IMPACTS OF LAND USE CHANGES AND LAND MANAGEMENT PRACTICES ON UPLAND CATCHMENT SEDIMENT DYNAMICS: PONTBREN, MID-WALES

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ABSTRACT

There is growing concern that the adoption of intensive agricultural land management practices in upland areas of the UK over the past 50-60 years may have affected hydrological responses and sediment transfer regimes in river catchments and could, therefore, be contributing to increased levels of flood risk and ecological disturbance. However, recent evidence from a research catchment at Pontbren in mid-Wales indicates that the implementation of a more sustainable livestock farming strategy could help to mitigate some of these impacts, raising the possibility that strategic land use planning could be used as a cost-effective, multi-functional river management option. The impacts of historical land use changes and land management practices on contemporary sediment dynamics in the study area are explored in this thesis through a system approach which acknowledges the importance of interrelationships between hydrological and geomorphological processes. Results from hydrological experiments and modelling exercises are used to inform analyses of spatial and temporal variation in sediment production and transfer from a variety of potential sources. Grazed, agriculturally-improved pastures were found to supply fine material to stream channels *via* both surface runoff and field drains. In particular, drain-derived sediment is likely to represent an important component of the total fine sediment yield in subcatchments where agricultural intensification has been widespread. Agricultural drainage ditches were also found to act as sources of sediment in such areas, along with eroding channel banks. Sediment production from bank sources may relate to historical changes in peak flows caused by agricultural intensification. Stream sediment yields are strongly related to differences in sediment supply from the aforementioned sources

and could therefore be reduced by limiting mobilisation at the point of origin within the landscape. In terms of channel-derived material, this could be achieved through peak flow reductions associated with woodland and hedgerow restoration.

ACKNOWLEDGEMENTS

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This thesis is dedicated to “Jack” Morton.

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1 INTRODUCTION

1.1 Introduction

It is widely acknowledged that land use changes and land management practices can influence sediment dynamics in river systems (Walling, 1999; Gregory, 2006). Anthropogenic activities such as mineral extraction, cultivation, urbanisation, afforestation and deforestation have been shown to affect the intensity and spatial distribution of erosion and sediment supply within catchments, often modifying sediment yields and instigating morphological responses downstream (e.g. Surell, 1841; Leopold, 1968; Trimble, 1983; Lewin and Macklin, 1987; Clark and Wilcock, 2000; Kondolf *et al*., 2002; Nelson and Booth, 2002; Gomez *et al*., 2003; Gaeuman *et al*., 2005). Such effects can have important implications for flood risk, as aggradation caused by enhanced sediment delivery to storage zones can reduce conveyance, thereby increasing water levels for a given discharge (e.g. James, 1999; Stover and Montgomery, 2001; Lane *et al*., 2007). Artificially elevated sediment loads can also degrade river habitats and reduce survival rates amongst fish and invertebrate populations (Marks and Rutt, 1997; Theurer *et al*., 1998; Suttle *et al*., 2004).

In Britain, geomorphological sensitivity to changes in land use and land management is typically greatest in upland environments, where a combination of steep topography, a relatively harsh climate and an abundance of non-cohesive glacial and fluvio-glacial sedimentary deposits beneath thin surface soils enhances the potential for erosion and channel adjustment (Harvey, 2001). This vulnerability has been extensively highlighted over the past 30 years by research into the impacts of commercial forestry on sediment dynamics in upland catchments (Stott and Mount, 2004). Studies have shown that moorland ditching, road construction and clearfelling activities associated with the practice can increase sediment yields and morphological activity in streams draining affected areas (e.g. Painter *et al*., 1974; Newson, 1980a; Robinson, 1980; Robinson and Blyth, 1982; Murgatroyd and Ternan, 1983; Burt *et al*., 1984; Petts, 1984; Duck, 1985; Moore and Newson, 1986; Stott *et al*., 1986; Ferguson and Stott, 1987; Francis and Taylor, 1989; Leeks, 1992; Stott, 1997a; b; Stott, 1999; Stott *et al*., 2001).

Research into the effects of recent changes in land use and land management associated with agriculture on sediment dynamics in British upland catchments has been comparatively limited. Studies have primarily focussed on direct links between increased livestock grazing and soil erosion (e.g. Tivy, 1957; Thomas, 1965; Evans, 1977; Birnie and Hulme, 1990), while little attention has been paid to the wider, catchment-scale geomorphological implications of agricultural expansion and intensification over the past 50-60 years. However, there is now a growing body of evidence which suggests that factors related to grassland improvement and consequent increases in stocking densities facilitate the transfer of significant amounts of eroded sediment from the land surface to watercourses (e.g. Collins *et al*., 1997a, b; Van der Post *et al*., 1997; Hatfield *et al*., 2008; Hatfield and Maher, 2009), and may enhance morphological activity within upland channel networks (e.g. Riley *et al*., 2003). Resultant changes in sediment yields could be contributing to flood inundation and environmental problems in river corridors downstream and, therefore, improved understanding of the processes and mechanisms that control the output of sediment from upland catchments affected by agricultural intensification is required in order to assess these risks and evaluate possible control strategies.

1.2 Aims and objectives

The research presented in this thesis aims to address knowledge gaps regarding the effects of land use changes and land management practices associated with British upland agriculture on catchment sediment dynamics. Field experiments, supported by desk- and laboratory-based analyses at the University of Nottingham, were undertaken in an instrumented upland catchment at Pontbren in mid-Wales to achieve the following objectives:

1) To identify sediment sources and transfer mechanisms that may have been created or affected by agricultural intensification in the British uplands.

2) To assess the significance of these sources, and identify controls of their activity and on their downstream influence.

3) To determine the extent to which insights obtained through (1) and (2) can explain spatial and temporal variation in river sediment yields.

4) To evaluate the utility of strategic land use changes and agricultural land management as methods of controlling sediment yields from British upland catchments.

The project forms a component of a major study into the prediction and management of flood risk by the Flood Risk Management Research Consortium (FRMRC): an interdisciplinary partnership of academic and industrial researchers from across the UK. The syndicate aims to develop tools and techniques to support more accurate flood forecasting and warning, improve flood management infrastructure, and reduce flood risk to people, property and the environment (Huntington *et al*., 2004; FRMRC, 2008).

1.3 Thesis structure

The thesis is structured as follows:

Chapter 2 documents historical developments and trends in British upland agriculture. The potential effects of these changes on erosion and sediment transfer are hypothesised following a literature review and interpretation of recent results from an affiliated FRMRC investigation in the Pontbren area into the hydrological impacts of upland agricultural practices. This information is used to identify sediment sources that could have been created or affected by factors associated with agricultural intensification in the study catchment.

Chapters 3 and 4 detail experiments undertaken to quantify the amount and calibre of sediment generated from: (i) a grazed, agriculturally improved pasture; and (ii) stream banks in the Pontbren area. Factors and processes that control the transfer of sediment from these sources to the channel network are explored.

Chapters 5 and 6 report results from studies of both coarse and fine sediment transport in the channel network. Spatial and temporal variation in sediment yields and sediment size characteristics are analysed in light of the process insights reported in Chapters 3 and 4 to assess the significance of sediment sources in the study catchment, and to evaluate the influence of land use changes and agricultural land management practices on catchment sediment dynamics.

Chapter 7 summarises the principal findings of the project and concludes by discussing their implications for sediment management. Topics for further research are also suggested.

Linkages between the various research components are described in Figure 1.1. The diagram illustrates known and potential process-response interactions relating to agricultural intensification in upland areas of Britain, and identifies the relevant chapters within the thesis in which they are explored in greater detail.

