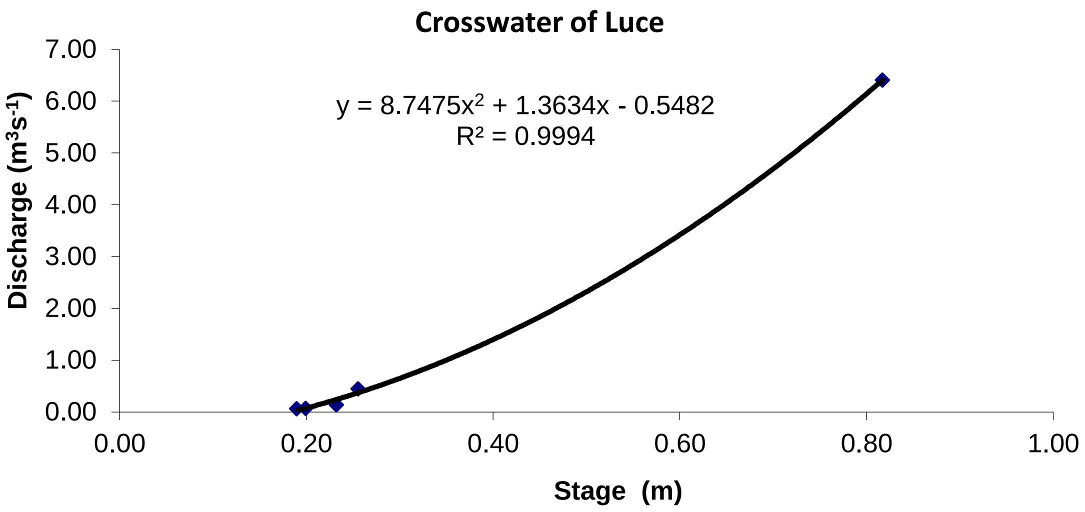


Figure 35. Rating equation for period 1 at the Crosswater of Luce

Period two – 15 January 2010 to 30 September 2010

The pressure transducer was dislodged in January 2010 and repositioned in March. Unfortunately it was discovered subsequently that the pressure transducer had not only been dislodged but damaged as well. A new sensor and logger were installed in June 2010 but the replacement logger only communicated briefly with the laptop between 18th June 2010 and 14th July 2010 before developing a fault, rendering the data unavailable, which could not be rectified by the manufacturer. The consequence of these misfortunes is that between 15th January 2010 and the end of the monitoring period on September 30th 2010, only a four week period of stage data exists. Two approaches were then considered to fill this extensive data gap.

1. Correlate with SEPA data from their Airyhemming gauging station further downstream on the Water of Luce catchment or

2. Correlate with the Crosswater catchment.

1. Using SEPA river discharge data

The Airyhemming gauging station (Figure 36) represents a 171 km^2 catchment, including the Crosswater of Luce. SEPA and the Centre for Ecology and Hydrology (CEH) hold gauged daily flow records dating back to 1967 and the strength of the relationship between the Crosswater of Luce and Airyhemming was tested using discharge from 2008. This was the baseline period for the Crosswater of Luce before any disturbance due to the wind farm.

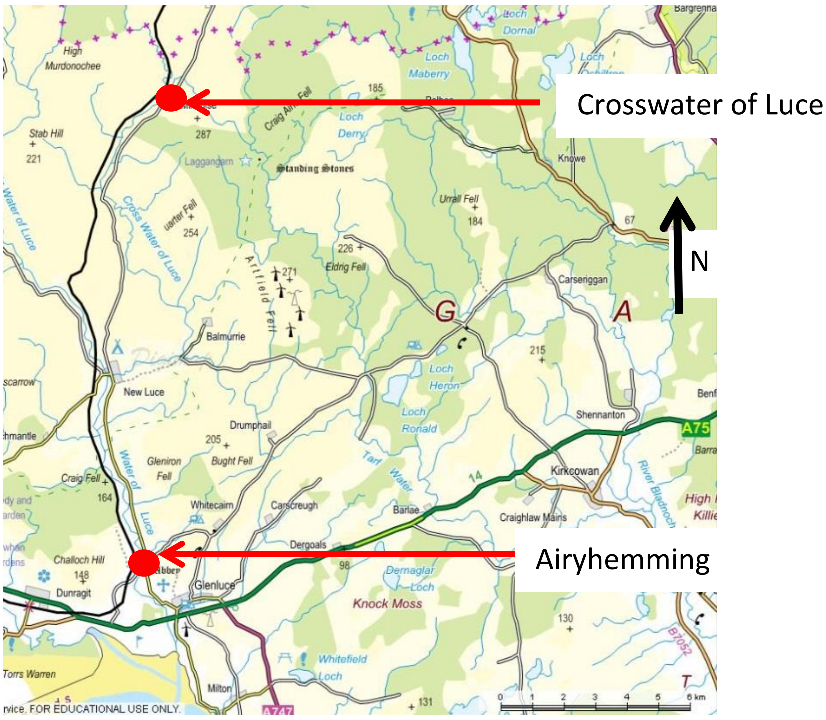


Figure 36. Location of the SEPA gauging station at Airyhemming relative to the Crosswater of Luce (Map based on Ordnance Survey material. Crown Copyright, 2004)

As is often the case with patterns of flow in natural river systems, neither the Water of Luce nor the Crosswater of Luce flow regimes exhibited a normal distribution. For example data for the Crosswater of Luce in 2008 were skewed to the left indicating that low flows influenced the system (Figure 37). Transforming the data generated a normal distribution for the 2008 Crosswater of Luce data (P = 0.145) but not the Water of Luce. Given the distance between the sites, one would also expect there to be a time lag in peak flows and other hydrological phenomena between the two sites resulting in a temporal offset of any peaks or pulses of DOC.

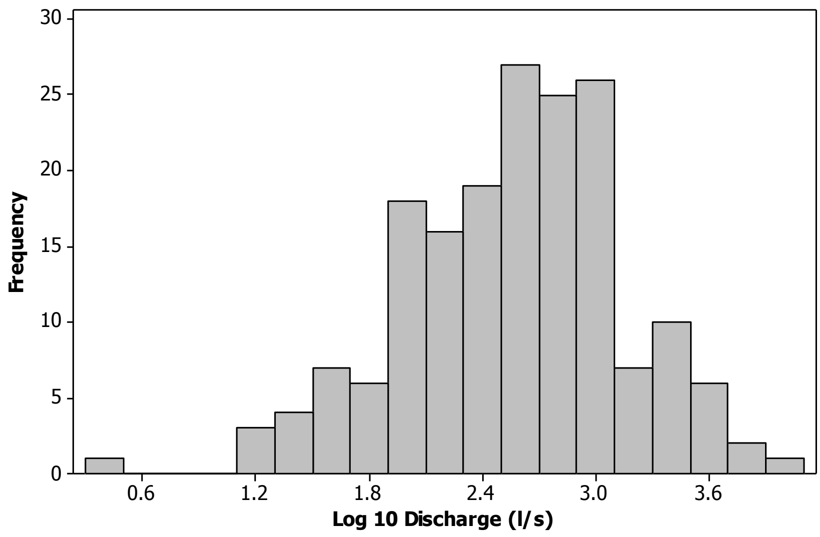


Figure 37. Frequency distribution of flow conditions at the Crosswater of Luce in 2008 using log transformed discharge values

The flow from the two rivers is positively correlated, with a Spearman rank correlation coefficient of 0.83 Using a table of critical values this was found to be significant at the 95 % confidence level (df =365). However it can be seen that there is a lot of scatter about the regression line (Figure 38), the explanation for which becomes clearer on inspection of the time series graph (Figure 39). Note that the two data sets have been plotted on separate axes to make for a more useful visual comparison of the peaks. An expected pattern would have been to see a lag between storm peaks from the two monitoring points with the maxima being seen on the upstream Crosswater of Luce first but this pattern is not evident here. Although many of the storm peaks coincide, there is often an element of disparity between them. On one occasion in March 2008 a significant event on the Water of Luce was missing from the Crosswater of Luce and it is possible that localised rainfall and storm movement may explain these unexpected observations. A regression fitted to the line shown in Figure 38 produced an R^2 of 55%.

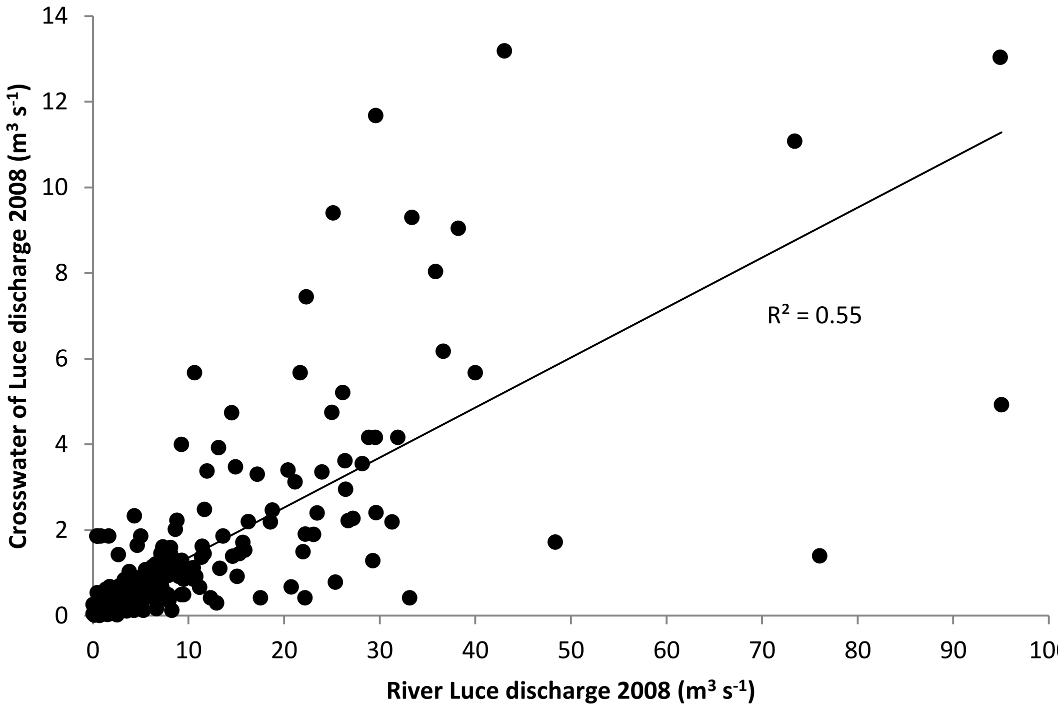


Figure 38. Fitted line plot for the relationship in discharge between the Crosswater of Luce (XL) and the Luce at the SEPA monitoring station, Airyhemming for 2008

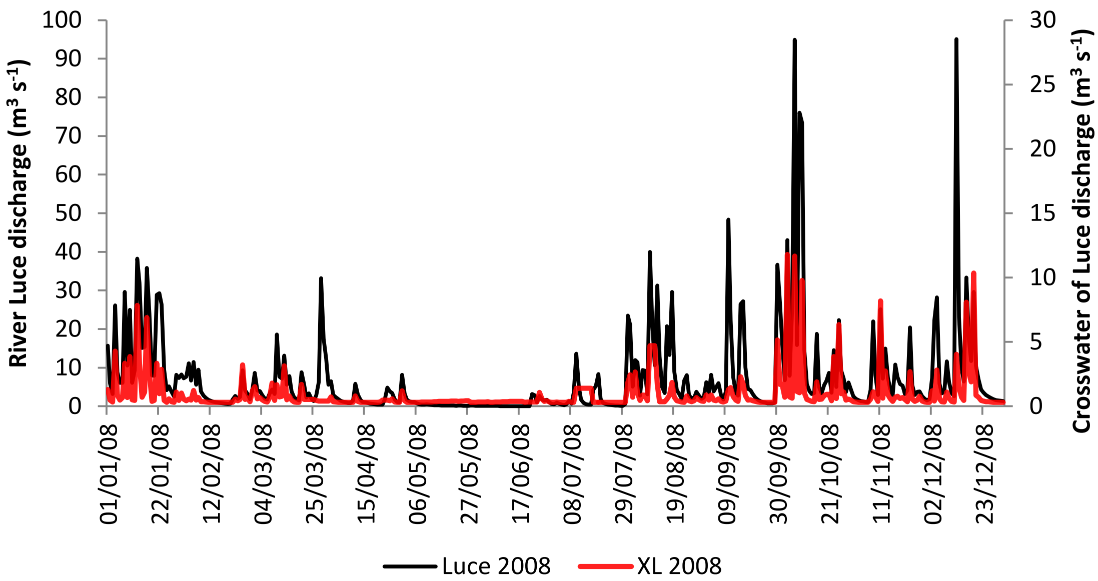


Figure 39. Time series plot of discharge at the Luce (SEPA monitoring station, Airyhemming) and the Crosswater of Luce (XL)

2. Using data from the Crosswater

As discussed earlier the water sampling point on the Crosswater has been acting as a control for the wind farm development as the catchment has been subject to relatively little disturbance and has only one turbine within its confines. With an area of 8 km^2 it is closer in size to the Crosswater of Luce (19.9 km^2) than the Water of Luce (171 km^2). Again the relationship between the two catchments was explored using mean daily flow data from 2008. There was a positive correlation between the two data sets with a Spearman rank coefficient of 0.77 and this was significant at the 95% confidence level (df=365).

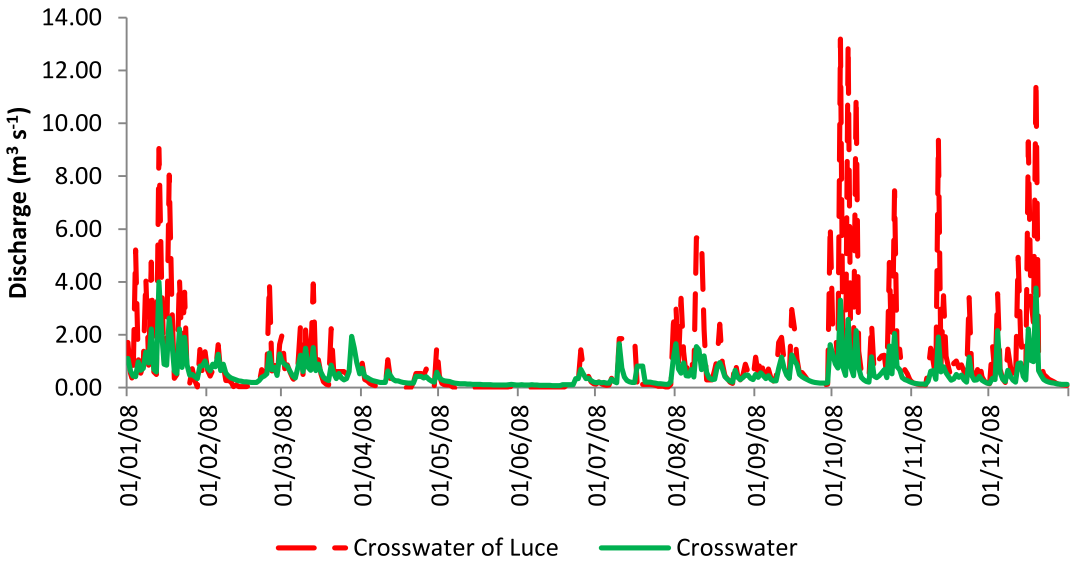


Figure 40. Discharge at the Crosswater and Crosswater of Luce sample points in 2008

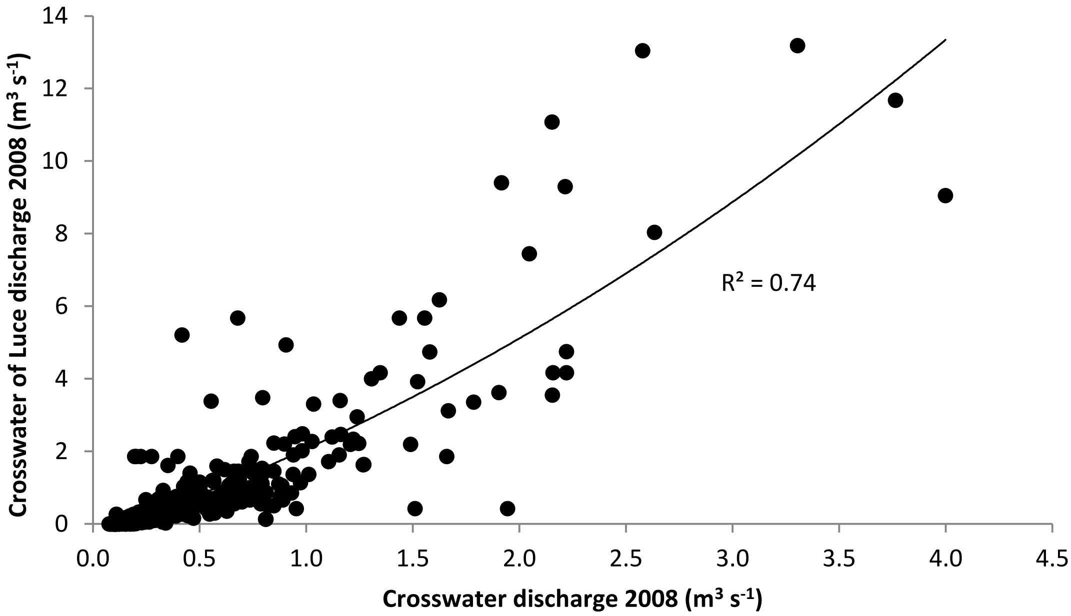


Figure 41. Fitted line plot for the relationship in discharge between the Crosswater of Luce and the Crosswater at the for 2008

The time series in Figure 40 illustrates the similarity in response to events between the two catchments and given the relatively high R^2 value of 74 % obtained from the fitted line plot in Figure 41 it would seem that the Crosswater would make a suitable candidate from which to generate a synthetic set of flow data for the Crosswater of Luce to cover the period between January and September 2010. These will also be the discharge values that will be used to estimate DOC flux at the Crosswater of Luce for that period.

The Tig stage – discharge relationship

The sample point on the river Tig was not instrumented until 22nd July 2009 when wind farm activity was already nearing its peak in this catchment. Baseline water quality data had been collected from a sample point nearly 10 km further downstream on the river (NGR NX 11777 83640) . However, this sample point was considered unsuitable for monitoring the wind farm construction both for logistic reasons – adding an extra day on to the monthly field trip – and because of the catchment characteristics making it a poor point of comparison with the Crosswater and Crosswater of Luce (less eat coverage and the dominance of agriculture). The new site was instrumented with a pressure transducer and data logger in the same way as the other two and this functioned correctly until 15th January 2010. In what was probably an incident similar to that which dislodged the pressure transducer at the Crosswater of Luce, the sensor at the Tig was also damaged. Although all of the stored data was successfully recovered up until January 15th, a replacement set of instruments was not installed until the end of May 2010. The situation is complicated further by the fact that there were insufficient gaugings taken across the Tig between July 2009 and January 2010 for a rating equation to be established. This produces three distinct periods within a relatively short time frame (Table 17) and once again creates the necessity to explore different means of filling this type of data gap.

Table 17. Stage and gauging information collected at the Tig representing three sets of data combinations and proposed adjustments to account for data gaps

	Time period	Data available	Solution
Period 1	August 2009 – December 2009	Stage but no gauging	Synthesise using later values
Period 2	January 2010 – May 2010	No stage	predict from Crosswater
Period 3	June 2010 – September 2010	Stage and gauging	Use rating equation

Period 1

22/07/09 – 14/01/10. Stage data but no gauging so no rating relationship.

For this period there is a full stage record but no rating curve to apply in the calculation of discharge. There is however a rating curve for period 3 on the Tig and this can be used to describe the relationship between stage and discharge in period 1 if two factors can be quantified and suitable adjustments made to the stage values in period 1.

The first factor is a possible variance in water levels due to differing underlying hydrological conditions between to the two periods. This was explored using the Crosswater catchment, which had a full stage record throughout the lifetime of the project.

1. Take a span of time where there is low flow and we have stage and gauging for both Crosswater and Tig.

01/09/2010 – 06/09/2010 (period 3 on the Tig).

2. Find a similar low flow period in the August – December 2009 period where we have no Tig gauging.

15/09/09 – 20/09/09 (Period 1).

3. Find the mean difference in stage at Crosswater between the two sets of data.

Stage in 2009 is 0.007 m higher than in 2010

This gives a total adjustment of 0.029 m added on to Tig stage 2009 values in period 1 and the change in stage achieved through this process can be seen in Figure 42. It shows the stage records obtained at 15 minute intervals during each period of time. Having done this it is then possible to apply the Tig rating equation for period 3 to the adjusted stage data from period 1.

$Q = 1.1762\text{stage}^2 + 1.4725\text{stage} – 0.1282 \quad R^2 = 0.900$

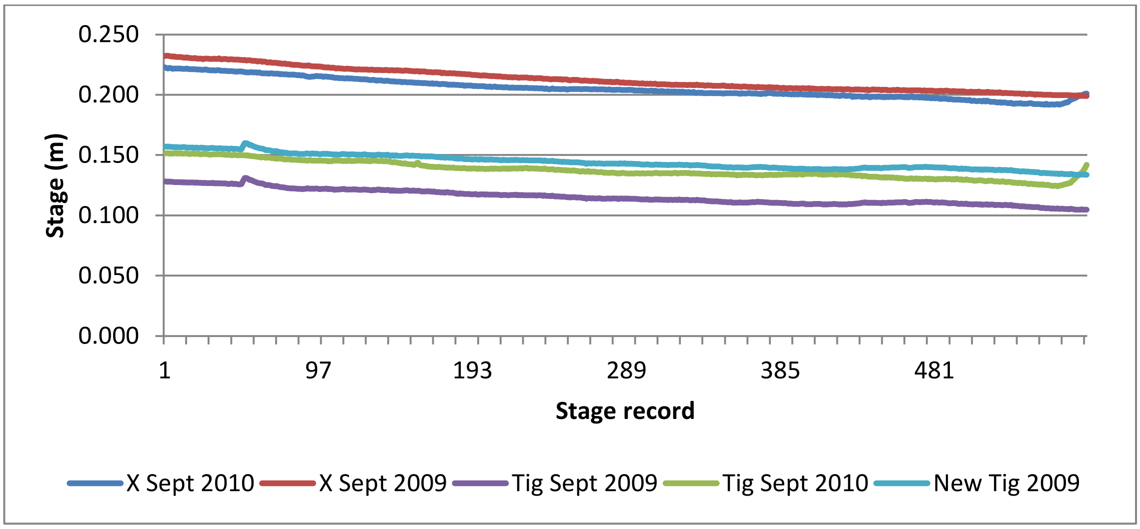


Figure 42. Adjustment to the stage record at the Tig to account for gaps in the data during 2009 using the relationship with stage at the Crosswater. The y axis gives the stage in metres obtained at 15 minute intervals shown on the x axis.

Period 2

15/01/10 – 25/05/10. No stage data

As neither stage nor gaugings exist for this period we will use the mean daily discharge from the Crosswater to predict values for the Tig. A regression analysis was carried out using mean daily discharge values on both catchments for August 2010 (Figure 43) and an R^2 of 86% obtained for the equation:

$Q_{Tig} = 0.9722Q_X + 0.0295 \quad R^2 = 0.86$

Using this equation it is possible to predict mean daily discharge at the Tig for period 2 using the values from the Crosswater.

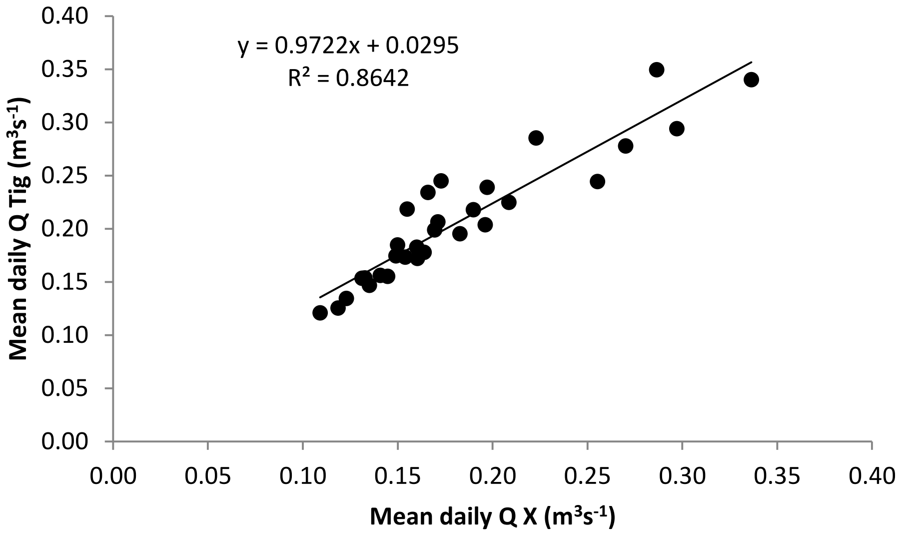


Figure 43. Mean daily discharge (Q) at the Tig plotted against the mean daily discharge (Q) and the Crosswater (X)

Period 3

25/05/10 – 30/09/10 Stage and gauging

There are both stage data and sufficient gaugings to generate a rating curve for this period. This was used to calculate discharge values for the Tig for period 3 (Figure 44).

$Q = 5.6553 * stage^{2.6}$ $R^2 = 0.958$

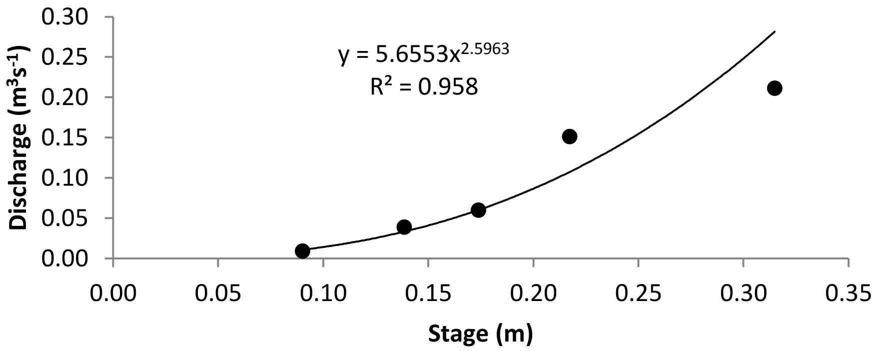


Figure 44. Rating relationship for the Tig during period 3

Thus the Crosswater alone has an uninterrupted data set with regard to discharge and DOC making it possible here to explore changes in discharge and DOC flux estimates through time. For the Crosswater of Luce this is feasible for 2008 and 2009. In 2010 while DOC was recorded directly, the discharge values are synthesised from a relationship with the Crosswater. Hence any analysis of DOC flux estimates or runoff from this period assumes the integrity of this relationship. This ignores the potential for the wind farm construction and forest harvesting to alter the hydrological regime of the Crosswater of Luce and this must be borne in mind when interpreting DOC flux estimates. Consequently it also removes the option to assess the impact of forest harvesting and wind farm construction on peatland hydrology and makes a meaningful comparison of DOC flux between the two catchments more limited. If one effect of forest harvesting is to enhance runoff in the short term due to less evapotranspiration, then it is likely that DOC flux estimates based on synthesised discharge values from the Crosswater will lead to an underestimate of DOC at the Crosswater of Luce.

2.5.5 **DOC Flux estimates**

Estimates of DOC flux at the three catchment sample points are shown in Table 18 where data is presented by hydrological year (October – September); calendar year, which allows the maximum use of the baseline data set that started in January 2008; and between January and June, which allowed the Tig catchment to be brought in to the comparison during 2010. A monthly breakdown of DOC flux is shown in Figure 45.

Annual DOC flux estimates across the three catchments ranged between 29.3 g C m^{-2} (October 2009 – September 2010 at the Crosswater of Luce) and 58.0 g C m^{-2} January – December 2008 at the Crosswater. Flux estimates found at Arecleoch are higher than those from other Scottish peatlands for example Waldron *et al.* (2009) estimated DOC flux for nine catchments with varying amounts of peat and forest cover, draining the Whitelee wind farm development and reported a range of 6.9 to 20.6 g C m^{-2} yr^{-1} (Waldron *et al.* 2009). Dinsmore *et al.* (2010) estimated a mean DOC flux of 25.4 g C m^{-2} yr^{-1} from Auchenforth Moss peatland in central Scotland over 2007 and 2008. This suggests that Arecleoch is either achieving greater levels of productivity or that the existing carbon store is being depleted as a consequence of generations of human interaction with the landscape. Worrall and Burt (2007) demonstrated that the dominant controlling factor on DOC export was not DOC production but hydrological and the high values of DOC in their study were due to the amount of water that had left the small catchments and the proximity between source and sampling. At Arecleoch the dense drainage network introduced for forestry and intense management make it likely that the high DOC flux estimates also represent a net loss of DOC.

The Crosswater (control catchment) lost more carbon as DOC per unit catchment area than the Crosswater of Luce in 2008 and 2009, which may be a function of the existing land use and catchment size. The Crosswater sample point was closer to the carbon rich, headwater streams and was largely afforested (~88 %) while the Crosswater of Luce had a smaller percentage of forest cover (~40 %) and the sample point was further from the headwaters allowing instream processing to remove DOC. The difference in DOC flux between the Crosswater and Crosswater of Luce was 23.1 g C m^{-2} in 2008 but only 11.0 g C m^{-2} in 2009, a reduction in the difference of 12.1 g C m^{-2}. This could mean an extra 12 g C m^{-2} being exported from the Crosswater of Luce in 2009 that may be attributable to activities associated with the wind farm development.

	DOC flux (g C m^{-2})		
	XL (SE)	X (SE)	Tig (SE)
2008	35.0 (1.9)	58.0 (0.9)	nd
2009	44.1 (1.6)	55.0 (0.3)	nd
2008 Jan - June	7.5 (0.9)	17.0 (0.3)	nd
2009 Jan - June	9.2 (0.8)	21.9 (0.1)	nd
2010 Jan - June	8.3 (2.0)	12.0 (0.1)	15.7 (0.1)
Oct 08 – Sept 09	42.3 (2.0)	53.8 (1.6)	nd
Oct 09 – Sept 10	29.3 (1.3)	41.7 (1.1)	37.9 (1.0)

Table 18. DOC flux estimates from the Crosswater (X), Crosswater of Luce (XL) and Tig catchments annually (Jan – Dec), half-yearly (Jan – June) and by hydrological year (October – September). nd = not determined for the Tig as sample point was instrumented from July 2009 onwards.

In the first six months of 2008 **21.4 %** of the annual C flux was exported from the Crosswater of Luce (7.5 g C m^{-2}) compared with **29.4 %** (17.0 g C m^{-2}) from the Crosswater. For the same period in 2009 the figures are **20.8 %** (9.2 g C m^{-2}) from the Crosswater of Luce and **39.8 %** (21.9 g C m^{-2}) from the Crosswater. In 2010 where values are available for the three catchments between January and June only, we can see that DOC flux from the Crosswater of Luce was 8.3 g C m^{-2}, a reduction of 0.9 g C m^{-2} over the same period in 2009. In the case of the Crosswater 12.1 g C m^{-2} was exported, which was a reduction of 9.9 g C m^{-2}. At the Tig the DOC flux was 15.8 g C m^{-2} over the first six months of 2010.

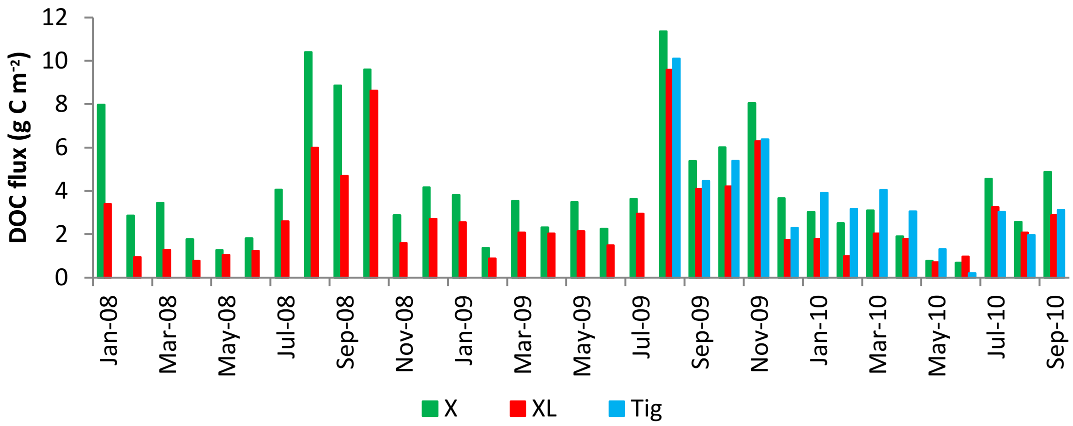


Figure 45. Monthly DOC flux at the Crosswater (X), Crosswater of Luce (XL) and Tig catchment sample points

This exercise was repeated this time separating the data according to hydrological years and seasons, thereby using less of the data from 2008 but more from 2010. This paints a different picture of the relationship within and between the catchments and whilst the Crosswater is still a larger exporter of DOC (Table 18). It can be seen that instead of increasing in the second year, flux from the Crosswater of Luce was less in the 2009 – 2010 hydrological year. Flux estimates were integrated monthly (Figure 45) and it is apparent that particularly high DOC fluxes in August and September 2009 were not matched in 2010 for the Crosswater of Luce leading to lower estimates in the October 2009 – September 2010 hydrological year.

Differences in monthly flux estimates between the Crosswater and Crosswater of Luce were examined statistically using the Mann-Whitney test and it was found that significantly more ($W = 1307$, $p = 0.005$) carbon was exported monthly from the Crosswater than the Crosswater of Luce per unit catchment area. A difference in DOC flux between catchments or years must be a result of changes in either DOC concentration, discharge or a function of both. It has to be remembered that discharge for the Crosswater of Luce in 2010 was synthesised from data at the Crosswater so the low flux estimates for August and September 2010 may be contingent upon these predicted values and not necessarily reflecting true values. While it is not possible to rule out this entirely, by considering DOC concentrations and discharge estimates separately for the different time periods we can see if a similar pattern emerges (Table 19 and Table 20). Thus at the Crosswater from 2008 to 2009 DOC concentration increases, discharge decreases and flux decreases. At the Crosswater of Luce DOC concentration also increases but so does discharge and flux. Thus it is the increase in discharge that has led to greater DOC flux in 2009 at the Crosswater of Luce.

Consequently we should be circumspect about interpreting the flux estimates in 2010 where we assume a stable relationship in discharge between the two catchments.

Table 19 Mean DOC concentrations (mg L^{-1}) at the Crosswater and Crosswater of Luce for calendar and hydrological years

	Mean DOC concentration (mg L^{-1})			
	2008	2009	Octo8- Sept 09	Oct 09- Sept 10
Crosswater	27.91	30.74	29.76	26.62
Crosswater of Luce	21.40	22.45	22.32	21.91

Table 20. Mean discharge (m^3/s) at the Crosswater and Crosswater of Luce for calendar and hydrological years

	Mean discharge (m^3/s)			
	2008	2009	Octo8- Sept 09	Oct 09- Sept 10
Crosswater	0.53	0.45	0.36	0.32
Crosswater of Luce	0.92	1.10	1.08	0.83

Activity scores from the Crosswater of Luce (Theme 3.2) show that wind farm construction work in the Crosswater of Luce catchment began to increase in intensity from May 2009. To determine whether this was reflected in DOC flux a comparison was made using monthly DOC flux (Crosswater of Luce/Crosswater ratio) between the periods January 2008 to April 2009 and May 2009 to September 2010. It was found that the flux ratio of Crosswater of Luce/Crosswater was significantly higher ($W = 344$, $p = 0.0248$) for the latter period than the former. This means that relatively more DOC was exported from the Crosswater of Luce than the Crosswater over the second half of the monitoring period.

2.6 Discussion

The aim of this theme was to describe the three catchments associated with Arecleoch forest in terms of their surface water regimes and carbon flux and to integrate this information with the natural and anthropogenic-induced conditions exerted on the landscape at the time.

The regime of a river is the expected pattern of flow through the year and it is suggested that flow records for a period of 10 - 20 years are needed in order for such a regime to be established with any certainty (Shaw, 1994). With three years' data in this study therefore it is appropriate only to comment on patterns of flow that contribute towards an understanding of the hydrology of Arecleoch. Total monthly discharge values from 2008 and 2009 reflected catchment size but when normalised for catchment area, specific discharge revealed that the Crosswater produced a higher mean monthly discharge than the Crosswater of Luce, particularly during 2008. This difference narrowed significantly in 2009 and it is hypothesised that aside from inter-catchment differences, changes in the discharge relationship were a result of forest harvesting in the Crosswater of Luce as part of the Arecleoch wind farm development that reduced the interception capacity of the catchment.

Two hypotheses were tested in this theme with the first being that **DOC export from the Crosswater catchment will be significantly higher than DOC export from the Crosswater of Luce catchment when standardised for catchment area**.

DOC flux estimates from the Crosswater ranged between 41.7 and 58.0 g C m^{-2} yr^{-1} compared with a range of 29.1 to 44.1 g C m^{-2} yr^{-1} from the Crosswater of Luce. Significantly more ($W = 1307$, $p = 0.005$) carbon was exported monthly from the

Crosswater than the Crosswater of Luce per unit catchment area thus supporting this hypothesis. The Crosswater was used a control catchment because it contained very little infrastructure of the Arecleoch wind farm whereas the Crosswater of Luce contained 31 of the 60 turbines. The higher flux estimates from the Crosswater both before and during the wind farm development are due to differences in size and land use – the Crosswater (8 km^2) was under commercial forestry (88 %) while the Crosswater of Luce (19.9 km^2) was mainly moorland and rough grazing with only 40 % forest cover.

The second hypothesis tested in this theme was that **the export of DOC from the Crosswater of Luce as a proportion of that from the Crosswater per unit area will be higher after wind farm activity starts in the Crosswater of Luce catchment.**

While the control Crosswater catchment had a higher annual DOC flux than the experimental Crosswater of Luce the difference in DOC flux between the two reduced by 12.1 g C m^{-2} from 2008 to 2009. Wind farm development activity in the Crosswater of Luce was at its most intense in 2009 and this could be interpreted as an extra 12.1 g C m^{-2} being exported from the Crosswater of Luce as a result of activities associated with the wind farm development thus supporting the hypothesis.

Theme 3. Land use change and anthropogenic sources of peatland disturbance at Arecleoch

3.1 Introduction

Superimposed on the two previous themes that described intrinsic properties of the three catchments of Arecleoch forest is this third theme that explores some of the environmental impacts of decisions made by humans as to how the land should be managed. In it I will place in context the way in which these choices have served, not only to shape the landscape visually, but also to set in train other, unintended changes to water quality. The specific aims of theme 3 are:

- Develop a novel method for relating changes in DOC concentration to specific wand farm activities;
- To assess the impact of the wind farm on DOC concentrations at different spatial scales; and
- To explore the potential of POC concentrations as indicators of disturbance.

Two hypotheses will be testes in this theme:

Firstly that **DOC concentrations at the sub-catchment scale will be higher in areas of and at times of greater wind farm activity**; and

Secondly that **POC as a proportion of ss will be significantly higher where disturbance is from forestry and turbine installation activities. It will be significantly lower where the elevated concentrations of ss are due to road runoff**.

3.1.1 **Defining disturbance**

Humans have not trodden lightly over the peat land of Arecleoch and the landscape bears the scars of each of these interventions. Many arguments over the deterioration in landscape quality have historically been, and continue to be, inextricably related to perceptions as to the value of that landscape. The perceived value of the peatland can be inferred by means of a stroll through the efforts of current and past land owners to convert it into something else more "valuable". The landscape value of a plantation forest as opposed to a wind farm development for example is subjective and, as such, hostage to cultural preferences at any point in time. In such cases it is necessary first to agree on what matters before research is commissioned to find out whether it has deteriorated. In general people like trees and regard their presence as a positive landscape attribute as well as having wider benefits. For example 82% of respondents in the Forestry Commission's 2011 Public Opinion Survey agreed with the statement that trees are good because they remove carbon from the atmosphere and 80% said that a lot more trees should be planted (Forestry Commission 2011).

Public opinion in relation to wind farms on the other hand is a more multifaceted subject. Surveys consistently demonstrate that there is broad general support for wind energy in both principle and practice (British Wind Energy Association (BWEA) 2005). However, developers in the past have been complacent in thinking that this general positive attitude will translate into support for specific projects. The reality is that planning applications for wind farms have often generated vociferous and passionate opposition from a wide range of parties. Explanations for opposition to or acceptance of wind farms have been explored and would appear to be more complex than sheer NIMBYism (Eltham, Harrison & Allen 2008; Jones & Eiser 2009).

Deeper issues such as disruption to place attachment (Devine-Wright & Howes 2010) are involved and the level of public support for developments may be closely linked to matters such as the degree of trust in the local authority and planning system. Sometimes public opinion is moulded by a desire either to return to or not to deviate from what is perceived to be the "natural "state of the landscape often forgetting that the choice is likely to between different but equally intensively managed options.

The degree of subjectivity involved is sometimes revealed in the language used to describe the landscape. For example Ruth Tittensor, author of "From Peat Bog to Conifer Forest: An Oral History of Whitelee, Its Community and Landscape" (Tittensor 2009) in the Radio 4 programme "Open Country" on Saturday 13 November 2010 told of how she interviewed the people who could tell the story of "How the landscape was changed from a bleak, wet moorland to a living, growing forest" in Whitelee forest. She went on to describe the state of the land when the Forestry Commission arrived as being incredibly poor with deep, thick peat, difficult to make a living. The judgements made here about the landscape value are based squarely in agricultural and economic terms.

Quantifying the nature and extent of landscape disturbance relies upon the parameters measured, and decisions about where resources should be focused are also shaped by the values of those involved in the research. Conservationists for example define the value ascribed to blanket peatland in terms of biological, physical, and hydrological features and processes that have led to the existing ecosystem (Coupar, Immirzi & Reid 1997). The development of the peatland is then influenced by a combination of internal and external processes, the latter including human involvement (Coupar, Immirzi & Reid 1997). Some of these processes may lead to degradation of the peatland but identifying the cause or causes of disturbance may be complex. Even a major disturbance to the peatland from a significant land management change is likely to have been preceded by a series of other disturbances from, for example, grazing or water table drawdown. Consequently the landscape that is presented as a canvas for research has to be viewed through this historical lens so that the current event can be placed in the context of a series of disturbances superimposed on one another (Tallis 1997). Disentangling this story to reveal the significance of a single phase of land use is destined to be challenging.

Causes and non-carbon store effects of disturbance

The traditional causes of peatland disturbance are many and varied for example;

- **Drainage to enable wider use of the land e.g. for forestry and hunting.** Artificial drainage of blanket peat has been used in the UK to lower the water table to improve marginal land productivity for agriculture, grazing and forestry and as a response to the perception that peat drainage will alleviate flood risks (Holden *et al.* 2006; Wallage, Holden & McDonald 2006).
- **Extraction of peat for horticulture and fuel products.** This may be a relatively minor source of peatland loss today compared with forestry, but it amounts to 10% of active peatlands lost over time outside of the tropics (Chapman *et al.* 2003).
- **Livestock grazing.** Degradation effects due to grazing pressures are thought to vary according to stock density. It is suggested that a low level of grazing by larger herbivores may have beneficial effects on plant species diversity (Hulme & Birnir 1997).
- **Burning** to improve food supplies and habitats for sheep and grouse and as a management tool through the practice of muirburn (Hamilton, Legg & Zhaohua 1997).