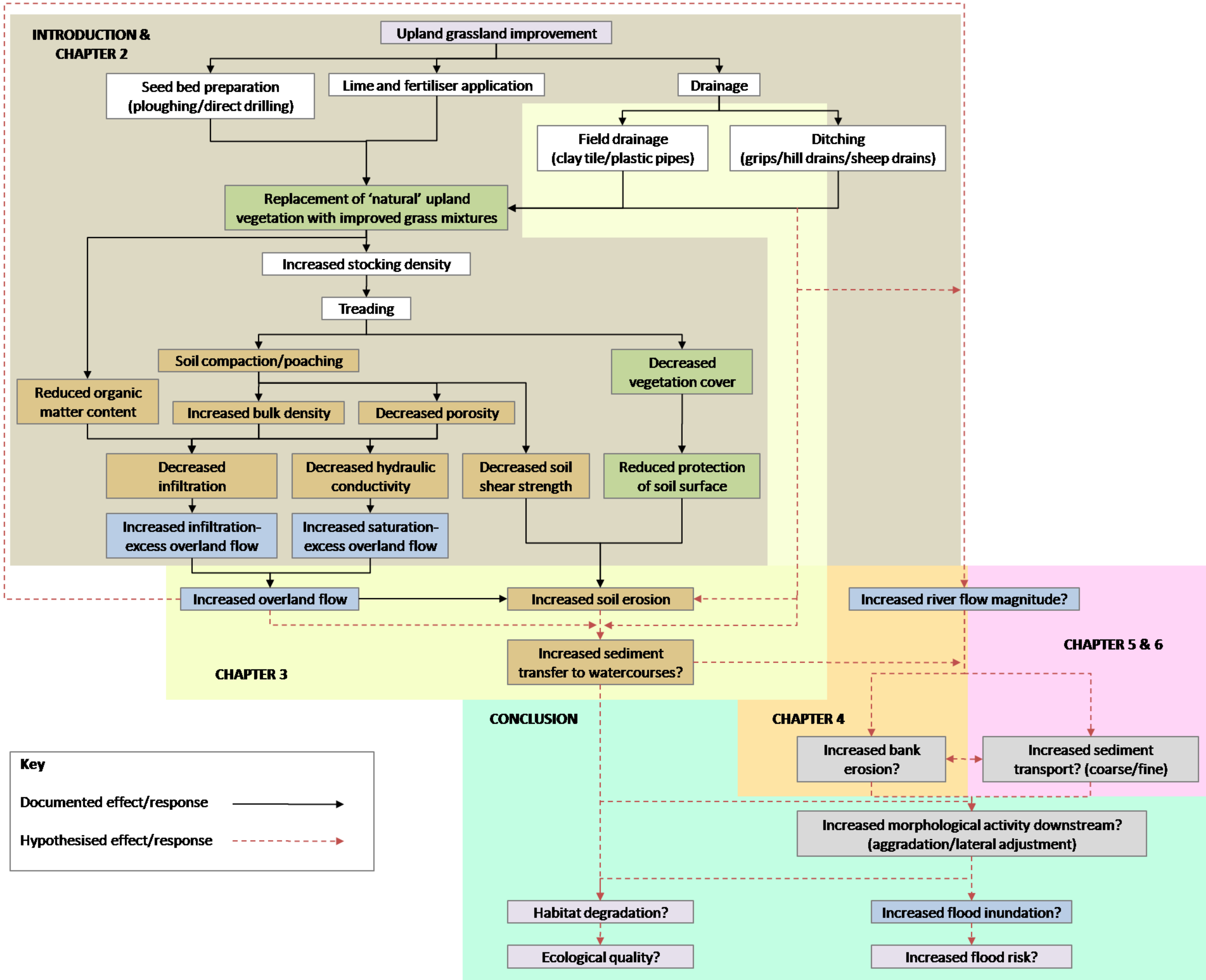


Figure 1.1 Thesis structure based on documented and hypothesised process-response linkages relating to agricultural intensification in upland Britain.

2 POTENTIAL EFFECTS OF AGRICULTURE ON SEDIMENT DYNAMICS IN BRITISH UPLAND CATCHMENTS: BACKGROUND TO RESEARCH AT PONTBREN

2.1 Introduction

This chapter reviews the history of agricultural development in the British uplands and identifies known geomorphological effects associated with post-World War II increases in livestock grazing. The results of recently published studies, which suggest that impacts could be more complex and far-reaching than previously considered, are then presented, and mechanisms that might explain the findings are hypothesised. These ideas the form basis for experimental research at the Pontbren research site in mid-Wales, to which background information is provided in the second half of the chapter.

2.2 Agricultural intensification in the British uplands

The relatively harsh climate, steep slopes, poor drainage and thin, acidic soils of the British uplands have historically restricted agricultural productivity and limited farmers to extensive livestock grazing. However, concerns over self-sufficiency in food production following the end of World War II prompted a series of wholesale reforms in British agriculture that have resulted in major changes to the rural landscape (O'Connell, 2007). The Hill Farming Act (UK, 1946) encouraged the intensification of livestock (predominantly sheep) grazing in upland and marginal regions by providing capital grants for grassland improvement, buildings, fencing and machinery. The investment facilitated the conversion of large areas of moorland and rough grazing land to permanent pasture by drainage, lime and fertiliser application, ploughing and reseeding with rye grass (*Lolium* spp.) and white clover

(*Trifolium repens*) (Newbould, 1975; Wathern *et al*., 1988). The practice was widespread throughout Britain but was particularly prevalent in upland areas of Wales, where economic pressures associated with a smaller average hill farm size compared to those in northern England and Scotland made pasture improvement essential (Eadie, 1984). While the exact spatial extent of upland grassland improvement is difficult to quantify due to variation in the level of improvement and the deterioration of swards back to pre-improvement conditions following neglect (Roberts *et al*., 1990), it is estimated that 100,000 ha of rough pasture (approximately 20% of the Welsh uplands) were improved in the 25 years prior to 1978 (Jones, 1978).

Field drainage to remove excess water from soils is a key element of most upland grassland improvement schemes. The technique was originally introduced into Britain during Roman times but has only become widespread over the last 200 years (Robinson, 1986a). The invention and subsequent exemption from tax of clay drainage pipes in the early nineteenth century initiated a period of intensive drainage in which an estimated 50,000 km^2 of England and Wales were underdrained (Trafford, 1970; Robinson, 1986a). Figure 2.1 illustrates how drainage rates were highest in the north and west during this period as farmers attempted to overcome environmental hindrances such as high rainfall and the dominance of low-permeability peat and clay soils which had historically constrained agricultural productivity in these regions (Robinson, 1986a). However, a downturn in the domestic agricultural industry in the late nineteenth century caused a major reduction in the number of new field drainage projects (Nicholson, 1943) until government assistance in the form of grants and free technical advice sparked a renewed period of activity after 1940 (Robinson and Armstrong, 1988). Drainage

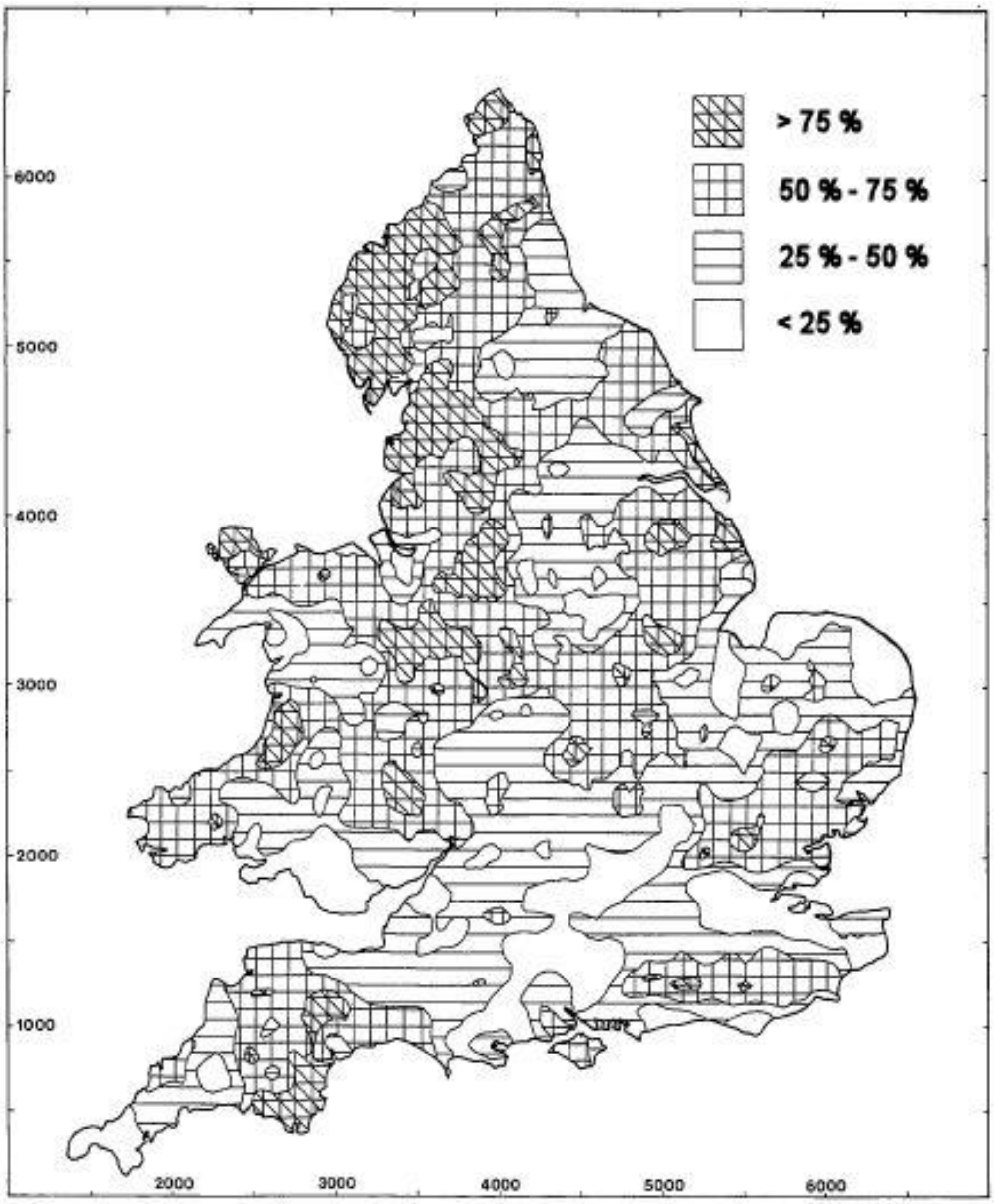


Figure 2.1 Distribution of land drained prior to 1939 in England and Wales (modified from Robinson, 1986a, p.83).

rates peaked at around 100,000 ha yr^{-1} during the 1970s, before activity subsided again following the withdrawal of government support funds in 1984 (Robinson and Armstrong, 1988; Armstrong and Harris, 1996). The majority of new underdrainage schemes in upland areas of Wales during the 1970s were installed to reduce the occurrence of spring water problems, where water moves laterally downhill over impermeable subsoils on steep slopes and emerges due to a sudden shallowing of the soil or flow convergence as a result of local topography (Robinson and Armstrong, 1988). Such drainage aims to intercept and remove 'foreign' water to nearby ditches and streams before it is able to reach the surface (Robinson and Armstrong, 1988).

Open drainage (in the form of plough-cut channels often referred to as grips, hill drains or sheep drains) was more common in peat-covered upland areas during the post-World War II period for economic reasons (Robinson, 1990). Open drains are usually 0.4-0.5 m deep, 15-35 m apart, and either run along contours or in a 'herring-bone' pattern (where short lateral feeder channels supply a central ditch which heads downhill; Stewart and Lance, 1983). The technique aimed to accelerate the rate at which surface runoff was removed from the land surface and to reduce the level of the water table in order to improve vegetation quality and growth rates to support livestock grazing (Stewart and Lance, 1983). While the practice was extensive, much less is known about the timing and spatial distribution of gripping compared to that of pipe drain installation in England and Wales due to data access restrictions designed to ensure confidentiality for farmers and landowners who received drainage grants (Robinson, 1990). However, Robinson (1990) in a study of drainage in Yorkshire identifies bursts of open drainage activity during the 1940s, 1950s and 1970s and suggests that over 50% of land in Arkengarthdale and the headwaters of the River Nidd were drained using this method. With concerns over the ecological damage caused by moorland drainage, the practice is now actively discouraged (Holden *et al*., 2004). Indeed, financial support is now available to help farmers and landowners to block existing open drains in upland areas (Defra, 2005).

Further political support for agricultural development in upland areas was provided following the introduction of livestock headage payments under European Economic Community (EEC) Directive 268/75 (EEC, 1975) on mountain and hill farming and farming in Less-Favoured Areas (LFAs). The scheme provided aid to farmers in areas unsuitable for arable crops and where agricultural production is severely limited by a combination of soil, relief, aspect and climate (Defra, 2008). This financial incentive, combined with widespread grassland improvement, resulted in an increase in sheep numbers throughout the UK, but population expansion was particularly remarkable in Wales and northern England (Fuller and Gough, 1999). Historical agricultural records (National Assembly for Wales, 2001; 2002; Welsh Assembly Government, 2007) reveal changes in the total number of sheep in Wales between 1867 and 2005 (Figure 2.2). The data highlight rapid population expansion following the end of World War II, with total sheep numbers increasing from 3.87 million in 1950 to a peak of 11.77 million in 1999. This increase was concentrated in upland areas, with 88% of the total Welsh flock estimated to be located in LFAs in 1995 (National Sheep Association, 1995). Although total sheep numbers have declined slightly since the late 1990s through a combination of a switch from headage payments to area-based subsidies following the introduction of Agenda 2000 (EC, 1998) and the outbreak of foot-and-mouth disease in the UK in 2001, stocking levels in Wales remain considerably higher than at almost all times in recorded history.

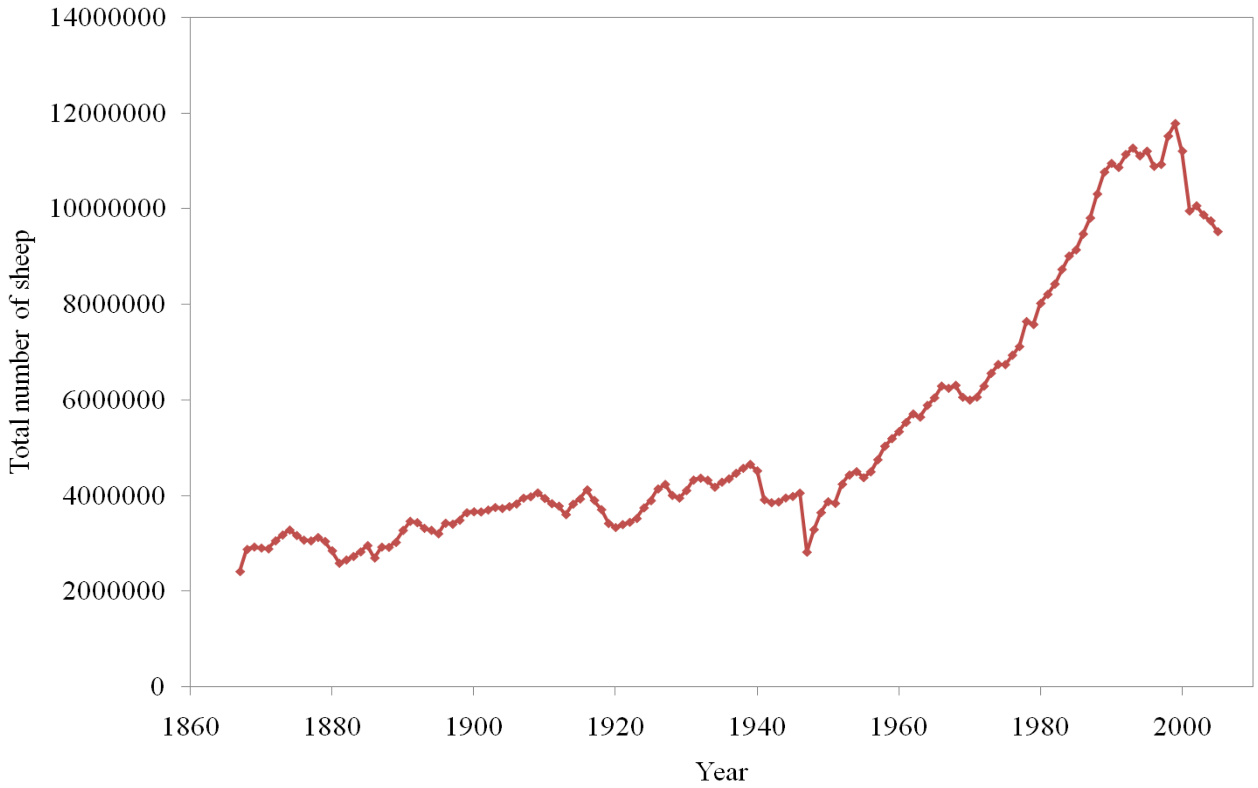


Figure 2.2 Historical changes in the sheep population of Wales (1867-2006). Graph constructed using published agricultural statistics (National Assembly of Wales, 2001; 2002; Welsh Assembly Government, 2007).

2.3 Geomorphological impacts of agricultural intensification in the British uplands

Modest peak rainfall intensities and a protective cover of relatively dense vegetation tend to limit natural soil erosion rates in upland Britain (Lewin *et al*., 1974; Moore and Newson, 1986). Nevertheless, recent national surveys have estimated that 2 % of land in upland England and Wales (McHugh *et al*., 2002) and 12% of upland Scotland are affected by soil erosion (Grieve, 1995), and the spatial extent of actively eroding land can be even greater locally. For example, Thomas (1965) calculated that 19 % of valley slopes studied in the Plynlimon area of mid-Wales were subject to soil loss.

Livestock grazing, recently intensified as a result of the drivers and policies outlined in Section 2.2, has been identified as a key cause of this erosion in a number of regions including mid-Wales (Thomas, 1965), the Peak District (Evans, 1977), the Southern Uplands (Tivy, 1957) and the Shetland Islands (Birnie and Hulme, 1990). Sheep can damage or even destroy surface vegetation to create areas of bare soil which are vulnerable to attack by sub-aerial processes (Evans, 1998; Sansom, 1999). Stocking density, soil wetness, altitude, aspect, time of year, and the length of time that livestock are allowed to graze a site can all influence the severity of erosion (Johns, 1998) and while improved pastures are generally more resistant to erosion than areas of 'natural' moorland, they are nevertheless prone to soil loss, especially when vegetation cover is damaged by trampling, the local gradient is steep, or ploughing and reseeding is undertaken (Costin, 1980; James and Alexander, 1998).