We must now add to this list the activities involved in constructing a wind farm. Research into disturbance to peatlands was initially focused on ecological concerns such as describing and quantifying habitat loss. This is unsurprising as the stability of British hillslopes, including peatlands, is controlled to a large extent by the upland vegetation growing on them. When this vegetation is disturbed the negative impacts include the reduction of species diversity, plant cover, productivity and peat accumulation (Tallis 1997). The processes of disturbance that lead to erosion are illustrated in Figure 46. Disturbance to vegetation also leads to the exposure of bare peat, which is then vulnerable to the full force of weather events. Re-colonisation following local disturbance has been recorded after as little as a year but may not be possible if further disturbance is allowed, there is a lack of seed or the substrate is unstable or infertile (Tallis 1997). Frost action and desiccation reduce structural cohesiveness and rain can penetrate the peat via desiccation cracks resulting in gully systems (Bragg & Tallis 2001; Labadz, Burt & Potter 1991). Further to this, channelled overland flow develops and large quantities of material underlying the surface soils and peat can be mobilised (Stott & Mount 2004). Drainage of peatland also allows oxygen to diffuse to greater depths. Increased aeration halts methanogenesis but allows oxidation, which proceeds far more quickly than anaerobic decomposition. This increases the rate of CO_2 carbon loss and can exacerbate an already heightened risk of subsidence (Cannell, Dewar & Pyatt 1993).

How land use in Scotland leads to carbon loss

We can see then that land management practice (together with climate and geology) plays a key role in determining the type of vegetation. As such it can be viewed as one of the initial controls on the amount of carbon in the terrestrial pool (Dawson & Smith 2007). In the carbon rich, organic soils of the Scottish uplands, land use has traditionally been limited to rough and improved pasture for sheep, plantation forestry, moorland for game pursuits and provision potable water sources.

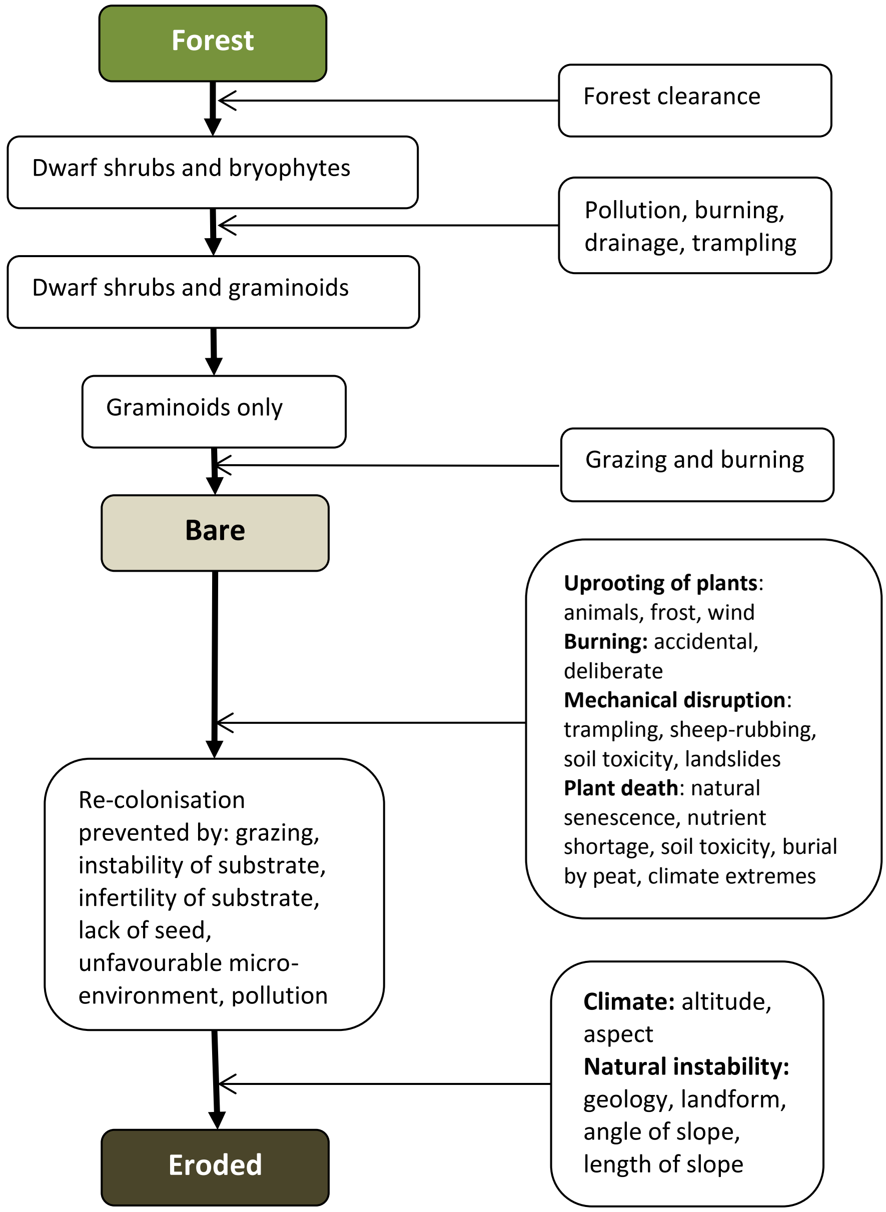


Figure 46. Process of disturbance leading to erosion (Tallis 1997)**. The column on the left illustrates the stages of moving from forest to bare land to eroded land when acted on by processes and factors on the right**

How does disturbance cause carbon to move from the soil to surface watercourses?

In the case of Arecleoch land use was mainly focussed on sheep grazing until the 1950s when forestry was introduced and it now is sharing those functions with renewable energy generation. Central to these land uses are activities including drainage, abstraction and habitat alteration, all of which place physical stress on the soil and can lead to carbon loss (Dawson & Smith 2007). Recent years have seen the focus of research into peatland disturbance moving towards carbon storage, driven by concerns over climate change and a growing evidence base supporting scientific opinion that peatlands are a vital store of terrestrial carbon.

DOC production has been discussed in Theme 1 so we move now to its transport from the soil to rivers and streams. There are three sinks that carbon enters once it is lost from the soil: the atmosphere, groundwater and surface waters and only the atmosphere route is not uni-directional (Dawson & Smith 2007)). The export of allochthonous DOC from peatlands to surface water can be considered as a three-stage process: (1) production of DOC from the partial decomposition of terrestrially fixed carbon, (2) transport of DOC to surface water from the terrestrial environment and (3) the modification of both quantity and composition of the DOC during this transport (Brooks, McKnight & Bencala 1999). Production of DOC is driven by anaerobic conditions in the soil with more production leading to higher DOC concentrations; transport is controlled by site hydrology. Therefore any disturbance to peatland that alters the production of DOC and/or hydrology of the system may be expected to alter the nature and quantity of DOC export (Strack *et al.* 2008).

3.1.2 **Forestry and Disturbance**

Introduction

Forestry has played a significant part in shaping the visual, social and environmental landscape of Scotland, which it is estimated currently hosts more than half of Britain's 3.8 billion trees (Forestry Commission 2011). The policy of converting as much land as possible to productive forestry came about as a result two world wars in the first half of the twentieth century, both of which placed enormous demands on Britain's indigenous forests (Farmer & Nisbet 2004). One result of this afforestation is that over the past 65 years, about 315 000 ha of shallow peats (<45 cm depth) and 190 000 ha of deep peatland (> 45 cm) in Britain have been forested with conifers (Cannell, Dewar & Pyatt 1993). The majority of this activity has taken place in Scotland and it has been estimated that 163 000 ha of peat soils >45cm deep in Scotland are covered by forest and 129 000 ha of forest lies on blanket mire (peat with a minimum depth of 1 m) (Coupar, Immirzi & Reid 1997). Putting this into a global perspective, it is estimated that present day losses of non-tropical peatland are due almost entirely to agriculture and forestry (>99.8%) (Chapman *et al.* 2003).

Many of the upland areas selected for afforestation were also water supply catchments and much of the initial research effort into the negative environmental effects of forestry was driven by the Water Industry and aimed at addressing concerns over water resources. As the rate of increase in demand for water slowed towards the end of the 1980s, concerns began to focus on land preparation aspects of forestry and their effects on soil erosion and siltation (Maitland, Newson & Best 1990; Nisbet 2001). Later, other environmental concerns such as the role of forestry in surface water acidification led to a broadening out of research to encompass a wider range of water quality parameters such as water colour (Reynolds, Kneale & McDonald 1996).

In 1988 following increasing concern over the impact of forestry practices on the environment, the UK Forestry Commission published a set of guidelines to address the major water quantity and quality issues. Subsequently revised and updated the Forests and Water Guidelines (4th edition) (Forestry Commission 2003) provide advice on best practice in all aspects of forestry to protect water draining from forest catchments.

The Forestry cycle

We will now look in more detail at the body of evidence amassed by the science community in an effort to answer questions surrounding the effects on soils and water of each of these stages. Before commencing though it is worth pausing to contextualise the environments in which many of the major studies were carried out. It must be remembered that early studies on the effects of forestry practices were inevitably products of their time. They were carried out before the introduction of the Forests and Water Guidelines in 1988 (as updated, 4th edition Forestry Commission 2003) and do not represent the methods now widely practised in the UK. Many investigations such as those at Balqhuhidder (Johnson 1991) and Plynlimon (Kirby, Newson & Gilman 1991) base their conclusions on paired catchment studies where one catchment undergoes some form of disturbance while the other represents the control. Obtaining robust data from field based studies is often challenging and careful selection of the paired catchments is vital so as to minimise any confounding differences between them. Ferguson *et al.* (1991) suggest that differences between catchments such as variability in discharge and initial suspended sediment concentrations can cast doubt on the reliability of data obtained from such a paired catchment study. Similarly caution should be exercised in interpreting data from "before and after" investigations also commonly used to assess the effects of land use change on water quantity and quality. Ferguson *et al.* (1991) note the importance of an adequate period of pre-disturbance monitoring so that short term variations in water quality due to rainfall variation can be quantified. A final note of caution over the use of paired catchment studies was expressed by Tetzlaff *et al.* (2007) who noted that these studies often compare a felled with a non-felled catchment where in reality commercial forests are sequentially felled over many years. Thus any impacts may be unlikely to affect an entire catchment and investigations are better placed in monitoring actual forest operations.

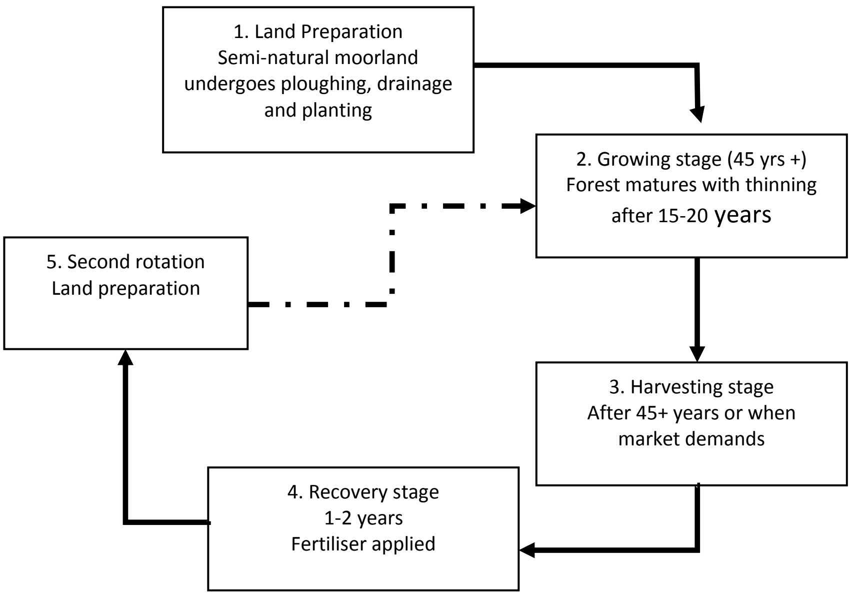


Figure 47. Commercial forestry cycle (from (Stott & Mount 2004))

Figure 47 shows the standard forestry cycle from a semi-natural moorland through the first rotation of trees, which are harvested and the ground prepared for the second rotation. Within this framework, much of which has been standardised by the Forests and Water Guidelines there can be a lot of variation in the methodologies used and length of time taken at each stage. The story at Arecleoch illustrates well both the evolution of forestry methods and the way in which this best practice policy is tailored to accommodate new situations and employed on the ground.

During the land preparation at Arecleoch double and single furrow 'cubby' ploughing was used. This was generally shallow until the early 1960s when deep ploughing became more standard and the plant density varied from 3500 ha to 2500 ha in the 1970s. Drains were spaced at 1.7 m intervals, changing to 2.0 m in the 1980s with all the ground being cross drained at about 20 m intervals. Fertilisers were heavily used, with P at planting, PK at year 5, P at year 10 and with a large part of the older block also having N. At the start it was spread by hand but then by using helicopters or fixed wing aircraft. It was monitored annually using foliar analysis techniques. C. *vulgaris* was also treated using 2,4-D, a common systemic pesticide/herbicide. It was applied with ULV sprayers or by fixed wing aircraft, streams drains and all. An eyewitness reported that "It was very dramatic as it defoliated all the spruce. However they returned with vigour and grew over a metre a year for the next five years or so". 2,4-D is still a widely favoured herbicide but there is now a whole regulatory framework in place controlling the use of pesticides, and the presumption has moved towards not applying anything unless it is needed.

Forest harvesting at Arecleoch deviated from the original design plan for the purposes of accommodating the wind farm. The recommended maximum harvesting rate is currently 25 % of an area over 5 years. It is of course possible to harvest intensively in a small part while keeping to the overall target for the area and in this way 15 years' felling was carried out in 2 years. It would be interesting to know if this had any impact on water quality. Given the evidence demonstrating that phased harvesting can reduce water quality deterioration as compared with standard harvesting (Neal, Smith & Hill 1992; Neal *et al.* 1998), it would seem a logical step to speculate that more intensive felling could achieve the opposite. Contrary to the standard forestry cycle as illustrated in Figure 47, there was no recovery stage for much of the restock, with trees being planted shortly after felling in many areas. In other areas the Google earth images (Figure 6) show that the land had been left bare for several years prior to replanting. Replanting has mostly been carried out under the latest iteration of the Forests and Water Guidelines (Forestry Commission 2003) and other technical guidance such as the "Forest Ground Preparation Guidance Note" (Forestry Commission 2002), which carry prescriptions for ground preparation. For deep peats this recommends shallow spaced ploughing and mounding for restock. It is also worth noting that no fertiliser was applied for the restock at Arecleoch.

Stage 1: Ground preparation

Here we will consider the starting point for the commercial forest cycle to be the preparation of moorland for planting. It must be remembered that although this is the point at which forestry-related disturbance has the potential to begin, the land may already have undergone varying degrees of stress from previous land management systems. Traditional views on forestry considered it to be fairly benign in terms of, for example, soil disturbance, until harvesting took place. However, this was based on studies carried out in the USA where forest drainage was not required (Robinson & Blyth 1982). In Britain where, as indicated above, many forests are planted on uplands with peat soils, artificial drainage is needed before planting can take place. In fact cultivation and drainage operations to prepare land for afforestation have the potential to create significant disturbance. A large amount of soil becomes exposed and improved drainage leads to increased velocity of rain runoff. These risks can also be compounded by the nature of the terrain and the weather conditions (Nisbet 2001).

Drainage and hydrology

Improving the drainage in a peatland has the potential to affect it in two main ways: by lowering the water table and by causing changes to runoff patterns. Studies on the hydrological response of peatland catchments to drainage have generated a plethora of contradictory outcomes, reporting for example both increased and decreased peak flows and runoff rates (Holden, Chapman & Labadz 2004). Robinson (1985) revisited one of the first investigations in this area by Conway and Millar (1960) and agreed with their observations that draining increased the peakiness of flow response but did not increase annual runoff efficiency. Robinson (1985); (1985) concluded however that there was insufficient evidence to support Conway and Millar’s assertion that drainage reduced low flows, and other studies have reported increases in low flow levels following drainage (Francis & Taylor 1989). This effect is thought to be either a result of better drainage efficiency or the dewatering of surface peat layers (Francis & Taylor 1989; Holden, Chapman & Labadz 2004).

It is now known that the effects of ditching may vary greatly according to the catchment characteristics, where on the catchment’s timeline the study is based and where in the catchment both the drainage and the investigations take place. Each of these factors will be discussed in turn.

1. Catchment characteristics and drainage techniques.

The nature of the land use and management, details of the catchment topography and specific drainage techniques employed are all interconnected. They can each contribute to changes in flood and annual runoff resulting in seemingly contradictory outcomes of similar investigations. Some of these effects are summarised in Table 21.

2. Where on the timeline the investigations are focused

Holden *et al.* (2006) also revisited the Conway and Millar (1960) study and found that while lowering the water table by drainage does indeed increase short term water storage and delays runoff response, more water is lost in the medium term (the point of drainage).

Table 21. Observed effects of land drainage (after Holden *et al.* (2004)**)**

Decrease in flood and annual runoff observed	*Increases in flood and annual runoff observed*
A reduction in hydraulic conductivity through lowering of the water table	Increased direct precipitation in drainage channels
loss of surface runoff in the upper peat layers	Flow increases by channel straightening, deepening and vegetation clearance from streams and ditches
Flow loss by storage on soil slopes and depressions caused by subsidence	Decreased evapotranspiration from drained but uncultivated land
Increased evaporation related to changes in vegetation	Increase in surface and groundwater slopes
Use of sluice canals that store water and increase evaporation	Increase in exposure of previously confined aquifers and artesian waters
	Increased drainage of previously closed marshy systems

Forty years on from Conway and Millar, Holden *et al.* (2006) found that the control catchments had not changed hydrologically but the drained catchments had less flashy hydrographs and showed some increases in lag times compared to the years immediately after drainage. The authors suggested that a series of consequences of drainage may have become apparent that would not have been evident in studies carried out immediately after drainage had been installed. Included in these is the increase in subsurface runoff from deeper peat layers. Drained peat catchments have a greater density of soil pipes and macropore flow due to changes in the peat structure. This change would take many years to develop and would not therefore result in hydrological flow path alterations in the immediate post-drainage period.

3. Position of drains and sample points in the catchment

If part of a catchment is drained it may delay runoff from an area where peak flows usually occur in advance of the catchment peak. This can result in the catchment and the drained sub-catchment peak flow timings coinciding to produce a higher peak discharge (Holden, Chapman & Labadz 2004). Consequently one study might conclude that the drained sub-catchment has a lower peak flow while a second looking further along the catchment could produce evidence of the opposite. Similarly, separate studies have also shown that artificial drainage of peat land can lead to raising and lowering of the water table or have no effect. Some of these different observations are outlined in Figure 48.

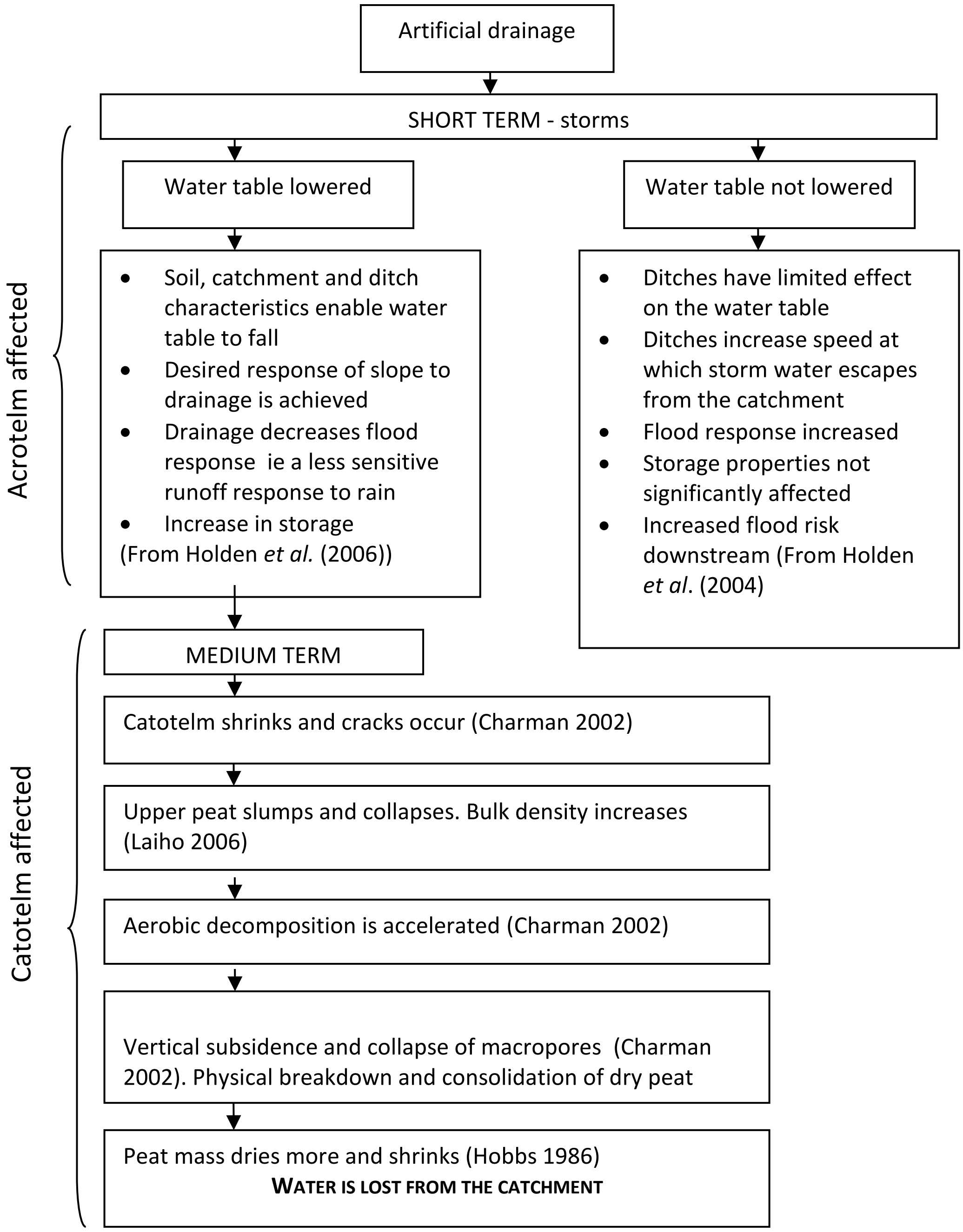


Figure 48. Some observed effects of artificial drainage on the water table

Townend *et al.* (1997) reported on subsidence to 50 ha of blanket peat in Caithness, Northern Scotland over a period of 30 years, which incorporated block planting of Sitka spruce and lodgepole pine. They found that the presence of blocks of trees led to measurable subsidence up to 40 m from the forest edge, as well as increased peat cracking, both indicating that drying had occurred. In the long term dewatering may also destabilise the peat leading to subsidence and causing the catchment to become more flashy so increasing the flood risk.

This matter also leads into the larger hydrological problem of how the outcomes of experiments into the cause and effects of land use change are affected by scale. Archer (2003) considers four factors that make it "difficult to identify clear hydrological signals resulting from land use change at the catchment scale". (1) Dominant processes at the plot scale may be interception, infiltration and storage. At the catchment scale channel processes become more important; (2) The patchwork nature of land use changes within a catchment mean that while conditions can be controlled at the plot scale, the spatial distribution of changes throughout a catchment may be dependent on factors such as government policy and landowners' interests; (3) Drainage activities at the plot scale may occur at well-defined intervals in time. Scaled up to the catchment level these changes may be spread over many years; and (4) Runoff varies at different timescales (storm event, seasonal, annual) and at the catchment scale it is difficult to separate out influences due to land use from those of climate. Archer (Archer 2003) also found that significant changes in flow variability in a small headwater only translated into minor changes downstream at the larger catchment scale.

Both the slope of the ground and the spacing between ditches influence catchment response to rainfall, and as this has been shown to vary considerably, it makes comparisons between studies very difficult. For example it was traditionally assumed that there would be equal drawdown on both sides of a drain or ditch. While this may be true on flat peatland, if the land slopes, a topographic effect may also be seen with a greater impact on downslopes (Holden *et al.* 2006). It has been suggested that under certain conditions (peaty gleys with a slope gradient less than 6°) the water table is lowered with intensive drainage at a spacing of less than 40 m (Ray, White & Pyatt 1992). More typically, forest drains are spaced at 7-20 m intervals (Worrall, Gibson & Burt 2007).

Drainage and carbon

Water table draw down can change the pattern and rate of mineralisation in peat. Laboratory experiments have shown that aerobic and anaerobic carbon mineralisation and emission increase while methane production and emission decrease (Blodau & Moore 2003). Short term disturbance also results in contrasting production rates and trace gas fluxes for different processes. Individual equilibrium times can range from instant in the case of transport to weeks for DOC production and months for CH_4 production (Blodau & Moore 2003).

In field studies water samples from artificially drained peatlands have been found to have significantly higher DOC concentrations and colour than intact peat (Strack *et al.* 2008; Wallage, Holden & McDonald 2006). It has been estimated that drainage of a Canadian peatland for horticultural peat would result in an increase in DOC export amounting to ~9 g of C per square metre per year (Strack *et al.* 2008). The authors also suggested that if this were to be delivered to the catchment in a pulse it could have a severe detrimental impact on downstream ecosystems, altering the light intensity, acidity, and nutrient and metal availability. They also found that the increase in DOC concentration commenced during the first season following water table draw down and persisted for many seasons thereafter. Going a step further, a model has been developed that predicts that drained catchments will export 15 - 33% more DOC over a 10 year period depending on the drain spacing (Worrall, Gibson & Burt 2007).

In contrast to the above, a significant decrease in stream total organic carbon (TOC) concentrations was found following ditching of a small, peat-covered, forested Finnish catchment (Astrom, Aaltonen & Koivusaari 2001). The authors attributed this reduction to a change in hydrological pathways following ditching, directing rain and snow-melt water downwards to the uppermost till layer. They suggest that this affects the mobilisation of humic substances in two ways: first, the shorter residence time of water in the upper peat layers was insufficient to mobilise dissolved humic substances and second, sorption of negatively charged humic substances onto positively charged oxyhydroxides in the near neutral till layer beneath the peat. It is recognised however, that the hydrochemical changes presented in this paper are only representative for catchments in which an unmineralised, carbonate-poor, till horizon beneath the peat is exposed by deep ditching.

This highlights the influence of soil type in explaining contrasting evidence from seemingly similar studies. If an increase in DOC surface water concentration following disturbance is found, it represents a change in the balance between DOC production and DOC export but does not allow us to assess specifically where these changes occur. Measurements of DOC quality for example by UV spectrometry may help to distinguish between sources of DOC and provide some insight into where in the soil profile it has originated. This type of measurement is the focus of theme 4 below. In organic soils the net production of DOC may be controlled by several factors such as temperature, soil moisture, soil solution chemistry, vegetation community and site hydrology (Strack *et al.* 2008).

Understanding the biotic and abiotic controls of decomposition in peatlands following water table draw down is important when trying to predict whether the peatland will remain a carbon sink or become a source under these circumstances. However, although it may seem mechanistically straightforward, the relationship between water level, decomposition and carbon sequestration is not simple (Laiho 2006). At its most basic, if the accumulation of new organic matter exceeds the decomposition losses from the old peat the peatland will remain a sink, if not the peatland will become a source of carbon to the atmosphere. In reality the role of vegetation composition in determining the rate of peat decomposition has not been well studied and may have important implications for differences between long and short term changes in decomposition following disturbance (Laiho 2006). It is also possible that the observed increases in DOC export do not represent a destabilisation of the peatland. Rather the high DOC export results from greater ecosystem productivity, potentially having little effect on net peatland carbon storage (Strack *et al.* 2008). The water table drawdown of (Strack *et al.* 2008) resulted in ecological succession and increased productivity in wetter areas of the ecosystem, which it was suggested was partially responsible for the higher DOC concentrations observed.

Forest roads

Although it is widely recognised that road building has the potential to create major disturbance to forest sites, it has been difficult to disentangle the effects of this particular activity from other forest operations usually occurring simultaneously (Nisbet 2001). Roads may be built into the land surface or floated and the material used to surface the roads may be vulnerable to erosion.

Disturbance from forest roads can result from the construction and operational phases and may be expected to modify the storm flow in two main ways: firstly, roads may intercept surface flow and channel it directly into streams (Ziemer 1981). Thus an increase in sediment concentration and changes to the storm hydrograph may be expected. Indeed in a study carried out by Reid & Dunne (1984) it was found that erosion from the surface of gravel forest roads was extremely sensitive to traffic intensity. When traffic was heavy – defined as more than four loaded trucks per day – sediment was delivered at 7.5 times the rate of the same roads on days when they were not used. Restricting the roads to light vehicle use decreased the sediment loss to 0.8% of that under heavy traffic. Road construction was also found to be the main source of sediment following clearfelling in an Appalachian catchment with two major storms providing significant contributions (Swank, Vose & Elliott 2001). Ziemer (1981) on the other hand found that road construction resulted in no change to any of the storm flow parameters measured and suggested that increases in peak flows may only be expected where road density occupies more than 12% of the catchment area. If the area of the road is smaller than this, any effects may not be detected. This is of course dependent upon the scale upon which the studies are based. This study did not investigate local disturbances associated with road construction and was concerned only with catchment scale impacts.

Secondly compaction of road surfaces may reduce infiltration and lead to faster runoff (Hutchings, Moffat & French 2002; Nugent *et al.* 2003) and it is likely that road-based traffic during the construction of a wind farm will exceed that of any phase of forestry in both its extent and intensity. A further consideration is that many forest sites now being converted to wind farms will have been forested before the publication of the Forests and Water Guidelines, thus the road network in these areas is unlikely to conform to current best practice. As a result they may contain a number of features such as steep embankments next to watercourses, steep road drain gradients and poorly designed culverts (Nisbet 2001). Many existing forest roads will need to be widened and upgraded to cope with larger vehicles associated with the wind farm development.

Road/ track construction and upgrading at Arecleoch

The two main access roads serving the wind farm site compound are partially within the Crosswater catchment. The forested area housing the wind farm already had a network of tracks and in addition to upgrading approximately 64 km of these, an additional 20 km of new road has been built. All of these are 6 m wide. The routes were designed to follow existing tracks where possible and to keep water crossings to a minimum. In the Environmental Statement it was proposed that where peat depths were less than 1.2 m, cut tracks would be used, in which the peat surface is removed. In practice it is estimated that only about 10 % of the roads were constructed in this way. The remainder used a floating road method which did not require the removal of any peat. For these 700 mm of crushed stone is laid over a geotextile grid to improve the resistance of the peat to compression. Some compression of the peat is inevitable though and as such there still exists an element of disturbance potential.

Stage 2: Growing

This is the longest stage in the forest cycle, lasting between 30-40 years depending on the species of tree (Giller & O'Halloran 2004).

Growing and hydrology

The first phase within this stage is from planting through to canopy closure, which may average 15 years and during which time there are few changes hydrologically (Maitland, Newson & Best 1990). As the crop matures, interception of rainfall by the canopy takes over from transpiration the major hydrological feature. Interception losses from mature forests reduce streamflow and affect water supply reservoirs and hydroelectric power reservoirs. Hydrological responses to forestry were modelled for the Balquhidder experimental catchments in Scotland (Johnson, 1995) and simulations predicted that mean flows in forested catchments would decrease. Paired catchment studies at Plynlimon in Wales demonstrated that evaporation loses from forests can be up to double those from grass (Marc & Robinson 2007). However it was also shown that the water balance changes over the lifespan of the forest. Felling resulted in increased flows and reduced evaporation losses but long term data shows that evaporation losses were already decreasing before felling. This was thought to be due to the aging crop and suggests that an even-aged crop may behave very differently to heterogeneous vegetation cover in terms of evaporation (Marc & Robinson 2007). Canopy closure also reduces light to the forest floor limiting any further growth of understory vegetation. Ditch furrows may fill with conifer needles, adding to the stream sediment load (Maitland, Newson & Best 1990).

Growing and carbon

Forestry plantations sequester substantial amounts of carbon in the trees, tree products and as forest soil. In the UK it is estimated that the net removal of CO_2 attributed to forestry amounts to 5.1 million tonnes of CO_2 per year. This figure, generated in 2008, represents a steadily declining estimate that peaked in 2004 at 16 million tonnes of CO_2 per year (Forestry Commission 2011).

As to whether conifer plantations on drained peatland represent a net loss or gain of carbon, it has been suggested that in the short term (50-200 years) forests can, depending on oxidation rates, increase net carbon sequestration but in the long term, the successive drainage and drying of peat may cause nearly all carbon not removed by erosion, to be oxidised, leading to a net loss of carbon (Cannell, Dewar & Pyatt 1993). As discussed above, some of the carbon moving out of peatland soils will be transferred into surface waters. Harriman *et al.* (2003) investigated trends in the long term chemistry of 37 acidified upland streams and lochs in the UK and found significant increases in DOC concentrations at both moorland and forested sites. However they found no major trend differences in DOC concentrations in surface waters between waters draining forested catchments and those draining moorland. They concluded that forestry exerted minor impacts on DOC export and supported the argument that increasing DOC concentrations were linked to climatic processes. Conversely, in another study, this time comparing TOC concentrations in soil solutions from under hillslope forest and moorland sites in western Scotland, soil solution TOC concentrations were up to 50% greater at the forested sites (Grieve & Marsden 2001). However, as will be discussed later, caution should be exercised in comparing data relating to DOC concentrations from studies at different scales.

Growing and other environmental impacts

Other than thinning, physical disturbance during this stage may be minimal but water quality can be affected by the application of aerial fertiliser, and increased scavenging of ions by trees as the canopy matures can lead to acidification (Giller & O'Halloran 2004). If no drain maintenance is carried out, much of the ditching introduced during afforestation becomes less effective due to sedimentation and vegetation growth reducing erosion of drain walls. Astrom *et al.* (2001) found no significant ($p = 0.01$) correlation between concentrations of suspended material and discharge in ditches of a stream that had been under forest cover for 30 years.

Stage 3: Harvesting

A lot of research has been carried out into different environmental impacts of commercial forestry practices, in particular harvesting. A significant contribution to this body of evidence has come from work in the experimental catchments of Plynlimon, mid-Wales. This study was set up to examine water balance differences between forested and moorland catchments but developed to include a wide range of water quality parameters, including DOC.

The significance of soil loss following disturbance such as forest harvesting varies according to the conditions under which the harvesting in question was carried out and the machinery used to do it. In the "Soft ground harvesting manual" (Forestry Commission 1991) it is suggested that most damage is caused by forwarders on soft ground, including peats. Forwarders are articulated machines used to transport cut logs from the forest floor to areas where they are collected by timber lorries. Mechanical harvesting can compact soils, reducing total porosity and consequently soil aeration, water infiltration rate and saturated hydraulic conductivity, leading to structural instability (Carling *et al.* 2001). Peat-based soils in particular are also susceptible to deep rutting from machinery used in harvesting and extraction (Nugent *et al.* 2003).

Harvesting and Hydrology

In the non-calcareous gley and humic gley soils of Loch Ard, Scotland, Tetzlaff *et al.* (2007) found the effects of forestry harvesting on flow regimes to be inconclusive. Some enhancement of flood peaks and low flows, limited to a period of three years, were observed. Felling small blocks in sequence limited effects on stream annual flows, average flows and high flows. Although Q95 values increased, it was not possible to isolate the impact of forest harvesting from wider, climatic influences. Higher mean daily specific discharges found in felled catchments may be indicative of a more rapid runoff response and provide evidence of short lived impacts on high flows as there were no differences at Q10 or Q5 levels. Water yield in a 59.5 ha non-peat, hardwood Appalachian catchment was found to increase by 28% above the flow expected without harvesting in the first year after clearfelling. Thereafter, the annual discharge decreased until by year five it was not significantly above pre-disturbance levels (Swank, Vose & Elliott 2001). Discharge also increased following clearfell in a non-peat catchment in North Carolina (Meyer & Tate 1983). Conversely Ziemer (1981) found no statistically significant differences between pre and post felling peak discharge measurements greater than 0.34 $m^3 s^{-1}$. Discharges above this value occurred for just 6% of the time but delivered 54 % of flow and 97 % of sediment. Logging therefore only significantly increased low flow discharges.

Harvesting and carbon

The impact of clearfelling and reforestation on blanket peat has been shown to lead to increases in DOC concentrations (Neal *et al.* 1992) but the evidence suggests that the relationship is far from straightforward. Neal *et al.* (2004) remarked that effects that may be seen at the local scale become masked at the catchment scale by the seasonally driven, natural variability within the system. (Grieve 1994) found a slight increase in DOC exports from a clear-felled catchment in west central Scotland compared with a control stream (both on organic soils). More noticeable were greater peak DOC concentrations (on average 5 mg L^{-1} more) in the clear-felled stream. These were attributed to the effect of warmer summer temperatures in the clear-felled catchment acting on organic debris in the stream. Elsewhere the increases in DOC concentration have also been found but were not seen uniformly across the strong seasonal DOC cycle. Rather the lower, winter values remained unchanged and it was only during the small or moderate late summer storms that increases were recorded during the higher DOC phase (Cummins & Farrell 2003; Tetzlaff, Malcolm & Soulsby 2007). Differences in average DOC exports between catchments on non-peat soils increased from 1 % to 74 % following felling. (Laudon *et al.* 2009). The most significant differences occurred during summer base and peak flows as well as during autumn base flow. Cummins and Farrell (2003) remarked on the consistency of the annual DOC cycle, with or without forestry, and concluded that this may be due to a strong dependence on seasonal factors associated perhaps with biological activity, which is higher in summer. Thus it is the rising amplitude of the seasonal variation that is the most noticeable indicator of DOC increase but for individual studies, the combination of the effects of forestry and lower annual rainfall over the study period may be important (Tetzlaff, Malcolm & Soulsby 2007). In another study extensive drainage and ploughing of peaty soils in Argyll, Scotland, did not lead to a deterioration in water clarity and water colour that could compromise standards in two public supply catchments, although there was some siltation impact to macroinvertebrates for two years after harvesting (Nisbet, Welch & Doughty 2002). They attributed the minimisation of disturbance to good forestry practice, specifically to the control of drainage, phasing of road construction and forest harvesting over five years and the use of silt traps, buffer areas, brash strips. Data from other studies into the impacts of forest harvesting on water quality have been inconclusive with regard to DOC. But some have shown that phased felling as opposed to the standard forestry rotation can mitigate negative impacts on other water quality parameters (Neal *et al.* 1992; Neal *et al.* 1998).

Harvesting and other environmental impacts

Forest harvesting is also associated with other environmental impacts, particularly increases in soil erosion and sediment transfer. Even when harvesting was carried out in accordance with the Forests and Water Guidelines (Forestry Commission 2003) a 39 % increase in suspended sediment yield was found compared to an adjacent forested catchment, and a statistically significant in main channel bank erosion rates (Stott *et al.* 2001). In another study, Stott (2005) showed that statistically significant increases in mean erosion rates took place in the two year period over which environmentally sensitive, plot-scale timber harvesting was carried out. The question then arises as to whether it is the absence of trees that increases sediment yield or if this is a result of the practices used in harvesting. Hotta *et al.* (2007) evaluated the influence of forest harvesting when soil disturbance is minimised as much as possible. Harvesting was carried out using skylines and branches were piled by hand. There were no forest tracks or skid trails in the catchments. Under these conditions it was found that although water yield increased in the clear cut catchment, there were no significant changes in suspended sediment yield characteristics following harvesting. This suggested that the harvesting of forests itself does not cause an increase in sediment yield but the practices associated with harvesting do.

Forest harvesting has also been shown to cause soil compaction. Hutchings *et al.* (2002) investigated soil compaction following standard forest clearance procedures using a harvester and forwarder. Increased soil penetration resistance was found to at least 45 cm after felling and increased after timber extraction. The extent of compaction also increased with the number of forwarder passes. Nugent (2003) investigated compaction of sensitive forest soils due to forest harvesting machinery and attempted to establish threshold levels with respect to peat. They found that compaction increased with the amount of traffic and the increment was significant in the top 40 cm of forest floor. However, up to 30 cm the forwarder induced a higher compaction beyond that caused by the harvester making 0-30 cm the critical depth range. The depth of brash mat made no significant difference to soil moisture levels.

Forest harvesting can have other, less direct effects on hydrology and water quality. Removing the forest canopy can reduce the rate of soil moisture depletion by evapotranspiration and a greater proportion of the annual precipitation will be available for moisture as interception is reduced. Ziemer (1981) investigated these effects and suggested that increased peak flows during the growing season in a felled catchment compared to a non-felled catchment were a result of differences in evapotranspiration. It was also found that canopy cover interception only played a role in small storm flow peaks because once the canopy is wetted it cannot contribute further to interception. A further conclusion was that once soil moisture has been recharged in the un-felled catchment to equal that in the felled catchment, further storms should produce similar peak flow responses until soil moisture differences develop once more. A further, indirect consequence of clearfelling is an increase in channel bank erosion (Stott 1999). The mechanism put forward to explain this was that removal of tree cover leads to a steepening of the bank versus air temperature relationship suggesting that the banks are more sensitive to changes in air temperature. This results in longer sub-zero periods in winter, which could possibly lead to more freeze-thaw cycles. Summer maximum bank temperatures would increase leading to greeter evaporative loses and consequently more extreme wetting and drying cycles (Stott 1999).

Forest harvesting at Arecleoch

The wind farm is situated within 3513 ha of commercial forestry, 3151 ha of which belongs to the Forestry Commission Scotland (FCS) and 362 ha is under private ownership (Eldridge Hill estate). In order to accommodate the wind farm, part of the forest (573 ha) hosting the turbines has been felled earlier than would normally have been the case (Figure 49).