Intensive grazing, and consequent soil erosion, in upland areas has been linked with a decline in upland habitat quality and increased farm management costs (e.g. Fuller and Gough, 1998; Hindmarch and Pienkowski, 2000; Henderson *et al*., 2004). While direct, local effects are important, it is also crucial to consider those effects associated with the transfer of eroded material away from the point of origin on the land surface (Warburton *et al*., 2003; Owens *et al*., 2005). As noted in the introduction to this thesis, there is mounting evidence that factors associated with agricultural intensification have not only increased the amount of soil erosion in the British uplands but also enhanced the supply of eroded sediment to watercourses. Analyses of lake bed sediment cores from sites in the Lake District have revealed large increases in the accumulation rate of sediment derived from catchment surface sources over the past 50-60 years that coincide with changes in stocking densities and grassland improvement activities upstream (Van der Post, 1997; Hatfield *et al*., 2008). Measured rates of recent sediment influx to Bassenthwaite Lake were found to be unprecedented over the scale of the mid-late Holocene (Hatfield and Maher, 2009), suggesting that the changes in land use and land management have had a major impact on sediment transfer within the affected systems. An analysis of suspended sediment samples using a composite fingerprinting approach has also shown that sediment derived from grazed pastures is an important, often dominant, component of the total suspended load of rivers in the Upper Severn basin (Collins *et al*., 1997a). This is despite the fact that large parts of the headwaters of the River Severn have been afforested for commercial timber production, a practice also considered to generate significant amounts of sediment (see Section 1.1). However, surprisingly little is known about the mechanisms and processes that control the transfer of sediment from intensively grazed pastures to channel networks in the British uplands (Bilotta *et al*., 2007; Stevens *et al*., 2008).

One potential sediment transfer pathway may be generated as a result of the effects of increased sheep numbers on the physical properties of soils. Increased bulk densities and reduced pore space and hydraulic conductivity have been widely reported in soils subjected to intensive grazing (Langlands and Bennett, 1973; Willatt and Pullar, 1983; Greenwood *et al*., 1997). Compaction of the soil surface due to trampling has been identified as a reason for statistically significant differences in rates of infiltration between grazed and ungrazed conditions (Gifford and Hawkins, 1978; Nguyen *et al*., 1998) and is common in grazed areas of upland Wales (Carroll *et al*., 2004a). Reduced organic matter content in soils under vegetation types associated with intensive grazing has also been shown to cause a decrease in soil porosity (Meyles *et al*., 2006). These effects can all lead to large increases in the volume and rapidity of surface runoff generated by rainfall in grazed pastures and this has been demonstrated in numerous studies at the plot scale (Heathwaite *et al*., 1989, 1990; James and Alexander, 1998; Elliot *et al*., 2002). This may enhance hydrological connectivity between the land surface and neighbouring streams and ditches (*c.f.* Heathwaite *et al*., 2005; Lane *et al*., 2006), thus facilitating the delivery to watercourses of fine sediment generated as a result of erosion caused by livestock.

Sediment transfer potential may be further strengthened by field drains, which have been shown to act as efficient pathways for sediment mobilised by surface erosion in arable and grassland catchments in lowland areas (e.g. Culley and Bolton, 1983; Culley *et al*., 1983; Kronvang *et al*., 1997; Russell *et al*., 2001). Sediment can pass down through the soil matrix following cracks and macropores generated during drainage pipe installation and by the subsequent drying effects of drainage on the soil (Walling *et al*., 2002). Foster *et al*. (2003) observed a four-fold increase in the annual amount of sediment supplied to a lake in Worcestershire following the installation of field drains in the 1960s. To date, however, the significance of their effects on catchment sediment dynamics in upland areas affected by agricultural intensification is unknown.

Drainage, along with increased levels of surface runoff, may also have implications for erosion and sediment transfer within channel networks. These could be direct, in the form of flow concentration and sediment mobilisation when ditches are excavated to assist pasture improvement (*c.f.* Newson, 1980a; Robinson, 1980), or indirect, through an increase in the erosive potential of flows in rivers and streams. Increased peak flows and reduced hydrological response times have been observed and modelled in catchments with drained peaty soils (e.g. Conway and Miller, 1960; Robinson, 1985; 1986b; 1990; Robinson *et al*., 1991; Dunn and Mackay, 1996; Holden *et al*., 2006). Holden *et al*. (2004) suggest these effects are caused by a disparity in the effectiveness of drainage to accelerate the transmission of storm runoff compared to its ability to increase soil moisture storage capacity through water table reduction. While both open and pipe drains are known to have a severely limited lateral influence in peat soils (Hudson and Roberts, 1982; Robinson and Newson, 1986; Stewart and Lance, 1991), they also transfer flow at much higher velocities than alternative routes through the soil matrix (Robinson, 1990).

A number of studies have found that drainage can moderate peak rates of runoff in stream networks and lengthen catchment response times (e.g. Burke, 1975a, 1975b; Newson and Robinson, 1983; Robinson, 1990). In some peaty soils, catchment and drainage characteristics enable water table lowering to such a degree that the water-retaining benefits of increased soil moisture storage capacity outweigh the effects of the expanded drainage network (Holden *et al*., 2004). Nevertheless, these effects may be short-lived as improved aeration and the drying of surface peat layers have been associated with increased soil bulk density as a result of shrinkage, decomposition and macropore collapse (Silins and Rothwell, 1998). In clay soils with slowly permeable lower horizons, drainage can increase soil moisture storage capacity and thus slow the rate of water movement (Newson and Robinson, 1983; Robinson, 1990). However, their drainage often involves an additional treatment known as 'moling', where a bullet-shaped piece of metal is dragged through the ground at depth to form additional subsurface tunnels (Robinson and Armstrong, 1988). This has been shown to increase the efficiency of drainage as surface water is able to move quickly through the series of cracks and fissures introduced by the technique, allowing runoff to pass through the drainage system into ditches and streams almost as rapidly as it would travel across the surface (Armstrong and Garwood, 1991).

At the large catchment scale, a number of studies have associated increased runoff, peak discharges and flood frequencies in rivers with particular features of agricultural intensification in upland areas, including the removal of natural moorland vegetation (Lewis, 1957), land drainage for grassland improvement (Howe *et al*., 1967; Higgs, 1987; Higgs and Petts, 1988) and higher stocking densities (Evans, 1990; Sansom, 1996). Given that the majority of erosion and sediment transport within upland channel networks is performed by large but infrequent flood events (Newson, 1980b), such effects could increase sediment yields and enhance morphology activity in headwater streams.

Hydrological evidence of increased peak flows caused by agricultural intensification in upland areas has, to date, been largely circumstantial and it has proved difficult to isolate signatures in long-term discharge records which relate to human activities from those associated with natural climate variability (Lane, 2003; Sullivan *et al*., 2004; Orr and Carling, 2006). Uncertainty in historical datasets also makes the detection of anthropogenic influences problematic (Beven *et al*., 2006). Nevertheless, support for the hypothesis is provided in the form of geomorphological evidence from Riley *et al*. (2003), who found that eroding stream banks, steeper bank angles, and areas of exposed bedrock on stream beds were more prevalent in New Zealand upland catchments where grassland was improved compared to those where it remained unmanaged. The findings indicate that factors associated with the development of upland areas for livestock grazing may increase the power and/or frequency of flows capable of performing erosion and sediment transport in headwater streams (*c.f.* Schumm, 1969). Such effects have been observed where other "ramped" (after Brunsden and Thornes, 1979) disturbances (e.g. urbanisation) have caused sustained alterations to the hydrological regime of rivers (e.g. Wolman and Schick, 1967; Roberts, 1989; Booth, 1990) and could have a major influence on channel morphology in British upland river systems, many of which are sensitive to relatively small changes in sediment supply and runoff (Lewin *et al*., 1988).

The preceding discussion illustrates that, although the effects of recent agricultural intensification on soil erosion in the British uplands are well known, little consideration has been given to the possible implications that associated changes in land use and land management practices could have for erosion and sediment transfer at the wider catchment level. These knowledge gaps provided the motivation for the field investigations and data analyses presented in this thesis.

2.4 Background to experimental research at Pontbren

The remaining sections of this chapter provide background information to the experimental research described in subsequent chapters of this thesis.

2.4.1 Overview of the Pontbren study area

Field studies to explore the geomorphological impacts of changes in land use and land management associated with upland agriculture were conducted at an FRMRC research site in Upper Severn basin in mid-Wales. The site, known as Pontbren, was established in late 2004 in the headwaters of the Afon Einion; a small gravel bed river (total drainage area = 18 km^2) that converges with the River Banwy near the village of Llanfair Caereinion in Powys (latitude: 52° 38' N, longitude: 3° 25' W). It is located approximately 16 km west of Welshpool and 32 km north-east of the Centre for Ecology and Hydrology (CEH, formerly Institute of Hydrology) research catchments at Plynlimon (Figure 2.3).

The physiographic and climatic characteristics of the local area are typical of large parts of mid-Wales. The land on which the site is situated ranges in elevation from 183 m AOD at its lowest point (marked by the confluence between the Nant Melin-y-grûg and the Nant Pont-bren-down) to 424 m AOD near the source of the Nant

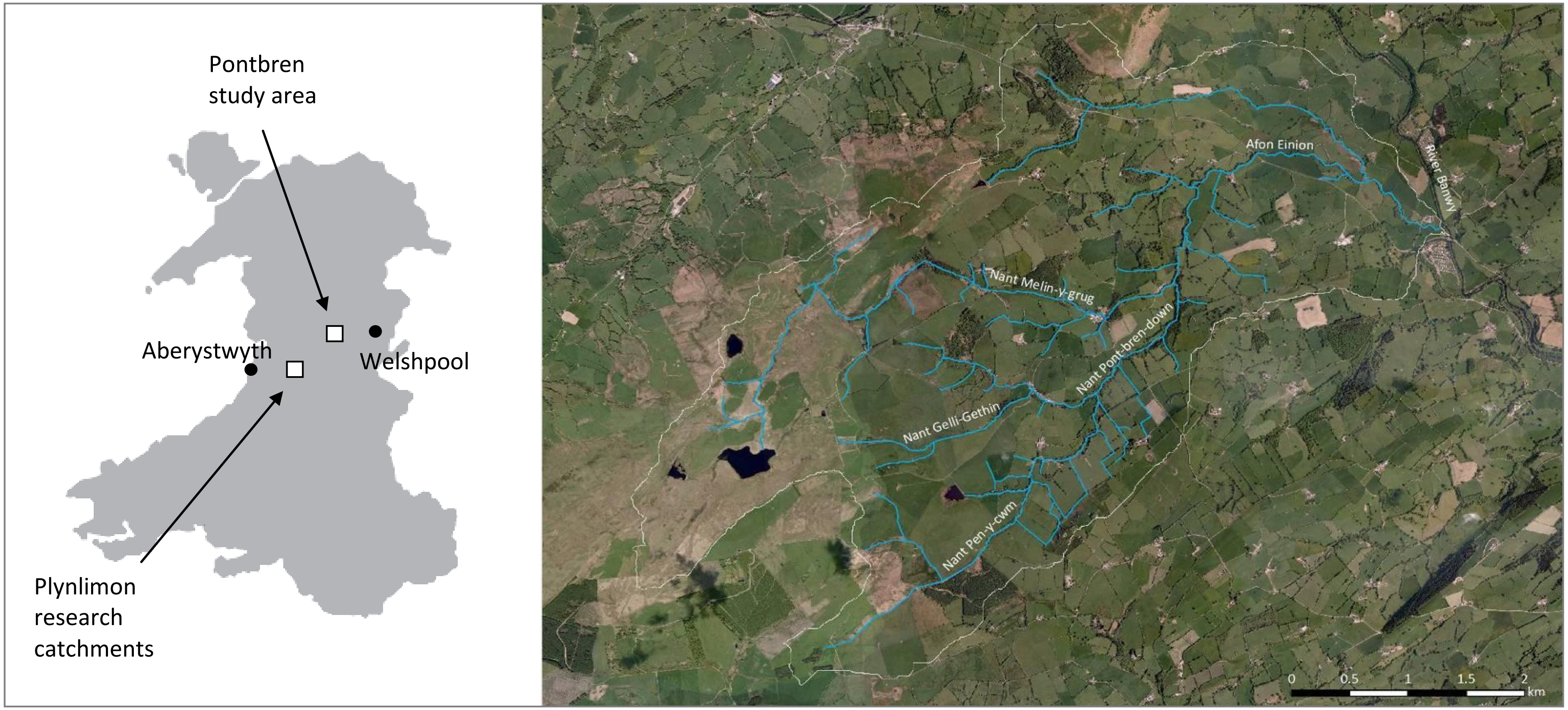


Figure 2.3 Location of the Pontbren study area and drainage network of the Afon Einion. Aerial photography provided by University of Wales Aberystwyth.

Melin-y-grûg (Figure 2.3), and is characterised topographically by gently undulating hills, with steeper slopes where rock outcrops are present. Long-profiles for the major streams in the area are shown in Figure 2.4. Average annual precipitation at the site is 1501 mm yr^{-1} (April 2005–April 2008; Marshall *et al*., 2009) and it has a mild, maritime climate. Rainfall is dominated by Atlantic weather fronts in autumn and winter, while convective storms during summer months can result in high rainfall intensities.

Bedrock beneath the study area consists of Silurian mudstones and greywacke sandstones (British Geological Survey, 1990). Overlying deposits of glacial till are visible where streams have incised and these are believed to be responsible for the widespread occurrence of stones and boulders in the upper profile of soils in the catchment (Bird *et al*., 2003). Figure 2.5 shows the distribution of soil series identified by a National Soils Research Institute (NSRI) survey undertaken in the study area during March and April 2005. Clay-rich cambic stagnogley soils belonging to the Cegin association are prevalent at low-medium elevations. They tend to be seasonally waterlogged due to the poor permeability of their lower horizons (Rudeforth *et al*., 1984). Wilcocks association soils with peaty surface layers are more common on higher ground and are usually permanently waterlogged or wet for long periods of the year (Rudeforth *et al*., 1984). The hydrological properties of the most abundant soil series at Pontbren are summarised in Table 2.1.

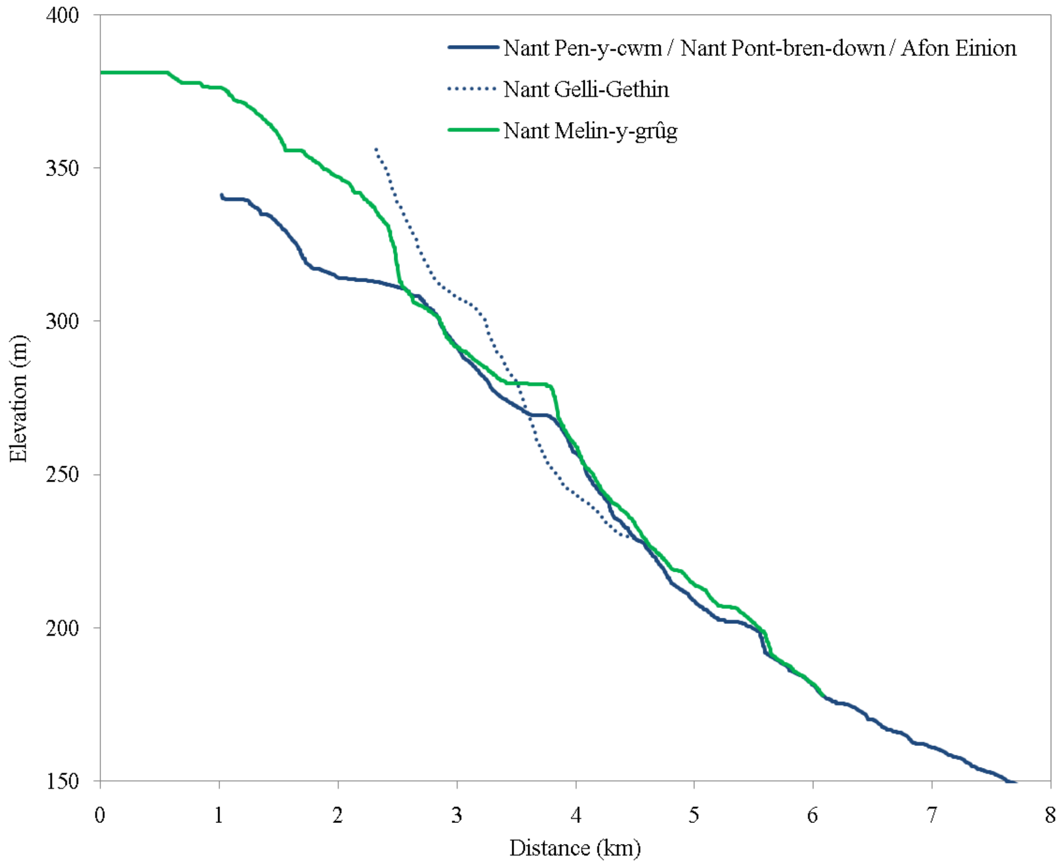


Figure 2.4 Long-profiles of major streams in the Pontbren study area. Constructed from NEXTMap 5 m DTM using Arc HydroTools.