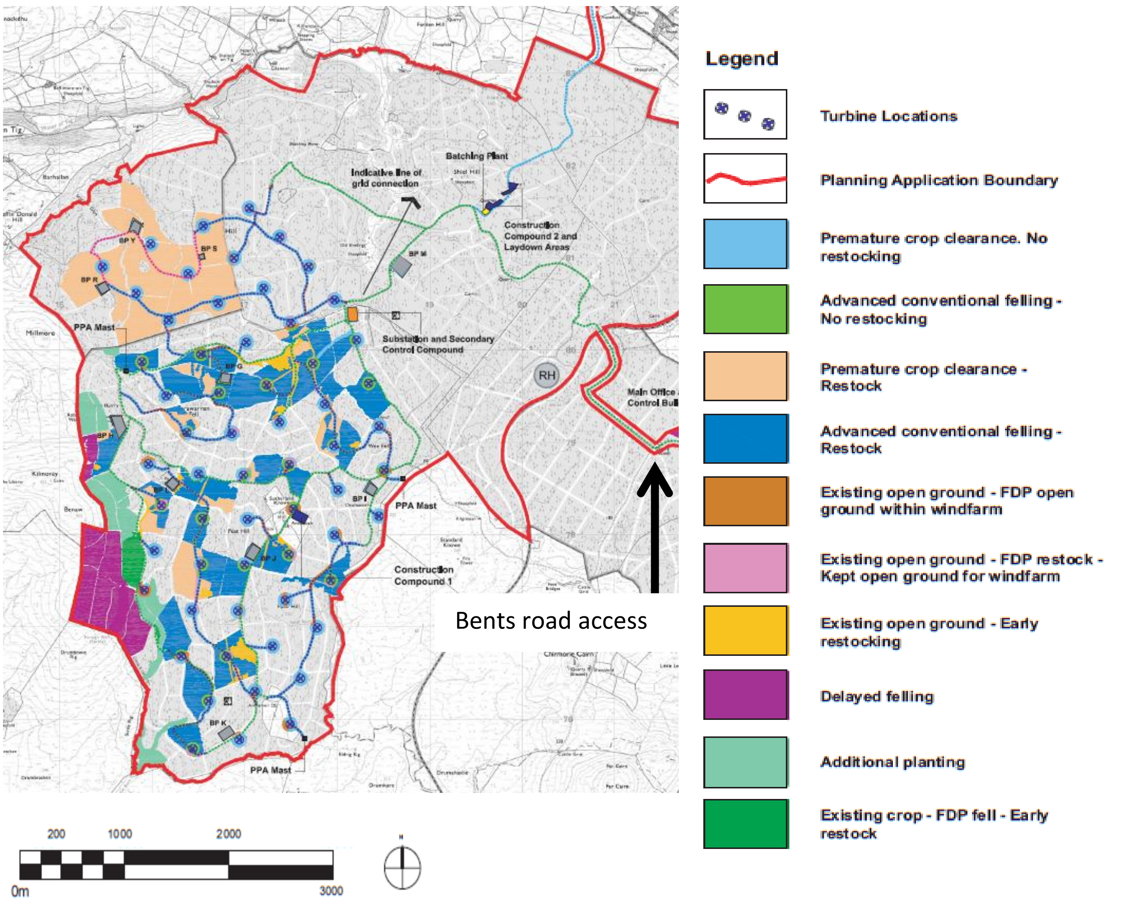


Figure 49. Forest harvesting plan at Arecleoch (from SPR Environmental Statement)

Many of these blocks have been replanted save for an 80 m radius “keyhole” around each turbine, which is left clear. In some areas (18 ha) trees will be felled later than usual and in others restocking may be brought forward. In addition to these clear fell and keyhole areas, 15 m is cleared around each item of infrastructure and a 30 m swathe removed for access roads (areas included in the totals given).

3.1.3 **Wind farms and peat land disturbance**

Research into the negative effects of the development of large scale wind farms has been mainly focused on receptors such as terrestrial flora and fauna (Stewart, Pullin & Coles 2007). Assessing the impacts of disturbance in relation to water quality has been largely overlooked by the academic community until recently. Unlike for commercial forestry, there is no best practice guidance relating to the minimisation of environmental damage, and the impacts of developments on sensitive landscapes such as peatlands have not been widely studied. Some of the pressures on peatland from wind farm construction will be similar to those from forestry and it is often the case that wind farms are constructed on land that was initially under commercial forestry and which is partially felled or clear felled before construction. However, as illustrated in Figure 50 the life cycle of a wind farm occurs in several phases some of which may be more akin to a construction site in the nature of the activities and scale of machinery used.

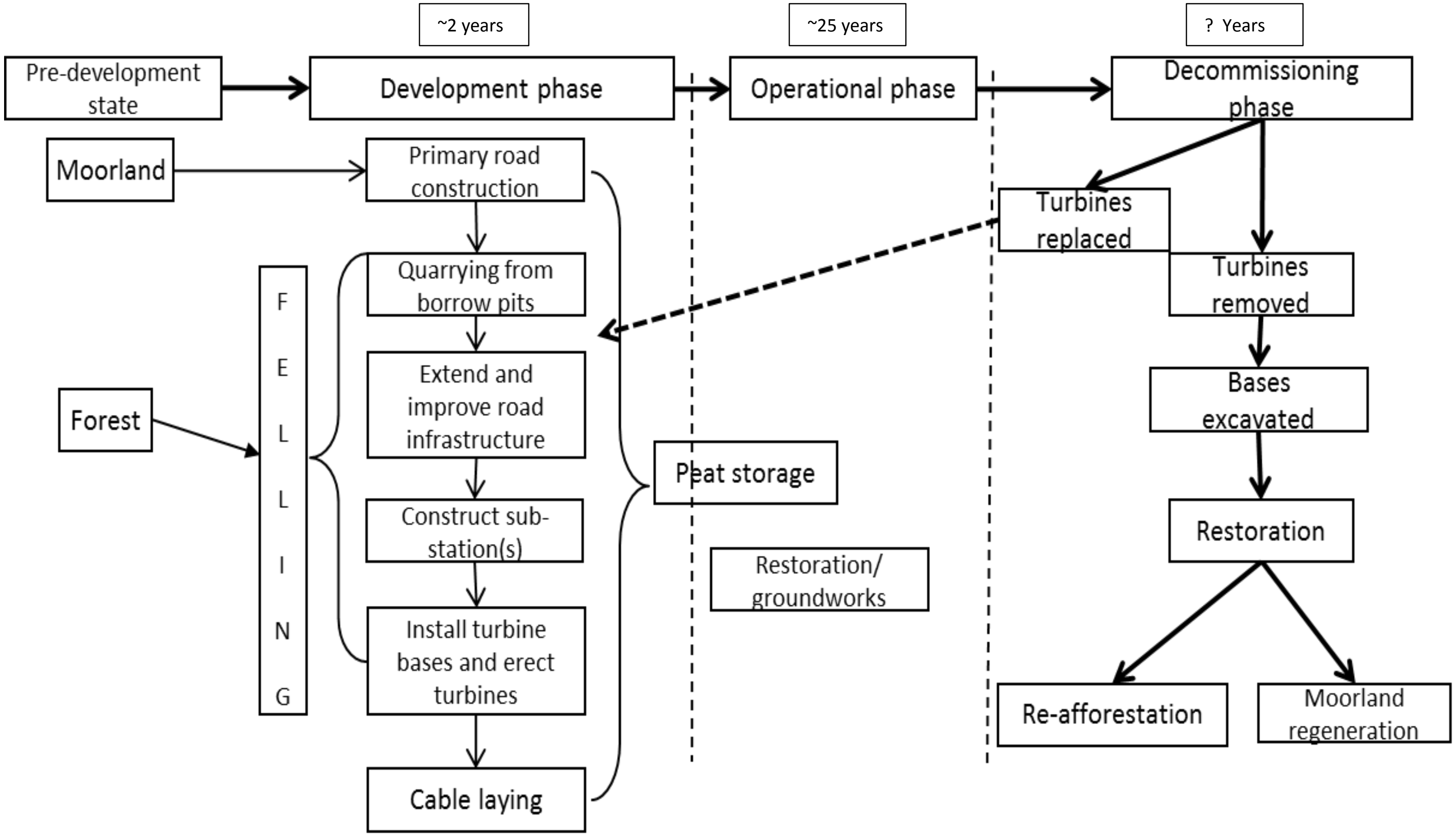


Figure 50. The wind farm cycle. The starting point is assumed to be either moorland or forest. In the case of the latter felling will extend across the development phase activities grouped in the {. Peat storage may take place as a result of excavations from all development phase activities and can extend into the operational phase if all the excavated peat is not reused.

App

The wind farm cycle

In this section the man wind farm activities will be described in general terms drawing on broad areas of research where available and describing specifically the disturbance potential at Arecleoch where appropriate. The starting point in the cycle (Figure 50) is dependent upon whether the land has been afforested, in which case the impact of afforestation and forest harvesting may contribute a response in the development phase and beyond. The impact of roads has been discussed above (3.1.2) under the heading of forestry.

Development phase

Turbine base excavations

Installation of turbine bases involves the excavation of peat and subsoil to expose bedrock and consequently the capacity of the excavation will vary from base to base depending on the position of the bedrock. In some cases the excavations will need to be dewatered. Some risks of pollution can be minimised through adherence to Pollution Prevention Guidelines (Environment Agency 2009). However, this advice focuses on measures to prevent water from entering an excavation or ways to discharge the effluent in a way that assumes either a foul sewer or non-saturated land to hand. Further, the emphasis is on trapping and settling out of silt from dewatering operations, which will not impede the loss of DOC. Timing of works may prove to be a more important factor in minimising the effects of disturbance. It has been demonstrated that spring cultivation allows re-vegetation/ re-colonisation of furrows before winter storms and Maitland et al (1990) considered that this practice was better at reducing sediment than a buffer strip.

Turbine base installation at Arecleoch

Construction of the 60 turbine foundations each required an area of approximately 23 m x 23 m of peat and subsoil to be removed so as to expose the underlying bedrock. Around this an area of hardstanding was excavated, which amounted to approximately 44 m x 34 m (Figure 51).

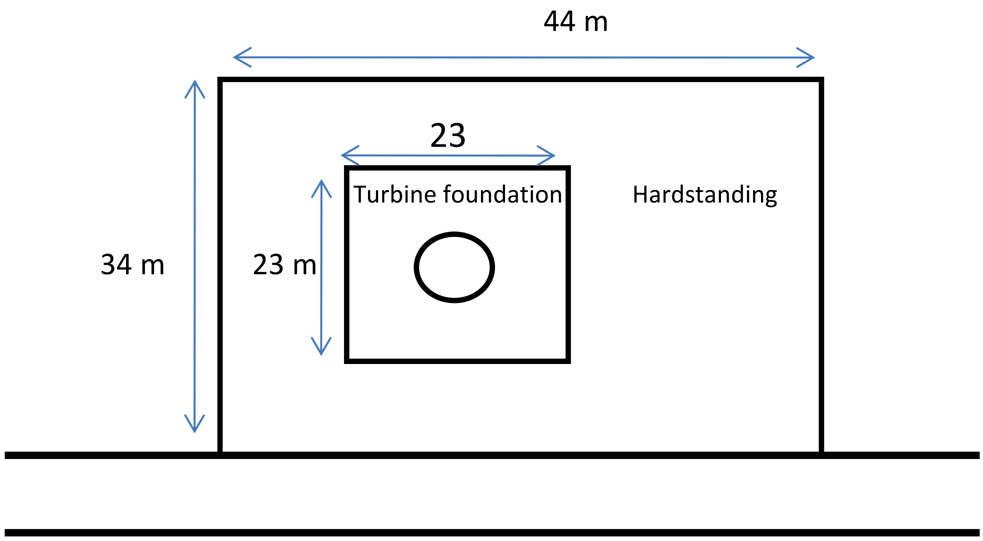


Figure 51. Schematic of the dimensions of a typical turbine base excavation

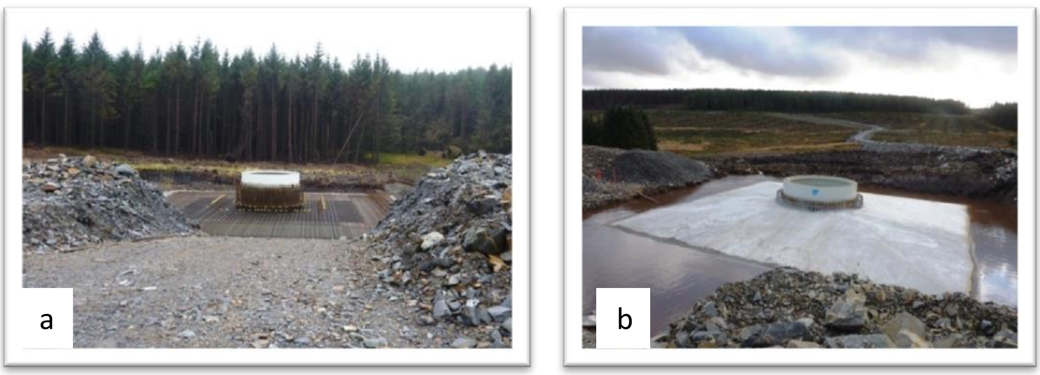


Figure 52. Turbine base installation at Arecleoch showing the rebar (left) and concrete surround (right). Both illustrate the extent of peat removal and disturbance potential and in the image on the right the excavation has filled with DOC rich water.

The depth of peat varied across the site but it was noted that for most of the turbines the peat layer was thin and less than indicated by the peat survey carried out as part of the EIA process. In Array 5 larger volumes of peat were excavated at six of the ten turbines where peat depth was greater (Pers. Comm. SPR). Activities involved in installing a turbine base can be grouped into intrusion, installation and remediation processes and the stages of each are listed in

Table 22. Excavation of the base and hardstanding areas, when the peat is removed and stored, presents an obvious disturbance potential (Figure 52a). In addition the activity scoring system also recorded work through the installation of the base components, up until the area was backfilled. For some turbines the excavated area filled with water that was very coloured indicating high DOC concentrations (Figure 52b). In some instances it was necessary to de-water these, offering the potential for the runoff to enter watercourses and lead to elevated DOC concentrations.

Table 22. Activities involved in installing a turbine base at Arecleoch wind farm

Intrusion	*Installation*	*Remediation*
Strip overburden Excavate base Excavate hardstanding Break rock in base area to form level	Blind concrete base Install insert rings Install rebar (reinforced steel cage) Pour concrete	Backfill base Backfill hardstanding Cap hardstanding Dress peat around base and hardstanding

Peat Storage

Large quantities of peat need to be removed from the land surface at borrow pits and where roads, sub-stations and turbines are to be constructed. Common practice is to store this peat and use some of it later for restoration works. Some may also be used to back fill borrow pits. Excavated peat may also be laid along the sides of roads. There is the potential here for DOC to be exported from the peat as it is exposed to the weather and physical disturbance. There is also the potential for particulate organic carbon (POC) to be exported from peat subject to disturbance of this kind and this is discussed in theme 3.5.

Cable-laying

The 60 turbines at Arecleoch are connected in six circuits or arrays for which the cabling was laid in trenches 900 mm x 900 mm and for which 40,400 m of cable trench was excavated (Figure 53). Cables were laid in granular material and the trenches backfilled with excavated sub-soil and topped with peat. Longitudinal drainage is reduced in the completed trenches by means of clay bunds at intervals along the length of the trench. While the trenches remained open awaiting backfilling the potential existed for preferential pathways of drainage to be established allowing transport of DOC from freshly disturbed peat to surface water courses.

Figure 53. Cable trench at the Arecleoch wind farm, indicated by the stone sign post

Operational phase

Re-vegetation

Like the growing stage of the forestry cycle this is the longest phase of a wind farm's life cycle. Unlike a growing forest, this period of 15 – 20 years will not produce a developing canopy with all the associated hydrological consequences. Depending upon the location of the wind farm some replanting of trees or other plants may take place but as Grieve and Gilvear (2008) reported, re-vegetation may not always follow swiftly and continuing drainage of areas around the turbines could alter the re-colonisation process. Effects of wind farm developments on biodiversity were investigated by Fraga *et al.* (2008). Quantitative and qualitative changes were investigated nine years after wind farm construction started in the Galician mountains of Spain. Areas impacted by wind farm construction had lower biodiversity than non-impacted areas. Most of the negative effects of wind farms on vegetation were found to arise from roads and restoration activities, which allowed for the colonisation of bogs by pioneer and invasive alien species typical of disturbed habitats.

Peat storage

This may continue throughout the operational phase of the wind farm if peat is scheduled to be used for reinstatement following decommissioning of the wind farm. No research to date has been carried out into the relative risks and merits of different methods of storage.

Many studies into the environmental effects of land use change where long term data is available have originally been set up as water balance studies. One consequence of this is that "the catchment is the fundamental unit for most hydrological research"

(Kirby, Newson & Gilman 1991). This type of research tends to use a black box approach which does not provide insight into small scale processes which interact to produce the catchment scale impacts. In order to understand how wind farm development affects the peatland upon which it is built, it is necessary to take a closer look at the individual processes involved in the development. It is reasonable to expect that the presence of a commercial forest on peatland subsequently developed for a wind farm will have an effect on the nature and extent of disturbance to the peat as manifested in changes to water quality and hydrology. Both the prior impact of the forest plantation and that of its harvesting need to be disentangled from the construction activities associated with the wind farm itself. This may prove difficult as any hydrological impacts relating to wind farm construction could possibly be obscured by the larger changes induced by forest harvesting such as reduction in evapotranspiration and reduced interception. Arecleoch wind farm is being developed on afforested peatland, much of it mature. Therefore the underlying peat has already undergone the hydrological and physical disturbances associated with the forest cycle described in chapter 5.

Research on wind farm development sites

Grieve and Gilvear (2008) carried out a paired catchment study to investigate the impact of a peatland wind farm development on fluxes and concentrations of DOC and suspended sediment at the Braes of Doune in central Scotland. DOC concentrations were found to be greater in disturbed streams than control streams with an estimated extra 5 g C m^{-2} yr^{-1} DOC lost as a result of disturbance associated with the wind farm construction. A lack of re-vegetation of exposed peat was thought to have allowed for an increased rate of decomposition of soil organic matter. Suspended sediment concentrations were also markedly higher in the disturbed tributaries and continued to be elevated after construction had ended. This was suggested to be a result of inadequate on-site measures for silt trapping. Whereas the wind farm studied by Grieve and Gilvear (2008) was developed on blanket-peat moorland, Waldron *et al.* (2008) investigated carbon and nutrient export from a wind farm development on peat-dominated, forested land. They found that differences in DOC concentrations between two catchments increased shortly after forest clearance and road construction for the wind farm commenced in one of them. While the catchment subject to disturbance had previously exhibited higher DOC concentrations than the control catchment, the differential increased as disturbance progressed. The changes were also observed outwith the development area, a factor that the authors suggest needs to be considered more by consultants preparing EIS for this type of project.

Lessons and departures from forestry

In terms of mitigating the negative impacts on water quality, many of the options available to the forest manager to reduce the degree of site disturbance and reduce sediment loss to streams will translate to the wind farm situation. These include the use of less disruptive practices, careful matching of machinery to site conditions, varying the timing and scale of operations according to site sensitivity and using a wide range of protective measures (Nisbet 2001). There are however several ways in which a wind farm development may impose different or additional pressures on the landscape at various stages of its lifecycle. Due to the relatively new nature of this technology, few, if any, opportunities have yet been available to study the decommissioning phase of the wind farm life cycle.

Calculating the impacts of wind farms on peatlands

Some of the ecological concerns arising from the construction of wind farms on peatland in Scotland were addressed by Scottish Natural Heritage (SNH) in a technical guidance note to be used in determining the carbon payback time for such developments (Scottish Natural Heritage 2003). In addition, the ECOSSE report (Estimating Carbon in Organic Soils – Sequestration and Emissions) (Smith *et al.* 2007) presented a model that enabled the prediction of the impacts of land use and climate change on greenhouse gas emissions from organic soils. Among the practical applications envisaged for this model was the potential for land managers to select management practices that protected organic soils. At the time, forestry was cited as the principal example of where this might be effective but in the intervening years the progression of onshore wind energy has resulted in a further need for the evidence base that this research provides.

The main focus of the SNH tool was on habitats and it did not attempt to model the major hydrological impacts of siting of wind farms on peatlands. This challenge was taken up by Nayak *et al.* (2008) who produced the first comprehensive carbon payback calculator using a combination of the ECOSSE model and a carbon balance approach. Central to the carbon payback calculator is a spread sheet onto which data are entered relating to all activities and processes that directly or indirectly cause carbon to be lost from the land. From this and other information surrounding the carbon costs of the infrastructure and efficiency of the wind farm, an estimate of the payback time for the wind farm is produced. This is also adjusted according to whether any mitigation measures are put in place following completion or decommissioning of the wind farm. Several efforts have been made to calculate CO_2 payback times using this model and other methods (Martinez *et al.* 2009; Mitchell, Grace & Harrison 2010). The outputs have been extremely variable and sensitive to the quality of the input data.

Mitchell *et al.* (2010) performed a life cycle assessment of disturbance due to a wind farm development built on a second-rotation forested peatland in north-east England. This study did not use the carbon calculator but instead took a retrospective approach applying field measurements of carbon stores and fluxes to estimate CO_2 payback time. They estimated the CO_2 payback time for the wind farm to be less than 3 years, well within the 20 year operational lifespan of the wind farm. They then went on to vary key factors to find which were most sensitive to change in terms of altering the payback time. Two of them, the load factor (the ratio of the net electricity generated by the wind turbine to the net generation that would have occurred if it were to operate continuously at its rated capacity), and the assumed carbon intensity of the grid electricity displaced by the turbine, stood out. Increasing the load factor from the industry standard of 27 % to 29.4 % reduced the CO_2 payback time by 80 days and increasing the assumed grid intensity to that of a coal fired power station reduced the payback time by 290 days. They found less sensitivity to change from ecosystem processes such as carbon sequestration and the area of disturbance.

In this introduction I have demonstrated that there are many different factors contributing to peatland disturbance at a site such as Arecleoch. These will now be explored by means of three experiments carried out during the wind farm construction. These are the Arecleoch spatial surveys; the Turbine 33 experiment and the use of particulate organic carbon and suspended sediment concentrations to distinguish between different types of disturbance. I also devised a scoring system to quantify the disturbance associated with specific wind farm activities.

The three experiments and activity score system are described individually below and the results presented separately as they investigate different aspects of disturbance. However I have used a single discussion at the end of the theme to bring together the findings and use them to understand better the impact of forest harvesting and wind farm development on the peatland.

We shall now focus on the way in which specific land management practices can lead to peatland disturbance and carbon loss. Given the recent land use history of Arecleoch, forestry will provide the main context for these activities. However it is necessary also to discuss the practice of grazing that preceded afforestation. It is not an exaggeration to say that a great deal of the uplands landscape, often considered natural, has largely been formed by sheep. However, in Scotland the number of sheep has declined by around 30 % from a peak of nearly 10 million in 1991 to 6.9 million in 2009 (Scottish Government). It is recognised that overstocking in the past has resulted in damage to Britain's uplands (Smith *et al.* 2007) but much of the evidence on the impact of livestock grazing on water quality and quantity points towards indirect rather than direct causes. Worrall *et al.* (2007; 2008) looked at the effects of managed burning and grazing on soil structure, water table depths and water quality. They found that grazing intensity had no effect on DOC concentrations and no structural changes to soil were evident even after 50+ years of grazing (Worrall & Adamson 2008). Depth to water table was less in grazed plots. While it was recognised that this would be consistent with soil compaction, the conclusion was that the effect on the water table was as a result of the effect of grazing on the vegetation. The removal of livestock allowed shrubby vegetation to develop and that led to increased evapotranspiration. Thus the conclusion was that land management controls water quality and hydrology by controlling vegetation development (Worrall, Armstrong & Adamson 2007).

3.2 Activity scores

The strong seasonal DOC cycle and inter-catchment differences pose challenges to the interpretation of in studies such as this. Also baseline data sets are often relatively short making the traditional BACI (before, after, control, impacted) approach integrated at the catchment scale inadequate to disentangle wind farm impacts. It is unrealistic to expect to be able to draw a single line on a time series with “before construction” on the left and “after construction” the right. A different approach is offered as a solution to this problem.

An activity scoring system has been devised representing a novel approach to quantifying the disturbance potential of specific on-site processes. It allows catchment scale DOC concentrations to be related to work on the Arecleoch wind farm. In essence this is a “construction footprint” that, in the absence of mitigation, can disturb the environment. The SPR daily site diaries at Arecleoch wind farm were used to plot the construction activities being carried out on site each day. Before describing how the scoring system works it will be useful to consider the activities contributing to the system. Activities were separated into work relating to road construction, turbine base installation, cable laying and forestry.

3.2.1 **Calculation of activity scores**

Work relating to the activities described above was recorded in the SPR daily site diaries. This information was collated into a spread sheet, divided by activity and according to which of the 60 turbines the work was related and cross-referenced by catchment. In this way the records could be collated on a monthly basis and a score attributed to a turbine whenever one of the above activities took place within its sub-catchment. For the purposes of the activity scoring system forestry was not included due to the diffuse nature of the work and insufficient detail in the SPR records. Neither was the erection of the turbine towers included separately but its disturbance potential is implicit in the inclusion of the hardstanding area at each turbine base. It is worth acknowledging here that not all activities have the same potential to disturb peat and release DOC. The concept of a detailed, quantitative disturbance score was explored and will be discussed below. However, given the limitations already set out, the more generic approach of activity scores was preferred for Arecleoch.

3.2.2 **Results of activity score analysis**

Figure 54 shows the total activity scores across the three catchments between February 2009 and August 2010 when the construction was at its busiest. The reduction in activity in December 2009 and January 2010 was due to the site being closed for several weeks over Christmas and then adverse weather conditions at the beginning of January 2010. Otherwise the trend was to a ramping up of activity to a peak over the spring of 2010 and there is a progression from roads to turbines to cable-laying contributing to the overall activity score.

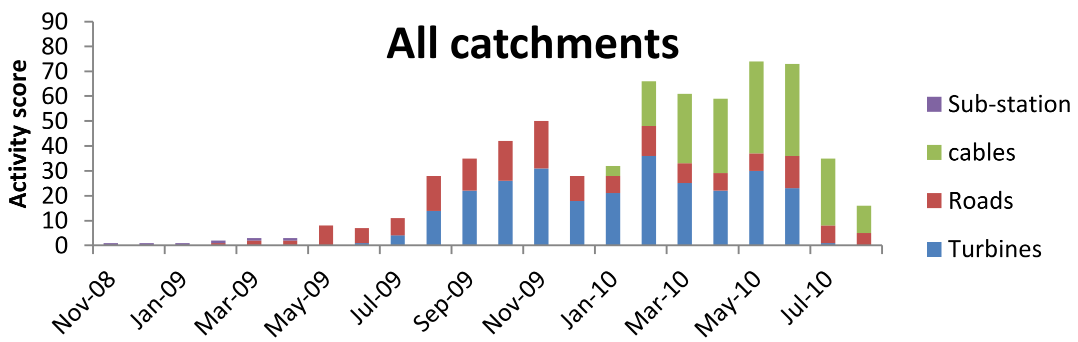


Figure 54. Scores for all activities across all catchments

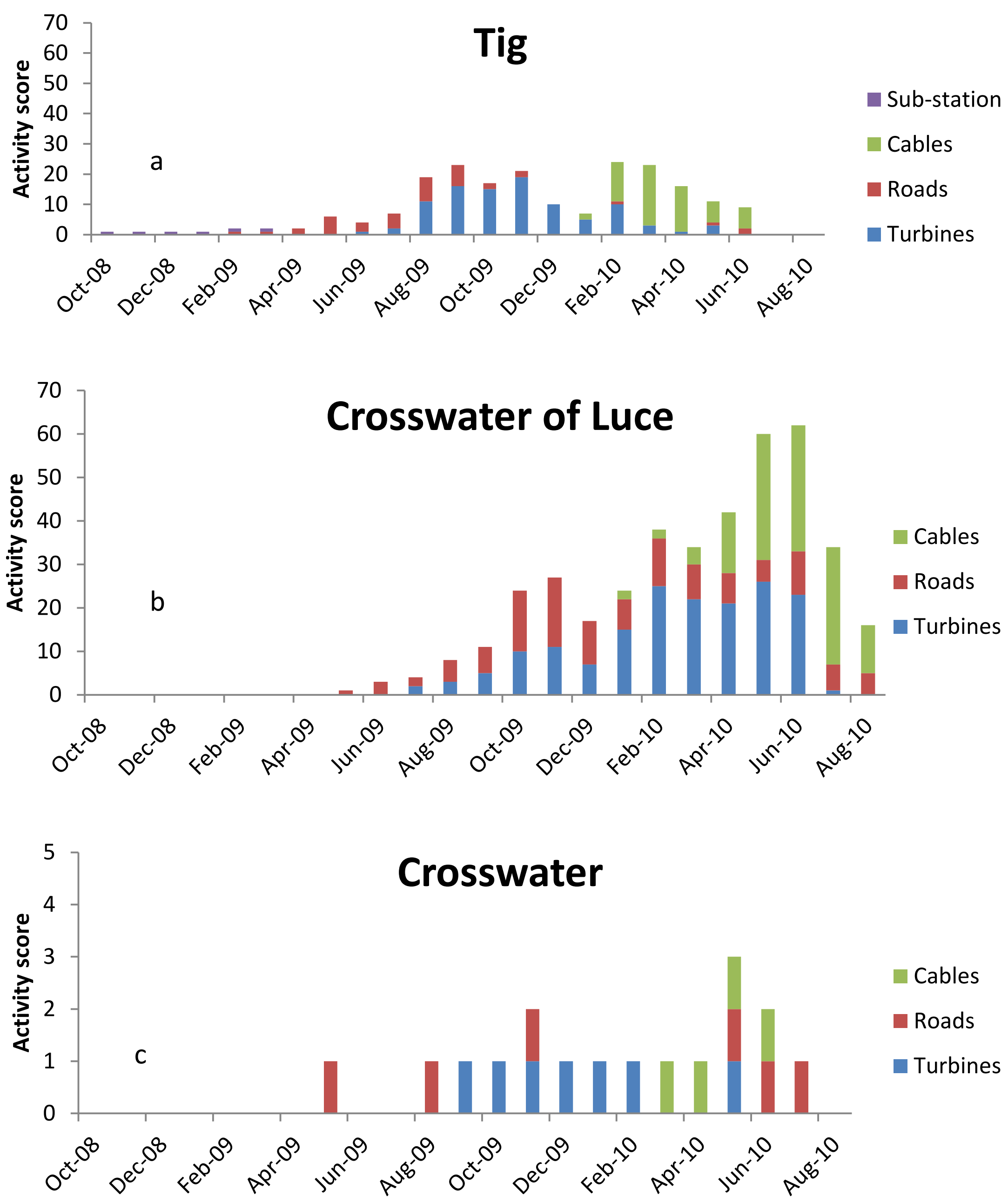


Figure 55. Activity scores by activity for a) the Tig, b) the Crosswater of Luce and c) the Crosswater (control catchment). Note differences in y axis scales.

When the activity scores are broken down by catchment a clearer picture emerges of where the construction work is taking place. For the Tig catchment (Figure 55a) there is an increase in activity, which, had the site not been closed over Christmas, would probably have plateaued over December 2009 and January 2010. Thereafter, a steady decline in activity was observed. Figure 55a shows that the overall activity score of the Tig was generated by a transition from road and turbine activity between March and November 2009 to turbine and cable laying activity from January 2010 to June 2010. The pattern of activity was different in the Crosswater of Luce (Figure 55b) where there was a steady ramping up of work, reaching a peak in June 2010 and declining sharply thereafter. This was due to the concurrent undertaking of road, turbine and cable laying work between January and May 2010. It should be noted that the total activity score for the Crosswater of Luce was approximately double that of the Tig. Figure 55c shows the corresponding activity scores and work details from the Crosswater catchment (note the different scale on the y-axis). It can be seen that the levels of overall activity remained fairly constant and low throughout the construction period. Indeed activity levels were an order of magnitude less than the Crosswater of Luce values. The daily work records used to collate this scoring system did not record activity relating to the upgrading of the Bents Farm access road (Figure 49) to the site compound, which would be within this catchment. As this was the main access road to the site for most of the construction period, it was used by all forestry trucks and other heavy plant entering and leaving the site. It was frequently rutted by surface runoff and had to be re-graded on a number of occasions.

Figure 56 gives a breakdown of the total activity score into the three catchments, illustrating the way in which work moved from north (Tig catchment) to south (Crosswater of Luce catchment). The subtlety of this progression would make any attempt at a comparison of DOC exports between the two catchments very difficult. Activity in the Crosswater control catchment was consistently low throughout the period suggesting that it may be fruitful to explore differences in DOC concentration between the Crosswater and the other two catchments along the development timeline.

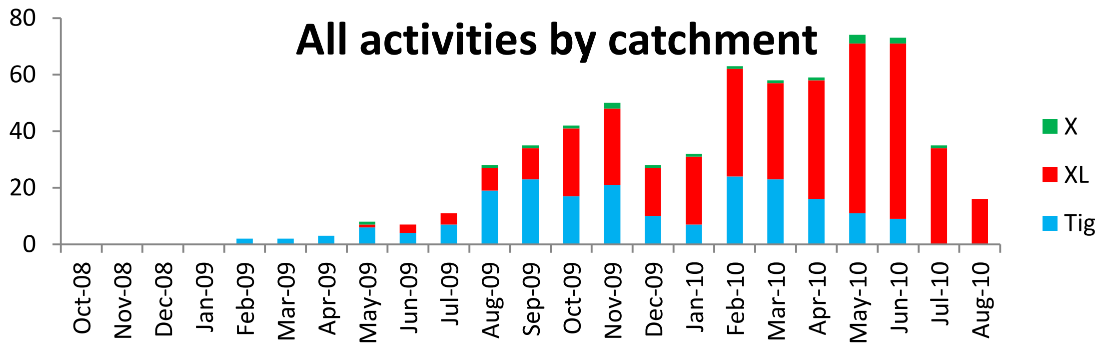


Figure 56. Activity scores divided by catchment. X = Crosswater (control catchment); XL = Crosswater of Luce

3.2.3 **Scaling up**

Having developed the first inception of a system to assess and quantify the level of potentially disturbing activity at Arecleoch, we will now investigate whether the general level of activity on site, as depicted by activity scores, is reflected in DOC concentration changes at the catchment scale. To recap, the Crosswater of Luce (XL) catchment hosts 32 of the 60 turbines and has experienced the full range of activities relating to the construction of the wind farm. The Crosswater (X) catchment was used as a control having very little wind farm activity and only one turbine in it. Instead of taking the raw DOC concentrations with all the inherent seasonal variability, the ratio of the concentrations between the two catchments was used for the comparison with activity scores. The Tig catchment was not used here due to the relatively short time period spanned by the data.

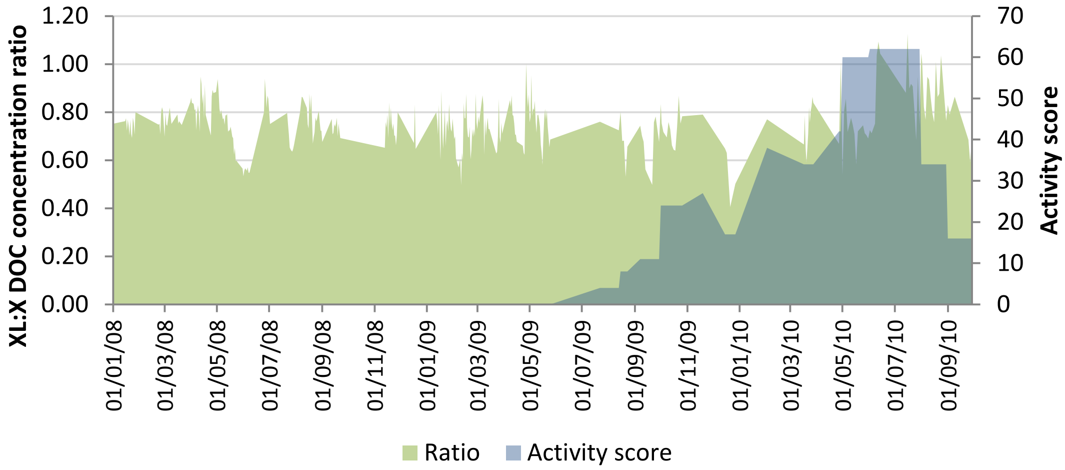


Figure 57. Activity scores for the Crosswater of Luce catchment overlain onto the ratio of DOC concentrations between the Crosswater of Luce (XL) and the Crosswater (X), integrated monthly.

Notwithstanding a lot of local noise in the relationship between the two catchments, the ratio of DOC concentrations (XL:X) appears to remain reasonably stable and below the 0.8:1 level until the middle of 2010 (Figure 57). After that the ratio increases towards 1:1 suggesting that the DOC concentrations in the Crosswater of Luce have become relatively higher. When the activity scores for the Crosswater of Luce catchment are overlaid on the DOC ratios an interesting picture emerges. SPR records show that forest harvesting in the Crosswater of Luce catchment started in March 2009 but the main construction work did not get underway until the second half of 2009, whereupon it ramped up to a peak in June and July 2010. This coincides with the change in the XL:X DOC concentration ratio as can be seen in Figure 57. There appears to be a lag of approximately a month in the response of the catchment DOC concentrations to increasing activity on site, which it has to be remembered, was occurring at a time of peak microbial activity and peat productivity. There will also be degradation of brash and other material left after forest harvesting.

Using the activity scores as a guide, the DOC ratio data were split into pre-construction (01/01/08 – 30/09/09) and construction (01/10/09 – 30/09/10) phases. These two data sets were then subjected to statistical analysis to explore differences between the two data sets using the non-parametric Mann-Whitney test. The results of this demonstrate that the XL:X DOC ratio was significantly higher ($W=48916$, $p=0.0396$) over the construction period meaning that the DOC concentrations at the Crosswater of Luce had become proportionately greater than pre-construction levels.

3.3 The Arecleoch spatial Surveys

The spatial survey was conducted in order to assess changes in water quality at the sub-catchment level, where impacts of land management measures could be detected most readily. During the survey period the land draining into these streams underwent significant disturbance from both forestry and wind farm construction activities. Where sampling at the catchment scale provides a general portrait of water quality, it is inevitably a product of the many source streams and the dilution and processing that has taken place along the way. Disentangling individual impacts from disturbance is not possible in an environment where a range of forestry and construction activities proceeds simultaneously. The aim of the spatial survey was therefore to isolate smaller sub-catchments and compare water quality across the study area at fixed points in time, and also to investigate temporal changes within small areas and match them to work patterns on the site. The activities being undertaken that had the potential to create disturbance were:

- Road building and use
- Forest harvesting
- Turbine base installation
- Cable laying

Arecleoch forest is served by a rich network of streams and drainage channels (Figure 58, Figure 59, Figure 60 , Figure 61). However, the selection of sample points during the first survey was limited by practicalities such as access. Before the wind farm development, vehicular access to the forest was restricted to the passable Forestry Commission tracks. Thus there are areas of the new wind farm, now served by good quality roads, that were inaccessible at the start of the project and, consequently, headwater streams of potential interest that have not been included in the survey.

3.3.1 **Sample collection**

Between October 2008 and August 2010, eight sets of water samples were collected from headwater streams across the three catchments within Arecleoch forest. The sample points are shown in Figure 62. Sample collection and analysis follows the protocol described above (1.3)

The first visit was on 21/10/08 and thereafter sampling was repeated seasonally (11/01/09, 01/05/09, 13/08/09, 20/11/09, 03/02/10, 24/05/10 and 02/08/10). Sampling was carried out within a 24 hour period for each survey and conditions under which sampling took place are described below (3.3.2). Initially, samples were collected from 29 burns and channels draining areas hosting some, all and none of the wind farm activities. During the remaining sample visits it was not always possible to collect the full sample set due to tree felling and construction works on site, which caused some areas to be closed off. However, a core of 22 sample points was maintained and these form the basis of the data set (Table 23). Sample points 15 – 19 were used as controls as there was no wind farm activity upstream of the sample point.

Figure 58. Sample point 8 in November 2009 during a storm event and under high flow

Figure 59. Sample point 23 in July 2011 showing competed turbines

Figure 60. Sample point 14 in 2009 showing a small stream with evidence of trees to the edge of the stream bank

Figure 61. Sample point 7 in November during a storm event. Road runoff in the foreground can be seen entering the stream.

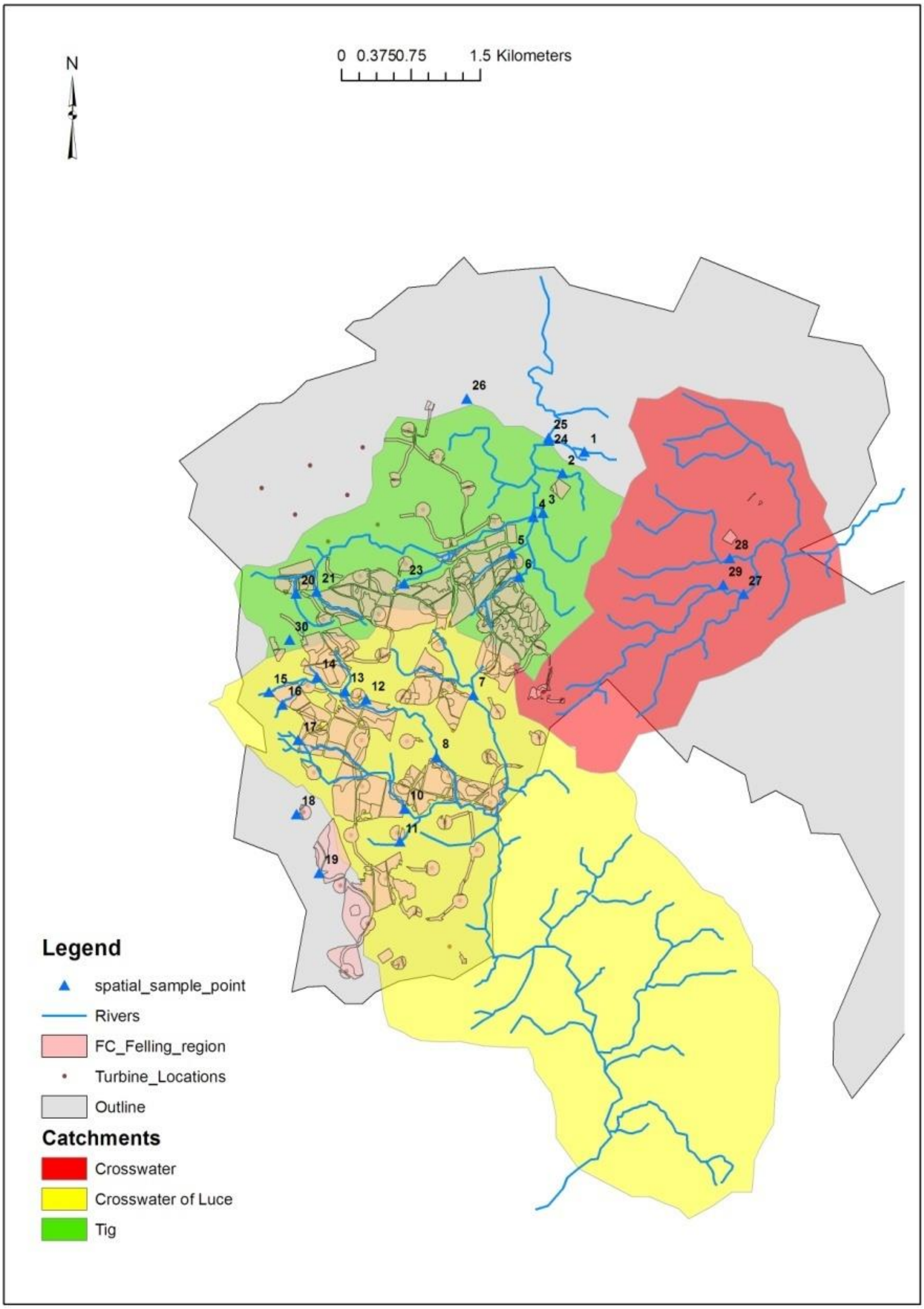


Figure 62. Three catchments draining Arecleoch and distribution of spatial survey sample points within each catchment (Map based on ArcGis material, partly supplied by SPR)

Table 23. Spatial co-ordinates (NGR) of spatial survey sample points, survey dates, number of samples collected over eight surveys and catchment area for each sample point.