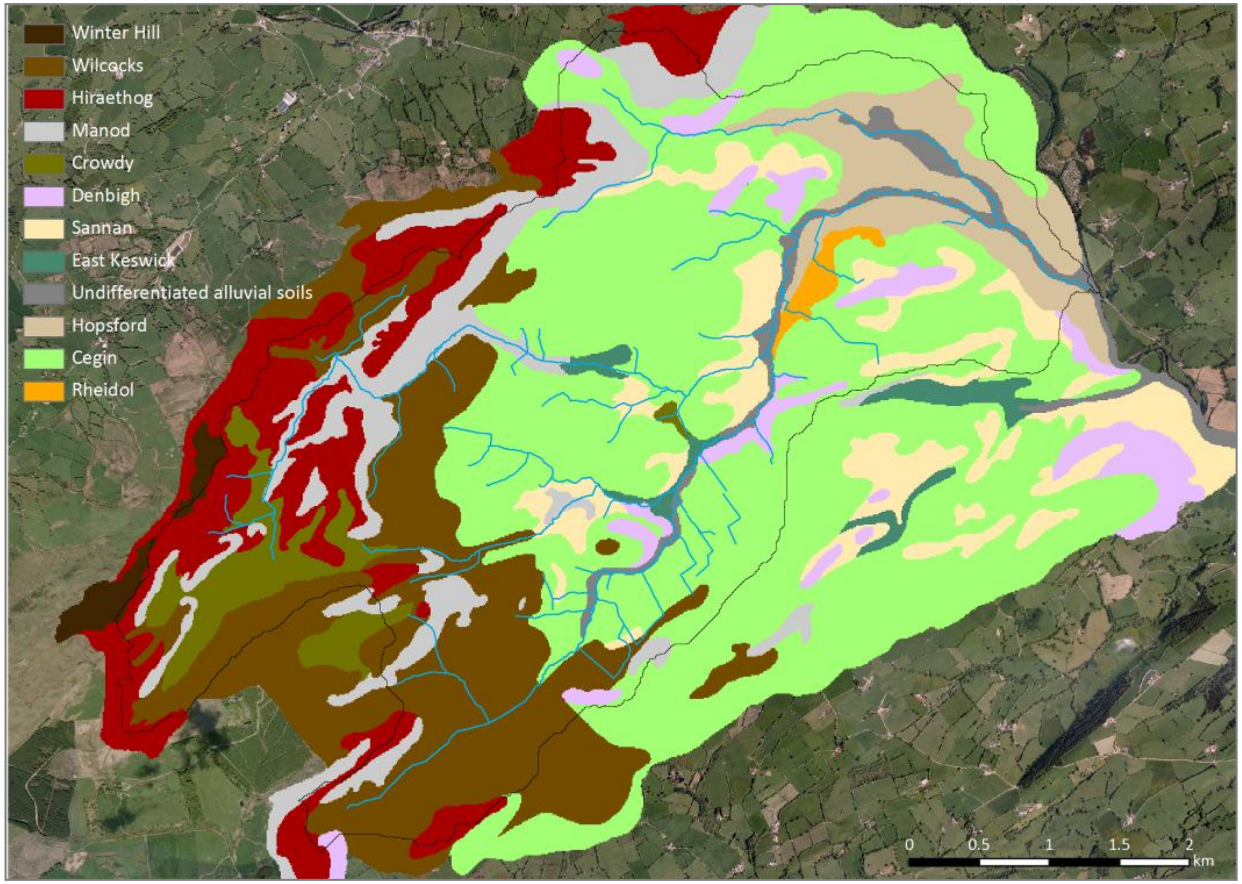


Figure 2.5 Map of soil series in the Pontbren study area (Hollis and Palmer, 2006).

Soil series	Broad texture group	Soil water regime	Soil parent material	HOST class	SPR (%)	BFI
Manod	Fine loamy over lithoskeletal	Well drained, moderately permeable, subsoils rarely wet	Mudstones and sandstones	17	29.2	0.61
Denbigh	Fine loamy over lithoskeletal	Well drained, moderately permeable, subsoils rarely wet	Mudstones and sandstones	17	29.2	0.61
East Keswick	Fine loamy	Well drained, moderately permeable, subsoils rarely wet	Drift with siliceous stones	6	33.8	0.65
Sannan	Fine silty	Slight seasonal waterlogging, subsoils slowly permeable	Glacial till with siliceous stones	18	47.2	0.52
Cegin	Fine silty	Slowly permeable, seasonally wet	Glacial till with siliceous stones	24	39.7	0.31
Wilcocks	Peaty surface layer over loamy	Seasonally waterlogged, topsoils wet for most of autumn, winter and spring, subsoils wet for most of year	Glacial till with siliceous stones	26	58.7	0.24
Hiraethog	Thin peat over loamy over lithoskeletal	Seasonally waterlogged, topsoils wet for most of autumn, winter and spring	Mudstone and sandstone	15	48.4	0.38
Crowdy	Deep peat	Permanently waterlogged	Humified peat	29	60.0	0.23
Winter Hill	Deep peat	Permanently waterlogged	Peat	29	60.0	0.23

Table 2.1 Hydrological properties of soil series found at higher elevations in the Pontbren study area (adapted from Palmer, 2005, p.2).

2.4.2 Historical changes in land use and land management in the Pontbren study area

Economic, political, social and environmental drivers have heavily influenced land use and land management practices in the study area over the last 150 years. During the mid-late nineteenth century, local tenant farmers managed small, mixed-purpose (arable and pastoral) holdings, growing crops such as oats, swedes and turnips, and farming small herds of cattle (Wheater *et al*., 2008). Several farms went out of business during the economic depression that followed World War I and the average farm size subsequently increased as the remaining farmers were able to purchase land at relatively low prices (Wheater *et al*., 2008).

Agriculture shifted to intensive livestock grazing following World War II in response to policies discussed in Section 2.2 and fields expanded as hedgerows were removed during grassland improvement works (Wheater *et al*., 2008). Drainage typically consisted of clay (and later plastic) pipes installed at a depth of 0.5-0.75 m and spaced between 9-15 m, and 'subsoiling' was also implemented in a number of pastures (D. Rowlands, pers. comm.). The technique involves the creation of 0.3-0.5 m deep trenches which are then backfilled with the excavated (and therefore more permeable due to disturbance) material. Local stocking levels increased dramatically as a result of the grassland improvement. For example, sheep numbers at Tyn-y-bryn farm in the upper part of the study area multiplied by a factor of six between 1969 and 1978 (Wheater *et al*., 2008). The average weight of breeding ewes on the farm also increased from 35 kg in the early 1970s to 65 kg in the mid 1990s (Wheater *et al*., 2008). Production has remained relatively high since the 1970s despite recent reductions in government subsidies (Wheater *et al*., 2008).

Stocking densities on some farms have been slightly reduced since their peak in the late 1990s as part of a sustainable faming strategy pioneered by members of the Pontbren Group; a consortium a ten farming families who own approximately 1000 ha of land in the study area. A core feature of the initiative is the creation of new woodlands and hedgerows to provide livestock with shelter. Areas of land are fenced off to exclude livestock and planted with native tree species such as silver and downy birch (*Betula pendula* and *Betula pubescens*), alder (*Frangula alnus*), blackthorn (*Prunus spinosa*), oak (*Quercus robur*) and ash (*Fraxinus excelsior*). The practice allows the grazing season to be extended through the winter and therefore reduces livestock housing and feed costs. It also improves habitat heterogeneity which is an important factor in maintaining local biodiversity (Moro and Gadal, 2007).

Planting increased the total wooded area on land belonging to the Pontbren Group from 1% in 1993 to approximately 5% in 2004 (Moro and Gadal, 2007). Figure 2.6a shows a 95 m x 18 m shelterbelt that was established in 1995. In this particular example, the trees have been orientated perpendicular to the slope in a grazed pasture, but planting has also been undertaken in riparian areas alongside some streams and ditches, and on sites previously occupied by hedgerows prior to post-World War II agricultural intensification. Other elements of the scheme include the construction of fences to prohibit livestock from trampling marginal areas of land around streams and ditches, and the creation of ponds and wetlands to encourage wildlife. The largest of these features is a small, shallow lake (approximately 1.4 ha in area) that was created in 2000 (Figure 2.6b).

Figure 2.6 Pontbren Rural Care Project features: (a) mature shelterbelt; (b) artificial lake.

The aforementioned changes in land use and land management were not, however, implemented uniformly throughout the study area and strong contrasts exist between areas of land surrounding the three main headwater tributaries of the Afon Einion; the Nant Pen-y-cwm, Nant Gelli-Gethin and Nant Melin-y-grûg (Figure 2.3). For example, widespread grassland improvement was undertaken in areas drained by the Nant Pen-y-cwm and Nant Gelli-Gethin, but agricultural development was far more limited in the upper reaches of the Nant Melin-y-grûg. The contrasting quality of grassland in the two areas is clearly visible in aerial photographs (Figure 2.3), in which improved swards appear green while unimproved moorland grasses appear light brown.