	NGR		Spatial survey date									
Sample Point	X	Y	21/10/08	11/01/09	01/05/09	13/08/09	20/11/09	02/02/10	24/05/10	02/08/10	Number of samples	Area (km^2)
1	1890	8130	x	x	x	x	x	x	x	x	8	0.37
2	1870	8105	x	x	x	x	x	x	x	x	8	0.27
3	1858	8093	x	x	x	x	x	x	x	x	8	0.40
4	1849	8063	x	x	x	x	x	x	x	x	8	1.56
5	18110	8027	x		x		x	x	x	x	6	0.23
6	1823	7992	x		x	x	x	x	x	x	7	0.44
7	1772	7865	x		x	x	x	x	x	x	7	0.83
8	1733	7797	x		x	x	x	x	x		6	1.57
10	1695	7705	x		x		x	x	x	x	6	1.00
11	1695	7697	x		x		x	x	x		5	0.20
13	1701	7983	x		x		x	x	x	x	6	0.25
14	1604	7885	x					x	x	x	4	0.13
15	1552	7868	x				x	x	x	x	5	0.12
16	1568	7855	x				x	x	x	x	5	0.08
17	1584	7817	x					x	x	x	4	0.27
18	1582	7737	x					x	x	x	4	0.19
19	1607	7673	x					x	x	x	4	0.54
20	1581	7975	x		x	x	x	x	x	x	7	0.37
21	1603	7977	x		x			x	x	x	5	0.15
23	1701	7983	x		x	x	x	x	x	x	7	0.59
24	1856	8143	x	x	x	x		x	x	x	7	0.44
25	1856	8143	x	x	x	x		x	x	x	7	6.40

3.3.2 **Description of surveys**

In order to set the scene for the presentation of the spatial survey data, a brief description of each of the sample trips will be given including weather conditions, activity on site and any notes of interest. I also include a panorama photograph taken on each visit giving a view of the eastern aspect of the development (Figure 63). Changes to the landscape from this distance and angle appear very gradual and are not really noticeable until survey 5 when the patches of clearfell enlarge. The emergence of the wind farm becomes apparent as the turbine towers make an appearance in the image of August 2010.

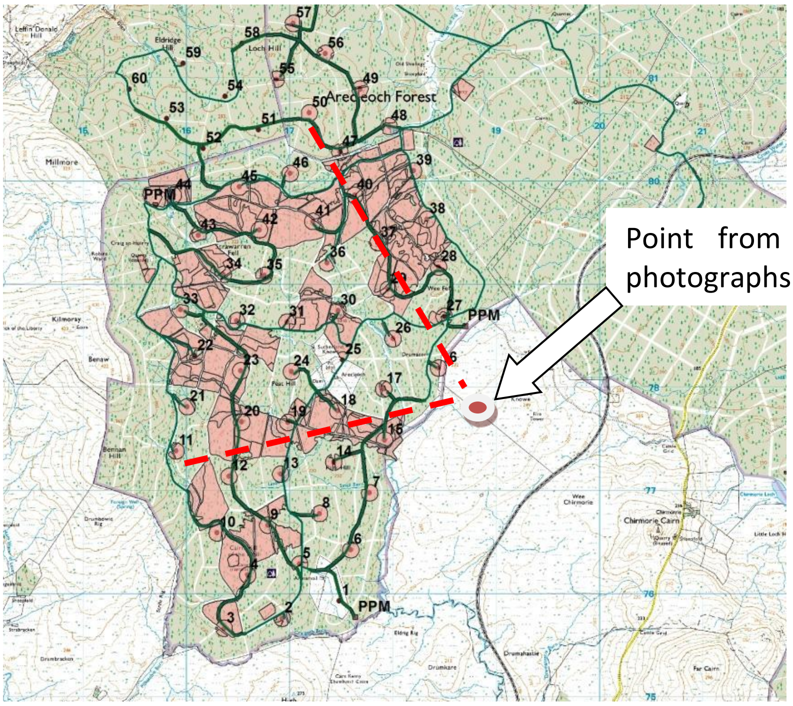


Figure 63. Location of vantage point used for panoramic photographs of Arecleoch over the wind farm development period between October 2008 and 5th October 2010 (Map based on Ordnance Survey material, ©Crown Copyright 2001 and supplied by SPR)

Survey 1
Date: 21st October 2008

Figure 64. Arecleoch panorama 1, 21st October 2008

Weather conditions: Dry and reasonably sunny. Streams all running
On site: Some machinery was in evidence and forest harvesting was underway near the road leading to the site. No wind farm construction activities were yet taking

place. This was the first visit to the interior of the site. Sample points were selected to give a good spatial distribution but access to watercourses was limited. Forestry ditches were still visible and although many were very overgrown some were still actively draining water.

Survey 2

Date: 11th January 2009

Figure 65. Arecleoch panorama 2, 11th January 2009

Weather conditions: Wet and windy. It had been very cold over recent days as some catchment samples were frozen in the autosamplers
On site: Contractors were beginning to move in and initial excavations were evident around SP2, which was very silty. Forestry harvesting was also widespread around the site entrance. Sample collection was limited as we were not allowed to proceed further into the site without an induction.

Survey 3
Date: 1st May 2009

Figure 66. Arecleoch panorama 3, 1st may 2009

Weather conditions: heavy and persistent rain at first, clearing later.
On site: Scottish Power were due to be on site full time from the following week. Forestry and road works were continuing. A wider range of samples could be collected as we had an escort from Scottish Power.

Survey 4
Date: 13th August 2009

Figure 67. Arecleoch panorama 4, 13th August 2009

Weather conditions: Dry, sunny at first then overcast.
On site: The turbine bases are starting to be excavated and more of the road network seems to be in place. Generally a lot of construction activity with a lot of heavy plant moving about the site. River and stream levels were very low.

Survey 5
Date: 20th November 2009

Figure 68. Arecleoch panorama 5 20th November 2009

Weather conditions: Mainly dry but the previous day had seen torrential rainfall.
On Site: Conditions on site the previous day were difficult with a lot of surface runoff and SUDS overwhelmed. Conditions had improved on the 20th but some of the roads were heavily rutted from the previous day's rain. River levels were very high and there were minor trails of silt still entering some of the watercourses. There were a lot of timber wagons moving on and off the site and a lot of heavy plant associated with road building/ maintenance.

Survey 6
Date: 2nd February 2010

Figure 69. Arecleoch panorama 6, 2nd February 2010

Weather conditions: Very cold, -5°C, snowing.
On site: Water levels varied in different streams and rivers, some being more frozen than others. The catchment sample point equipment had suffered substantial damage it is thought from pieces of ice colliding with it. The spatial samples were collected successfully though and all sample points had flow. Construction work was held back by the weather. Good conditions for road and water crossing work but not for turbine base installation as it was too cold to pour concrete.

Survey 7
24th May 2010

Figure 70. Arecleoch panorama 7, 24th May 2010

Weather conditions: Warm, sunny, very dry.
On site: Water levels at all sample points were very low. A lot of clearfelling seems to have gone on since the previous visit. The site appeared very different with large areas between turbines bare. It was the greatest visual impact to date. A lot of construction activity is now in the south of the site and most of the turbine bases are in place or being excavated. Turbine towers and blades were seen arriving on flatbed trucks.

Survey 8
2^{nd} August 2010
Weather conditions: Mixture of sun and heavy rain.
On site: There was less construction and timber traffic and the site was quieter. Turbine towers were being delivered and beginning to appear on the horizon. The photograph shows grey patches of the turbine bases for the first time. Road runoff was seen entering watercourses in the area of sample points 1, 2, and 3. SP3 (downstream of the road) was very turbid but on the upstream side of the road the water was running clear suggesting ingress to the culvert via a leak in the pipe.

Figure 71. Arecleoch panorama 8 2^{nd} August 2010

The last two photographs record the latter stages of the wind farm construction and cement the visual realignment of the landscape. What they also demonstrate is that far from representing a transformation from forest to wind farm, the development at Arecleoch will, for the next 25 years, be intimately connected with the new rotation of trees with the lower parts of the turbines appearing to be subsumed by the forest as it grows.

30 August 2010

Figure 72. Arecleoch panorama 9, 30^{th} August 2010

O5 October 2010

Figure 73. Arecleoch panorama 10 5th October 2010

3.3.3 **Results**

3.3.3.1 Data collated by sample point

Figure 74 gives a graphical display of the range of DOC concentrations found at each of the 22 sample points. The mean DOC concentration from the pooled data is 37.73 mg L^{-1} and this is represented by the horizontal line on Figure 74. It can be seen that all DOC concentrations from sample points 15, 17, 18 and 19 lie below that mean value. These are four of the five sample points (15 – 19) designated as controls throughout the eight surveys as none has had any potentially disturbing activity upstream of the collection point and samples were collected on the upstream side of the road. The other undisturbed sample point, SP16 maintained DOC concentrations below the overall mean except for survey 8 when the value was 43.2 mg L^{-1}.

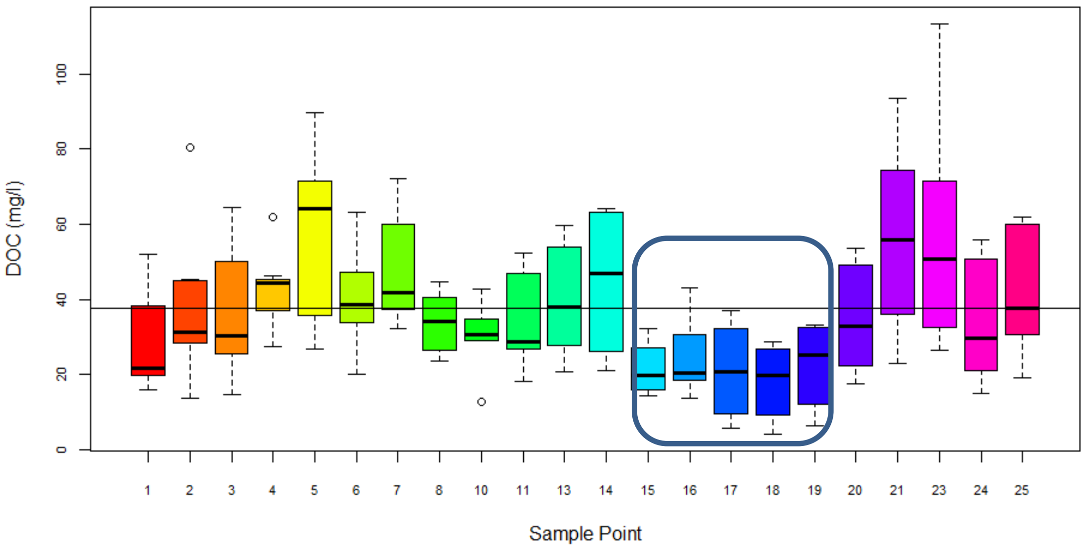


Figure 74. Range of DOC concentrations at the 22 spatial survey sample points. Sample points 15 – 19, within the box, were used as controls.

Data from the eight surveys across the 22 sample points was pooled and then separated into broad categories. The data straddle a range of flows and no attempt has been made to disentangle this effect but a distinction was drawn according to whether land draining into a sample point was subject to disturbance at the time of sampling. All data from the first survey was considered to represent undisturbed sites and thereafter, disturbance was assessed by cross-referencing Scottish Power's daily work records with the survey dates. Once a sample point had been designated as disturbed, it remained so even after work in its catchment area had been completed. Samples were also separated according to the type of disturbance to which they could be exposed. Divisions were made according to whether the samples could be influenced by road activity alone (R) or by both roads and turbine-related work (R+T) (Figure 75). Differences between these groupings were explored and while median concentrations were higher within the disturbed sub-set than the undisturbed

(33.67 mg L^{-1} cf. 32.17 mg L^{-1}) this difference was not statistically significant (Mann-Whitney W = 2187.0, p = 0.1471).

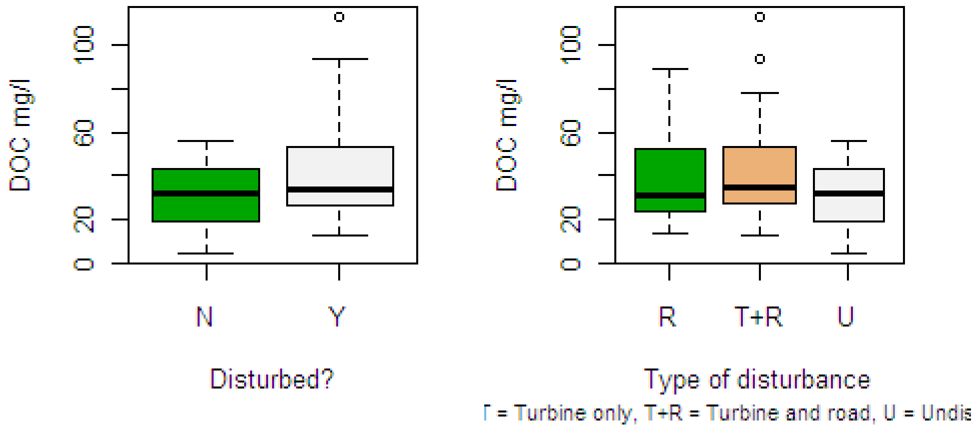


Figure 75. DOC concentrations (mg L^{-1}) from Arecleoch spatial survey samples points comparing (a) median values between disturbed (Y) and undisturbed (N) sites and (b) sites subject to disturbance from road building only (R), turbine installation and road building (T+R) and not disturbed by wind farm activities (U)

Comparisons were tested between the types of disturbance using the Kruskal-Wallace test (Table 24) and found to be significant only between median DOC concentrations of undisturbed samples (U) and those exposed to disturbance from both roads and turbines (T+R). The fact that disturbance from roads only did not give rise to significant differences in mean DOC concentrations from the other sub-sets may indicate that it is the turbine base element that is responsible for the increase in DOC concentration.

Table 24. Results of Kruskal-Wallace post hoc tests on differences in median DOC concentrations for spatial survey samples exposed to disturbance from roads (R), roads and turbines (R+T) and undisturbed samples (U). Difference = TRUE indicates a statistical difference significant at the 95 % confidence level

Samples	*Observed difference*	*Critical difference*	*difference*
R-T+R	15.097768	19.97668	FALSE
R-U	5.753383	22.26206	FALSE
T+R-U	20.851151	19.46023	TRUE

3.3.3.2 Data collected by survey

Table 25 provides summary statistics for DOC concentrations at each of the eight spatial surveys. The low sample count in survey two is explained above. The mean DOC concentration from each survey varies from 27.58 mg L^{-1} (survey 2) to 56.97 mg L^{-1} (survey 8) but much of this variation is accounted for by the seasonal DOC cycle discussed above. Figure 76 illustrates the minimum, mean and maximum DOC concentrations recorded at each survey. Surveys 4 and 8 carried out in summer produced the highest concentrations in each banding as expected from the annual DOC cycle. The minimum values show a slight decrease over the eight surveys while there is a stronger upward trend in the maximum DOC concentrations. Survey 8 had the highest maximum DOC concentration (113.4 mg L^{-1} at sample point 23) and the second highest minimum value (27.56 mg L^{-1} at sample point 17).

Table 25. Summary statistics for DOC concentrations (mg L^{-1}) from eight spatial surveys at Arecleoch. SE = standard error of the mean, StDev = standard deviation, CoefVar = coefficient of variation, Min = minimum, Max = maximum

Survey	*Date*	*Count*	*Mean*	*SE*	*StDev*	*CoefVar*	*Min*	*Max*
1	21/10/2008	22	40.18	1.94	9.11	22.69	24.96	56.03
2	11/01/2009	6	27.58	3.92	9.61	34.86	18.68	44.76
3	01/05/2009	16	28.75	2.14	8.55	29.76	14.71	52.28
4	13/08/2009	11	51.6	3.81	12.63	24.48	31.49	78.33
5	20/11/2009	15	27.98	3.05	11.81	42.21	13.82	59.35
6	02/02/2010	22	30.09	3.10	14.56	48.39	13.60	69.18
7	24/05/2010	22	31.80	4.75	22.30	70.12	4.12	74.39
8	02/08/2010	22	56.97	4.56	21.85	38.36	27.56	113.4

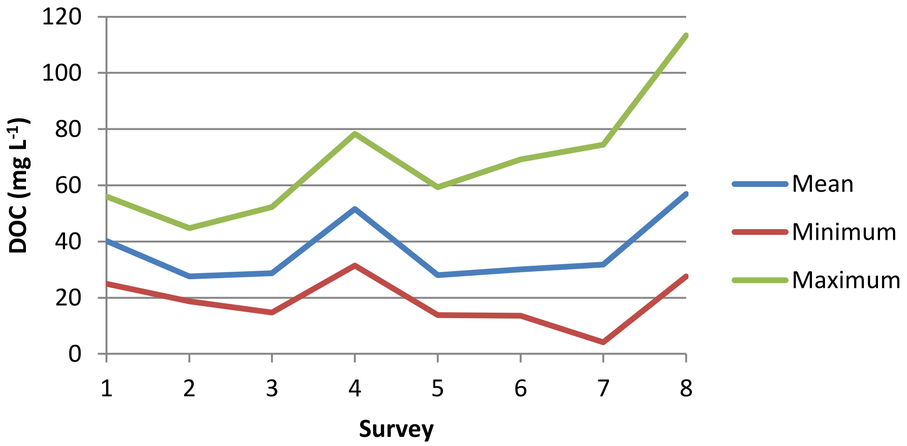


Figure 76. Minimum, mean and maximum DOC concentrations (mg L^{-1}) recorded at each of the eight spatial surveys at Arecleoch (October 2008 – August 2010)

Standard deviation values more than double from 9.11 mg L^{-1} in survey 1 to 21.85 mg L^{-1} in survey eight. Within this range there are two distinct step changes; the first a jump from 8.55 mg L^{-1} in survey 3 to 12.63 mg L^{-1} in survey 4 and the second a larger increase from 14.56 mg L^{-1} in survey 6 to 22.30 mg L^{-1} in survey 7. Standard deviation is a measure of variability showing how much dispersion there is from the mean DOC concentration and large values may indicate that something could be happening within the sampling area leading to the DOC concentrations being spread over a larger range of values. Once again though the seasonal distribution of DOC concentration values must be considered and the standard deviations placed in context with the largely differing mean concentrations between the two surveys. Coefficient of variation, the ratio of the standard deviation to the mean, is a dimensionless measure of dispersion and is of more use than standard deviation where the mean values being compared are very different. From Table 24 we can see that the coefficient of variation decreases from survey 3 to survey 4, but increases from 48.39% in survey 6 to 70.12% in survey 7. There is also a sharp rise between survey 4 (42.21%) and survey 5 (42.21%). This suggests that further investigation into what was happening on site and in the wider environment during the period spanning these surveys may yield some insight into the causes of the increases.

Each of the step changes in coefficient of variation will now be examined in more detail. The aim is to establish whether it is possible to identify the cause of the apparent difference in variability between surveys. Data from individual sample points will be assessed taking into consideration precipitation, antecedent soil moisture and the location and nature of the work being carried out across the wind farm site.

3.3.3.3 Step change 1, survey 4 to survey 5

13 August 2009 to 20 November 2009. These were the busiest months on the site for road and turbine work (Figure 55).

To standardise for the large seasonal difference in mean DOC concentration between August and November, variability was compared using the deviation from the mean DOC concentration as a proportion of the mean (equation 4).

Variability = x-mean/mean **Equation 4**

A large, positive deviation from the mean DOC concentration indicates that DOC concentrations may be elevated as a result of disturbance to the land within the catchment of that sample point.

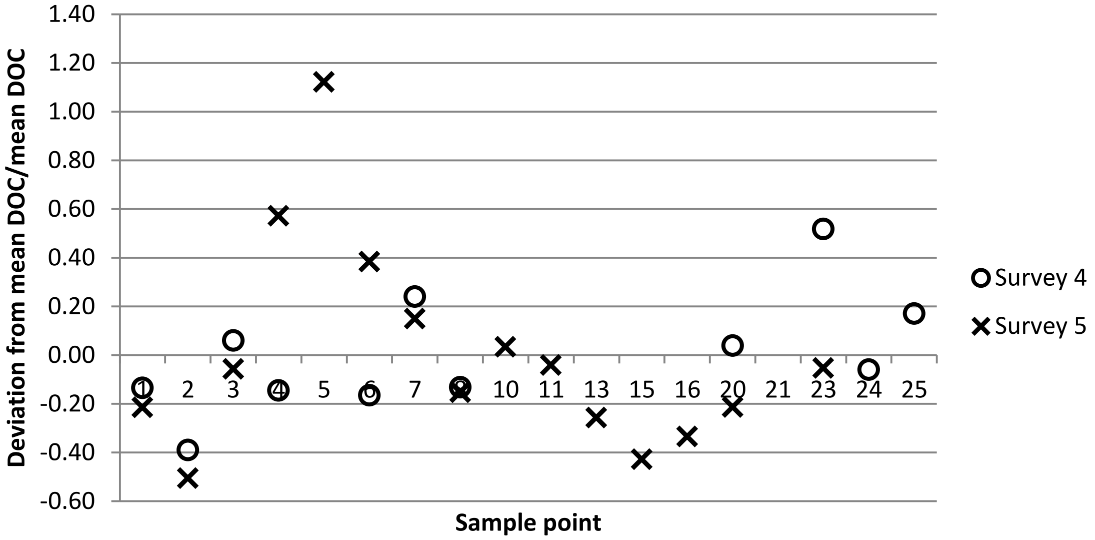


Figure 77. Deviation from mean DOC concentrations (mg L^{-1})as a proportion of mean values for spatial surveys four and five (August 2009 and November 2009)

For survey 4, relative deviations from the mean DOC concentration were greatest at sample points 2, 7 and 23. At sample point 23 a specific DOC concentration of 78.33 mg L^{-1} was 26.73 mg L^{-1} greater than the mean DOC concentration for the sample set. For survey 5, deviations from the mean were greatest at sample points 2, 4, 5, 6 and 15. At sample point 5 the specific DOC concentration was 59.35 mg L^{-1}, more than double the mean DOC for the sample set, which was 27.98 mg L^{-1}. It is apparent that much of the variability within survey 5 would have been caused by the high DOC concentration at sample point 5. No sample was collected from this sample point in survey 4 the comparison was repeated using only those sample points where samples were collected at both surveys.

Table 26. Summary statistics for DOC concentrations (mg L^{-1}) from survey four (Aug 2009) and survey five (Nov 2009) at Arecleoch. N = number of samples, SE = standard error, StDev = standard deviation, CoefVar = coefficient of variation

Variable	*N*	*Mean*	*SE Mean*	*stDev*	*CoefVar*	*Minimum*	*Maximum*
Survey 4 (13/08/09)	9	50.97	4.57	13.72	26.92	31.49	78.33
Survey 5 (20/11/09)	9	27.69	3.08	9.24	33.38	13.82	43.98

Now it can be seen (Table 26) that the difference in the coefficient of variation between the two surveys has decreased. Of the nine sample points common to both surveys it is clear that sample points 4 and 6 account for a large part of the greater variability in survey 5 (Figure 78), although this will be offset by the DOC concentration at sample point 23 in survey 4 which was 78.33 mg L^{-1}.

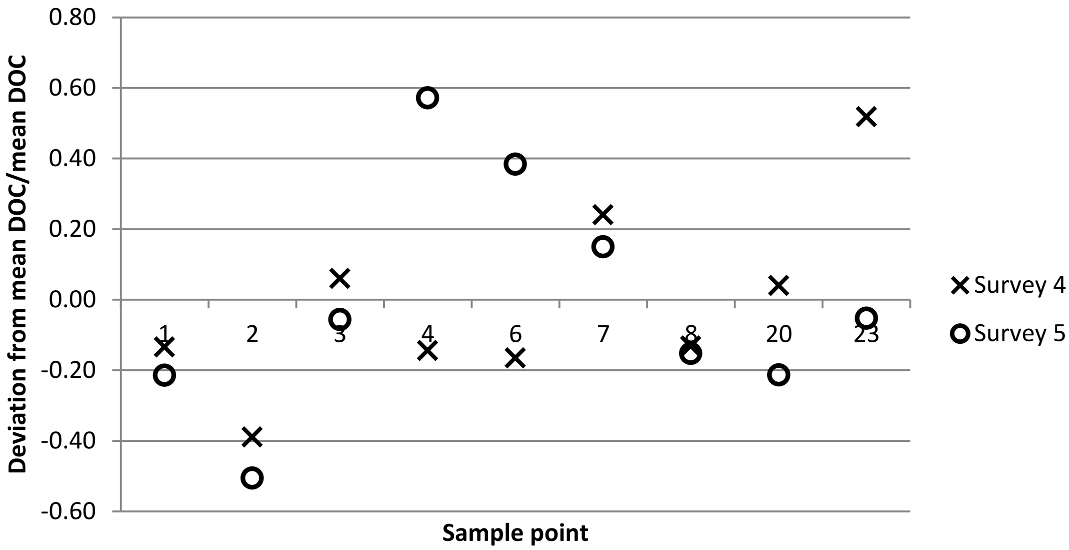


Figure 78. Deviation from mean DOC concentrations as a proportion of mean values for spatial surveys four (Aug 2009) and five (Nov 2009) showing only sample points where samples were obtained on both surveys

Sample point 6 is a stream with a small catchment area of 0.44 km^2. Disturbances to the land that could have an impact on its water quality are restricted to the felling area in pink (Figure 79) work on turbine 37 and road related activity between turbines 39 and 38 and turbines 37 and 40 (there was no cable laying at this time on site). SPR site diaries record that the excavation and installation of the base for turbine 37 was carried out in the second half of October 2009 (records from 15/10/09 – 28/10/09). The spur road for T37 was laid between 18/08/09 - 15/09/09. There was therefore a lot of activity in the area draining into sample point 6 that could have led to elevated DOC concentrations though sample point 4 has a larger catchment area (1.56 km^2) and receives inputs from tributaries containing sample points 5 and 6.

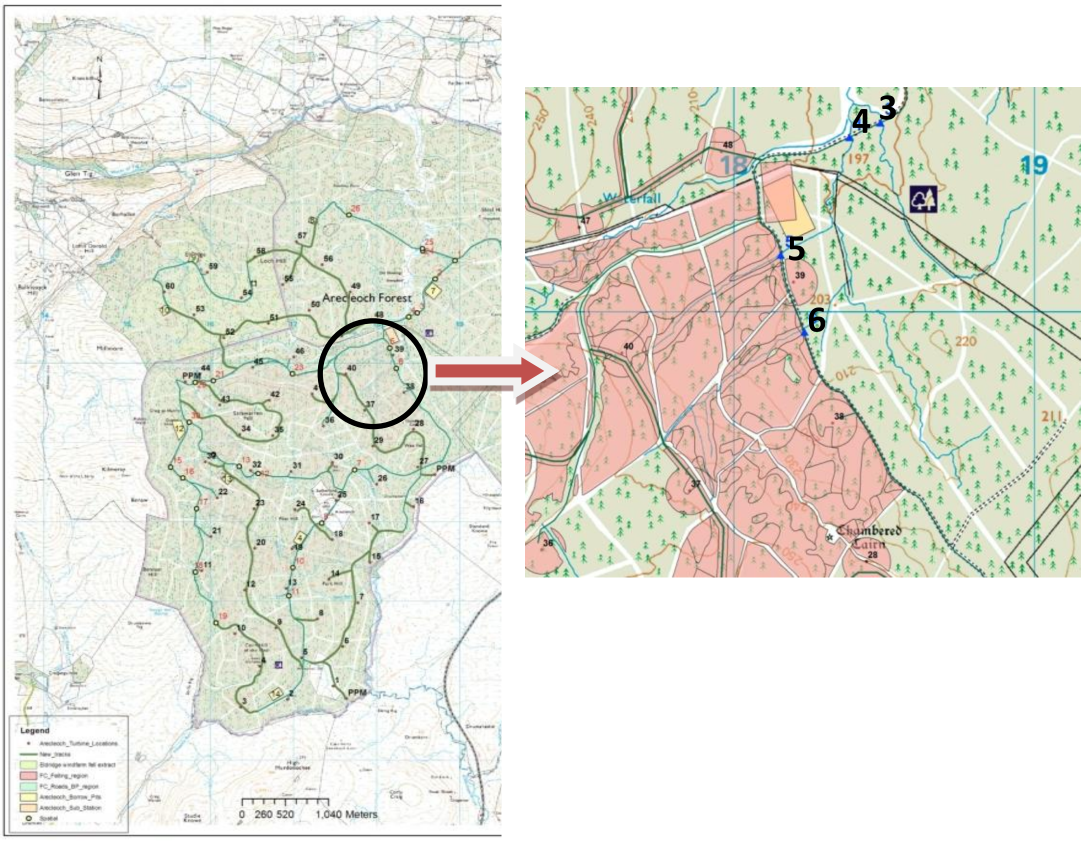


Figure 79. Locations of spatial survey sample points 3, 4, 5 and 6 and associated wind farm infrastructure nearby. (Map based on Ordnance Survey material, ©Crown Copyright 2001 and supplied by SPR)

Turbine	Catchment	Sample point	SP25	Turbines Aug-09	Turbines Sep-09	Turbines Oct-09	Turbines Nov-09	Road Aug-09	Road Sep-09	Road Oct-09	Road Nov-09
12	XL										
13	XL	11									
14	XL										
15	XL										
16	XL										
17	XL										
18	XL										
19	XL	10									
20	XL	10									
21	XL	10									
22	XL	10									
23	XL	10									
24	XL	8									
25	XL										
26	XL										
27	X										
28	XL	4									
29	XL	7									
30	XL	7									
31	XL	7									
32	XL	8									
33	XL	8, 14									
34	XL	8, 13									
35	XL	7									
36	XL	7									
37	T	4, 6	x								
38	T	4	x								
39	T	4	x								
40	T	4, 5	x								
41	T		x								

Figure 80. Section of a spread sheet collating information from SPR daily site records showing where work was being carried out every month in relation to each turbine base. Green= Tig catchment, yellow = Crosswater of Luce (XL) and red = Crosswater (X). The red ellipse highlights work around turbine 37 the impact of which could affect water quality at spatial survey sample points 4 and 6

Activities relating to turbines 28, 37, 38, 39 and 40 and the road from the site compound to the substation could have an impact on the receiving waters in this catchment.

Figure 80 shows that turbine and road related work was carried out at all these points during the interval between the two surveys. Excavation of the turbine bases, the most intrusive part of the turbine base installation process was completed in August. Road works in the vicinity of some of these turbines was also undertaken during this period. Weather conditions on 20 November 2009 were pleasant with only 0.2 mm of rain recorded but the preceding 24 hours were very wet with 17 mm of rain and 200 mm since the start of the month. Conditions on site that day were still very wet and surface water on the roads, particularly around the area of the substation, was seen to overwhelm the SUDS measures, causing visible plumes of sediment to enter the receiving waters draining these areas. It is clear that there was a high concentration of potentially disturbing activities between surveys 4 and 5. However as Figure 80 shows, this was a period of intense activity across the site with similar levels of work on turbines 29 -31 and 35, 36, any disturbance from which would have an impact on SP7.

3.3.3.4 Step change 2, survey 6 to survey 7

02 February 2010 – 24 May 2010

Here the situation is more straightforward because water samples were collected from the same 22 sample points making available a more comprehensive comparison of DOC concentrations in streamwater across the site. The period from February to May 2010 represents a phase of concentrated activity across the wind farm development site at Arecleoch with turbine base installation, road works and cable-laying being undertaken concurrently, as well as ongoing forestry.

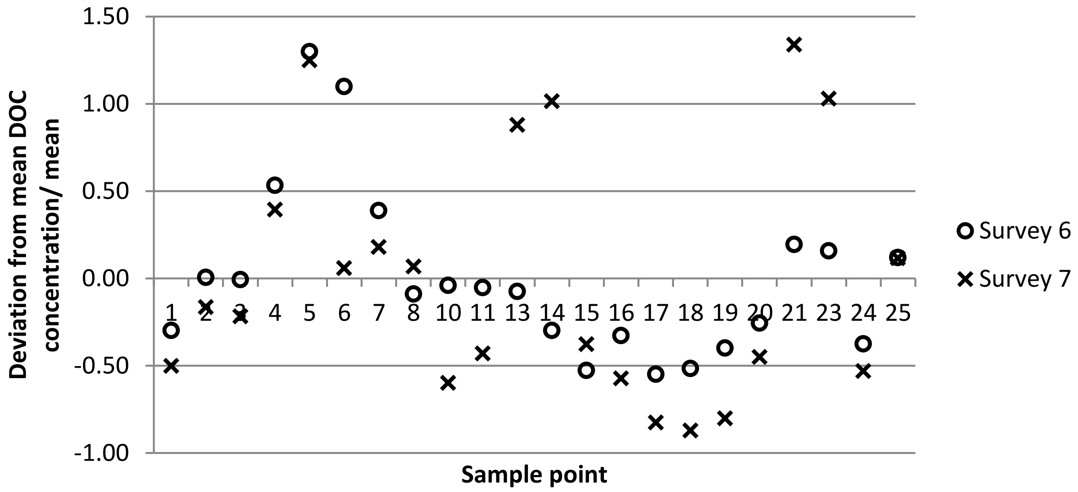


Figure 81. Deviation from mean DOC concentrations as a proportion of mean values for spatial surveys six and seven (February and May 2010)

It can be seen from Figure 81 that the greatest differences in variability of DOC concentration occurred at sample points 6, 13, 14, 21 and 23. In all cases except for sample point 6, there was an increased positive deviation for samples in survey 7.

Sample points 14 and 21 have no turbines in their catchment areas. Sample point 13 will receive water from the area draining turbine 34 and sample point 23 will receive the impacts of disturbances from the installation of turbine 42. SPR daily site diaries indicate that bases for turbines 34 and 42 were completed by the end of January 2010. The diaries also record that cable trenches for these turbines were excavated and backfilled along a similar time frame. Cable trench work associated with turbines 33 and 32 would have the potential to disturb land draining into sample points 13 and 14 but beyond February 2010 the records only show the extent of cable trench activity to the array level of detail and not by specific turbine. Thus it is not possible to postulate further on any linkage between elevated DOC concentrations and work in a particular area.

Coefficient of variation values indicate that the variability in DOC concentrations across the 22 sample points in survey 7 was greatly increased from those in survey 6. A possible cause of this could be disturbances to the peat on the wind farm site leading to more DOC being transported to the receiving waters. However while there was a lot of activity across the site during this period of time, the records available do not suggest any particular linkage between potentially disturbing activities and the elevated DOC concentrations. A further note to add is that for survey 8 the coefficient of variation has decreased again to 38.36%

3.3.3.5 Analysis of the Tig catchment sample point data

Please refer to Figure 82 for a guide to the locations of turbines and sample points. Sample point 25 (sp25) in the spatial survey is also the Tig catchment sample point. With a catchment area of 6.4 km^2, it is substantially larger than any of the other sub-catchments in the survey. It drains much of the north east of the site, an area that accommodates 19 turbines and the sub-station, and receives water from ten of the other spatial survey sample points. DOC concentrations from the ten sample points and sp25 were plotted using GIS software (ArcGIS 10) (Figure 83). DOC concentrations were grouped into five bands each with a range of 20 mg L^{-1}. These are represented on the map by dots of different colour and size. This provides a visual representation of the relative contributions of each of the tributaries to the overall DOC concentration at sp25. It also highlights any potential hotspots of high DOC concentration. The data from selected sample points discussed in more detail are also tabulated to show the extent by which they exceed the mean values for their survey (Table 27).

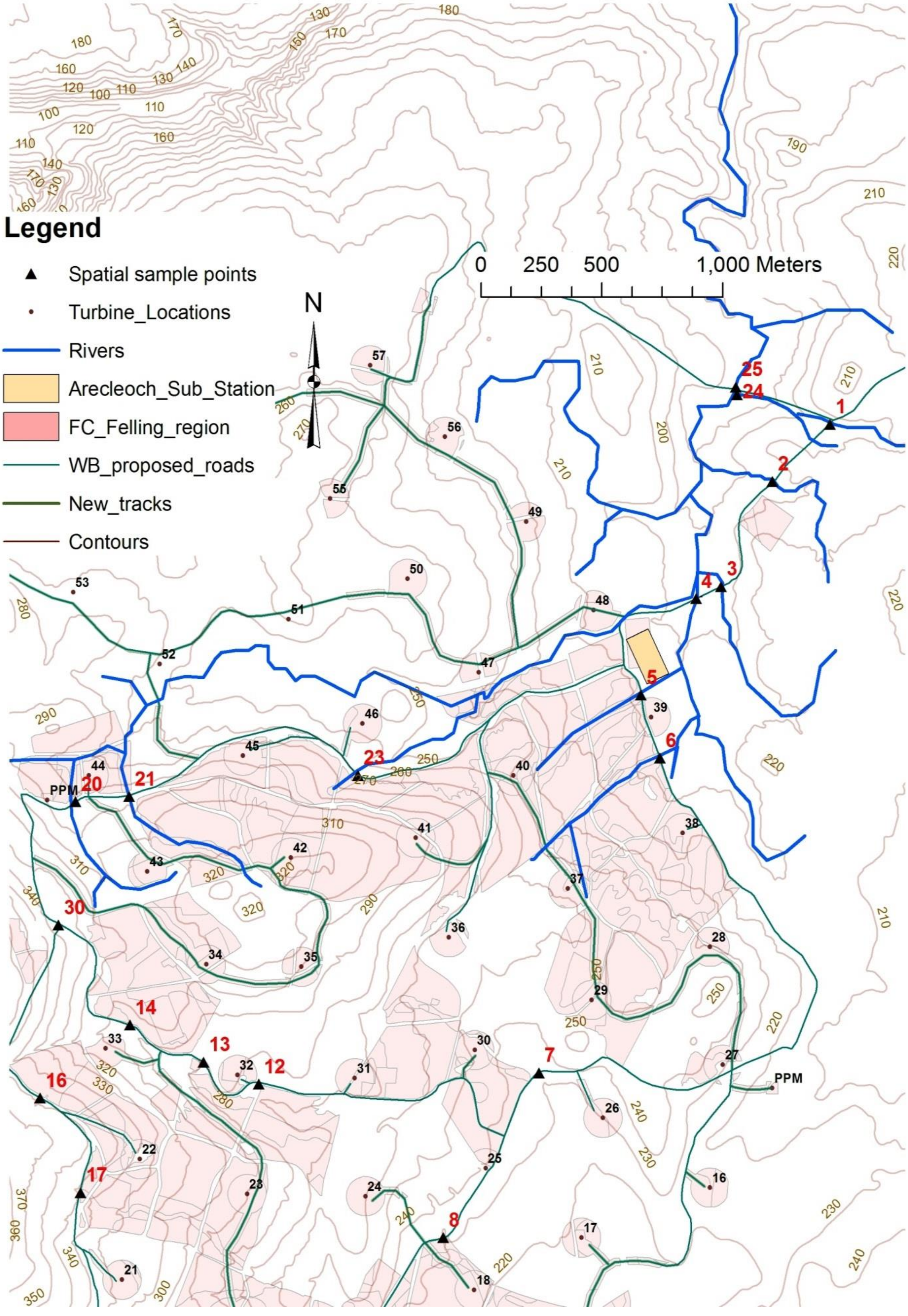


Figure 82. Spatial survey sample points located within the Tig catchment

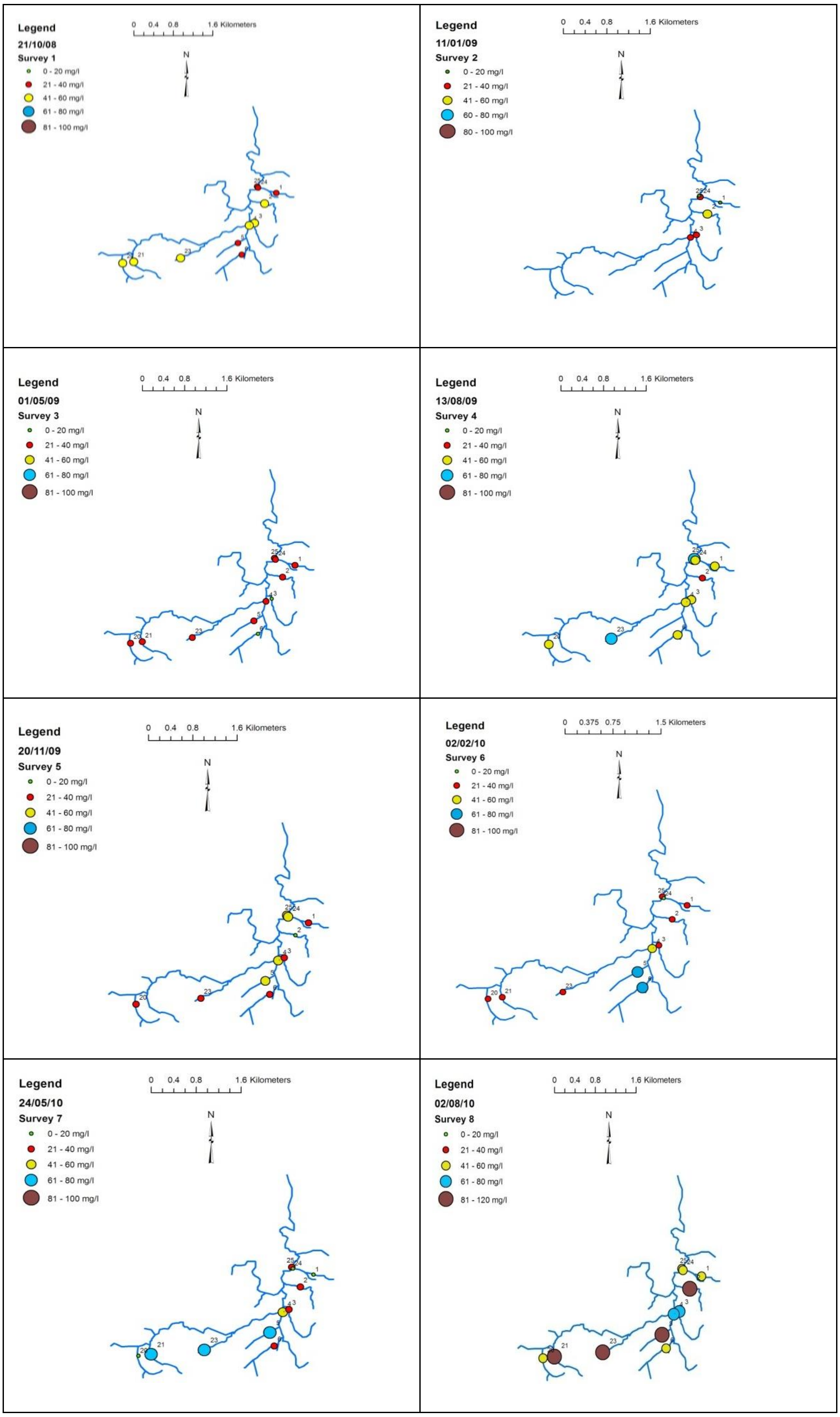


Figure 83. DOC concentrations at sample points within the Tig catchment across eight spatial surveys

For surveys 1, 2 and 3 the range of DOC concentrations is fairly uniform with none being separated from sp25 by more than one banding. Survey 4 was carried out on 13 August 2009 when DOC concentrations are reaching their annual peaks. From Figure 83 it can be seen that the DOC concentrations at sp23 and sp25 appear to stand out as being the only ones in the blue band. At sp23 the DOC concentration was 78.33 mg L^{-1}, exceeding the mean DOC concentration for the entire survey by 51.8 % (Table 27). This was also the highest individual value for the survey. At sp25 the DOC concentration was 60.36 mg L^{-1}, which was 16.98 % above the survey average. As sp25 is not in a location that would be subject to any direct inputs resulting from disturbance from the wind farm, the elevated concentration is likely to be a result of upstream contributions.

Table 27. DOC concentrations mg $L^{-1)}$ for sample points at spatial surveys 4, 7, and 8 with values also given for the mean DOC concentration for each survey and the percentage by which each individual concentration exceeded the mean for its survey.

Survey	*Sample point*	*DOC concentration (mg L^{-1})*	*Mean DOC concentration for survey (mg L^{-1})*	*% by which mean is exceeded*
4	23	78.33	51.60	51.80
4	25	60.36	51.60	16.98
6	5	69.18	30.09	129.9
6	6	63.19	30.09	110.0
7	5	71.54	31.80	124.9
7	21	74.39	31.80	133.9
7	23	64.56	31.80	103.0
8	2	80.42	56.97	41.16
8	5	89.57	56.97	57.22
8	21	93.53	56.97	64.17
8	23	113.4	56.97	99.05

Sp23 is from a stream draining an area of just 0.59 km^2. Water quality could be affected only by activities relating to turbine 42, the road and cable trenches in the immediate vicinity and localised tree harvesting. SPR records show that at the time there was no cable laying and forest harvesting is not specified in that area. The records do indicate that excavation work for the T42 base was being carried out during the first week of August and that work on the spur road between T42 and T35 was undertaken during the first half of July. It is therefore possible that disturbances to the peat from either or both of these activities resulted in the elevated DOC concentration seen in sp23. In survey 6 (02 February 2010) samples from sp5 and sp6 stand out as having elevated DOC concentrations although with a value of 63.19 mg L^{-1} at sp6 it is at the lower end of the blue banding. Both of these results are more than double the mean DOC concentration for the survey (30.09 mg L^{-1}). Sp5 and sp6 are on neighbouring tributaries of the stream that leads to sp4. Samples are collected on the downstream side of the road that crosses both sample points and links T38 and T39. The source of the sp5 stream is close to T40 and T37 is near to a branch of the stream on which sp6 is located. The road between these two turbines is up gradient of the streams. In addition T39 is located between the two sample points. SPR diary entries reveal that the base for turbine 40 was being excavated around the 19th and 20th of January and that work was further ahead at T37 where the base was recorded as being filled over the following week.

Moving on to survey 7 on 24th May 2010 and three samples returned DOC concentrations more than double the total survey mean and where they were two bands above the sample from sp25. Sample points 5 and 23 have been described above but the third, sp21 has not previously appeared as anomalous within any of the sample sets. Stream water arriving at sp21 is most likely to be carrying evidence of peat disturbance from work associated with cable trenches or roads around T43 and T42. Both turbines 43 and 42 lie in array 2 of the wind farm networks and cable trench work was not recorded in this array after April. There were also no road works recorded in the area meaning that no obvious source of the elevated DOC concentrations at sp21. SPR records from that time indicate that work on turbine base T40,which could affect water quality at sp5, had been completed at the end of April and there was also nothing noted that would relate directly to water quality at sp23.

Finally we arrive at survey 8 (2nd August 2010) where the highest DOC concentrations from all the spatial surveys were returned. Sample points 5, 21 and 23 once again stood out, this time moving into the highest category, symbolised by brown dots and they were joined in this group by sp2. To be placed in this category, streamwater samples must have a DOC concentration above 80 mg L^{-1}. From Table 26 we can see that the sample from sp2 is only just placed in this bracket with a DOC concentration of 80.42 mg L^{-1}. Samples from sp5, sp21 and sp23 crossed the border more convincingly with DOC concentrations of 89.57 mg L^{-1}, 93.53 mg L^{-1} and 113.4 mg L^{-1} respectively. Indeed the DOC concentration at sp23 was the highest recorded in any of the surveys. At this time peat-disturbing activity on site had decreased greatly with only work on cable laying in Array 5 and some road dressing in the south of the site. The SPR records do not shed any light on the possible causes of the elevated DOC concentrations so it is necessary to consider other factors operating at the time, which may help to explain these unusually high results. The time of year is relevant in that relatively high DOC concentrations would normally be expected in August. The mean DOC concentration across all sample points for survey 4 in August 2009 was 51.6 mgL^{-1} compared with 56.97 mg L^{-1} for survey 8 in August 2010, not a large difference when presented as an average. Rainfall for the two weeks preceding survey 8 totalled 76 mm whereas for the fortnight leading up to survey 4 a year previously it was 113 mm making 2010 a relatively dry period and not likely to generate runoff rich in carbon.

Also factors such as rainfall and antecedent soil moisture would affect other sample points in a similar fashion. It seems likely therefore that localised impacts resulting from forest harvesting and construction activities would have been the cause of the elevated DOC concentrations. SPR site records do not contain sufficient detail to determine whether this was the manifestation of small, cumulative disturbance events or if there were specific, unrecorded, local activities that were responsible for the elevated concentrations of DOC.

3.4 Turbine 33 experiment

For each of the 60 turbines, an area of approximately 23 m x 23 m is excavated to bedrock in order to install the turbine base. The volume of peat removed is therefore dependent upon its depth. The same is true of the hardstanding area adjacent to the turbine base required to site cranes used to erect the turbine. Here an area of approximately 44 m x 34 m is excavated. Although a peat depth survey was carried out as part of the EIA process, actual volumes of peat removed were far less than anticipated (pers. comm. Scottish Power). Only in array 5 was the quantity of peat described as substantial and then only for six of the ten turbine bases.

Turbine 33 (T33) was considered a suitable candidate for monitoring the impact of turbine base installation on water quality. The choice of T33 was made based on the proximity of suitable upstream and downstream water sample points and ease of access to these (Figure 84). It belongs to Array 4 and installation was planned for early in 2010. A detailed work schedule is not available more than two weeks in advance and even then there are many factors on the ground that can result in changes to that schedule.

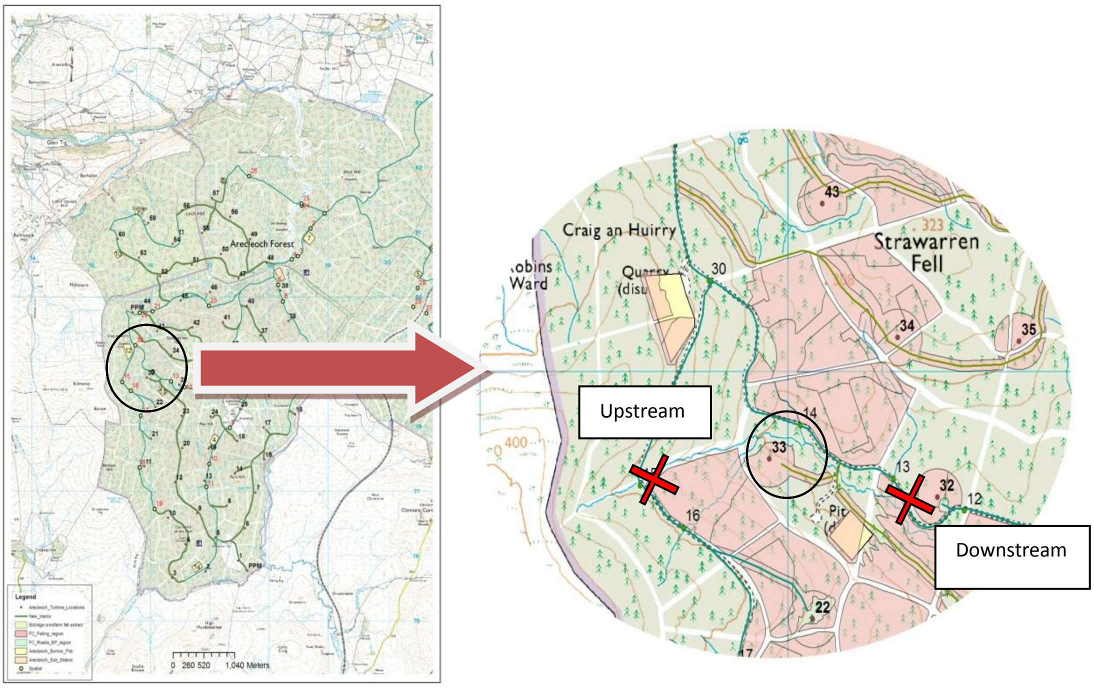


Figure 84. Location of Turbine 33 relative to other turbines at Arecleoch (left) and position of the sample points upstream (T33 up) and downstream (T33 down) of the turbine base installation (right). (Map based on Ordnance Survey material Crown Copyright 2001 and supplied by SPR)

3.4.1 **Sample collection**

Two automatic water samplers of the type described above (1.2.1) were installed, one upstream of T33 and one downstream. The upstream sample point (T33Up) was located approximately 412 m from the proposed position of the turbine base. It had a catchment area of 0.1 km^2 and, positioned near the western boundary of the development area, bordering an SAC, was not subject to any wind farm related disturbance. The second sample point (T33Down) was situated 370 m downstream of T33 and would receive any runoff from either the area of the turbine base or the access road serving it. It drained an area of 0.7 km^2. Sample collection and analysis for DOC, absorbance and suspended sediment followed the protocol described above (1.2.1).

The sampling equipment was installed on December 16th 2009, the intention being to collect water quality data before the main work began on T33. With the entire site being closed for two weeks over Christmas it was also minimising the risk of unscheduled disturbance to the area. Unfortunately the weather confounded this planning as on December 17th 2009 there commenced a period of unusually low temperatures and heavy snow that lasted through into the beginning of January 2010. This period of sustained sub-zero temperatures led to the small streams, including those housing the sample equipment, remaining frozen for many weeks. As a consequence, sampling only started on 2nd February 2010, by which time preparations for the installation of T33 had started and it is more difficult to assess the possible reasons for differences between T33Up and T33Down. Unfortunately at this stage in the development there was no opportunity to repeat the experiment at another turbine.

Daily Diary records kept by Scottish Power reveal that tree felling in the turbine area was carried out in March 2009. Between Jan 22nd and March 12th 2010 work was carried out on the formation of the access road between T33 and T23, the spur road in to T33 and the hardstanding for T33. On March 10th 2010 it was recorded that the excavation of the base area for T33 was complete. Construction of the base then began and on March 5th concrete was poured into the base area and by March 14th the base area was being backfilled. Finally on 18th March capping of the road between T33 and T23 was taking place.

Superimposed over these construction activities was the ongoing forestry harvesting. As well as areas of clear fell the Forestry Commission has also employed the technique known as keyholing whereby a circle of diameter 80 m, amounting to approximately 2 ha is removed from a turbine location. The exact dates of forest harvesting associated with the area around T33 are not recorded.

3.4.2 **Results**

Stream water downstream of turbine 33 (T33down) had a significantly higher ($p < 0.05$) median concentrations of DOC and ss than upstream (T33up) and the water colour, measured by absorbance at 400 nm, was significantly darker ($p < 0.05$) (Table 28). The downstream samples also demonstrate greater variability, especially in suspended sediment concentration where a maximum value of 140.41 mg L^{-1} was recorded at T33down, against a maximum of 27.00 mg L^{-1} at T33up.

A time series plot of DOC concentration against day (Figure 85a) and boxplot of upstream and downstream values (Figure 85b) show that DOC concentrations upstream of T33 were consistently lower than those downstream. The difference in DOC concentrations was explored statistically using the Mann-Whitney test and found to be significant at the 95 % confidence level (W=1171.0, p= 0.0008).

Table 28. Descriptive statistics for water chemistry parameters measured downstream (Down) and upstream (Up) of the installation of Turbine base T33

Variable	*Position*	*Mean*	*SE Mean*	*Minimum*	*Median*	*Maximum*
Suspended Sediment (mg l^{-1})	Down	13.14	2.07	0.71	6.87	140.41
	Up	1.80	0.54	0.00	0.43	27.00
Absorbance 400nm (ATU m^{-1})	Down	12.70	0.29	7.88	12.18	21.93
	Up	10.67	0.16	5.65	10.43	15.15
DOC(mg l^{-1})	Down	16.50	0.39	9.77	15.84	27.94
	Up	13.87	0.25	9.62	13.12	21.84

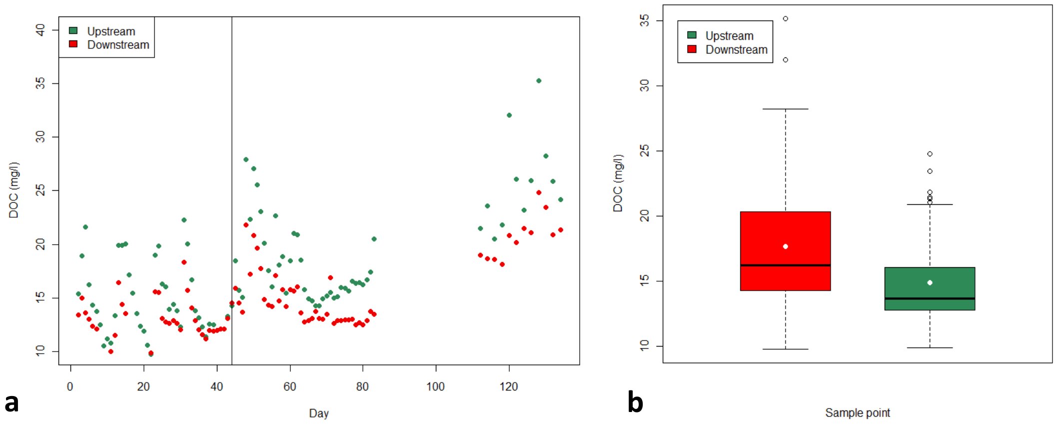


Figure 85. (a) Time series of DOC concentration against day (Day 1 = February 2nd 2010) upstream and downstream of turbine base installation T33. The vertical line indicates the date at which work on T33 was completed according to SPR records. (b) Range of DOC concentrations upstream and downstream of turbine base installation T33. White dot represents mean values

It is not possible to draw substantive conclusions as to the reasons behind these findings as they may be due to inherent differences in the catchment characteristics at each point or the wind farm activities taking place generating disturbances to the land draining into the downstream sample point. The vertical line at day 44 on Figure 85a indicates where excavation work at T33 was completed in March 2010, and it seems that the difference in DOC concentration between the upstream and downstream sample points increases with time. This can be seen more clearly in Figure 86 which plots the difference in DOC concentration between the “T33 up” and “T33 down” and has a regression line fitted. However if the period before and after day 44 are compared statistically, there is no significant difference at the 95 % confidence level in the DOC concentrations between these sets of points. Again the incremental nature of the wind farm construction work, and thus the disturbance, makes the identification of impact difficult over such a small timescale.

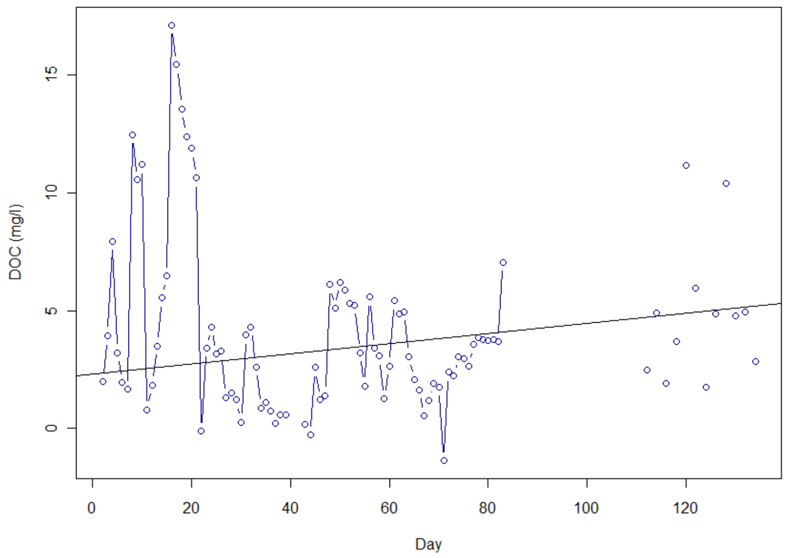


Figure 86. Time series of the difference in DOC concentration between T33 up and T33 down with a regression line fitted (Day 1 = February 2nd 2010

3.5 Particulate Organic Carbon (POC) and suspended sediment (ss)

Another important potential pathway by which carbon travels through aquatic systems is in the form of POC. However, it is frequently overlooked, with many studies estimating riverine carbon flux not including POC in the calculations (Wilson *et al.* 2011). In this section the role of POC will be explored with the intention of testing the hypothesis that **POC as a proportion of ss will be significantly higher where disturbance is from forestry and turbine installation activities. It will be significantly lower where the elevated concentrations of ss are due to road runoff.**

This is because ss associated with road runoff will contain more inorganic C and mineral material from hard core and this will not be lost during ashing at 375˚C. The POC:ss ratio will be used to test this hypothesis.

POC is likely to be an important component of both the overall carbon budget and suspended load of aquatic systems. The total suspended sediment load of a fluvial system is composed of a minerogenic/inorganic fraction and an organic component that includes POC. This association with the suspended load means that POC concentration is often linked with flow. While mean POC concentrations therefore may be low, maxima are often achieved during storm events. For example Dawson *et al.* (2004) found that POC concentrations increased by up to 23 mg L^{-1} during high flows from a sampling mean at all flows of < mg L^{-1}. However, unlike DOC, POC displays little seasonal variation. POC exports are greatest in disturbed landscapes affected by erosion. Within the overall carbon budget, POC losses are very variable but can reach up to 100 g C m^{-2} yr^{-1} in eroding systems (Billett *et al.* 2010). The extent of activities such as heather burning, stock grazing, and construction of hill land tracks in a catchment have also been shown to affect POC exports (Grieve 1994).

Average annual POC fluxes have been shown to be very variable as have their contribution to total carbon flux. Worrall *et al.* (2003) estimated a POC flux of 19.9 g C m^{-2} yr^{-1} for an upland peat catchment in northern England making it the most important release route of carbon in the study. Labadz *et al.* (1991) arrived at a POC flux of 38.82 g C m^{-2} yr^{-1} for a peatland in northern England and Dawson *et al.* (2004) found that average annual POC fluxes from seven sites comprised 10-30% of the total organic C flux. Hope *et al.* (1997) carried out a study to provide an estimate of organic carbon fluxes in British rivers. They estimated POC flux using suspended sediment concentrations assuming a carbon content of 14% in all regions and taking data from routine bi-weekly sampling programmes between 1989 and 1993. In 1993 they estimated that POC exports in individual rivers comprised 12% of the total carbon flux in the regions where they were able to estimate both DOC and POC. Regional differences were also found and they estimated the contribution of POC to the total carbon flux in English rivers to be 28% compared to 4% for Scottish rivers. However, the authors do point out that their flux estimates of both POC and DOC are likely to be underestimates since the routine sampling programmes would not adequately represent storm events where substantial proportions of the annual DOC and POC exports can be accounted for in a matter of a few hours. Indeed they conclude that, based on suspended sediment loads from other detailed studies, compiled by Walling and Webb (1981), the actual POC exports, including storm events, could be an order of magnitude higher than their estimates.

The relationship between annual DOC flux and annual POC flux may be a clear linear one (Tipping *et al.* 2007) or variable (Hope, Billett & Cresser 1994) with the relative importance of POC tending to increase with river size. A DOC:POC ratio below 10 is generally seen in temperate forested watersheds where particulates are retained whereas nearly all organic carbon is exported as DOC in wetland catchments (Hope *et al.* 1997). Average POC fluxes were found to be lower in the main stem of the system than the tributaries and increasing downstream within a single catchment. However the total POC load leaving the river system was lower than the summed POC loads from the five contributing upstream sites, indicating that POC is either lost from the catchment or retained within it. (Dawson et al 2004). In the case of the former POC may be converted to gaseous and dissolved phases during transport (Pawson *et al.* 2008), whereas in the latter it has been noted that a significant proportion of POC is stored in sedimentary deposits (Worrall *et al.* 2003). Indeed Billett *et al.* (2010) draw attention to the significance of POC removal in aquatic systems draining eroding peatlands.

3.5.1 **Estimating POC**

As with DOC the definition of POC is an operational one with POC being the fraction retained on a filter with pore size between 0.45 and 1.0 µm (Dawson *et al.* 2002). POC is often estimated from suspended sediment concentration or flux values. In order to do this two measurements or conversion factors are needed; firstly the proportion of the suspended load that is organic material and secondly the amount of carbon in that organic component. These conversions can be made either by direct measurement or assumption and the values used in the latter vary. In carbon rich soils a figure of around 50% is commonly used as an estimate of the amount of organic matter (Moore *et al.* 2011). Worrall *et al.* (2003) estimated POC from suspended sediment flux values by assuming that most of the suspended load is organic material and that POC content is 50% of the suspended organic load. However, many other values have been found for the organic portion of suspended sediment ranging from 95% by Francis and Taylor (1989) down to 1 % by Carling (Carling 1983).

Loss on ignition (LOI) is a quick and inexpensive method of estimating organic matter content. However, it does carry with it the potential for significant measurement error. If the furnace temperature is too high carbon dioxide can be driven off from carbonates and dehydroxylation of clay minerals can take place (Pribyl 2010).The determination of POC by means of loss on ignition also involves invoking a conversion factor to estimate organic carbon content from the original measurements of organic matter.

Most of the values ascribed to the conversion of organic matter to POC relate to estimations of soil rather than fluvial organic matter. As discussed above it is commonly assumed that soil organic matter is 58 % carbon, producing a factor of

1.724 for converting soil organic carbon measurements into estimates of soil organic matter. Developed in the 19th century this became known as the van Bemmelen factor and has been widely used ever since (Pribyl 2010). In a review of this conversion factor Pribyl (2010) unearthed the origins of the 1.724 figure, explored more recent empirical data and concluded that 1.724 was too low ie the value of 58 % for the proportion of organic matter in soil that is carbon is too high. He also argued more widely that any single figure, while convenient, is bound to be inaccurate and that direct determination is the only satisfactory way of obtaining reliable values. Cresser *et al.* (2007) investigated the best way to take into account information on soil parent material, soil layer position in the soil profile and type of soil horizon when predicting organic carbon % from LOI. They found significant differences in the relationship between organic C % and LOI with both parent material and soil layer position.

Ball (1964) also examined the relationship between LOI (at 850°C and 375°C) and organic carbon content of soils and found good correlations at both temperatures. However, there was greater accuracy found using the 375°C ignition temperature for 16 hours because this avoided the loss of structural water from clay minerals. The regression equation derived for non-calcareous soils at this temperature has been used widely ever since to estimate POC (Dawson *et al.* 2002; Robroek, Smart & Holden 2010).

$Y=0.458x - 0.4$ (equation 5)

(Where y = organic carbon and x = LOI)

Therefore whilst LOI is the commonest method for estimating organic matter content, the lack of a standard method for determining POC or converting organic matter values into organic carbon estimates is potentially problematic. This is reflected in the degree variation found between studies of the furnace temperature and ignition times used, for example 850 °C (Grieve & Marsden 2001), 550°C for 1 hour (Carling 1983) and 24 hours at 40°C (Moore *et al.* 2011).

3.5.2 **Sample selection**

A sub-set of 117 samples was selected for POC determination based on their suspended sediment concentration with a nominal *de minimis* value set at 10 mg L^{-1}. This value was chosen on the basis that it would remove samples where no visible suspended sediment was present and thus where concentrations of POC would be low. The data set included samples from all spatial scales: catchment sample points, T33 upstream and downstream and spatial surveys.

To determine POC concentrations, the filters used for suspended sediment analysis, having already been dried at 105°C, were ashed at 375°C for 16 hours and re-weighed. This loss on ignition was expressed as a percentage of the weight lost after air-drying and used to estimate the POC content of the sample, using equation 5.

It has to be recognised that a potentially significant limitation to this experiment is the failure to account for and isolate forestry activities. These have the potential to cause disturbance and generate the release of high concentrations of suspended sediment and, by association, POC (Stott & Mount 2004). Unfortunately records kept on site were not of sufficient detail to allow a spatial distribution of daily forest harvesting to be established. It has to be accepted therefore that forestry activities are superimposed over this data set and have the potential to influence the POC and suspended sediment concentration values presented here.

Samples were coded according to whether the water quality could be influenced by road runoff only or a combination of road runoff and turbine installation activity. Some of the samples were from undisturbed sites as controls.

3.5.3 **Results**

Descriptive statistics for the POC, DOC and SS concentrations of the pooled data are given in Table 29. The maximum suspended sediment concentration was 427.3 mg L^{-1}, a very high value and one obtained from sample point 3 of spatial survey 2 (11 January 2009). The weather on this day was wet and windy and there was work on the surface water drainage system being carried out around sample points 2 and 3. This was causing a lot of sediment to be disturbed, much of which was overwhelming the fledgling SUDS systems that were not yet fully operational. Four of the samples were not analysed for DOC due to instrument failure. DOC concentrations ranged from 2.38 mg L^{-1} to 74.39 mg L^{-1}. The latter was from sample point 21 on spatial survey 7 (24/05/10). This is not a time of year normally associated with elevated DOC concentrations but it did coincide with high levels of potentially disturbing construction activity on site. POC concentrations showed a large range, varying from 0.98 mg L^{-1} to 138.02 mg L^{-1}. In this case the maximum value was obtained from the same sample that returned the highest suspended sediment concentration. One explanation for this unusually high result is that the surface water drainage works mentioned above, taking place in the area of sample points 2 and 3 created some disturbance to the peat which caused organic matter to enter the surface water system along with the usual road runoff.

Table 29. Descriptive statistics for POC concentrations of pooled data from Arecleoch

Variable	*N*	*Mean*	*SE Mean*	*Minimum*	*Median*	*Maximum*
POC (mg L^{-1})	117	9.12	1.23	0.98	6.49	138.02
DOC (mg L^{-1}l)	113	31.08	1.43	2.38	28.65	74.39
SS (mg L^{-1})	117	37.7	4.6	10.0	23.3	427.3

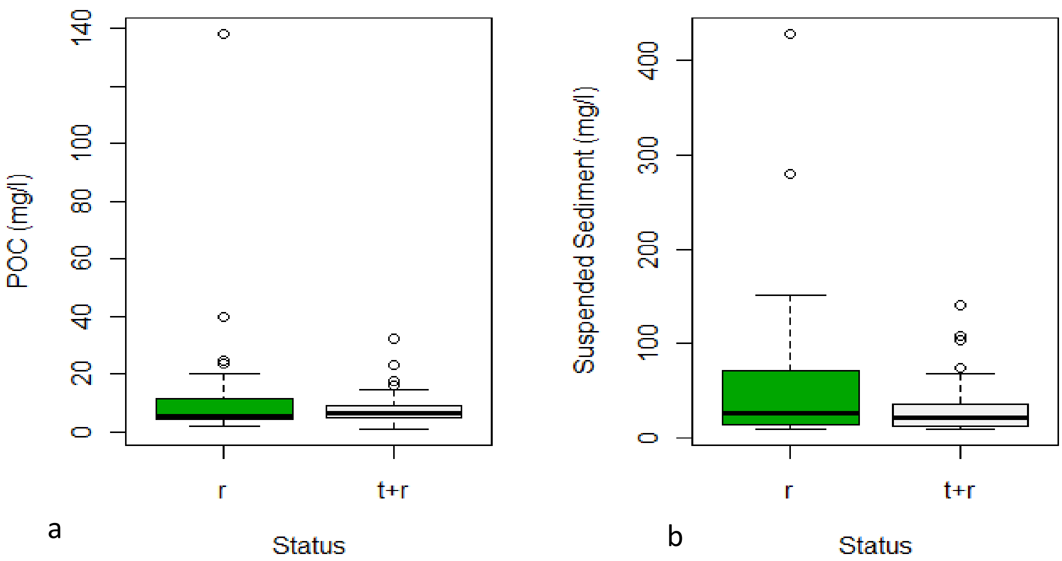


Figure 87. POC (a) and suspended sediment (b) concentrations of pooled data for Arecleoch samples points exposed to disturbance from road building only (r) and turbine installation and road building (t+r)

Samples were divided in the same way as described above and results are shown in Figure 87a and b. POC concentrations for the roads only group were heavily influenced by the outlier at 138.02 mg L^{-1} which, as discussed above also had the highest SS concentration (427.3 mg L^{-1}). The other outlier in the roads only SS concentration data set (280 mg L^{-1}) was from a sample that had a POC concentration of 39.6 mg L^{-1} (spatial sample point 3, 1st May 2009). POC:SS ratios were calculated and although there is considerable overlap between the two groups, the POC:SS ratio is lower for water samples where only road activity can affect water quality Figure 88 and Table 30. Although there were almost three times as many samples in the turbines and roads group as the roads only group, the variability within each group is similar. From these results we can observe that POC makes up less of the total SS concentration and this difference was found to be significant the 95% confidence level (W=1329.5, p =0.0281) using the Mann-Whitney non-parametric statistical test.

Table 30. Descriptive Statistics for POC:SS ratios of pooled data for Arecleoch samples points exposed to disturbance from road building only and both turbine installation and road building

Variable	*N*	*Mean*	*SE Mean*	*St Dev*	*Min*	*Med*	*Max*
Turbines + road	85	0.328	0.02	0.16	0.009	0.332	0.654
Roads only	29	0.256	0.02	0.13	0.032	0.294	0.561

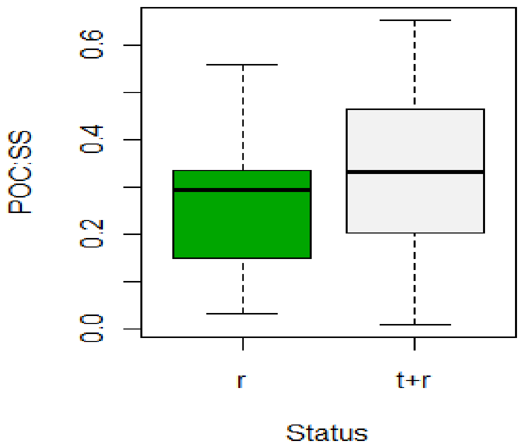


Figure 88. POC:SS ratios of pooled data for Arecleoch samples points exposed to disturbance from road building only and both turbine installation and road building

The spatial survey samples were then isolated and the data analysed separately. These samples were collected from headwater streams within the wind farm development site and are more intimately connected to any disturbance happening to the peat on site (see above 3.3 for sample point descriptions). It would be expected that these samples would be more sensitive to any local disturbance than the samples collected from the catchment outlets. Once again the samples with the potential to be affected by both road and turbine disturbance have a greater proportion of the SS concentration comprising POC (Figure 89). This difference has increased compared to using the whole data set and is now statistically significant at the 99 % confidence level (W = 183.0, p = 00062).

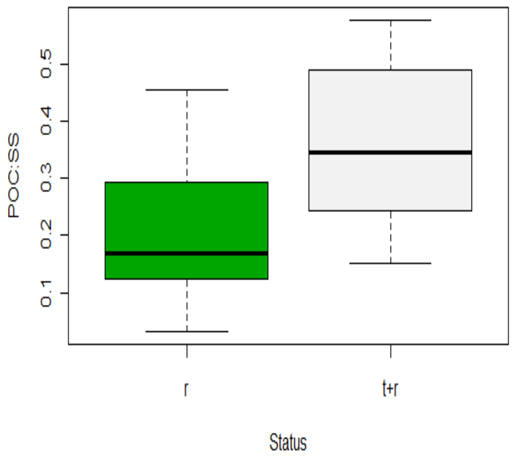


Figure 89. POC:SS ratios for spatial survey samples at Arecleoch

3.6 Discussion

This theme has focussed on human interactions with the landscape of Arecleoch and in doing so has touched upon several features from themes 1 and 2 and common to many studies involving DOC. The development of a 60 turbine wind farm on Arecleoch forest has provided an opportunity to integrate the intrinsic properties of DOC and its seasonal cycle with an external pressure in the form of land use change and to find ways of disentangling these elements.

3.6.1 **Quantifying disturbance using activity scores**

The relationship between DOC concentrations at the catchment scale and the development activities taking place at Arecleoch was explored through the novel approach of an “Activity Score” system. It is an elementary measure of work intensity that illustrates the progress of different elements of the construction process through time and across the site. Activity scores show temporally the progress of work across a site and can be used to inform the interpretation of data such as that relating to DOC concentrations. For example at the outset of the project the Crosswater of Luce was identified as the main test catchment due to its housing half of the turbines. At this stage an assumption was made that direct comparisons could be made with the control Crosswater catchment but it soon became apparent that this was a simplistic and inaccurate representation of the construction process. Figure 54 illustrates the sequential nature of the development and this sequence of events was replicated five times (the wind farm is arranged in five arrays) with each successive start point overlapping another. At Arecleoch the start point was forest harvesting to make space for roads, turbines and other infrastructure. Forest harvesting moved approximately from north to south as did the turbine base excavations. Thus, from the activity scores we can see that work in the Crosswater of Luce catchment did not really get underway until mid-2009, some eight months after the official start date of the development. This means that the first eight months of data from the Crosswater of Luce do not truly represent conditions under disturbance. The activity scoring system can greatly aid our understanding of the subtleties of work across a complex development such as a wind farm construction site.

3.6.2 **Spatial variability within a catchment**

The eight spatial surveys conducted in the heart of Arecleoch during the construction of SPR's wind farm were intended to extract information relating to DOC concentration at the sub-catchment scale. In this way some of the catchment scale differences that make identification of anthropogenic impacts difficult can be minimised. However it is recognised that even here, in addition to the strong annual DOC cycle, factors such as precipitation, vegetation type, wetland cover and catchment physiography can influence DOC concentrations of small, upland headwaters that appear, superficially, to be very similar (in aspect, climate and altitude) (Aitkenhead, Hope & Billett 1999; Rees 1989). Differences may be to different soil profiles, the ease with which drainage water can pass through organic soils and the contribution of baseflow to streamwater (Rees 1989).

At Arecleoch, the 22 spatial survey sample points varied in area from 0.08 km^2 (sp16) to 6.5 km^2 (sp 25). All were located on peat but of differing thickness. Vegetation type varied from degraded blanket bog to commercial forest and drainage had been altered in many areas, primarily for the purposes of commercial forestry. Thus even at this local scale, the sub-catchments possessed a number of properties that could influence DOC concentrations aside from the land use change superimposed over the entire area. The mean DOC concentration for the whole data set was 37.73 mg L^{-1}. This was higher than the mean values from the catchment sample points over the research period (Crosswater = 28.41 mg L^{-1}, Crosswater of Luce = 21.70 mg L^{-1} and Tig = 35.13 mg L^{-1}). Median DOC concentrations were lower at sample points unaffected by the wind farm development but when aggregated, values associated with no disturbance were not significantly different from DOC concentrations potentially affected by wind farm activities. However, when the data were further divided a significant difference was revealed between those samples potentially disturbed by both road building and turbine base installation and the undisturbed samples. This contrasted with no significant difference in median DOC concentrations between undisturbed samples and those potentially suffering disturbance from roads alone. The inference could be drawn therefore that disturbance resulting from turbine base installation added significantly to median DOC concentrations, but the absence of a forestry category in the data imposes a caveat on the strength of this association. Across the eight spatial surveys over a two year period maximum DOC concentrations increased more than mean or minimum values. This phenomenon was explored further taking the group of samples within the Tig catchment where the highest DOC concentrations were found. The eight surveys were treated as two sets for each season and comparisons made between year one and year two for each. Values of DOC at each sample point could then be compared and in some cases increases from year one to year two could be matched to activity on the wind farm site. However, for the largest increases found between surveys 4 and 8, carried out in August 2009 and 2010 respectively these changes could not be attributed to a single source.

Variability in DOC concentration between surveys was also investigated using the coefficient of variation, a term that allows comparisons of DOC concentration ranges to be made between data sets that have inherent differences such as a seasonal cycle. By calculating the coefficient of variation for DOC concentrations at each survey it became apparent that there were step changes between surveys 4 and 5 and between surveys 6 and 7. While the increase in variability between surveys 4 and 5 could be matched to specific wind farm activities this as not the case for the step change seen between surveys 6 and 7.

3.6.3 **Turbine 33 experiment**

The excavation for and installation of turbine base T33 was investigated through intensive sampling upstream and downstream of the construction activity. DOC concentrations were significantly higher downstream but this could not be attributed to the construction activities as the differences existed throughout the monitoring period and data could not be matched to forestry harvesting. Although the difference in DOC concentration between upstream and downstream samples increased with time, comparisons of values before and after commencement of construction work did not yield statistically significant differences.

Thus the data from the activity scores, spatial surveys and T33 experiment support the hypothesis that **DOC concentrations at the sub-catchment scale will be higher in areas of and at time of greater wind farm development activity**, but the associations are too tentative to be assigned a causal relationship.

3.6.4 **POC and its potential as an indicator of the type of disturbance**

The group of values from sample points downstream of areas potentially being disturbed by both road and turbine activity had a greater proportion of POC in the total SS concentration than those samples downstream of only roads. Using POC concentration as a proportion of total SS concentration therefore does bring about a distinction between the two levels of activity.

The results could indicate that in the case of the roads only samples, the suspended load comprises a greater proportion of inorganic matter that would be indicative of surface runoff from road or other areas of hardstanding. Conversely it could mean that the difference was due to elevated POC concentrations in samples from streams draining areas receiving inputs from turbine activity as well as roads, due to disturbance to the peat. From the spatial survey data presented here representing a small sample set, it appears that the difference was due to disproportionately high SS concentrations in some of the roads only samples. A confounding factor implicit across the entire data set is of course the forestry effect. There are no records available with sufficient spatial resolution to make it possible to disentangle the felling and tree clearance work from the road and turbine activity. It is likely that forest harvesting would have an effect on both POC and SS concentrations in water courses downstream of these operations and thus could alter the POC:SS ratio in either direction.

It would be an interesting exercise to build a larger data set, distinct groupings of disturbance and some undisturbed sites to act as a control. In this way it could be possible to establish a typical range of POC:SS ratios that could be used as proxy measures for organic and inorganic disturbance requiring simple and inexpensive analytical techniques.

Finally the evidence presented supports the hypothesis that **POC as a proportion of ss is significantly higher where disturbance is from forestry and turbine installation activities.** It has also been shown that **POC as a proportion of ss is significantly lower where the elevated concentrations of ss are due to road runoff**.

Theme 4. Measures of DOC quality as indicators of peatland disturbance

4.1 Introduction

Theme 4 turns to the composition of DOC being exported from the peatlands of Arecleoch, exploring DOC quality across a range of spatial scales and using a variety of methods. As well as attempting to quantify DOC loss from Arecleoch over the course of the wind farm development, this research project also investigates whether the basic composition of DOC was different according to the level of disturbance experienced by the land and thus whether the composition of DOC could be used as a proxy for disturbance.

The specific aims of theme 4 are to:

- Use a variety of metrics for assessing DOC quality based on UV absorbance and DOC concentrations;
- Assess the potential of these metrics for discriminating between differing levels of disturbance at Arecleoch using a subset of samples covering a range of spatial scales.

This theme will test the hypothesis that: **Streamwater draining areas subject to disturbance will contain DOC that has a higher degree of humification than DOC in streamwater draining undisturbed areas.**

The smallest scale under investigation was that of soil water and for this an experiment was set up to compare DOC composition on an area where peat was stored with that in soil pore water from a nearby area subjected only to forest harvesting. In addition to these data, a subset of samples from the catchment sample points, spatial surveys and turbine 33 experiment were selected for DOC quality analysis. The selection process for each is described below (4.6).

As described in Theme 1 DOC comprises a complex mixture of molecules that vary in size and structure. Residing at one end of the scale are simple sugars and acids while at the other are large, humic, mainly aromatic structures (Bourbonniere 2009). The composition of DOC is significant both ecologically and economically. In the case of the former this relates to carbon cycling and the biodegradability of organic matter, whereas the latter refers to the association between DOC composition and water colour and the associated treatment costs incurred by Water Companies to remove the colour (Dawson *et al.* 2009).

While most work on DOC has focused on measuring concentrations and fluxes, there is a body of evidence that demonstrates differences in DOC composition that may be related to external pressures such as a consequence of the long term recovery of surface waters from acid deposition (Saari *et al.* 2009; Wallage & Holden 2010; Worrall & Burt 2010). Elsewhere DOC quality changes found 20 years on from rewetting a drained peatland suggest lower concentrations of aromatic substances that are hardly degraded and a greater contribution from smaller, readily biodegradable organic molecules (Holl *et al.* 2009). In this case it was thought that it may be due to anaerobic conditions being unsuitable for decomposition. Conversely it might be expected that disturbances to a peatland that lower the water table or expose previously waterlogged organic matter to aerobic conditions will lead to a greater proportion of aromatic molecules and higher DOC concentrations. If it were possible to demonstrate this then an index of disturbance, based on the properties of DOC, could be developed.

Characterising DOC can be undertaken in many ways and there is no standardised protocol agreed across the science community at present. One method of classifying DOC takes the humic substances, which are coloured, amorphous compounds and divides them into a humic acid and a fulvic acid component. Humic acids are dark brown in colour and insoluble at pH2 whereas fulvic acids are lighter brown, remain soluble at pH2 and have lower molecular weights (Bourbonniere 1989; Wallage, Holden & McDonald 2006) (Figure 90). The non-humic fraction of DOC is not coloured and comprises relatively simple compounds of low molecular weight, such as carbohydrates, proteins, amino acids, peptides, fats and waxes (Wallage, Holden & McDonald 2006).