Analysis of historical land cover data was undertaken to quantify changes in land use in the two areas (henceforth referred to as the Upper Melin-y-grûg and the Upper Pontbren subcatchments) between the early 1930s (prior to post-World War II changes in agricultural policy) and the late twentieth century (at the peak of agricultural intensification in the British uplands). Scanned images of maps produced as part of the Land Utilisation Survey of Great Britain from 1931-35 and Phase I Terrestrial Habitat Survey of Wales data from 1979-90 were used to calculate the percentage of land covered by "Heath, moorland and rough pasture", "Permanent/improved grassland", "Arable land", "Forest and woodland", "Urban areas", and "Water" in the two subcatchments. Images of maps from the Land Utilisation Survey of Great Britain were accessed through Historic Digimap (EDINA, 2007), amalgamated, georeferenced, and classified using the ArcScan extension in ArcGIS 9.2. The Phase I Terrestrial Habitat Survey of Wales used a much broader range of land use types compared to the Land Utilisation Survey of Great Britain and therefore "Bracken", "Marshy grassland", "Unimproved acid grassland", "Basin mire”, “Wet heath/acid grassland mosaic”, and “Semi-improved acid grassland” were all grouped under the “Heath, moorland and rough pasture” category for the purpose of this analysis. Table 2.2 documents the percentage coverage by each land use category in the Upper Pontbren and Upper Melin-y-grûg subcatchments at the time of each survey, along with the percentage by which each changed between the two dates. The spatial distribution of land cover types in each subcatchment at the time of both surveys is shown in Figure 2.7.

The results show that both catchments were dominated by unimproved rough grazing land during the early 1930s. Some grassland improvement had already been undertaken in both subcatchments by this point, mainly at lower altitudes. This is consistent with observations by Robinson (1986a), who calculated that 25–50% of agricultural land in the Montgomeryshire region contained field drains that had been installed prior to 1939. Arable farming was also significant at lower elevations in the Upper Pontbren subcatchment. However, while land use in the Upper Melin-y-grûg subcatchment remained largely unaltered over the next 50-60 years, major changes occurred in the Upper Pontbren area. The combined percentage area of the subcatchment occupied by rough grazing and arable land fell from 74.0% to 15.6% between the dates of the two surveys, being largely replaced by permanent/improved grassland. In addition to substantial grassland improvement, the percentage of forest and woodland also increased as a result of the establishment of an 18.5 ha coniferous forest plantation (c.1988) on land adjacent to the upper reaches of the Nant Pen-y-cwm. The disappearance of a small lake which is believed to have originally spilled into the Nant Gelli-Gethin is also noteworthy. Analysis of historical Ordnance Survey maps indicates that the lake, which measured approximately 1.8 ha in area, was drained between the late 1950s and early 1960s.

Subcatchment	Land use	Land cover (%)		Change (%)
		1931-1935	1979-1990	
Upper Pontbren	Heath, moorland, rough pasture	58.2	12.3	-45.9
	Permanent/improved grassland	23.8	79.6	+55.8
	Arable land	15.8	3.3	-12.5
	Forest and woodland	1.8	4.4	+2.6
	Urban areas	-	0.2	+0.2
	Water	0.4	0.2	-0.1
Upper Melin-y-grûg	Heath, moorland, rough pasture	81.7	81.9	+0.2
	Permanent/improved grassland	12.6	13.0	+0.3
	Arable land	0.8	1.4	+0.6
	Forest and woodland	1.6	1.1	-0.5
	Urban areas	-	-	-
	Water	3.3	2.6	-0.7

Table 2.2 Historical changes in land use in the Upper Pontbren and Upper Melin-y-grûg subcatchments.

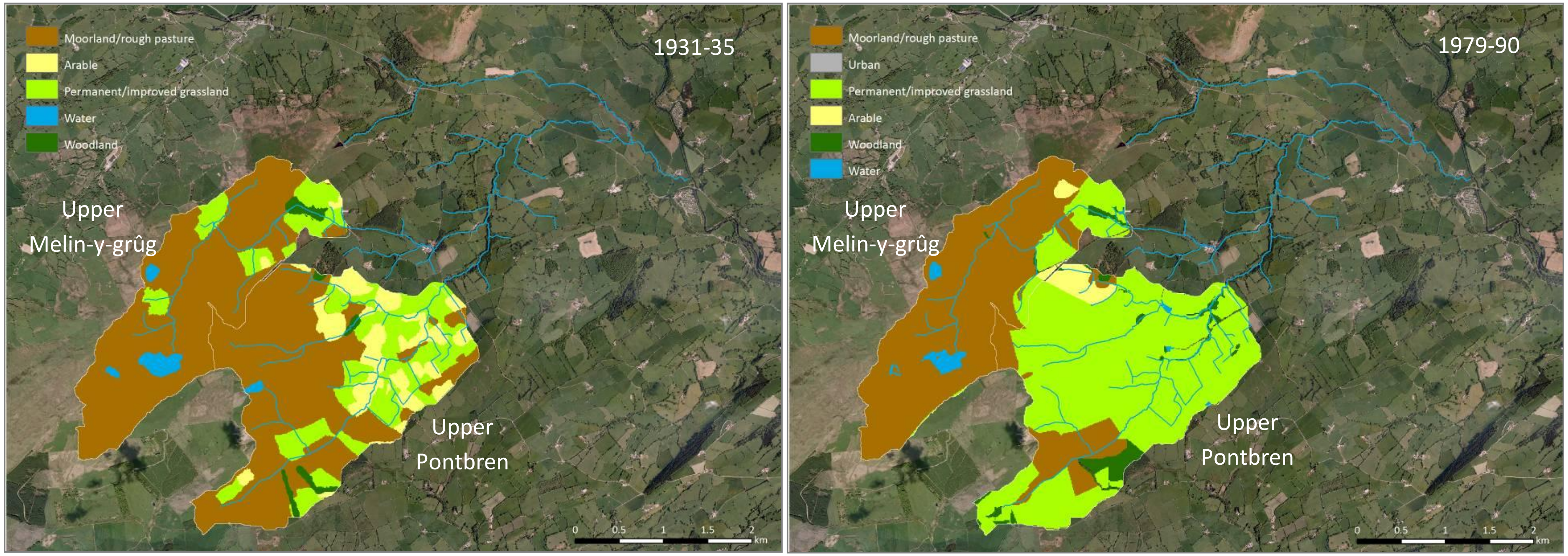


Figure 2.7 Spatial distribution of historical changes in land use in the Pontbren study area.

Land use changes and land management related to the Pontbren Rural Care Project have followed a similar spatial pattern to those associated with agricultural intensification (Figure 2.8). No tree planting or wetland creation has been undertaken in the Upper Melin-y-grûg catchment as only small areas of the land are owned by members of the Pontbren Group. The scheme has been actively implemented in parts of the Upper Pontbren area, particularly around the middle course of the Nant Pen-y-cwm. Livestock are now excluded from the majority of streams and ditches in this reach, and the land is also the site of the artificial lake pictured in Figure 2.6b. Nevertheless, large proportions of the subcatchment remain essentially the same as depicted in the Phase I Terrestrial Habitat Survey of Wales from 1979-90.

2.4.3 Implications of changes in land use and land management for erosion and sediment transfer in the Pontbren study area: preliminary assessment

Literature reviewed in Section 2.3 suggests that historical changes in land use and land management could influence contemporary sediment dynamics in the study area. The growth in livestock numbers and size facilitated by grassland improvement during the second half of the twentieth century is likely to have increased the probability of erosion and surface runoff generation within fields. Drains and ditches associated with the agricultural development may also perform a dual function as sediment transfer pathways (which act to increase the connectivity between improved pastures and the natural stream channel network) and sources of sediment in the own right. Such effects could be expected to result in increased sediment delivery to streams draining areas where agriculture has intensified and may lead to elevated sediment yields downstream. In addition, erosion of the beds