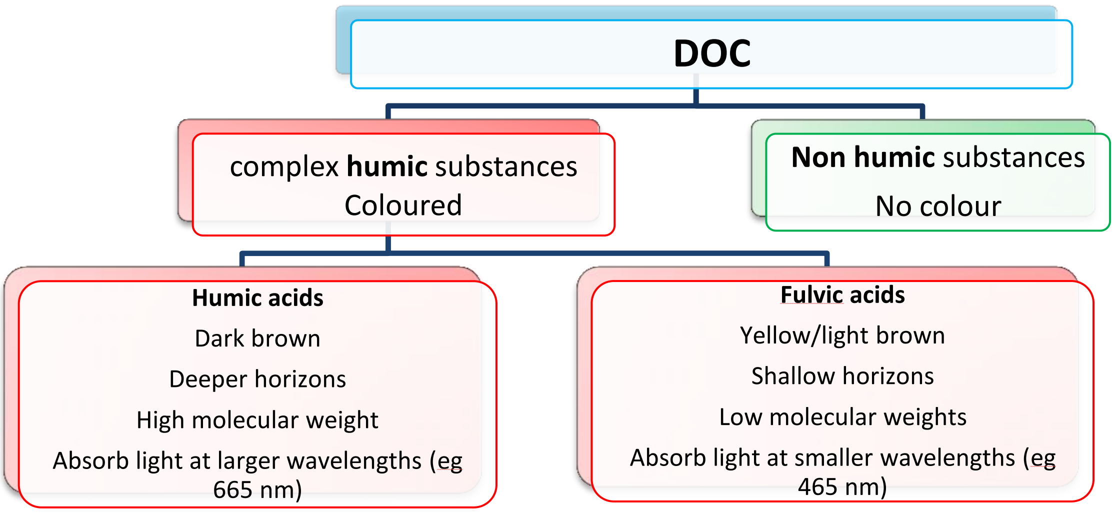


Figure 90. Characterising DOC by dividing into humic and non-humic fractions and further division of the humic fraction into fulvic and humic acids (derived from Bourbonniere (2009)**).**

Another way of characterising DOC is by dividing it into hydrophobic and hydrophilic fractions according to whether it sorbs to XAD-8 resin (Dilling & Kaiser 2002). This is an important distinction both in terms of understanding the way that DOC interacts in the environment and in a practical, applied sense for the range of analytical methods that become available to look for changes in the composition of DOC. The hydrophobic fraction often contains most of the aromatic moieties in the form of acidic products arising from the oxidative degradation of lignin, and it is low in organically bound nutrients such as N, P and S (Dilling & Kaiser 2002). These aromatic elements are stable, unlike the carbohydrates, which are the main substrates for microorganisms (Kalbitz *et al.* 2003). The hydrophobic elements are also responsible for the colouration of water and associated with higher ultraviolet (UV) absorbance allowing this metric to be used to infer changes in DOC quality (Weishaar *et al.* 2003). DOM characteristics that generally enhance its biodegradability are high contents of carbohydrates, organic acids and proteins for which the hydrophilic neutral fraction seems to be a good estimate. In contrast, aromatic and hydrophobic structures that can also be assessed by UV absorbance decrease DOM biodegradability, either due to their recalcitrance or due to inhibiting effects on enzyme activity. (Marschner & Kalbitz 2003). UV absorbance has been used for this purpose at a variety of wavelengths (Table 31).

Absorbance at 260 nm was found to be significantly higher for hydrophobic fractions of soil pore water than hydrophilic fractions (Dilling & Kaiser 2002) and absorbance at 272 nm was shown to be a good predictor of the percentage of aromatic carbon (Traina, Novak & Smeck 1990). Baker *et al.* (2008) investigated the spectrophotometric properties of DOC at a sub-catchment scale and found that its components were more aromatic and had a larger molecular size in a peat sub-catchment than in a peaty-gley sub-catchment. The potential of UV spectrophotometry as a selective absorber of hydrophobic DOM and its concomitant use as a relative measure of aromaticity is very attractive. UV spectrophotometry requires very little sample preparation, needs only a small amount of sample and is faster and cheaper than fractionation with XAD-8. One possible drawback however is that it requires samples to be low in other UV-absorbing compounds such as NO_3 (<25 mg L^{-1}) and Fe (< 5 mg L^{-1}) (Dilling & Kaiser 2002; Jaffrain *et al.* 2007).

Table 31. Some commonly used wavelengths for characterising DOM giving the specific property being investigated. (adapted from Jaffrain *et al.* (2007))

Wavelength	*Property*	*Reference*
250	Aromaticity, apparent molecular weight	(Peuravuori & Pihlaja 1997)
254	Aromaticity	(Haitzer *et al.* 1999), (Armstrong *et al.* 2010)
260	Hydrophobic carbon content	(Dilling & Kaiser 2002)
265	Relative abundance of functional groups	(Chen *et al.* 2002)
272	Aromaticity	(Traina, Novak & Smeck 1990)
280	Hydrophobic carbon content, humification index, apparent molecular size	(Chin, Aiken & Oloughlin 1994; Kalbitz *et al.* 2003)
285	Humification index	(Kalbitz *et al.* 2000)
300	Characterisation of humic substances	(Artinger *et al.* 2000)
340	Colour	(Scott *et al.* 2001)
365	Aromaticity, apparent molecular weight	(Peuravuori & Pihlaja 1997)
400	Humic substances characterisation	(Armstrong *et al.* 2010)
436	Quality indicator	(Haitzer *et al.* 1999)
465	Relative abundance of functional groups	(Chen *et al.* 2002)

The use of single wavelength spectrophotometric analysis to infer DOC concentrations in pore water of blanket peat was investigated by (Wallage & Holden 2010). They concluded that water colour was not a reliable proxy for DOC concentration for the following reasons; there was a low level of accuracy, especially at low concentrations and the colour-carbon relationship changed according to land use and season. Therefore under these conditions a single regression relationship for pooled data sets could not be applied without the risk of an error in DOC concentration values of up to 50 %. This they pointed out throws doubt on some studies using long term water colour records to infer DOC concentrations. However it is the intention here to investigate whether this “spanner in the works” could provide a useful tool for detecting disturbance in peatlands by the very fact of a changing relationship between DOC and colour.

The extent of the natural variability of DOC composition in surface waters was further demonstrated by (Strack *et al.* 2011) in a set of experiments on a cutover and restored peatland in Canada. They found that the while there was no significant difference in DOC quality between the cutover and restored sites, DOC composition did change during hydrological events and seasonally.

4.2 SUVA

Specific UV absorbance (SUVA) is the UV absorbance of a water sample at a given wavelength normalised for DOC (Weishaar *et al.* 2003) and it has been widely used to study the composition of DOC (Table 32). Weishaar *et al.* (2003) found SUVA at 254 nm ($SUVA_{254}$) to be strongly correlated with percentage aromaticity and suggested that it could be a good indicator of DOC concentration. A higher absorbance per unit of DOC suggests a greater degree of humification and by extension could infer an element of disturbance or presence of older DOC comprising the more recalcitrant, aromatic fractions.

Table 32. Some commonly used wavelengths for SUVA analysis

SUVA wavelength	*Reference*
250	(Dawson *et al.* 2009)
254	(Jaffrain *et al.* 2007; Kalbitz *et al.* 2003; Preston, Eimers & Watmough 2011; Weishaar *et al.* 2003)
280	(Glatzel *et al.* 2003)

Dawson *et al.* (2009) used $SUVA_{250}$ to investigate changes in DOC quality in two upland acidic streams for which 22 years of water quality data existed. They found a decreasing trend in $SUVA_{250}$ values but with a lot of inter and intra-annual variability. The results indicated a decrease in the hydrophobic fraction, which suggests that DOC is becoming more hydrophilic with time and that there is a greater proportion of total DOC load that is easily degradable (subject to the proviso that aliphatic organic compounds are not stable in their biodegradability). The choice of method here was based on maintaining consistency with earlier studies and to allow for direct comparisons between data sets. The authors suggested that in fact $SUVA_{250}$ was not the ideal metric for representing the DOC-UV relationship. Incidentally, this comment has arisen elsewhere in the literature with Traina *et al.*, (1990) remarking that their use of 272 nm did not provide the best wavelength for isolating aromatic structures. 254 nm was suggested as a better alternative but they wanted to make a comparison with earlier studies that used 272 nm and were confident that this wavelength incorporated the region containing a sufficient number of important aromatic constituents. SUVA 254 is considered to be a good indicator of the humic fraction of DOC and a reliable surrogate for DOC aromaticity (Weishaar *et al.* 2003).

SUVA at 280 nm has been used to investigate soil pore DOC composition at a rewetted fen and values were significantly lower than those at a site that had been partially drained, indicating that lower concentrations of aromatic compounds are barely degraded (Holl *et al.* 2009). $SUVA_{280}$ also varied with depth but a spatial pattern (lowest at 10 cm, highest at 60 cm) was only apparent at the rewetted fen during winter. There was also a seasonal pattern with $SUVA_{280}$ values at their highest in summer and decreasing during winter. DOC concentration and $SUVA_{280}$ showed a significant ($p<0.001$) and inverse non-linear correlation in summer but less pronounced and linear in winter (Holl *et al.* 2009).

4.3 UV absorbance ratios

Ratios of UV absorbance at some of the wavelengths, shown in Table 32 have been used to focus more specifically on certain properties of DOC such as molecular weight and aromaticity. Agren *et al.* (2008) used Abs_{254}/Abs_{365}, which is a measure of molecular weight and encompasses aliphatic and aromatic components. They argued that this was a better measure of the bioavailability of DOC than simply using $SUVA_{250}$. Known as the E4/E6 ratio, it compares the level of absorbance at 465nm to that at 665 nm for each water sample. This allows a measurement of the proportion of fulvic acid to humic acid in the coloured component of DOC and acts as a humification index. Ratios are higher for fulvic acids (8 to 10) and lower for more mature humic acids (2 to 5) (Wallage, Holden & McDonald 2006). The E4/E6 ratio can also be used to determine where in the peat profile the DOC has originated as it has been found to vary spatially, decreasing with depth through a peat core (except for a central portion where it increased (Zaccone, Miano & Shotyk 2007).

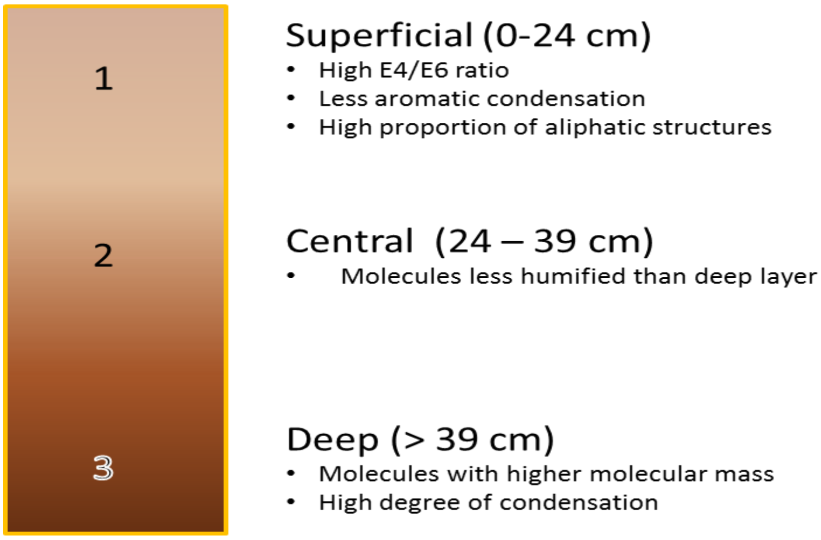


Figure 91. A three-tier model to illustrate the peat profile, showing the pore water DOC composition at each level (Zaccone, Miano & Shotyk 2007)

That study proposed a three tier model of the peat profile presented in Figure 91.

Baker et el. (2008) used E4/E6 as well as 254/365 and 254/410 and found none to correlate with DOC concentration indicating that observed variations had more to do with differences in DOC composition.

4.4 Sample methodology and study area

Peat removed as part of the turbine base excavations was stored on site in a number of areas waiting final repositioning during landscape works. The peat store chosen for this experiment (Figure 92a) was located at the roadside near turbine 52 and forms part of the Tig catchment. The control site (Figure 92b) was approximately 50 m east along the same road, essentially the only difference being the lack of a disturbed peat overlayer.

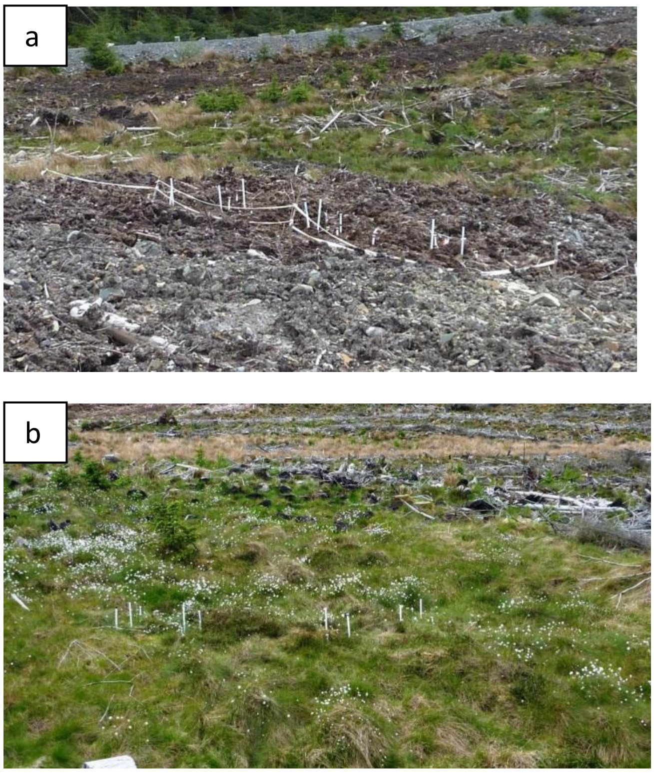


Figure 92. a) Peat store and b) control site at Arecleoch wind farm. Nests of piezometers are visible distributed across the area.

Eight nests of piezometers were set up, four in the peat store and four in the control site. Each nest consisted of individual piezometers inserted into the peat to collect water at depths of 0 cm (surface runoff), 5 cm, 10 cm, 20 cm and 40 cm. These depths were chosen based on previous studies into soil pore water DOC quality where samples were collected down to a depth of 40 cm (Preston, Eimers & Watmough 2011; Wallage & Holden 2010). This represents the acrotelm and was assumed to be the range over which the peat was most susceptible to changes in water table height and because it is the main source of mobilised DOC (Zak & Gelbrecht 2007).

Soil water from the peat store tubes was extracted as passively as possible from each depth using a 50 ml plastic syringe and vinyl tubing. The syringe and tubing were rinsed with distilled water between samples and the samples were transferred to pre-washed, acid rinsed 125 ml plastic bottles.

Samples were collected approximately every four weeks between February and October 2010 but on some occasions not enough water could be collected from all piezometers for analysis. All samples were transported to the laboratory and stored in the dark at 4°C until analysis. Absorbance was measured (as described in 2.1) at 400 nm, 465 nm and 665 nm and the absorbance readings were converted to standard units of AU/m from which the E4/E6 ratios were calculated by dividing the sample UV absorption at 465 nm by that at 665 nm.

4.5 Results from peat store experiment

A total of 153 samples were collected from piezometers at the peat store and control site across ten sample trips and the spatial distribution of the sample set is presented in Table 33

Table 33. Total number of water samples collected from each depth at the peat store and control sites

Depth (cm)	*Number of samples*	
	Peat store	Control
0	21	28
5	22	24
10	6	6
20	13	8
40	13	12

DOC quality and disturbance

Pooled depth data from the peat store and control site respectively were analysed to provide an overview of differences in DOC quality according to the degree of disturbance and explored statistically using the Mann-Whitney test. From Figure 93a it can be seen that that water colour indicated by Abs_{400} was darker at the peat store than the control site and this difference was found to be significant ($W = 7709$, $p = 0.000$). The E4/E6 ratio (Figure 93b) was significantly lower at the peat store (W =

6903, p = 0.000) suggesting a greater degree of humification in soil pore water from the peat store. Material at the peat store was deposited there from turbine base excavations and would have undergone a degree of mixing during this process. The darker colour and greater humification of soil water from the peat store may therefore be representative of a greater proportion of deeper peat material deposited on the surface of the store. Exposure of the peat during excavation, transport and deposition may also allow for an increase in the aerobic decomposition pathways that would process the less recalcitrant material that is lighter in colour.

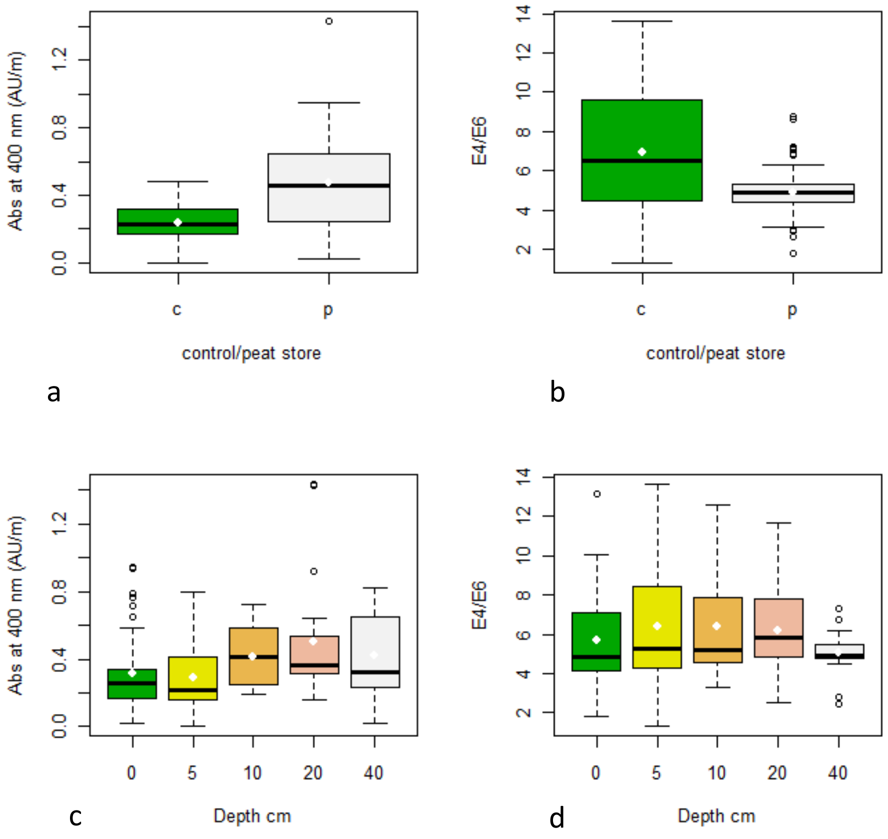


Figure 93. Comparison between pooled data at the peat store and control site for a) absorbance at 400 nm and b) the E4/E6 ratio.

Absorbance at 400 nm (c) and E4/E6 ratios (d) for all data divided according to depth

DOC quality and depth

Data from both sites were then pooled and tabulated according to depth. Differences in E4/E6 ratios were examined statistically using the Kruskal-Wallis test. Water colour as determined by Abs_{400} showed a general darkening with depth (Figure 93c) from the surface although differences in median values were not significant ($H = 2.87$, $p = 0.580$). The mean values, superimposed as white dots on the boxplots demonstrate the way in which one or two outliers as in the case of absorbance (400 nm) at 20 cm (Figure 93c) can increase the overall value. E4/E6 ratios across both sites were quite variable at each depth (Figure 93d) but did not demonstrate a pattern as depth increased. The most notable feature of the data thus presented is the decrease in E4/E6 at 40 cm and the tighter clustering of values around the median value.

DOC quality vs disturbance and depth

The data were further sorted by both depth and treatment to determine whether patterns emerged within each of the two sites through the peat profile. We have already demonstrated that water colour was significantly darker in samples from the peat store than from the control site but that there were no significant differences in colour between the five depths. We can now see how this evidence evolves when viewed at a finer resolution. Taking water colour first there is a general increase in Abs_{400} median values with depth of sample at the peat store but with greater variability at 20 cm (Figure 94a). At the control site this pattern is not observed and indeed samples from 40 cm are less dark than those from 20 cm (Figure 94b). Turning lastly to DOC quality and the E4E6 ratios, we know that values were significantly lower at the peat store but, again, there were no significant differences between median depths in the pooled data set. When the data is separated as described above a clearer picture emerges of differences in DOC quality, as inferred from E4/E6 values, laterally between sites and longitudinally within each site (Figure 94 c and d).

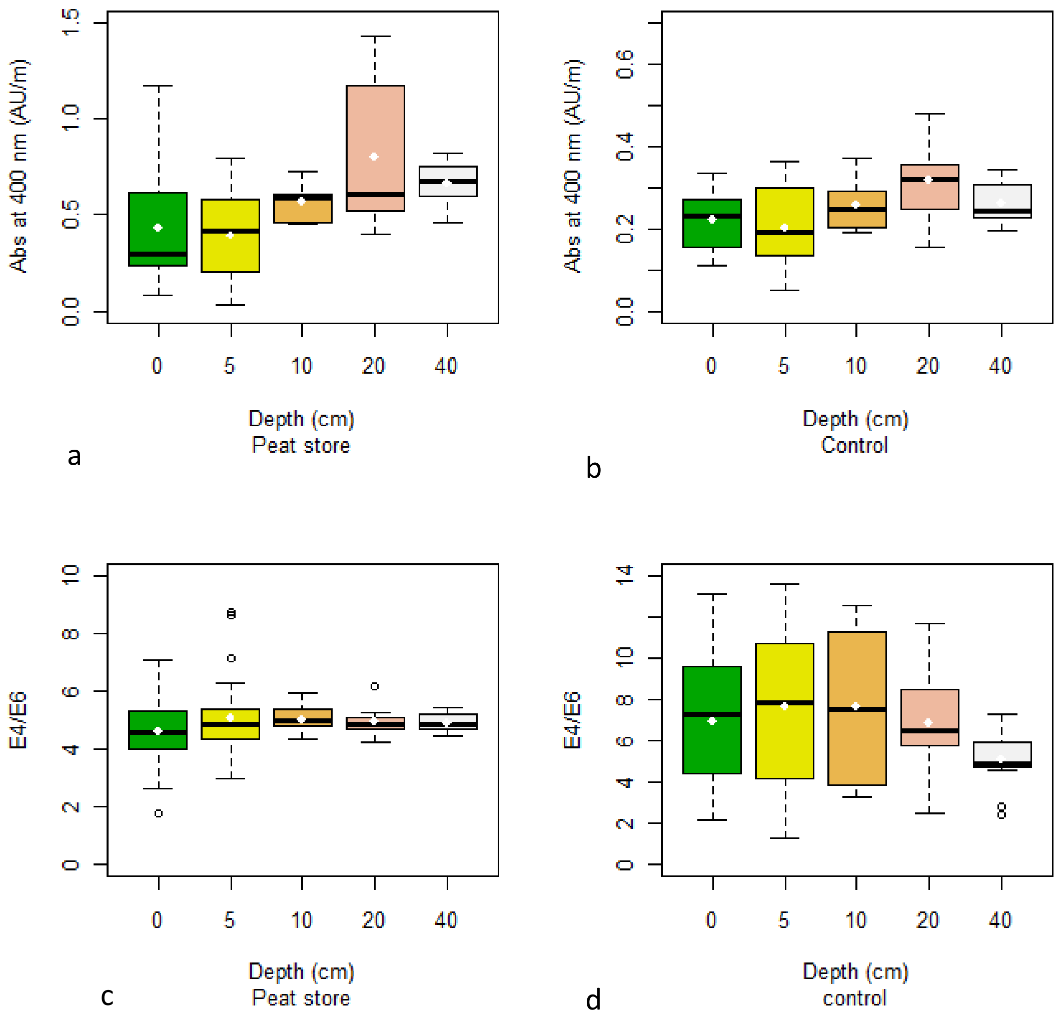


Figure 94. Absorbance at 400 nm for samples collected at different depths from (a) the peat store and (b) he control site.

E4/E6 ratios for samples collected at different depths from (c) the peat store and (d) the control site.

At the control site a large degree of variability is apparent at all depths except 40 cm and this is in sharp contrast to the peat store where values cluster more about the median at each depth. The lower variability in E4/E6 ratios with depth at the peat store may be indicative of the material undergoing mixing during excavation that leaves a largely homogenous mass of peat that has lost its structural integrity and layering. Differences in both absorbance and E4/E6 values are not significant at the 95 % confidence level between depths at either site.

4.6 Other DOC quality data

4.6.1 **E4E6 ratios**

In addition to measurements taken from soil pore water at the peat store and control site, absorbance at 400 nm, 465 nm and 665 nm was also recorded from a selection of water samples at other sample points associated with this research project. The results of these are presented below and help to provide a fuller picture of DOC quality using E4E6 ratios temporally and spatially at Arecleoch.

4.6.1.1 Turbine 33

Across the monitoring period E4/E6 ratios were above 5 for all but three samples (T33 downstream in all cases) (Figure 95). Values were higher upstream of T33 than downstream and it can be seen that this was the case from the start of the experiment suggesting that DOC in water downstream of the turbine location was already dominated by more mature humic acids than that in upstream samples. This corresponds with higher DOC concentrations at the downstream site discussed above (Chapter 4.19.2). Figure 95 also illustrates the difference in variability between the two datasets and if the upstream samples are considered to demonstrate natural levels of variability it is clear that this is exceeded downstream, particularly between days 20 (23/02/10) and 40 (15/03/10).

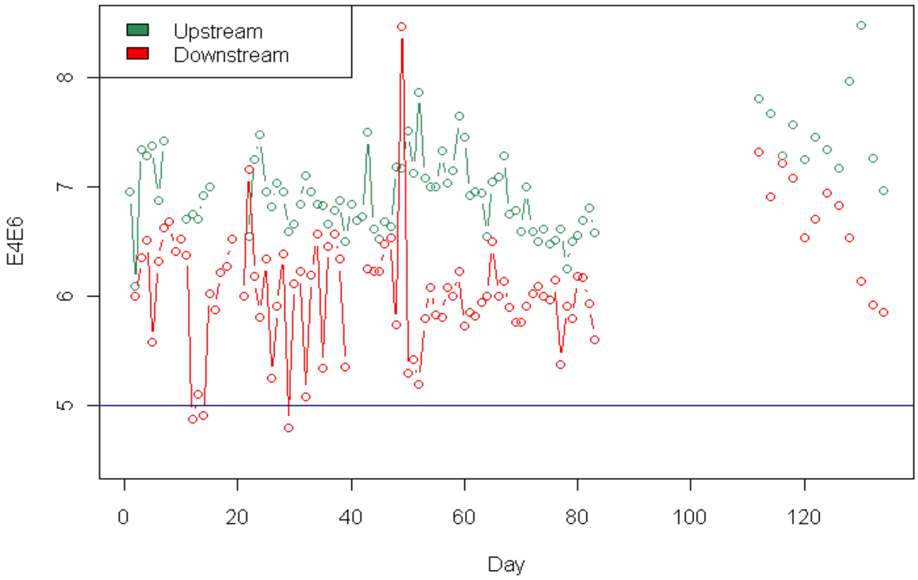


Figure 95. E4/E6 ratios for T33 upstream and T33 downstream samples. samples collected on consecutive days are shown connected by a line. Day 1 = 3rd February 2010. The horizontal line indicates a nominal transition between humic (<5) and fulvic (>5) substances

Within the downstream dataset one value stands out as anomalous with an E4/E6 ratio of 8.465 on day 49 (24/03/10). It was a result of the water sample having a slightly higher E4 value and a lower E6 value on that day. The corresponding DOC concentration was 22.33 mg L^{-1} and the Abs_{400} was 16.525 AU/m both of which fit within their respective time series. It is not thought that this result was erroneous but it does indicate the sensitivity of the measurement. It would be possible to achieve a higher than usual E4/E6 value if, for example surface runoff caused a dilution of the DOC that day. However in such a circumstance it would be expected that this would show up in a reduction in water colour, and hence a lower Abs_{400} reading, and this was not observed.

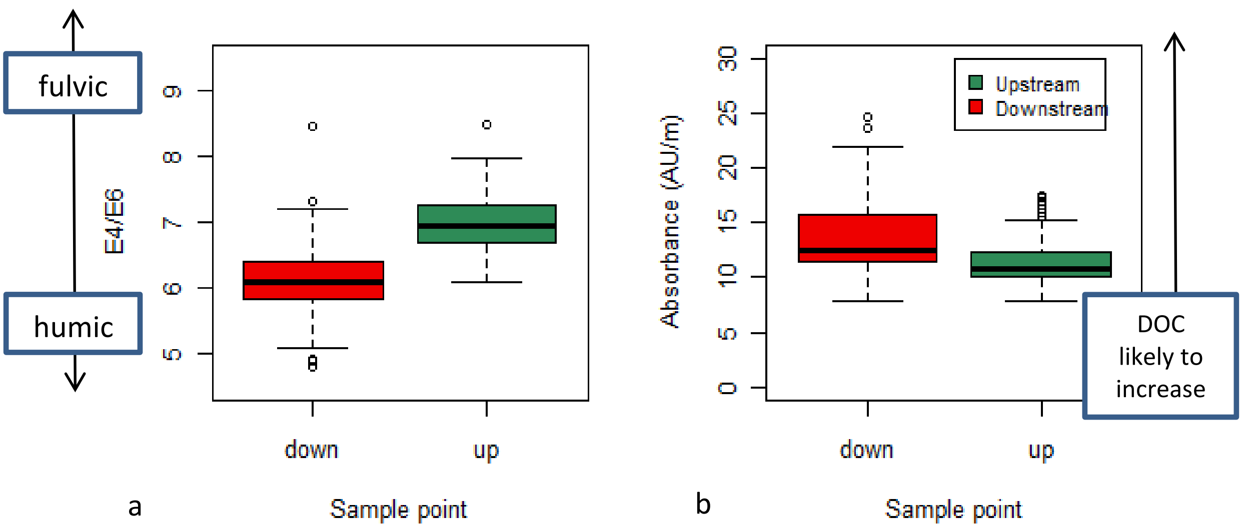


Figure 96. E4/E6 ratios (a) and absorbance at 400 nm for T33 upstream and T33 downstream samples

When the E4/E6 values are grouped as presented in Figure 96a the overall difference between T33 upstream and T33 downstream is apparent and this difference in median values is significant when analysed with the Mann-Whitney test ($W = 766$, $p = 0.00$). Water colour is also significantly darker ($W = 6027$, $p = 0.00$) for the downstream samples as determined by Abs_{400} (Figure 96b).

Associations between carbon quality indicators (Abs_{400} and E4/E6) and DOC concentrations were investigated and found to be strongly positive except for E4/E6 vs DOC (Figure 97). Correlations between DOC concentration and both E4/E6 ratios and water colour were performed using the Spearman's Rank function to test the strength of the associations. All were found to be significant (Critical value > 0.208, for $p < 0.05$) except for the T33 downstream DOC vs E4/E6 association, and with Abs_{400} demonstrating a stronger relationship with DOC than the E4/E6 ratio (Table 34).

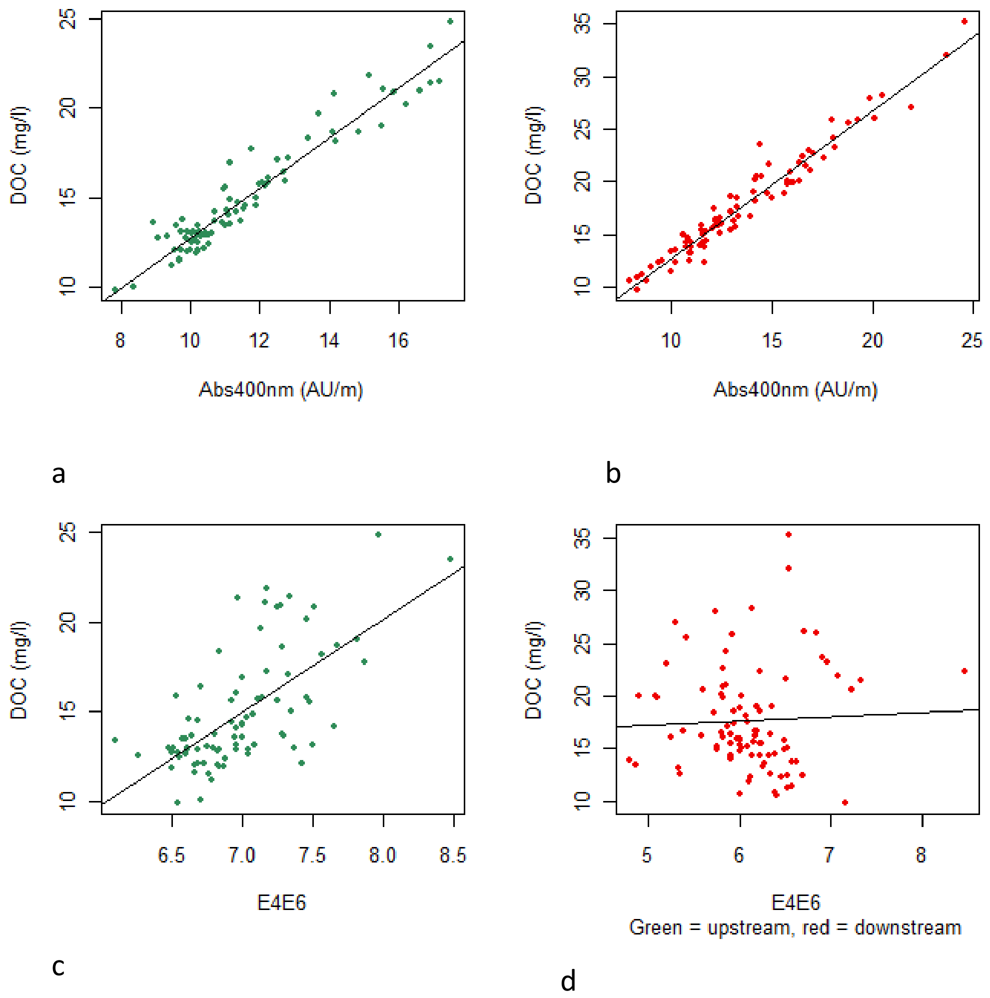


Figure 97. Scatterplots of Absorbance vs DOC concentration for T33 upstream (a) and T33 downstream (b); and E4/E6 ratios vs DOC concentration for T33 upstream (c) and T33 downstream (d). Fitted line for linear regression shown in black.

At T33 upstream positive associations of DOC with the E4E6 ratio and Abs_{400} suggest that as DOC concentrations increase, albeit within a narrow range of values, the nature of the DOC becomes less humified although it is darker in colour. For T33 downstream the association between DOC concentration and the E4/E6 ratio is very weak. Despite the regression line in Figure 97d pointing towards a positive association, the Spearman Rank test suggests a weak negative correlation which is not duplicated when a Pearson correlation test is performed.

Table 34. Correlation coefficients for associations between DOC concentrations [DOC], and E4/E6 ratios and [DOC] vs Absorbance at 400 nm (Abs $_{400}$). Up = T33 upstream, Down = T33 downstream. * denotes significance at the 95 % confidence level for the Spearman Rank test (exceeding critical value of 0.208).

	E4E6 Up	*E4E6 Down*	*Abs_{400} Up*	*Abs_{400} Down*
[DOC] Up	0.638*		0.898*	
[DOC] Down		-0.105		0.966*

This discrepancy is understandable given the spread of the data displayed in Figure 97d from which no clear association between variables is obvious. Most of the E4/E6 ratios are clustered between 5.5 and 6.5 and indicating little change in DOC composition as concentrations increase. Thus DOC at higher concentrations had higher proportions of more humified matter. One reason for this could be that disturbances to the peat in the catchment of T33 downstream have resulted in changes to the peat structure leading to a greater contribution from humic fractions or fewer fulvic components. This could be as a result of these more bioavailable fulvic substances having been processed after being subjected to aerobic conditions.

4.6.1.2 Spatial Survey

Absorbance at 465 nm and 665 nm was measured for all samples collected in the eight spatial surveys and E4E6 ratios calculated. As with DOC concentrations there is a distinction between values from undisturbed sites (15 – 19) and those from disturbed sites (Figure 98) with the undisturbed sites having higher E4/E6 values (Figure 98a) indicating a composition comprising less humified carbon compounds. In general the E4E6 values mirror well DOC concentrations for each sample point. The data were then pooled, firstly according to whether the sample point was considered to be within a sub-catchment subject to disturbance, the results of which are shown in

Figure 99, and secondly at a finer resolution according to the type of disturbance. This mirrors the distinction made earlier in the chapter.

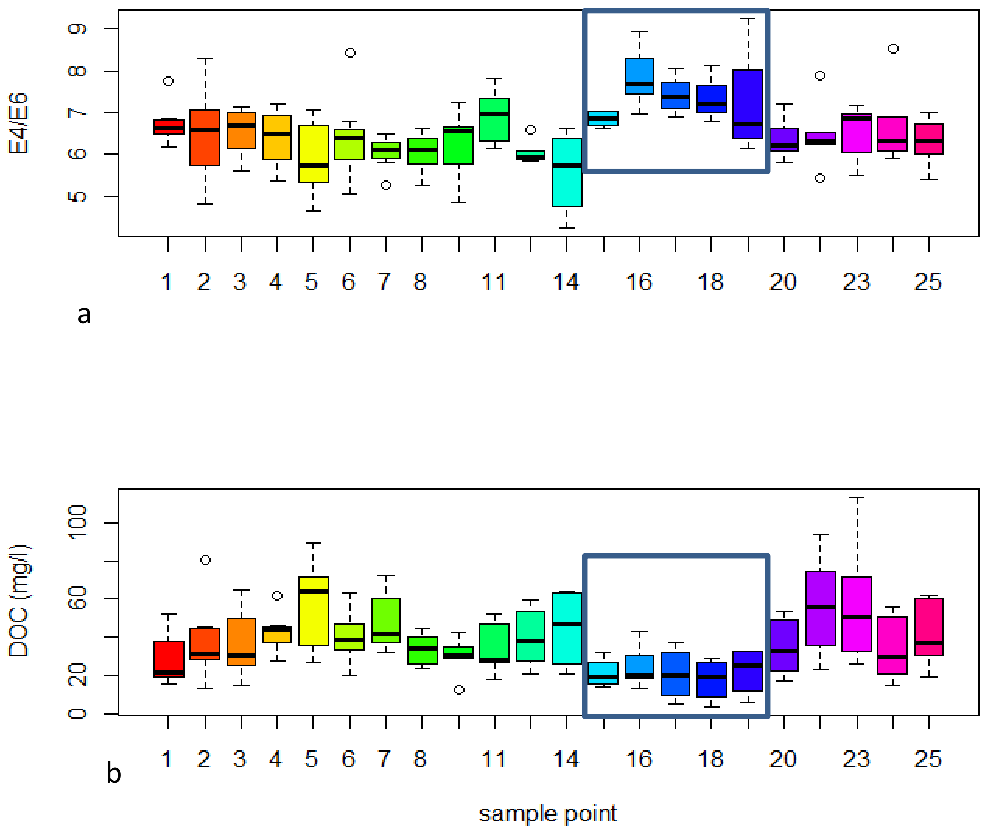


Figure 98. E4/E6 ratios (a) and DOC concentrations (b) for spatial survey samples at Arecleoch. The box in each chart indicates the control sample points 15 - 19

Statistical differences in median values were explored using the Mann-Whitney test and applying a 95 % confidence level. For absorbance at 400 nm there is no significant difference between the disturbed and non-disturbed sample points ($W = 2291$, $p = 0.057$) but differences are significant for DOC and for E4E6 ratios ($W = 2274$, $p = 0.0470$; $W = 3911$, $p = 0.000$ respectively). Thus a distinction can be drawn between DOC quality and quantity according to disturbance but not in terms of water colour.

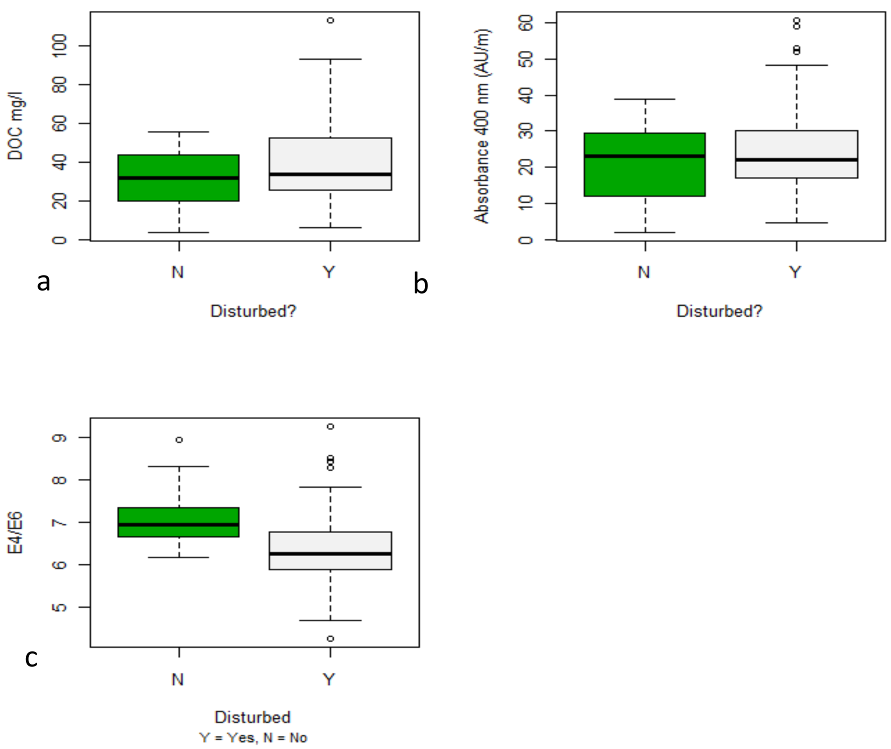


Figure 99. DOC concentrations (a), Absorbance at 400 nm (b) and E4/E6 ratios (c) for spatial survey samples at Arecleoch comparing potentially disturbed (Y) sites with undisturbed (No) sites.

When the data were separated according to the type of disturbance, the categories used were; roads (R), turbines and roads (T+R) and undisturbed (U) (Figure 100). It was not possible to isolate disturbance related solely to turbine activity because of the concurrent road building work that was always present. Here it can be seen that for DOC concentration (Figure 100a) and absorbance (Figure 100b) three of the four outliers observed among the disturbed samples are to be found within the sub-set of T+R. This suggests that turbine base construction may be play a part in the elevated DOC concentrations and darker water colour. When investigated statistically however using the Kruskal-Wallis test , no significant differences were found between the three categoreies (DOC: $H = 4.59$, $p = 0.101$; absorbance: $H = 4.13$, $p = 0.123$). In the case of E4/E6 ratios the picture is different (Figure 100c). As expected the undisturbed site return higher E4/E6 ratios indicating a lower proportion of humified substances and significant differences were found between the three status types (H = 36.52, p = 0.000). post hoc comparison testing confirmed that the significant differences in median E4E6 values lay between undisturbed sites and both roads and turbines and roads (Table 35). There was no significant difference between the sites potentially affected by roads and those potentially affected by turbines and roads. Thus it it not possible here to isolate the type of disturbance causing the lower E4/E6 ratio.

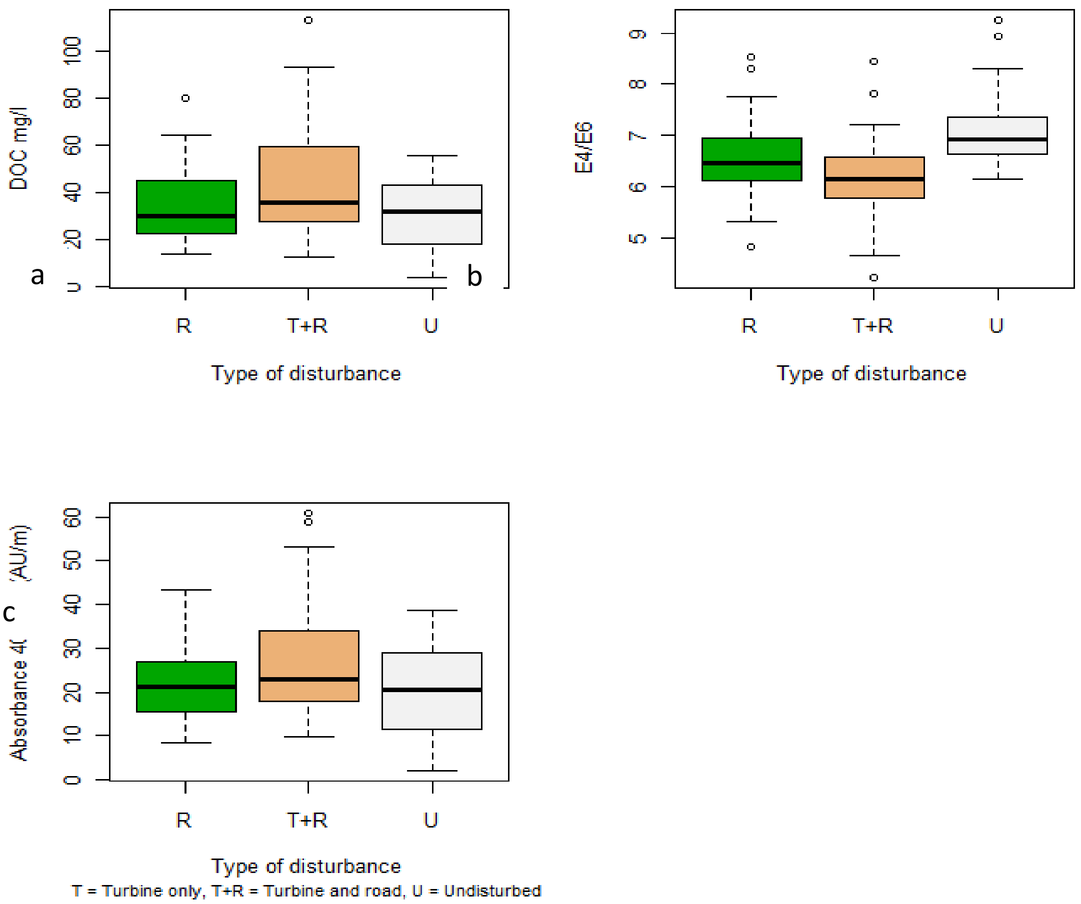


Figure 100. DOC concentrations (a), E4/E6 ratio (b) and Absorbance at 400 nm (c) for spatial survey samples at Arecleoch comparing disturbance associated with roads (R), turbines and roads (T+R) and undisturbed sites (U).

Table 35. Post hoc Comparisons comapring the significance of differences in pairs of E4/E6 values between spatial survey sample points exposed to potential disturbance due to roads (R), turbines and roads (T+R) and undisturbed (U) sites.

Type of disturbance	*Obs dif*	*Critical dif*	*difference*
R vsT+R	19.24464	19.97668	FALSE
R vs U	30.40338	22.26206	TRUE
T+R vs U	49.64803	19.46023	TRUE

4.6.1.3 Catchment sample points

The pattern of DOC concentrations between and within the three catchments over a three year period has been discussed in Theme 1. Here the aim is to focus on a subset of samples for which absorbance at 465 nm and 665 nm was also measured between 25th May and 1st October 2010, still within the development phase of the wind farm and coinciding with the time frame of the soil pore water sampling described above. This amounted to a data set comprising 69 samples each from the Tig and Crosswater of Luce and 65 from the Crosswater but not all are triplicates. A summary of the range of values is presented in Table 36 and Figure 101.

Table 36. Summary statistics for Absorbance at 400 nm, E4/E6 ratios and DOC concentrations at the Crosswater (X), Crosswater of Luce (XL) and Tig sample points

Variable	*site*	*N*	*Mean*	*SE Mean*	*Coef of variation*	*Min*	*Median*
Absorbance at 400nm (AU/m)	Tig	69	33.23	0.88	21.97	20.98	32.80
	X	65	23.33	0.97	33.46	8.78	19.93
	XL	69	22.24	0.74	27.65	10.83	23.63
E4/E6 ratio	Tig	69	6.86	0.06	6.67	6.11	6.76
	X	65	6.79	0.06	7.37	5.92	6.70
	XL	69	7.07	0.08	9.15	6.32	6.85
DOC (mg L^{-1})	Tig	69	46.53	1.18	21.08	28.20	47.34
	X	65	37.15	1.12	24.26	21.87	41.33
	XL	69	32.47	1.08	27.51	15.40	34.24

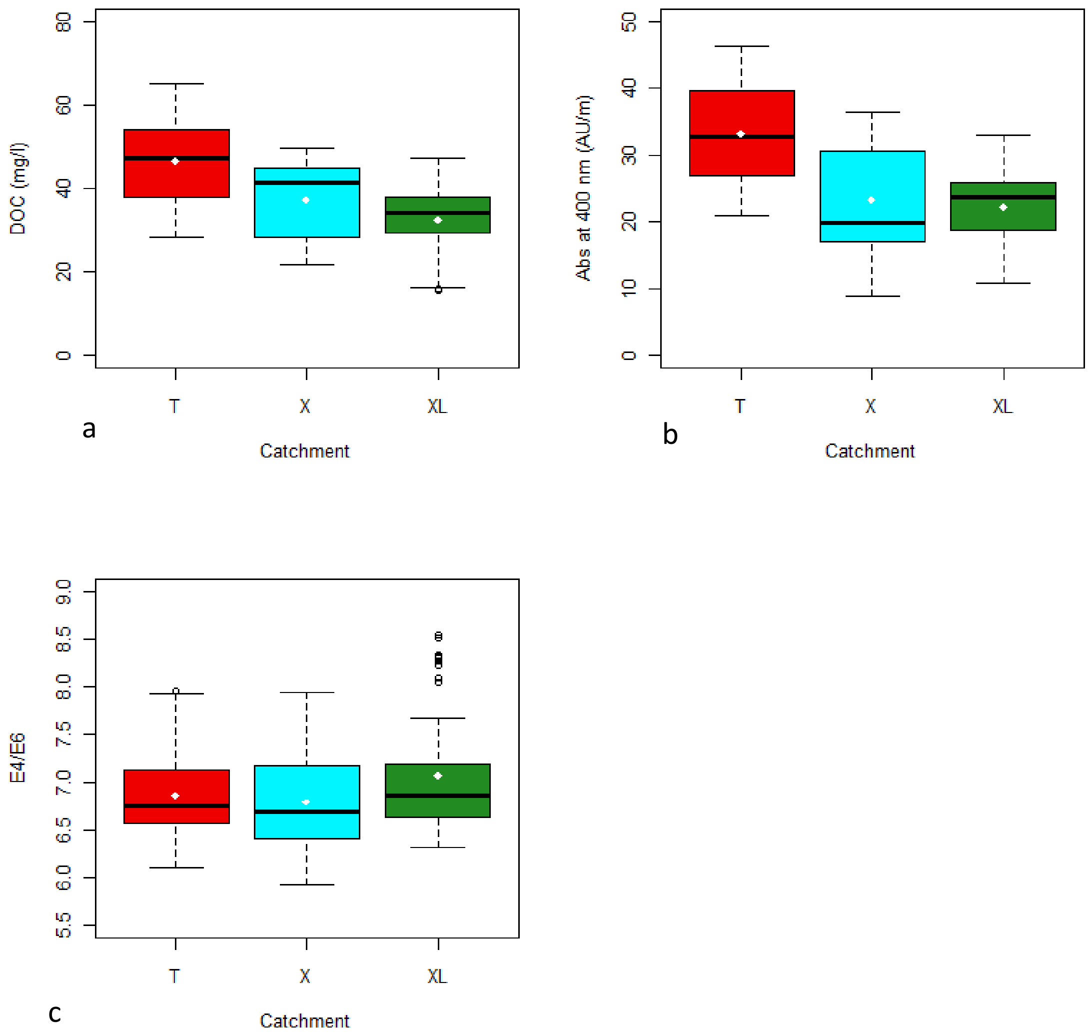


Figure 101. DOC concentrations (a), Absorbance at 400 nm (b) and E4/E6 ratios (c) at the Tig (T),Crosswater (X) and Crosswater of Luce (XL).

Over this short time span, which represents a period in the annual DOC cycle of steadily increasing concentrations, median DOC values are highest at the Tig and lowest at the Crosswater of Luce. Water colour, interpreted through the median Absorbance values at 400 nm, is also darker for the Tig samples. However we see the median water colour at the Crosswater of Luce being slightly higher than the Crosswater albeit with a complete overlap within the interquartile range. Finally the E4/E6 values suggest that DOC composition is similar at the three sample points except for a few elevated values at the Crosswater of Luce. As the largest catchment by far there would be more opportunity for instream processing to break down some of the more recalcitrant elements so raising the E4/E6 ratio.

These observations were tested statistically using the Kruskal-Wallis rank sum test and it was found that differences in median values of DOC concentration and absorbance were significant at the 95 % confidence level (H = 54.25, p = 0.00; H= 62.46, p = 0.00 respectively) but no significant differences could be found between E4/E6 ratios (H=6.69, p=0.035). Post hoc testing of significant differences in DOC and absorbance revealed that for DOC concentration, differences in median values were significant between all three sites whereas this was only true between the Tig and Crosswater and Tig and Crosswater of Luce in the case of absorbance.

Table 37. Spearman rank correlation coefficients and regression equations for associations between DOC concentration and E4/E6 ratios (top three rows) and absorbance at 400 nm (lower three rows) at the Tig, Crosswater (X) and Crosswater of Luce (XL). Critical value for Spearman Rank correlation = 0.245. * denotes significant at the 95 % confidence level.

	Catchment	*Correlation*	R^2	*Regression equation*	*n*
DOC vs E4E6	X	- 0.71	53.7	DOC = 127 - 13.3 E4:E6	67
	Tig	- 0.62	45.8	DOC = 147 - 14.6 E4:E6	69
	XL	- 0.56	67.4	DOC = 113 - 11.4 E4:E6	69
DOC vs Absorbance	X	0.73	54.9	DOC = 17.1 + 0.861 A_{400}	67
	Tig	0.94	89.8	DOC = 4.16 + 1.27 A_{400}	69
	XL	0.99	97.2	DOC = 0.611 + 1.43 A_{400}	69

The existence of correlations between DOC, absorbance and E4/E6 was tested for at the three sites. DOC concentration was significantly correlated with Abs_{400} (positive correlations) and E4/E6 (negative correlations) in the three catchment sample points (Table 37 and Figure 102).

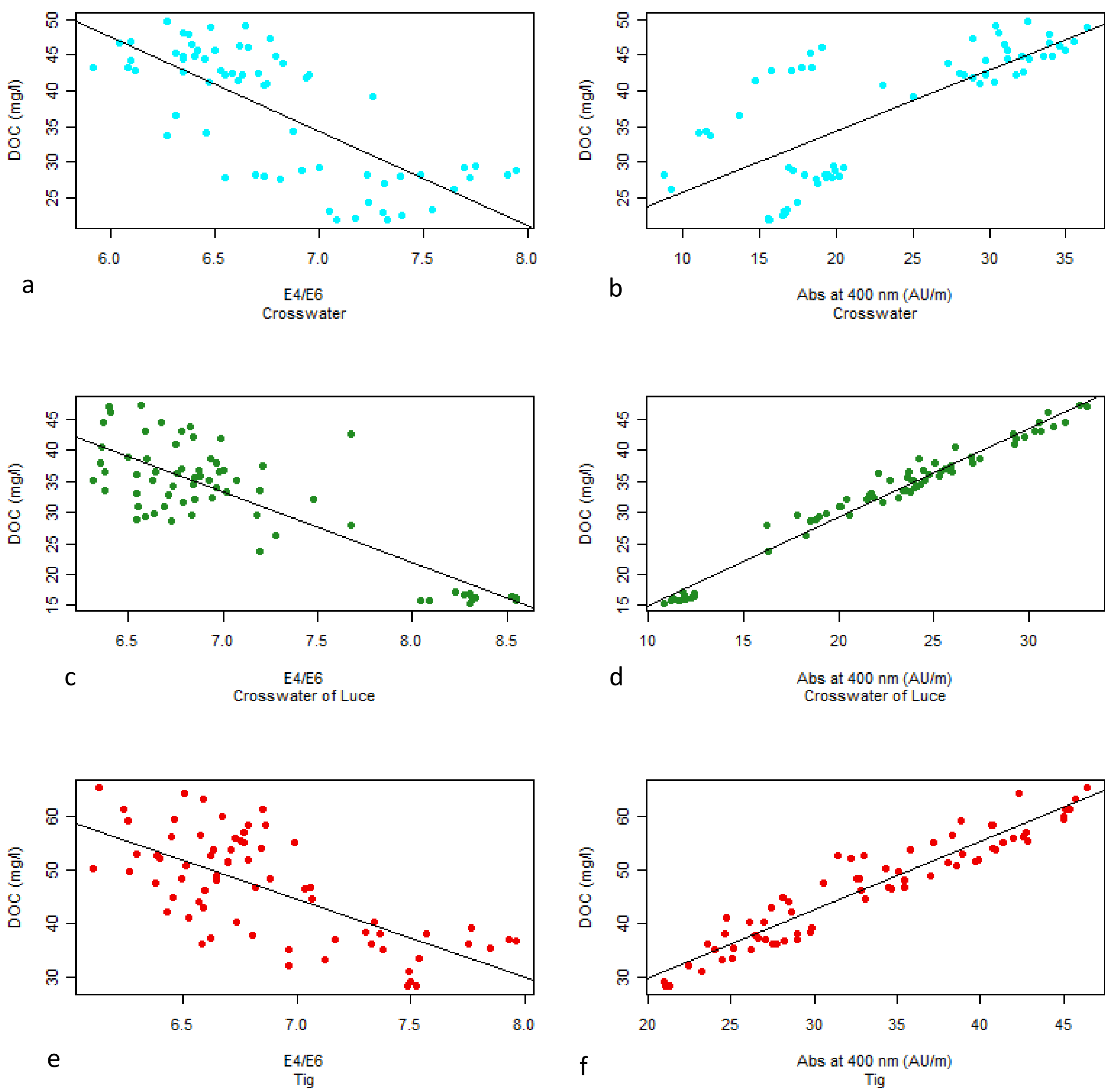


Figure 102. Comparison of E4/E6 ratios with DOC concentration and Absorbance at 400 nm with DOC concentration at the Crosswater, Crosswater of Luce and Tig sample points at Arecleoch.

DOC concentration showed the strongest correlation with the E4E6 ratio at the Crosswater (- 0.71) but the best regression fit for the E4/E6 ratio was at the Crosswater of Luce (R^2 = 67.4). This could suggest that while there is a greater association between DOC concentration and E4E6 ratios at the Crosswater, E4E6 ratios are better predictors of DOC concentration at the Crosswater of Luce. Although there was a strong relationship between absorbance at 400 nm and DOC concentrations at all a sites, other work has shown that significant variations in this relationship can occur between peat layers, with different management regimes and across time.(Wallage & Holden 2010). At Arecleoch the strongest correlation (0.99) and best regression fit (R^2 = 97.2) with absorption (ie water colour) was found at the Crosswater of Luce.

For Abs_{400} at the Crosswater evidence of a double association is visible from Figure 102b. The lower set of samples originates from the group collected between 8th July 2010 and 1st August 2010 and retrieved from the autosamplers at Arecleoch on 2nd August. A similar but less distinct split in the DOC absorbance association is visible at the Tig (Figure 102f). Here the lower line consists of two sets of samples; those collected between 29th June and 20th July and extending partially across two blocks of samples, then those collected between 7th September and 5th October and retrieved from the autosampler on October 5th. An interpretation of this feature, particularly at the Crosswater, is that for the lower subset of samples, for every unit of increase in DOC concentration, there is a smaller increase in water colour, suggesting the release of less coloured components of DOC.

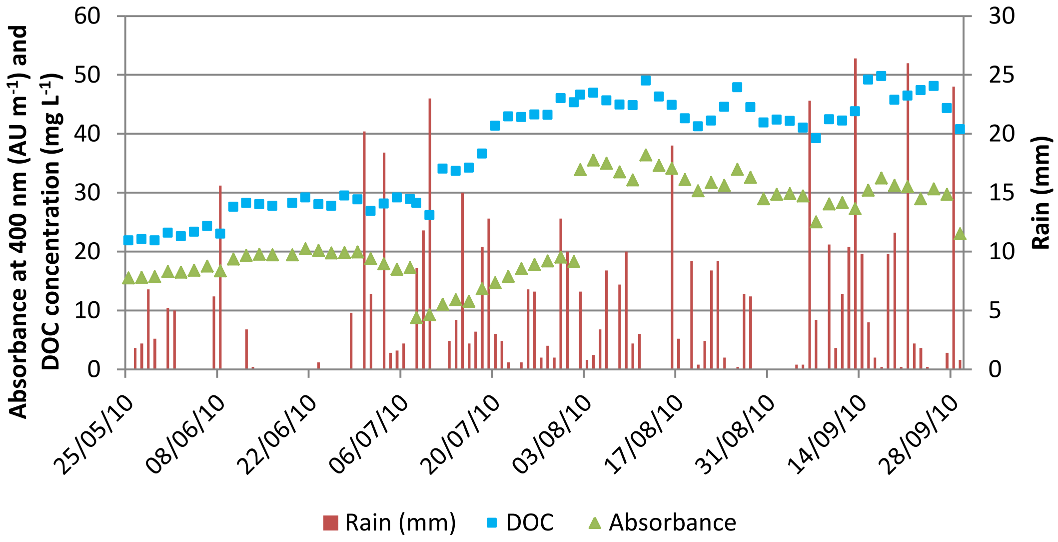


Figure 103. Absorbance and DOC concentration at the Crosswater with daily mean rainfall at the SEPA Lagarfater station between 25/05/10 and 30/09/10.

This can be seen in Figure 103 where DOC concentration and Absorbance at 400 nm for the Crosswater are plotted separately and daily mean rainfall is included from the SEPA station at Lagarfater. Between July 8th and July 30th DOC concentrations decrease whereas there is no corresponding drop in Absorbance. This time span follows a period of rain after 2 weeks of very dry weather. A decrease in absorbance at high flow with no corresponding decrease in DOC concentration could indicate that the DOM released is less degraded and has a lower molecular weight (Austnes *et al.* 2010). Under these conditions at the Crosswater and at this time of year it might be that the rain events were flushing out new DOC from the acrotelm that is less degraded and not as dark in colour.

4.6.2 **SUVA**

In order to explore the relationship between UV absorbance, DOC and land use a subset of water samples was processed through a UV-Vis spectrometer designed for continuous, in-situ monitoring of water quality. Known as the Spectrolyser™, this is a multi-parameter probe, which records absorbance between 200 nm and 735 nm at intervals of 2.5 nm. An explanation of the functioning of the Spectrolyser™ can be found in Grayson and Holden (2011). For the purposes of this experiment values at 250 nm, 280 nm and 400 nm have been extracted, to use for SUVA calculations (250 nm and 280 nm) and as a general colour indicator (400 nm). The data set comprises water samples collected from the catchment autosamplers (Tig, N=14, 48 hourly; Crosswater, N=14, 48 hourly; Crosswater of Luce, N=24, 24 hourly) and the spatial survey samples (N= 22) from the field visit made on 24th and 25th May 2010. DOC concentrations were also measured as a matter of routine and absorbance at 465 nm and 665 nm have already been discussed above as part of the E4/E6 ratio work.

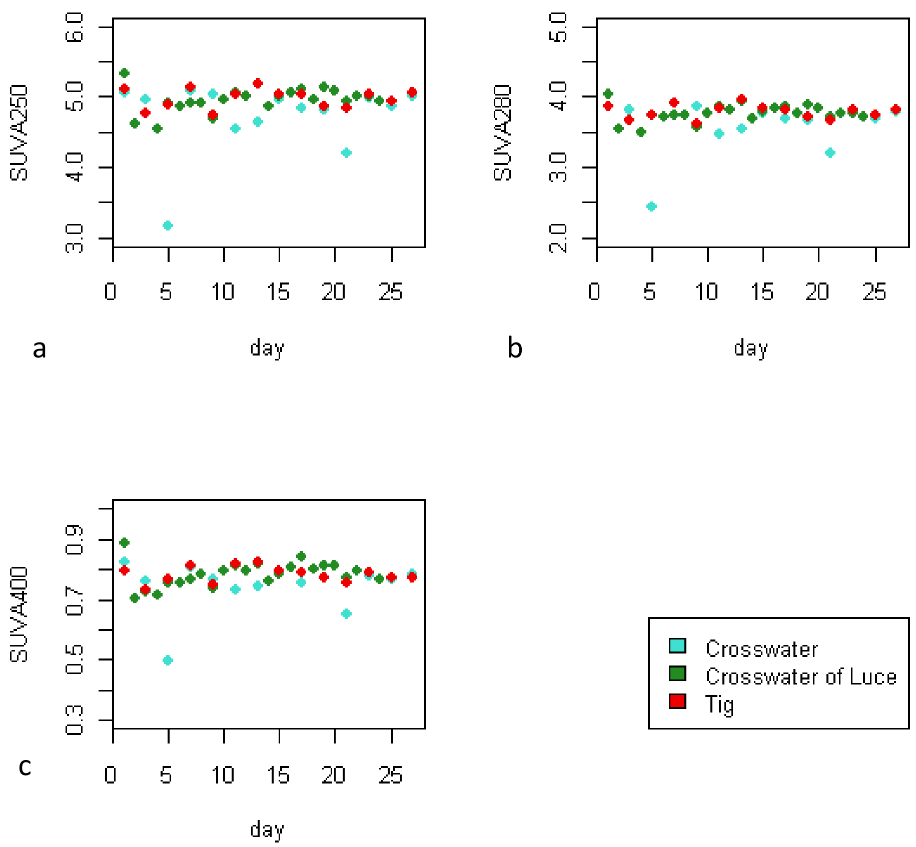


Figure 104. Time series of SUVA values at 250 nm (a), 280 nm (b) and 400 nm (c) at the Crosswater, Crosswater of Luce and Tig sample points

SUVA values are very similar between the three catchments at each of the three wavelengths over the brief timescale offered by the data set (Figure 104 a-c) and no significant differences could be identified between catchments at any of the SUVA wavelengths using the Kruskal-Wallis rank sum test. Relatively high DOC concentrations at the Crosswater on day 5 (1^{st} May 2010; 23.74 mg L^{-1}) and day 21 (17^{th} May 2010; 23.74 mg L^{-1}) account for the lower SUVA values seen at all wavelengths, suggesting that the elevated DOC concentration is not a result of the release of more humified compounds or those contributing to water colour. It may therefore be the release of newer DOC causing concentrations to be elevated briefly. The reasons for this remain a matter for conjecture; antecedent soil moisture conditions would have been dry, there was no significant rainfall in the preceding week and anyway a precipitation event would have affected the other catchments similarly. SPR work records do not indicate any activities in the Crosswater catchment on either of those days.

Moving to the spatial survey data and comparing the SUVA values at three wavelengths across 22 sample points, it can be seen that sample points 14, 20, 21 and 23 are lower in SUVA at 250 nm and 280 nm value than the rest (Figure 105). The reason for this is unclear as none of these sites is undisturbed and indeed sample point 14 lies in an area where several wind farm activities were taking place at the time. Extracting information from the SPR records and associated activity scoring system could not isolate these sample points as being subject to inputs likely to lead to lower SUVA values.

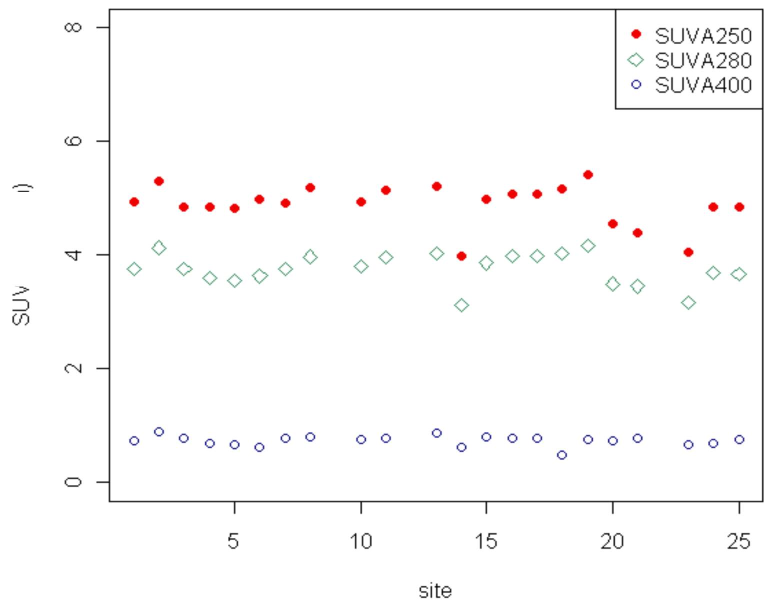


Figure 105. SUVA values at 250 nm, 280 nm and 400 nm for the spatial survey sample points at Arecleoch

4.7 Discussion

The experiments and analysis described above extract data from across a broad spatial spectrum ranging from soil pore water to medium size rivers, via headwater streams and their confluences. The aim was to investigate whether a disturbance signal could be identified by utilising simple metrics of UV absorbance at different wavelengths. Beginning at the smallest spatial scale (Table 38) water colour was found to be significantly darker in soil pore water from disturbed peat than from undisturbed peat and the E4/E6 ratio was lower. However neither water colour nor E4/E6 ratios were significantly different moving through the soil profile to a depth of 40 cm at either the peat store or the control site. This is in contrast to the findings of Wallage *et al.* (2006) where DOC, E4/E6 and water colour (Abs_{400}) varied significantly with soil depth in a similar experiment for peat soil water at an intact site, a drained site and a site where drains had been blocked.

Table 38. Summary of water colour (Abs400), DOC concentration E4/E6 ratios and SUVA values at different spatial scales. ND = not determined, Down = downstream of T33, Up = upstream of T33, X = Crosswater, XL = Crosswater of Luce, Sig = statistically significant (p < 0.05 , > = significantly greater (p < 0.05), < = significantly less (p < 0.05), an equals sign signifies no significant difference (p > 0.05).

Scale	Colour	DOC	E4/E6	SUVA
Soil water	Disturbed > undisturbed Depth - no diff	ND	Disturbed < undisturbed Depth - no diff	ND
Sub-catchment Headwaters	disturbed = undisturbed	Disturbed > undisturbed	Disturbed < undisturbed	disturbed = undisturbed
Sub-catchment T33	Down > up Sig up and ⟵ down	Down > up CORRELATED ⟶	Down < up Sig up only	ND
Catchment	X = XL X < Tig XL < Tig Sig X, XL, Tig⟵	X > XL X < Tig XL < Tig CORRELATED ⟶	X = XL X = Tig XL = Tig Sig X, XL, Tig	X = XL X = Tig XL = Tig

Moving from soil water to headwater streams no difference in water colour could be found between sample points in sub-catchments subject to wind farm related disturbance and those sample points in undisturbed sub-catchments. However at the disturbed sample points, stream water had significantly higher DOC concentrations and lower E4/E6 ratios. Further statistical interrogation of the data failed to isolate the nature of the disturbance responsible for these differences. Stream water collected from a headwater stream downstream of an area where a turbine base was being installed (T33) installed had significantly (p < 005) higher DOC concentrations, darker water colour and lower E4/E6 values than samples upstream of the work. For the upstream samples DOC was significantly correlated with water colour (positive) and E4/E6 ratios (negative) whereas for T33 downstream only DOC and absorbance were significantly correlated (positive, p < 0.05 in all cases). This suggests a modification in the composition of DOC between the two sample points.

At the catchment scale DOC was significantly correlated with water colour and E4/E6 ratios at all three sites. Median DOC concentrations were significantly different between the three sample points, two of which received water from streams draining the wind farm development. Water colour measured by abs_{400} was statistically similar at the Crosswater (control) and Crosswater of Luce (disturbed) but both had significantly less colour than the Tig (disturbed). Thus the Crosswater had significantly higher DOC than the Crosswater of Luce but the water was no different in colour. It was not possible to discriminate between the three catchments in terms of E4/E6 ratios.

The colour – carbon relationship was explored for a small sub-set of samples using SUVA at 250 nm, 280 nm and 400 nm. For the relatively small data set no differences could be found between water from disturbed and undisturbed sample points at either the headwater or catchment scale. No one wavelength appeared to provide a finer discrimination of carbon quality than any other.

These results provide equivocal evidence of the potential utility of UV absorbance in identifying and quantifying peatland disturbance. The application of simple UV-Vis absorbance measurements (254 nm and 400 nm) to test for changes in water colour following drain blocking on peatlands has been undertaken (Armstrong *et al.*, 2010) and some evidence of reductions in DOC concentrations and water colour was found following drain blocking. However caution has also been advised in applying causal relationships to such results. Given the heterogeneous nature of DOC and spatial and temporal variability of its properties, one should maybe limit the use of SUVA to within site comparisons (Marschner & Kalbitz 2003) or restrict studies to relative variations in specific absorbance that indicate relative differences in DOC quality such as the aromaticity (Jaffrain *et al.* 2007). The relatively short time frame over which data were collected for this study may also have exacerbated efforts to identify a disturbance marker and it has been suggested that one should carry out monitoring for more than 5 years (Holl *et al.* 2009). Short term studies on peatland restoration have shown elevated DOC due to flushes (Wilson *et al.* 2009) but longer term monitoring has revealed lower DOC concentrations (Holl *et al.* 2009; Wallage, Holden & McDonald 2006) which indicates that there are different mechanisms at play. Also there are seasonal differences in DOC quality with an accumulation of aromatic compounds in summer accompanying higher DOC concentrations. Baker *et al.* (2008) working at the Coalburn experimental site in northern England, found mean DOC concentrations to be nearly 33% higher in water samples from a peat sub-catchment than at a neighbouring peaty gley sub-catchment. Also with the peat sub-catchment they found significantly higher DOC concentrations in water from drainage ditches in forested areas than in water from ditches in moorland areas. Samples from drains within the peat sub-catchment (ie the micro-catchment scale) indicated that colour/DOC ratios and SUVA 340 values were higher from forested sample points than from moorland sample points. They consequently concluded that forestry did not cause more DOC to be released into drainage ditches but that the organic matter produced had a higher molecular weight and was more aromatic and highly coloured. This illustrates the way in which measures of DOC quality and quantity can be used together to build a more complete picture of DOC behaviour in disturbed landscapes. Based on the small sub-set of samples use for this study and the parameters tested it seems that the E4/E6 ratio has the most potential as a possible indicator of DOC quality, being able to distinguish differences at all spatial scales. Austnes *et al.* (2010) also found absorbance ratios (E2/E3) to be more robust than SUVA measurements as the former produced a smoother trend. Further work would be useful to extend the range of wavelengths included in the study in order to explore the potential of these metrics further.

Concluding comments

Four main Themes address the aims of this project. The main focus has been on DOC, but other parameters included were hydrological data, POC, suspended sediment and major ions. In Theme 4 DOC quality was addressed in order to investigate potential measures of disturbance based on UV absorbance. Similarly Themes 1 and 2 were anchored at the catchment scale while Theme 3 focused in on headwater streams and Theme 4 incorporated data from all the previous scales and added to it with a study of soil pore water from a peat store.

The first aim was *to describe landscape losses of DOC from a peatland on which first stood Arecleoch forest and latterly stands Arecleoch wind farm, primarily through DOC concentrations and fluxes.* This was addressed at the catchment scale and showed that DOC concentrations at the three catchments draining Arecleoch forest exhibited the familiar seasonal sine wave pattern with maxima in late August/ early September and minima between February and March. DOC concentrations across the catchments followed the order: Tig > Crosswater > Crosswater of Luce. DOC flux ranged from 34.97 g C m^{-2} yr^{-1} at the Crosswater of Luce in 2008 to 55.03 g C m^{-2} yr^{-1} from the Crosswater in 2009. These values are high for UK peatlands where a range of 19 – 27 g C m^{-2} yr^{-1} is considered typical (Billett *et al.* 2010). Thus what has been presented at Arecleoch may be indicative of a landscape that was highly disturbed, even before the arrival of SPR's wind farm development. The strong seasonal DOC cycle here, as elsewhere, is a major inhibitor to the use of short term data sets to compare DOC concentrations through time.

The second aim was to *appraise the significance of the impacts of wind farm construction on the peatland in terms of the quantity and quality of aquatic carbon loss* *and make recommendations to developers as to how to minimise such impacts*. This was investigated at spatial scales ranging from soil pore water to catchment and the conclusions are notable as much for the insights gained on challenges in addressing the questions as for the data obtained. At the catchment scale the major impediment to assessing the impact of the wind farm development was one of disentangling the forestry effect from other activities. The incremental and piecemeal nature of the forest harvesting meant that there were no clean lines to be drawn between peatland areas pre and post disturbance. It is also important to remember that this effect relates not only to the intense phase of harvesting that took place for the wind farm but reflects earlier events. The original planting of Arecleoch forest took place in a fragmentary fashion between 1951 and 1991, following the sequence of acquisitions described in theme 3. The Google™ earth Image taken in 2005 (Figure 50) shows that some of that first rotation had been felled by then. The current FCS stock map (Arecleoch FDP 17) reveals that while some of these areas in the north remained clear, replanting took place in other felled areas between 2000 and 2004. A consequence of the fact that planting and felling were carried out at different times was that DOC data from monitoring at Arecleoch was recording simultaneously the effect of both recent and more distant felling. A similar challenge was found with the wind farm construction activities in that these also varied spatially and temporally and the diffuse nature of the forest cycle and the lack of detail in the SPR records at Arecleoch rendered it unrealistic to isolate the “chronic” forest harvesting disturbance from the more “acute” wind farm construction activities.

The pattern for the proportion of the catchment potentially subject to disturbance from the wind farm development was Tig (31 %) > Crosswater of Luce (21 %) > Crosswater (0.005 %). Thus while the Tig experienced the greatest burden of disturbance and returned the highest DOC concentrations, the Crosswater, used as a control site due to its isolation from wind farm activities, had higher DOC concentrations than the Crosswater of Luce throughout the monitoring period. Despite these limitations it is possible to make a tentative estimate of an extra 12 g C m^{-2} being exported from the Crosswater of Luce in 2009, compared to the Crosswater, which may have been a result of wind farm and/or forestry activities in the catchment. This is more than double the values obtained by Grieve and Gilvear (2008) for the Braes of Doune wind farm.

At the sub-catchment scale, comparisons of DOC concentrations upstream and downstream of turbine 33 did not yield statistically significant differences that could be assigned to the wind farm development. Freezing weather conditions and sampling equipment failure prevented the collection of data form before construction work started and the blanket effect of forest harvesting could not be separated out. Exchanging intensive for extensive sampling in the spatial surveys of headwater streams yielded interesting results in that hot spots of high DOC concentration were found during the latter surveys that may be caused by specific wind farm activities taking place at the time. Further spatial surveys would reveal if this was a temporary phenomenon possibly caused by the wind farm development, in which case one might expect values to decrease with time to levels found pre-construction.

Disturbance at Arecleoch was also explored in terms of changes to DOC quality and it was found that E4/E6 ratios could be used at different spatial scales to identify changes in DOC quality related to disturbance such as increases in the darker, more humified constituents of DOC that have lower E4/E6 ratios. It is suggested that combining some measure of DOC quality with the more conventional concentration and flux estimates could provide a more complete picture of what happens to aquatic carbon under situations of land use change as found by Baker *et al.* (2008).

SUVA calculations were made using the Spectrolyser™ in-situ device that can measure absorbance at a range of specified wavelengths as well as determining DOC concentrations from the absorbance values. While the outcome of the SUVA calculations at 250 280 and 400 nm did not successfully discriminate between the three catchments in terms of DOC quality, the ability to measure absorbance at multiple wavelengths and infer DOC concentrations in-situ gives it the potential to provide a fast and relatively inexpensive means of monitoring both DOC quantity and quality in the field.

The third and fourth aims are linked and can be discussed together. *Aim three was to provide useful information to feed into the carbon calculator in terms of DOC losses* and aim four set out to *develop practical tools for predicting and appraising negative effects of land use change on peatlands using information on DOC quality and POC concentrations*.

This research has highlighted the need for creative approaches to DOC monitoring if we are to understand more fully the relative impacts of different activities involved in constructing a wind farm (and by extension other developments on peatlands). This concept has been recognised elsewhere, for example the impacts of forest harvesting on DOC concentrations were investigated by Öhman *et al.* (2009) who developed a conceptual model using DOC concentration as a factor in traditional forest planning. They used the model to optimise the distribution and timing of harvesting in a 6780 ha watershed in northern Sweden so that target DOC concentrations downstream were not breached. They suggested that this approach could be used as an alternative to legislative “rule of thumb” restrictions such as restricting harvesting to 30 % of a watershed area in a certain time period. At Arecleoch this has been explored through the use of DOC ratios between catchments where simple BACI studies will not suffice. It has also proposed a novel approach to relate wind farm impact to DOC concentrations at the catchment scale in the form of Activity scores. This system, even in its first iteration has shown promise in that a relationship could be observed between overall construction activity and the ratio of DOC concentrations between the Crosswater and Crosswater of Luce. Activity scores could, together with other information gathered from site records, be useful to developers as an indicator of the most likely periods for peat disturbance. Linking activity scores to DOC values at the sub-catchment scale across the site would require a larger data set than the current spatial survey sample. It should ideally be large enough to allow a multiple parameter comparison to be carried out using season, sample point, disturbance and characteristics such as peat depth. The current incarnation of the system also makes the assumption that the potential for disturbance is the same for each of the activities (ie all disturbance is equal). The next step would be to refine the system to include a weighting that takes into account the disturbance potential of different activities and the quantity of peat disturbed. Thus If one unit of disturbance were equal to 10 m^3 of peat, then approximately 10 m of cable trench in an area where peat depth was at least 1 m, would equal a unit of disturbance. Likewise the disturbance score for each turbine base could be calculated. Central to this system is the need for a comprehensive database of peat depths across the site but this is something that is commonly provided in the Environmental Statement as part of the planning application (but not always found to be reliable in practice). Extrapolation of point peat depths would be necessary and would introduce a potentially large error into the system.

The carbon payback calculator developed by Nayak *et al.* (2008) has been discussed above (4.14). It includes a section relating to CO_2 losses for DOC and POC. The output is generated from estimates of the total carbon loss where it is assumed that 10% of this is leached as DOC and that 100% of this DOC is emitted as CO_2 (Nayak *et al.* 2008).

The 10% value (subsequently refined for future iterations of the C calculator to allow for a higher or lower input value) was chosen following the work of Dillon & Molot (1997) and Worrall *et al.* (2003). It makes the assumption that the rate of carbon release as a proportion of total carbon loss remains constant irrespective of the extent and nature of disturbance taking place. By incorporating a refined system of activity scores into the calculator it would be possible to allow for the possibility that not all disturbance is equal and to fine tune the payback time accordingly. Knowledge of the differing disturbance potential of the various activities could also enable developers to focus efforts on methods of preventing carbon loss rather than remediation *ex post*.

We have seen through the different strands of research comprising this project that water quality at Arecleoch, as described by DOC, is characterised primarily by a well-defined seasonal pattern. However, while the outline across the seasons conforms to a well- established pattern, the absolute values populating the sine wave tell a more subtle story of a highly managed landscape. For whilst soil type, in this case peat, is known to be a major control on DOC concentration (Dawson & Smith 2007), it is also recognised that catchment hydrology and land use both have an important role in controlling the transport of carbon to streams (Hope *et al.* 2004; Dawson and Smith 2007). DOC fluxes from before the wind farm development were already at the upper end of the scale reported for UK peatlands implying that Arecleoch was already responding to earlier management decisions and making it more difficult to detect further change. There is a natural progression now to the question of where best to site wind farms. This has been raised before by Waldron *et al.* (2009) and Mitchell *et al.* (2010). With the latter suggesting that:

"Siting a wind farm in either afforested or natural peatlands can produce relatively short CO_2 payback times of around four years. However, when comparing the two options, degrading and disturbing forested peatland as opposed to natural moorland may represent the lesser of two evils".

This serves as an important reminder that while advances in sampling and analytical tools such as the ones proposed in this study might help to reduce some of the uncertainty in the science surrounding these options, human perceptions of landscape value and emotionally charged debates over what function we want it to perform must also be given space.

Key points and take home messages from this research

This research has:

1. Added three new catchments to the detailed knowledge base of DOC concentrations and fluxes from UK peatlands. It has also presented some of the highest known values for such areas. It also provides one of only four studies to investigate concentrations and fluxes of DOC in water courses draining land subject to disturbance relating to wind farm construction (Grieve & Gilvear 2008; Murray 2012; Waldron *et al.* 2009);

2. Confirmed the persistence and dominance of the seasonal pattern of DOC through a period of land use change and shown how the pattern was modified by two harsh winters;

3. Highlighted at the catchment scale an impact from wind farm development on DOC concentrations and fluxes;

4. Elucidated some activities that led to elevated DOC concentrations and fluxes, for example turbine base installation and forest harvesting;

5. Introduced activity scores as a novel means of attributing changes in DOC to the type and intensity of development activity; and

6. Used E4/E6 ratios as a way of detecting changes to DOC composition resulting from land use change.

Finally it must be recognised that the story of Arecleoch's passage through this latest land use change is incomplete on two counts; firstly the period of calm after the development phase should be studied in order to understand the peatland's recovery and the extent to which DOC concentrations and fluxes may decline given that their starting point was one of pre-existing disturbance. Secondly, to describe fully the impacts of wind farm construction in any context, one must consider the decommissioning phase. This is something which has yet to gain much purchase in the research and industry communities but will surely prove to be challenging to achieve without further disturbance to the landscape. Both of these offer significant future research opportunities and would require comprehensive monitoring programmes. Building on some of the ideas explored in this thesis such as in-situ sampling utilising the Spectrolyser™ or similar and using E4/E6 ratios could make such endeavours more time-efficient, less costly and generate comprehensive data sets that allow a robust interrogation of the scale and nature of the impact of such activities on water quality and carbon storage.

Appendix 1- Summary of samples collected

Table 39. Summary of water samples collected

Sample type/experiment	*Dates*	*Catchment*	*Number of samples*	*Description*
Routine	01/01/08 – 30/09/10	Crosswater	667	Daily/ 48 hourly
Routine	01/01/08 – 30/09/10	Crosswater of Luce	498	Daily/ 48 hourly
Routine	22/07/09 – 30/09/10	Tig	274	Daily/ 48 hourly
High flow	Eight events	Crosswater	21	Rising stage sampler
	Five events	Tig	17	Rising stage sampler
Spatial	21/10/08 – 02/08/10	All. Headwaters	153	8 surveys seasonally over 2 years
Turbine 33	02/02/10 – 30/06/10	Crosswater of Luce	192	Upstream and downstream of T33 during base construction
Peat store	Feb – Oct 2010	Tig	153	Comparison of soil water in a peat store and moorland area

References

Agren, A., Berggren, M., Laudon, H. & Jansson, M. (2008). Terrestrial export of highly bioavailable carbon from small boreal catchments in spring floods. *Freshwater Biology,* **53**, 964-972.

Aitkenhead, J.A., Hope, D. & Billett, M.F. (1999). The relationship between dissolved organic carbon in stream water and soil organic carbon pools at different spatial scales. *Hydrological Processes,* **13**, 1289-1302.

Aitkenhead-Peterson, J.A., Smart, R.P., Aitkenhead, M.J., Cresser, M.S. & McDowell, W.H. (2007). Spatial and temporal variation of dissolved organic carbon export from gauged and ungauged watersheds of Dee Valley, Scotland: Effect of land cover and C : N. *Water Resources Research,* **43**, W05442.

Archer, D. (2003). Scale effects on the hydrological impact of upland afforestation and drainage using indices of flow variability: the River Irthing England (vol 7, pg 325, 2003). *Hydrology and Earth System Sciences,* **7**, 782-782.

Armstrong, A., Holden, J., Kay, P., Francis, B., Foulger, M., Gledhill, S. *et al.* (2010). The impact of peatland drain-blocking on dissolved organic carbon loss and discolouration of water; results from a national survey. *Journal of Hydrology,* **381**, 112-120.

Artinger, R., Buckau, G., Geyer, S., Fritz, P., Wolf, M. & Kim, J. (2000). Characterization of groundwater humic substances: influence of sedimentary organic carbon. *Applied Geochemistry,* **15**, 97-116.

Astrom, M., Aaltonen, E. & Koivusaari, J. (2001). Effect of ditching operations on stream-water chemistry in a boreal forested catchment. *Science of the Total Environment,* **279**, 117-129.

Ates, N., Kitis, M. & Yetis, U. (2007). Formation of chlorination by-products. in waters with low SUVA-correlations with SUVA and differential UV spectroscopy. *Water research,* **41**, 4139-4148.

Austnes, K., Evans, C.D., Eliot-Laize, C., Naden, P.S. & Old, G.H. (2010). Effects of storm events on mobilisation and in-stream processing of dissolved organic matter (DOM) in a Welsh peatland catchment. *Biogeochemistry,* **99**, 157-173.

Baker, A., Bolton, L., Newson, M. & Spencer, R.G.M. (2008). Spectrophotometric properties of surface water dissolved organic matter in an afforested upland peat catchment. *Hydrological Processes,* **22**, 2325-2336.

Ball, D.F. (1964). Loss-On-Ignition as Estimate of Organic Matter + Organic Carbon in Non-Calcareous Soils. *Journal of Soil Science,* **15**, 84-&.

Billett, M.F., Charman, D.J., Clark, J.M., Evans, C.D., Evans, M.G., Ostle, N.J. *et al.* (2010). Carbon balance of UK peatlands: current state of knowledge and future research challenges. *Climate Research,* **45**, 13-29.

Billett, M.F., Deacon, C.M., Palmer, S.M., Dawson, J.J.C. & Hope, D. (2006). Connecting organic carbon in stream water and soils in a peatland catchment. *Journal of Geophysical Research-Biogeosciences,* **111**.

Billett, M., Palmer, S., Hope, D., Deacon, C., Storeton-West, R., Hargreaves, K. *et al.* (2004). Linking land-atmosphere-stream carbon fluxes in a lowland peatland system. *Global Biogeochemical Cycles*, **18**, GB1024.

Blodau, C. & Moore, T.R. (2003). Experimental response of peatland carbon dynamics to a water table fluctuation. *Aquatic Sciences*, **65**, 47-62.

Bouchard, A. (1997). Recent lake acidification and recovery trends in southern Quebec, Canada. *Water Air and Soil Pollution*, **94**, 225-245.

Bourbonniere, R.A. (1989). Distribution Patterns of Dissolved Organic-Matter Fractions in Natural-Waters from Eastern Canada. *Organic Geochemistry*, **14**, 97-107.

Bourbonniere, R.A. (2009). Review of Water Chemistry Research in Natural and Disturbed Peatlands. *Canadian Water Resources Journal*, **34**, 393-413.

Bragg, O.M. & Tallis, J.H. (2001). The sensitivity of peat-covered upland landscapes. *Catena*, **42**, 345-360.

British Wind Energy Association (BWEA) (2005). *BWEA Briefing Sheet: Public Attitudes to Wind Energy in the UK*. BWEA, London.

Brooks, P.D., McKnight, D.M. & Bencala, K.E. (1999). The relationship between soil heterotrophic activity, soil dissolved organic carbon (DOC) leachate, and catchment-scale DOC export in headwater catchments. *Water Resources Research*, **35**, 1895-1902.

Cannell, M.G., Dewar, R.C. & Pyatt, D.G. (1993). Conifer Plantations on Drained Peatlands in Britain: a Net Gain or Loss of Carbon? *Forestry*, **66**, 353-369.

Carling, P.A. (1983). Particulate Dynamics, Dissolved and Total Load, in 2 Small Basins, Northern Pennines, Uk. *Hydrological Sciences Journal-Journal des Sciences Hydrologiques*, **28**, 355-375.

Carling, P.A., Irvine, B.J., Hill, A. & Wood, M. (2001). Reducing sediment inputs to Scottish streams: a review of the efficacy of soil conservation practices in upland forestry. *The Science of the total environment*, **265**, 209-227.

Chapman, S., Buttler, A., Francez, A., Laggoun-Defarge, F., Vasander, H., Schloter, M. *et al.* (2003). Exploitation of northern peatlands and biodiversity maintenance: a conflict between economy and ecology. *Frontiers in Ecology and the Environment*, **1**, 525-532.

Charman, D. (2002). *Peatlands and environmental change*. Chichester : John Wiley.

Chen, J., Gu, B., LeBoeuf, E., Pan, H. & Dai, S. (2002). Spectroscopic characterization of the structural and functional properties of natural organic matter fractions. *Chemosphere*, **48**, 59-68.

Chin, Y., Aiken, G.R. & Oloughlin, E. (1994). Molecular-Weight, Polydispersity, and Spectroscopic Properties of Aquatic Humic Substances. *Environmental science & technology*, **28**, 1853-1858.

Clair, T., Pollock, T. & Ehrman, J. (1994). Exports of Carbon and Nitrogen from River Basins in Canadas Atlantic Provinces. *Global Biogeochemical Cycles*, **8**, 441-450.

Clark, J.M., Bottrell, S.H., Evans, C.D., Monteith, D.T., Bartlett, R., Rose, R. *et al.* (2010). The importance of the relationship between scale and process in understanding long-term DOC dynamics. *Science of The Total Environment,* **408**, 2768-2775.

Clark, J.M., Lane, S.N., Chapman, P.J. & Adamson, J.K. (2007). Export of dissolved organic carbon from an upland peatland during storm events: Implications for flux estimates. *Journal of Hydrology,* **347**, 438-447.

Clark, J.M., Lane, S.N., Chapman, P.J. & Adamson, J.K. (2008). Link between DOC in near surface peat and stream water in an upland catchment. *The Science of the total environment,* **404**, 308-315.

Clark, M., Cresser, M., Smart, R., Chapman, P. & Edwards, A. (2004). The influence of catchment characteristics on the seasonality of carbon and nitrogen species concentrations in upland rivers of Northern Scotland. *Biogeochemistry,* **68**, 1-19.

Clutterbuck, B. & Yallop, A.R. (2010). Land management as a factor controlling dissolved organic carbon release from upland peat soils 2 Changes in DOC productivity over four decades. *Science of the Total Environment,* **408**, 6179-6191.

Clymo, R.S., Turunen, J. & Tolonen, K. (1998). Carbon accumulation in peatland. *Oikos,* **81**, 368-388.

Conway, V.M. & Millar, A. (1960). The hydrology of some small peat-covered catchments in the northern Pennines. *J Inst Water Eng,* **14**, 415-424.

Cooper, D. & Watts, C. (2002). A comparison of river load estimation techniques: application to dissolved organic carbon. *Environmetrics,* **13**, 733-750.

Cooper, R., Thoss, V. & Watson, H. (2007). Factors influencing the release of dissolved organic carbon and dissolved forms of nitrogen from a small upland headwater during autumn runoff events. *Hydrological Processes,* **21**, 622-633.

Coupar, A., Immirzi, P. & Reid, E. (1997). The nature and extent of degradation in scottish blanket mires. *Blanket mire degradation: causes, consequences and challenges* (eds J.H. Tallis, R. Meade & P.D. Hulme), pp. 90-99. Macaulay Land Use Research Institute, Aberdeen, UK.

Cresser, M.S., Gonzalez, R.L. & Leon, A. (2007). Evaluation of the use of soil depth and parent material data when predicting soil organic carbon concentration from LOI values RID F-1122-2011. *Geoderma,* **140**, 132-139.

Cummins, T. & Farrell, E.P. (2003). Biogeochemical impacts of clearfelling and reforestation on blanket-peatland streams - II. major ions and dissolved organic carbon. *Forest Ecology and Management,* **180**, 557-570.

Dawson, J.J.C., Bakewell, C. & Billett, M.F. (2001). Is in-stream processing an important control on spatial changes in carbon fluxes in headwater catchments? *The Science of the total environment,* **265**, 153-167.

Dawson, J.J.C., Billett, M.F., Hope, D., Palmer, S.M. & Deacon, C.M. (2004). Sources and sinks of aquatic carbon in a peatland stream continuum. *Biogeochemistry,* **70**, 71-92.

Dawson, J.J.C., Billett, M.F., Neal, C. & Hill, S. (2002). A comparison of particulate, dissolved and gaseous carbon in two contrasting upland streams in the UK. *Journal of Hydrology,* **257**, 226-246.

Dawson, J.J.C., Malcolm, I.A., Middlemas, S.J., Tetzlaff, D. & Soulsby, C. (2009). Is the Composition of Dissolved Organic Carbon Changing in Upland Acidic Streams? *Environmental science & technology,* **43**, 7748-7753.

Dawson, J.J.C. & Smith, P. (2007). Carbon losses from soil and its consequences for land-use management. *The Science of the total environment,* **382**, 165-190.

Dawson, J.J.C., Soulsby, C., Tetzlaff, D., Hrachowitz, M., Dunn, S.M. & Malcolm, I.A. (2008). Influence of hydrology and seasonality on DOC exports from three contrasting upland catchments. *Biogeochemistry,* **90**, 93-113.

Devine-Wright, P. & Howes, Y. (2010). Disruption to place attachment and the protection of restorative environments: A wind energy case study RID D-2847-2011. *Journal of Environmental Psychology,* **30**, 271-280.

Dilling, J. & Kaiser, K. (2002). Estimation of the hydrophobic fraction of dissolved organic matter in water samples using UV photometry. *Water research,* **36**, 5037-5044.

Dillon, P. & Molot, L. (1997). Effect of landscape form on export of dissolved organic carbon, iron, and phosphorus from forested stream catchments. *Water Resources Research,* **33**, 2591-2600.

Dinsmore, K.J., Billett, M.F., Skiba, U.M., Rees, R.M., Drewer, J. & Helfter, C. (2010). Role of the aquatic pathway in the carbon and greenhouse gas budgets of a peatland catchment. *Global Change Biology,* **16**, 2750-2762.

Eimers, M.C., Buttle, J. & Watmough, S.A. (2008). Influence of seasonal changes in runoff and extreme events on dissolved organic carbon trends in wetland- and upland-draining streams. *Canadian Journal of Fisheries and Aquatic Sciences,* **65**, 796-808.

Eimers, M.C., Watmough, S.A. & Buttle, J.M. (2008). Long-term trends in dissolved organic carbon concentration: a cautionary note. *Biogeochemistry,* **87**, 71-81.

Eltham, D.C., Harrison, G.P. & Allen, S.J. (2008). Change in public attitudes towards a Cornish wind farm: Implications for planning. *Energy Policy,* **36**, 23-33.

Environment Agency (2009). *Pollution Prevention Guidelines*.

Evans, C.D., Chapman, P.J., Clark, J.M., Monteith, D.T. & Cresser, M.S. (2006). Alternative explanations for rising dissolved organic carbon export from organic soils. *Global Change Biology,* **12**, 2044-2053.

Evans, C.D., Monteith, D.T. & Cooper, D.M. (2005). Long-term increases in surface water dissolved organic carbon: Observations, possible causes and environmental impacts. *Environmental Pollution,* **137**, 55-71.

Evans, C. & Monteith, D. (2001). Chemical trends at lakes and streams in the UK Acid Waters Monitoring Network, 1988-2000: Evidence for recent recovery at a national scale. *Hydrology and Earth System Sciences,* **5**, 351-366.

Evans, M.G., Burt, T.P., Holden, J. & Adamson, J.K. (1999). Runoff generation and water table fluctuations in blanket peat: evidence from UK data spanning the dry summer of 1995. *Journal of Hydrology,* **221**, 141-160.

Farmer, R. & Nisbet, T. (2004). An overview of forest management and change with respect to environmental protection in the UK. *Hydrology and Earth System Sciences,* **8**, 279-285.

Fellman, J.B., D'Amore, D.V. & Hood, E. (2008). An evaluation of freezing as a preservation technique for analyzing dissolved organic C, N and P in surface water samples. *Science of the Total Environment,* **392**, 305-312.

Ferguson, R.I., Grieve, I.C. & Harrison, D.J. (1991). Disentangling Land-Use Effects on Sediment Yield from Year to Year Climatic Variability. *Sediment and Stream Water Quality in A Changing Environment : Trends and Explanation,* **203**, 13-20.

Forestry Commission (1991). *Soft Ground Harvesting: review of methods to minimise site damage. Internal Report*, Edinburgh.

Forestry Commission (2002). *Forest Ground Preparation. Information Note ODW 10.01*

Guidance accessed online 12/08/11

http://www.forestry.gov/.uk/pdf/ODW1001.pdf/$FILE/ODW1001.pdf. Forestry Commission, Dumfries.

Forestry Commission (2003). *Forests and water guidelines*, Edinburgh.

Forestry Commission (2009). *Galloway Forest District Strategic Plan 2009 - 2013*. Forestry Commission Scotland, Edinburgh.

Forestry Commission (2011). *Forestry Statistics 2010*. Forestry Commission, Edinburgh.

Fraga, M.I., Romero-Pedreira, D., Souto, M., Castro, D. & Sahuquillo, E. (2008). Assessing the impact of wind farms on the plant diversity of blanket bogs in the Xistral Mountains (NW Spain). *Mires and Peat,* **4**.

Francis, I.S. & Taylor, J.A. (1989). The Effect of Forestry Drainage Operations on Upland Sediment Yields - A Study of 2 Peat-Covered Catchments. *Earth Surface Processes and Landforms,* **14**, 73-83.

Freeman, C., Evans, C.D., Monteith, D.T., Reynolds, B. & Fenner, N. (2001). Export of organic carbon from peat soils. *Nature,* **412**, 785-785.

Freeman, C., Fenner, N., Ostle, N.J., Kang, H., Dowrick, D.J., Reynolds, B. *et al.* (2004). Export of dissolved organic carbon from peatlands under elevated carbon dioxide levels. *Nature,* **430**, 195-198.

Freeman, C., Ostle, N. & Kang, H. (2001). An enzymic 'latch' on a global carbon store. *Nature,* **409**, 149-149.

Garnett, M.H. & Stevenson, A.C. (2004). Testing the use of bomb radiocarbon to date the surface layers of blanket peat. *Radiocarbon,* **46**, 841-851.

Giller, P.S. & O'Halloran, J. (2004). Forestry and the aquatic environment: studies in an Irish context. *Hydrology and Earth System Sciences,* **8**, 314-326.

Glatzel, S., Kalbitz, K., Dalva, M. & Moore, T. (2003). Dissolved organic matter properties and their relationship to carbon dioxide efflux from restored peat bogs. *Geoderma,* **113**, 397-411.

Gorham, E. (1991). Northern Peatlands: Role in the Carbon Cycle and Probable Responses to Climatic Warming. *Ecological Applications,* **1**, 182-195.

Grayson, R. & Holden, J. (2011). Continuous measurement of spectrophotometric absorbance in peatland streamwater in northern England: implications for understanding fluvial carbon fluxes. *Hydrological Processes,* , n/a-n/a.

Grieve, I.C. (1984). Concentrations and Annual Loading of Dissolved Organic-Matter in A Small Moorland Stream. *Freshwater Biology,* **14**, 533-537.

Grieve, I.C. (1990). Seasonal, Hydrological, and Land Management Factors Controlling Dissolved Organic-Carbon Concentrations in the Loch Fleet Catchments, Southwest Scotland. *Hydrological Processes,* **4**, 231-239.

Grieve, I.C. (1991). *Dissolved Organic-Carbon Trends in Small Streams, Land-Use Effects and Models of Temporal Variation*.

Grieve, I.C. (1994). Dissolved Organic-Carbon Dynamics in 2 Streams Draining Forested Catchments at Loch Ard, Scotland. *Hydrological Processes,* **8**, 457-464.

Grieve, I.C. & Gilvear, D. (2008). Effects of wind farm construction on concentrations and fluxes of dissolved organic carbon and suspended sediment from peat catchments at Braes of Doune, central Scotland. *Mires and Peat,* **4**.

Grieve, I.C. & Marsden, R.L. (2001). Effects of forest cover and topographic factors on TOC and associated metals at various scales in western Scotland. *The Science of the total environment,* **265**, 143-151.

Haigh, M. (2006). Environmental change in headwater peat wetlands, UK. *Environmental Role of Wetlands in Headwaters,* **63**, 237-255.

Haitzer, M., Abbt-Braun, G., Traunspurger, W. & Steinberg, C. (1999). Effects of humic substances on the bioconcentration of polycyclic aromatic hydrocarbons: Correlations with spectroscopic and chemical properties of humic substances. *Environmental Toxicology and Chemistry,* **18**, 2782-2788.

Hamilton, A., Legg, C. & Zhaohua, L. (1997). Mire research in north-west scotland: A view from the front. *Blanket mire degradation: causes, consequences and challenges* (eds J.H. Tallis, R. Meade & P.D. Hulme), pp. 47-53. Macaulay Land Use Research Institute, Aberdeen, UK.

Harriman, R., Watt, A.W., Christie, A.E.G., Moore, D.W., McCartney, A.G. & Taylor, E.M. (2003). Quantifying the effects of forestry practices on the recovery of upland streams and lochs from acidification. *The Science of the total environment,* **310**, 101-111.

Helliwell, R., Ferrier, R., Johnston, L., Goodwin, J. & Doughty, R. (2001). Land use influences on acidification and recovery of freshwaters in Galloway, south-west Scotland. *Hydrology and Earth System Sciences,* **5**, 451-458.

Holden, J. & Burt, T.P. (2003a). Hydrological studies on blanket peat: the significance of the acrotelm-catotelm model. *Journal of Ecology,* **91**, 86-102.

Holden, J. & Burt, T.P. (2003b). Runoff production in blanket peat covered catchments. *Water Resources Research,* **39**, 1191.

Holden, J., Chapman, P.J. & Labadz, J.C. (2004). Artificial drainage of peatlands: hydrological and hydrochemical process and wetland restoration. *Progress in Physical Geography*, **28**, 95-123.

Holden, J., Evans, M.G., Burt, T.P. & Horton, M. (2006). Impact of land drainage on peatland hydrology. *Journal of environmental quality,* **35**, 1764-1778.

Holl, B.S., Fiedler, S., Jungkunst, H.F., Kalbitz, K., Freibauer, A., Drosler, M. *et al.* (2009). Characteristics of dissolved organic matter following 20 years of peatland restoration. *The Science of the total environment*, **408**, 78-83.

Hongve, D. & Akesson, G. (1996). Spectrophotometric determination of water colour in Hazen units. *Water research*, **30**, 2771-2775.

Hope, D., Billett, M.F. & Cresser, M.S. (1994). A Review of the Export of Carbon in River Water - Fluxes and Processes. *Environmental Pollution,* **84**, 301-324.

Hope, D., Billett, M.F. & Cresser, M.S. (1997). Exports of organic carbon in two river systems in NE Scotland. *Journal of Hydrology,* **193**, 61-82.

Hope, D., Billett, M.F., Milne, R. & Brown, T.A.W. (1997). Exports of organic carbon in British rivers. *Hydrological Processes,* **11**, 325-344.

Hotta, N., Kayama, T. & Suzuki, M. (2007). Analysis of suspended sediment yields after low impact forest harvesting. *Hydrological Processes,* **21**, 3565-3575.

Hulme, P.D. & Birnir, R. (1997). Grazing-induced degradation of blanket mire: Its measurement and management. *Blanket mire degradation: causes, consequences and* *challenges* (eds J.H. Tallis, R. Meade & P.D. Hulme), pp. 163-173. Macaulay Land Use Research Institute, Aberdeen.

Hutchings, T.R., Moffat, A.J. & French, C.J. (2002). Soil compaction under timber harvesting machinery: a preliminary report on the role of brash mats in its prevention. *Soil Use and Management,* **18**, 34-38.

Jaffrain, J., Gerard, F., Meyer, M. & Ranger, J. (2007). Assessing the quality of dissolved organic matter in forest soils using ultraviolet absorption spectrophotometry. *Soil Science Society of America Journal*, **71**, 1851-1858.

Johnson, R.C. (1991). *Effects of upland afforestation on water resources: The Balquhidder experiment 1981 - 1991*. Wallingford, UK.

Jones, C.R. & Eiser, J.R. (2009). Identifying predictors of attitudes towards local onshore wind development with reference to an English case study. *Energy Policy,* **37**, 4604-4614.

Joosten, H. & Clarke, D. (2002). ***Wise use of mires and peatlands - Background and principles including a framework for decision making***. International Mire Conservation Group and, Finland.

Kalbitz, K., Schmerwitz, J., Schwesig, D. & Matzner, E. (2003). Biodegradation of soil-derived dissolved organic matter as related to its properties. *Geoderma,* **113**, 273-291.

Kalbitz, K., Solinger, S., Park, J., Michalzik, B. & Matzner, E. (2000). Controls on the dynamics of dissolved organic matter in soils: A review. *Soil Science,* **165**, 277-304.

Kirby, C., Newson, M.D. & Gilman, K. (1991). *Plynlimon Research: The First Two Decades*. Wallingford, UK.

Labadz, J.C., Burt, T.P. & Potter, A.W.R. (1991). Sediment Yield and Delivery in the Blanket Peat Moorlands of the Southern Pennines. *Earth Surface Processes and Landforms*, **16**, 255-271.

Laiho, R. (2006). Decomposition in peatlands: Reconciling seemingly contrasting results on the impacts of lowered water levels. *Soil Biology & Biochemistry,* **38**, 2011-2024.

Laudon, H., Hedtjarn, J., Schelker, J., Bishop, K., Sorensen, R. & Agren, A. (2009). Response of Dissolved Organic Carbon following Forest Harvesting in a Boreal Forest. *Ambio,* **38**, 381-386.

Littlewood, I.G. (1992). *Estimating contaminant loads in rivers: a review. Institute of Hydrology*. CEH, Wallingford.

Lofgren, S. & Zetterberg, T. (2011). Decreased DOC concentrations in soil water in forested areas in southern Sweden during 1987-2008. *Science of the Total Environment,* **409**, 1916-1926.

Maitland, P.S., Newson, M.D. & Best, G.A. (1990). *The impact of afforestation and forestry practice on freshwater habitats*. Nature Conservancy Council, Peterborough, UK.

Marc, V. & Robinson, M. (2007). The long-term water balance (1972-2004) of upland forestry and grassland at Plynlimon, mid-Wales. *Hydrology and Earth System Sciences,* **11**, 44-60.

Marschner, B. & Kalbitz, K. (2003). Controls of bioavailability and biodegradability of dissolved organic matter in soils. *Geoderma*, **113**, 211-235.

Martinez, E., Sanz, F., Pellegrini, S., Jimenez, E. & Blanco, J. (2009). Life-cycle assessment of a 2-MW rated power wind turbine: CML method. *International Journal of Life Cycle Assessment*, **14**, 52-63.

McCartney, A., Harriman, R., Watt, A., Moore, D., Taylor, E., Collen, P. *et al.* (2003). Long-term trends in pH, aluminium and dissolved organic carbon in Scottish fresh waters; implications for brown trout (Salmo trutta) survival. *Science of the Total Environment,* **310**, 133-141.

McDowell, W. & Likens, G. (1988). Origin, Composition, and Flux of Dissolved Organic-Carbon in the Hubbard Brook Valley. *Ecological Monographs*, **58**, 177-195.

Meyer, J.L. & Tate, C.M. (1983). The Effects of Watershed Disturbance on Dissolved Organic-Carbon Dynamics of A Stream. *Ecology,* **64**, 33-44.

Milne, R. & Brown, T.A. (1997). Carbon in the vegetation and soils of Great Britain. *Journal of environmental management,* **49**, 413-433.

Mitchell, J.T., Grace, J. & Harrison, G.P. (2010). CO_2 payback time for a wind farm on afforested peatland in the UK. *Mires and Peat,* **4**.

Monteith, D.T., Stoddard, J.L., Evans, C.D., de Wit, H.A., Forsius, M., Hogasen, T. *et al.* (2007). Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry. *Nature,* **450**, 537-540.

Moore, S., Gauci, V., Evans, C.D. & Page, S.E. (2011). Fluvial organic carbon losses from a Bornean blackwater river. *Biogeosciences,* **8**, 901-909.

Murray, H. (2012). *Assessing the impact of windfarm-related disturbance on streamwater carbon, phosphorus and nitrogen dynamics: a case study of Whitelee catchments*.

Nayak, D.R., Miller, D., Nolan, A., Smith, P. & Smith, J. (2008). *Calculating carbon savings from wind farms on Scottish peat lands - A New Approach*.

Neal, C., Fisher, R., Smith, C.J., Hill, S., Neal, M., Conway, T. *et al.* (1992). The Effects of Tree Harvesting on Stream-Water Quality at An Acidic and Acid-Sensitive Spruce Forested Area - Plynlimon, Mid-Wales. *Journal of Hydrology,* **135**, 305-319.

Neal, C., Reynolds, B., Adamson, J., Stevens, P., Neal, M., Harrow, M. *et al.* (1998). Analysis of the impacts of major anion variations on surface water acidity particularly with regard to conifer harvesting: Case studies from Wales and Northern England RID G-6292-2011. *Hydrology and Earth System Sciences,* **2**, 303-322.

Neal, C., Reynolds, B., Neal, M., Pugh, B., Hill, L. & Wickham, H. (2001). Long-term changes in the water quality of rainfall, cloud water and stream water for moorland, forested and clear-felled catchments at Plynlimon, mid-Wales. *Hydrology and Earth System Sciences,* **5**, 459-476.

Neal, C., Reynolds, B., Neal, M., Wickham, H., Hill, L. & Williams, B. (2004). The impact of conifer harvesting on stream water quality: the Afon Hafren, mid-Wales. *Hydrol Earth Syst Sci,* **8**, 503-520.

Neal, C., Reynolds, B., Wilkinson, J., Hill, T., Neal, M., Hill, S. *et al.* (1998). The impacts of conifer harvesting on runoff water quality: a regional survey for Wales. *Hydrology and Earth System Sciences,* **2**, 323-344.

Neal, C., Smith, C.J. & Hill, S. (1992). *Forestry impact on upland water quality*. IOH, Wallingford.

Neal, C., Davies, H. & Neal, M. (2008). Water quality, nutrients and the water framework directive in an agricultural region: The lower Humber Rivers, northern England. *Journal of Hydrology,* **350**, 232-245.

Nisbet, T.R. (2001). The role of forest management in controlling diffuse pollution in UK forestry. *Forest Ecology and Management,* **143**, 215-226.

Nisbet, T.R., Welch, D. & Doughty, R. (2002). The role of forest management in controlling diffuse pollution from the afforestation and clearfelling of two public water supply catchments in Argyll, West Scotland. *Forest Ecology and Management,* **158**, 141-154.

Nugent, C., Kanali, C., Owende, P.M.O., Nieuwenhuis, M. & Ward, S. (2003). Characteristic site disturbance due to harvesting and extraction machinery traffic on sensitive forest sites with peat soils. *Forest Ecology and Management,* **180**, 85-98.

Ohman, K., Seibert, J. & Laudon, H. (2009). An Approach for Including Consideration of Stream Water Dissolved Organic Carbon in Long Term Forest Planning. *Ambio,* **38**, 387-393.

Pawson, R.R., Lord, D.R., Evans, M.G. & Allott, T.E.H. (2008). Fluvial organic carbon flux from an eroding peatland catchment, southern Pennines, UK. *Hydrol Earth Syst Sci,* **12**, 625-634.

Peuravuori, J. & Pihlaja, K. (1997). Molecular size distribution and spectroscopic properties of aquatic humic substances. *Analytica Chimica Acta,* **337**, 133-149.

Prepas, E.E., Burke, J.M., Whitson, I.R., Putz, G. & Smith, D.W. (2006). Associations between watershed characteristics, runoff, and stream water quality: hypothesis development for watershed disturbance experiments and modelling in the Forest Watershed and Riparian Disturbance (FORWARD) project. *Journal of Environmental Engineering and Science,* **5**, S27-S37.

Preston, M.D., Eimers, M.C. & Watmough, S.A. (2011). Effect of moisture and temperature variation on DOC release from a peatland: Conflicting results from laboratory, field and historical data analysis. *Science of the Total Environment,* **409**, 1235-1242.

Pribyl, D.W. (2010). A critical review of the conventional SOC to SOM conversion factor. *Geoderma,* **156**, 75-83.

Ramchunder, S.J., Brown, L.E. & Holden, J. (2009). Environmental effects of drainage, drain-blocking and prescribed vegetation burning in UK upland peatlands. *Progress in Physical Geography,* **33**, 49-79.

Ray, D., White, I.M.S. & Pyatt, D.G. (1992). The Effect of Ditches, Slope and Peat Thickness on the Water Regime of A Forested Gley Soil. *Soil Use and Management,* **8**, 105-111.

Rees, R. (1989). Soil effects on water chemistry in 3 adjacent upland streams at Glendye in northeast Scotland. *Water research,* **23**, 511-517.

Reid, L.M. & Dunne, T. (1984). Sediment Production from Forest Road Surfaces. *Water Resources Research*, **20**, 1753-1761.

Reynolds, S.E., Kneale, P.E. & McDonald, A.T. (1996). Quantifying the store of water soluble colour in upland peaty soils: The effect of forestry. *Scottish Forestry,* **50**, 22-30.

Robinson, M. (1985). The Hydrological Effects of Moorland Gripping - A Reappraisal of the Moor House Research. *Journal of environmental management,* **21**, 205-211.

Robinson, M. & Blyth, K. (1982). The Effect of Forestry Drainage Operations on Upland Sediment Yields - A Case-Study. *Earth Surface Processes and Landforms,* **7**, 85-90.

Robroek, B.J.M., Smart, R.P. & Holden, J. (2010). Sensitivity of blanket peat vegetation and hydrochemistry to local disturbances. *Science of The Total Environment,* **408**, 5028-5034.

Roulet, N. & Moore, T.R. (2006). Environmental chemistry: Browning the waters. *Nature*, **444**, 283-284.

Rowson, J.G., Gibson, H.S., Worrall, F., Ostle, N., Burt, T.P. & Adamson, J.K. (2010). The complete carbon budget of a drained peat catchment. *Soil Use and Management,* **26**, 261-273.

Roy, R. & Campbell, P. (1997). Decreased toxicity of Al to juvenile Atlantic salmon (Salmo salar) in acidic soft water containing natural organic matter: A test of the free-ion model. *Environmental Toxicology and Chemistry,* **16**, 1962-1969.

Saari, P., Saarnio, S., Kukkonen, J.V.K., Akkanen, J., Heinonen, J., Saari, V. *et al.* (2009). DOC and N2O dynamics in upland and peatland forest soils after clear-cutting and soil preparation. *Biogeochemistry*, **94**, 217-231.

Scott, M.J., Jones, M.N., Woof, C. & Tipping, E. (1998). Concentrations and fluxes of dissolved organic carbon in drainage water from an upland peat system. *Environment international,* **24**, 537-546.

Scott, M., Jones, M., Woof, C., Simon, B. & Tipping, E. (2001). The molecular properties of humic substances isolated from a UK upland peat system - A temporal investigation. *Environment international,* **27**, 449-462.

Scottish Government *Abstract of Scottish Agricultural statistics 1982 to 2009*.

Scottish Natural Heritage (2003). *Wind Farms and Carbon Savings, SNH Technical Guidance Note. pp. 11*.

Smith, P., Smith, J., Flynn, H., Killham, K., Rangel-Castro, I., Foereid, B. *et al.* (2007). *ECOSSE: Estimating Carbon in Organic Soils - Sequestration and Emissions: Final Report*.

Soulsby, C., Gibbins, C., Wade, A., Smart, R. & Helliwell, R. (2002). Water quality in the Scottish uplands: a hydrological perspective on catchment hydrochemistry. *Science of the Total Environment,* **294**, 73-94.

Spencer, R.G.M., Bolton, L. & Baker, A. (2007). Freeze/thaw and pH effects on freshwater dissolved organic matter fluorescence and absorbance properties from a number of UK locations. *Water research,* **41**, 2941-2950.

Stewart, G.B., Pullin, A.S. & Coles, C.F. (2007). Poor evidence-base for assessment of windfarm impacts on birds. *Environmental Conservation,* **34**, 1-11.

Stoddard, J.L., Karl, J.S., Devinev, F.A., DeWalle, D.R., Driscoll, C.T., Herlihy, A.T. *et al.* (2003). *Response of surface water chemistry to the Clean Air Act Amendments of 1990, Report No. EPA 620/R-03/001.* United States Environmental Protection Agency, North Carolina.

Stott, T. (1999). Stream bank and forest ditch erosion: Preliminary responses to timber harvesting in mid-wales. *Fluvial Processes and Environmental Change* (eds A.G. Brown & T.A. Quine). John Wiley & Sons, Chichester.

Stott, T. (2005). Natural recovery from accelerated forest ditch and stream bank erosion five years after harvesting of plantation forest on Plynlimon, mid-Wales. *Earth Surface Processes and Landforms,* **30**, 349-357.

Stott, T., Leeks, G., Marks, S. & Sawyer, A. (2001). Environmentally sensitive plot-scale timber harvesting: impacts on suspended sediment, bedload and bank erosion dynamics. *Journal of environmental management*, **63**, 3-25.

Stott, T. & Mount, N. (2004). Plantation forestry impacts on sediment yields and downstream channel dynamics in the UK: a review. *Progress in Physical Geography,* **28**, 197-240.

Strack, M., Toth, K., Bourbonniere, R. & Waddington, J.M. (2011). Dissolved organic carbon production and runoff quality following peatland extraction and restoration. *Ecological Engineering,* **37**, 1998-2008.

Strack, M., Waddington, J.A., Bourbonniere, R.A., Buckton, E.L., Shaw, K., Whittington, P. *et al.* (2008). Effect of water table drawdown on peatland dissolved organic carbon export and dynamics. *Hydrological Processes,* **22**, 3373-3385.

Swank, W.T., Vose, J.M. & Elliott, K.J. (2001). Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment. *Forest Ecology and Management*, **143**, 163-178.

Tallis, J.H. (1997). The southern pennine experience: An overview of blanket mire degradation. *Blanket mire degradation: causes, consequences and challenges* (eds J.H. Tallis, R. Meade & P.D. Hulme), pp. 7-15. Macaulay Land Use Research Institute, Aberdeen, UK.

Tetzlaff, D., Malcolm, I.A. & Soulsby, C. (2007). Influence of forestry, environmental change and climatic variability on the hydrology, hydrochemistry and residence times of upland catchments. *Journal of Hydrology*, **346**, 93-111.

Tipping, E., Smith, E.J., Bryant, C.L. & Adamson, J.K. (2007). The organic carbon dynamics of a moorland catchment in NW England. *Biogeochemistry,* **84**, 171-189.

Tittensor, R.M. (2009). *From peat bog to conifer forest: An oral history of whitelee, its community and landscape* . Packard Publishing Ltd.

Townend, J., Shotbolt, L. & Anderson, R. (1997). Hydrological effects of forest plantations on blanket peat at rumster forest, caithness. *Blanket mire degradation: causes, consequences and challenges* (eds J.H. Tallis, R. Meade & P.D. Hulme), pp. 85-87. Macaulay Land Use Research Institute, Aberdeen, UK.

Traina, S.J., Novak, J. & Smeck, N.E. (1990). An Ultraviolet Absorbance Method of Estimating the Percent Aromatic Carbon Content of Humic Acids. *Journal of environmental quality*, **19**, 151-153.

Tranvik, L.J. & Jansson, M. (2002). Climate change (Communication arising): Terrestrial export of organic carbon. *Nature,* **415**, 861-862.

VANNOTE, R., MINSHALL, G., CUMMINS, K., SEDELL, J. & CUSHING, C. (1980). River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Sciences*, **37**, 130-137.

Vuorenmaa, J., Forsius, M. & Mannio, J. (2006). Increasing trends of total organic carbon concentrations in small forest lakes in Finland from 1987 to 2003. *Science of the Total Environment*, **365**, 47-65.

Waldron, S., Flowers, H., Arlaud, C., Bryant, C. & McFarlane, S. (2009). The significance of organic carbon and nutrient export from peatland-dominated landscapes subject to disturbance, a stoichiometric perspective. *Biogeosciences,* **6**, 363-374.

Waldron, S., Flowers, H., Arlaud, C., Bryant, C. & McFarlane, S. (2008). The significance of organic carbon and nutrient export from peatland-dominated landscapes subject to disturbance. *Biogeosciences Discuss,* , 1139-1174.

Wallage, Z.E. & Holden, J. (2010). Spatial and temporal variability in the relationship between water colour and dissolved organic carbon in blanket peat pore waters. *Science of the Total Environment,* **408**, 6235-6242.

Wallage, Z.E., Holden, J. & McDonald, A.T. (2006). Drain blocking: An effective treatment for reducing dissolved organic carbon loss and water discolouration in a drained peatland. *The Science of the total environment,* **367**, 811-821.

Walling, D.E. & Webb, B.W. (1981). Water quality. *Brritish Rivers* (ed J. Lewin). George Allen & Unwin, London.

Walling, D.E. & Webb, B.W. (1985). Estimating the Discharge of Contaminants to Coastal Waters by Rivers - some Cautionary Comments. *Marine pollution bulletin,* **16**, 488-492.

Warburton, J., Holden, J. & Mills, A.J. (2004). Hydrological controls of surficial mass movements in peat. *Earth-Science Reviews,* **67**, 139-156.

Webb, B.W., Phillips, J.M. & Walling, D.E. (2000). A new approach to deriving 'best-estimate' chemical fluxes for rivers draining the LOIS study area. *The Science of the total environment,* **251**, 45-54.

Weishaar, J.L., Aiken, G.R., Bergamaschi, B.A., Fram, M.S., Fujii, R. & Mopper, K. (2003). Evaluation of specific ultraviolet absorbance as an indicator of the chemical composition and reactivity of dissolved organic carbon. *Environmental science & technology,* **37**, 4702-4708.

Wilson, D., Alm, J., Laine, J., Byrne, K.A., Farrell, E.P. & Tuittila, E.S. (2009). Rewetting of Cutaway Peatlands: Are We Re-Creating Hot Spots of Methane Emissions? *Restoration Ecology,* **17**, 796-806.

Wilson, L., Wilson, J., Holden, J., Johnstone, I., Armstrong, A. & Morris, M. (2011). Ditch blocking, water chemistry and organic carbon flux: Evidence that blanket bog restoration reduces erosion and fluvial carbon loss. *Science of the Total Environment,* **409**, 2010-2018.

Worrall, F. & Adamson, J.K. (2008). The effect of burning and sheep grazing on soil water composition in a blanket bog: evidence for soil structural changes? *Hydrological Processes,* **22**, 2531-2541.

Worrall, F., Armstrong, A. & Adamson, J.K. (2007). The effects of burning and sheep-grazing on water table depth and soil water quality in a upland peat. *Journal of Hydrology,* **339**, 1-14.

Worrall, F., Burt, T. & Adamson, J. (2004). Can climate change explain increases in DOC flux from upland peat catchments? *The Science of the total environment,* **326**, 95-112.

Worrall, F., Burt, T., Adamson, J., Reed, M., Warburton, J., Armstrong, A. *et al.* (2007). Predicting the future carbon budget of an upland peat catchment. *Climatic Change,* **85**, 139-158.

Worrall, F., Burt, T. & Shedden, R. (2003). Long term records of riverine dissolved organic matter. *Biogeochemistry*, **64**, 165-178.

Worrall, F. & Burt, T.P. (2007). Flux of dissolved organic carbon from U.K. rivers. *Global Biogeochemical Cycles*, **21**.

Worrall, F. & Burt, T.P. (2005). Predicting the future DOC flux from upland peat catchments. *Journal of Hydrology,* **300**, 126-139.

Worrall, F. & Burt, T.P. (2008). The effect of severe drought on the dissolved organic carbon (DOC) concentration and flux from British rivers. *Journal of Hydrology*, **361**, 262-274.

Worrall, F. & Burt, T.P. (2010). Has the composition of fluvial DOC changed? Spatiotemporal patterns in the DOC-color relationship. *Global Biogeochemical Cycles*, **24**, GB1010.

Worrall, F., Burt, T.P. & Adamson, J. (2006). The rate of and controls upon DOC loss in a peat catchment. *Journal of Hydrology*, **321**, 311-325.

Worrall, F., Burt, T.P., Jaeban, R.Y., Warburton, J. & Shedden, R. (2002). Release of dissolved organic carbon from upland peat. *Hydrological Processes*, **16**, 3487-3504.

Worrall, F., Burt, T.P., Rowson, J.G., Warburton, J. & Adamson, J.K. (2009). The multi-annual carbon budget of a peat-covered catchment. *The Science of the total environment*, **407**, 4084-4094.

Worrall, F., Gibson, H.S. & Burt, T.P. (2007). Modelling the impact of drainage and drain-blocking on dissolved organic carbon release from peatlands. *Journal of Hydrology,* **338**, 15-27.

Worrall, F., Harriman, R., Evans, C.D., Watts, C.D., Adamson, J., Neal, C. *et al.* (2004). Trends in dissolved organic carbon in UK rivers and lakes. *Biogeochemistry,* **70**, 369-402.

Worrall, F., Burt, T. & Adamson, J. (2003). Controls on the chemistry of runoff from an upland peat catchment. *Hydrological Processes,* **17**, 2063-2083.

Worrall, F., Reed, M., Warburton, J. & Burt, T. (2003). Carbon budget for a British upland peat catchment. *The Science of the total environment,* **312**, 133-146.

Zaccone, C., Miano, T.M. & Shotyk, W. (2007). Qualitative comparison between raw peat and related humic acids in an ombrotrophic bog profile. *Organic Geochemistry,* **38**, 151-160.

Zak, D. & Gelbrecht, J. (2007). The mobilisation of phosphorus, organic carbon and ammonium in the initial stage of fen rewetting (a case study from NE Germany). *Biogeochemistry,* **85**, 141-151.

Ziemer, R.R. (1981). Storm Flow Response to Road Building and Partial Cutting in Small Streams of Northern California. *Water Resources Research,* **17**, 907-917.