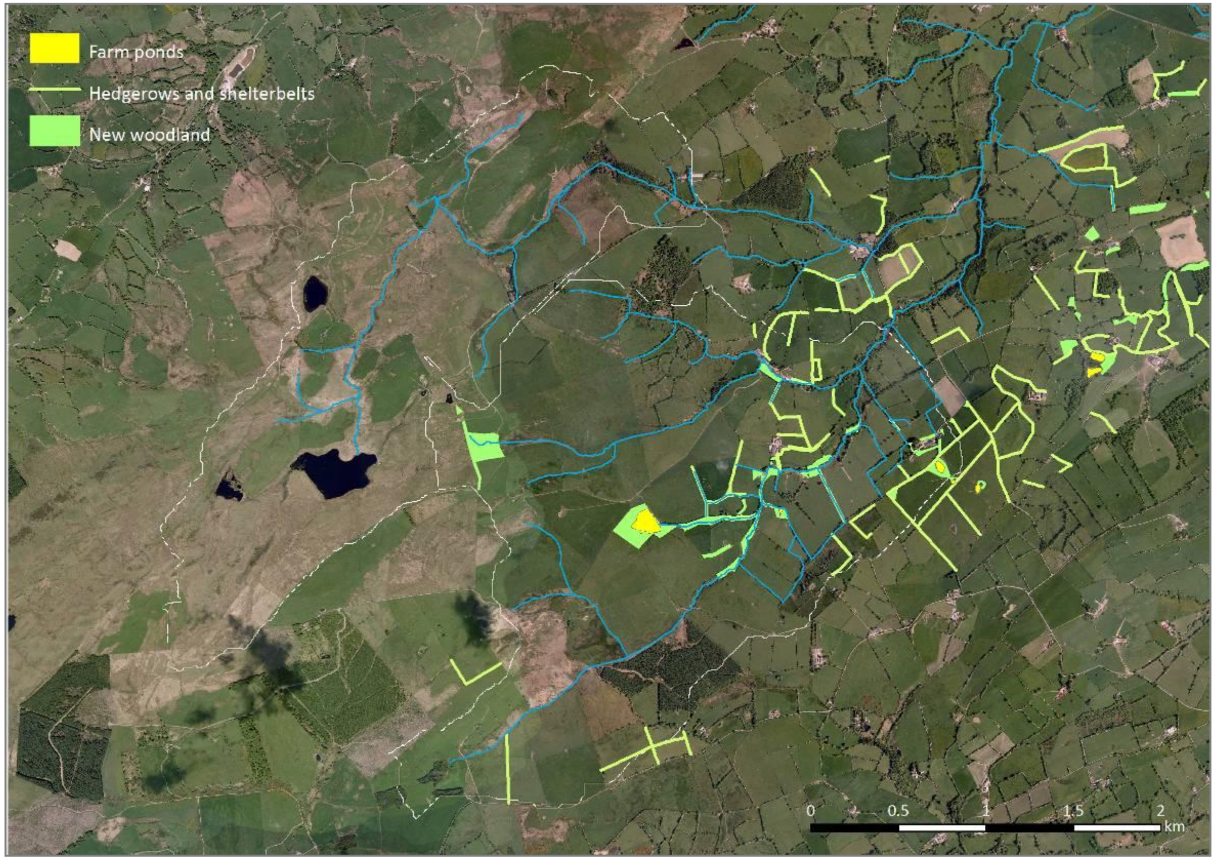


Figure 2.8 Spatial distribution of woodland and wetland features created through the Pontbren Rural Care Project.

and banks of mainstream channels could have increased if drainage and amplified levels of surface runoff have enhanced the capability of river flows to mobilise sediment.

Sediment supply from other sources external to the natural stream channel network at Pontbren is likely to be limited. While gullies and landslides are known to act as important sediment sources in some British upland regions (e.g. Harvey, 1974; Reid *et al*., 2007), their development at Pontbren and many other parts of mid-Wales is largely restricted by the gently undulating nature of the terrain. However, evidence discussed in Section 1.1 has shown that drainage systems for commercial forests in upland areas can supply large amounts of sediment to streams. For this reason, the small conifer plantation that was established in the upper reaches of the Nant Pen-y-cwm in the late 1980s was also considered to be a theoretically plausible sediment source.

A preliminary assessment of the viability of these hypotheses was made during 2005 using a variety of scoping methods. Local knowledge resources were explored during interviews by researchers from the University of Wales Bangor with farmers from the area (T. Pagella, pers. comm.). The consultations revealed that, in general, erosion within grazed pastures is not considered to be major problem in the study area as preventative and reactive measures are implemented to limit its occurrence. Livestock are removed from fields in winter and rotated around farms to allow grass to recover from intensive grazing. Where possible, feeders are placed on hardstanding and the use of heavy machinery is avoided during wet periods to prevent damage to the soil. However, poaching can be an issue in sensitive areas of fields such as around feeding areas on grass, ditches and streams where livestock access is unrestricted, and on steep slopes. This is particularly evident during wet periods and following quick thaws. Erosion problems only tend to be noted by farmers when severe (i.e. bare ground is observed) but that does not necessarily preclude the existence of more gradual, less dramatic soil erosion within grazed pastures. Overland flow during and following heavy rainfall is reported to be more common and widespread in fields where grass has been improved and stocking densities have increased and, therefore, while unlikely to be as significant as in catchments dominated by arable farming (e.g. Evrard *et al*., 2007), material eroded within fields could represent an important component of the total sediment yield of streams that drain areas where agricultural intensification has been widespread.

Present-day and historical levels of channel network-based morphological activity are considered to be much higher in the Upper Pontbren subcatchment compared to the upper reaches of the Nant Melin-y-grûg. The bed of the Nant Melin-y-grûg is thought to be relatively stable and its flow reported to be reasonably clear, although peaty in colour, even during spate conditions. Conversely, frequent changes in bed structure and the position of stones and boulders have been observed in the Nant Pen-y-cwm, Nant Gelli-Gethin, and Nant Pont-bren-down in recent years, and water colour during high flows in these streams was compared to that of “milky coffee” by interviewees. No quantitative data on historical levels of morphological activity in the different headwater streams exists but farmers did identify two significant erosion events during the late 1960s and 1980s. Large floods caused dramatic streambed incision (>1.5 m) and channel widening in some mainstream reaches of the Nant Pen-y-cwm and Nant Gelli-Gethin but the geomorphological response of the Nant Melin-y-grûg was more muted. Over 600 m^3 of sediment is estimated to have been deposited in a reach of the Nant Pen-y-cwm near Tyn-y-bryn farm during the most recent event (R. Jukes, pers. comm.), providing an indication of the level of disturbance.

Floods capable of performing geomorphological work of such magnitude are rare in upland environments and thus represent extremes. They are commonly associated with intense summer rainfall (e.g. Anderson and Calver, 1977; Newson, 1980b; Carling, 1986; Harvey, 1986) but the Pontbren events are alleged to have been caused by quick thaws of snow-covered ground combined with heavy rainfall. Although unusual, similar conditions caused the UK's most catastrophic river floods of the last 200 years in March 1947 (Howe *et al*., 1967; RMS, 2007). The geomorphological response of the Nant Pen-y-cwm and Nant Gelli-Gethin to the floods in the late 1960s and 1980s in comparison to that of the Nant Melin-y-grûg may provide further indication that differences in land use and land management could influence sediment dynamics through their effect on runoff efficiency. Incision is a quintessential feature of disequilibrated fluvial systems and tends to occur where there is an increase in the potential to transport sediment relative to its supply from upstream and/or external sources (Simon and Rinaldi, 2006). Enhanced peak flows for reasons described in Section 2.3 may explain the perceived greater geomorphological effectiveness of flows in the Upper Pontbren subcatchment.

Stream reconnaissance (following Thorne, 1998) substantiated local perceptions of strong geomorphological contrasts between streams in the Upper Pontbren and Upper Melin-y-grûg subcatchments. The upper reaches of the Nant Melin-y-grûg are largely straight and appear to be very stable, with little evidence of major geomorphological activity in recent history (Figure 2.9). The bed of the main channel is composed of coarse-grained sediment up to 850 mm in diameter, interspersed by

(a)

(b)

Figure 2.9 Nant Melin-y-grûg at (a) Hirrhos Bridge and (b)Hirrhos Uchaf.

areas of bedrock. Step-pool sequences, where repetitive cross-stream lines of cobbles and boulders separate depressions containing finer material to produce a staircase-like longitudinal profile (Chin, 1989), are evident in sediment-lined reaches. The features are common in steep upland streams (Grant *et al*., 1990; Montgomery and Buffington, 1997) and help to maintain channel stability under low-moderate flow conditions through energy dissipation (Chin, 1998; 2003). Channel banks are generally low, well-vegetated, and formed from glacial till, bedrock or peat. There is little visible evidence of bank erosion except where in-channel obstructions such as large boulders or debris deflect flow into the channel boundary. The majority of coarse sediment transport in the Nant Melin-y-grûg is therefore likely to consist of material derived mainly from the channel bed.

The bed and banks of headwater streams in the Upper Pontbren subcatchment are composed of similar materials to those found in the upper reaches of the Nant Melin-y-grûg. However, sediment-lined sections of the Nant Pen-y-cwm and Nant Gelli-Gethin tend to be heavily incised (Figure 2.10a) and, although step-pool features are visible in places, bed substrate arrangement is generally irregular. The channels have very steep banks that are largely devoid of vegetation and there is evidence of lateral erosion, with exposed tree roots and deposits of slumped material at the base of banks (Figure 2.10b). Downstream of the confluence between the Nant Pen-y-cwm and the Nant Gelli-Gethin, the Nant Pont-bren-down adopts a slightly more sinuous planform and lateral bars are present in the channel (Figure 2.10c). Evidence of bank erosion is also widespread, although the stream is less degraded than its upstream tributaries.

(a) (b) (c)

Figure 2.10 (a) Exposed bridge buttresses and (b and c) steep banks due to channel incision in the Upper Pontbren subcatchment.

Broader exploration of the study area revealed little visual indication of potential sediment sources external to the main channel network in the Upper Melin-y-grûg subcatchment. Land surrounding the upper reaches of the stream is well-vegetated, with no obvious signs of disturbance by livestock (Figure 2.11). A general lack of grassland improvement has meant that drainage and ditching has been negligible and hillslopes are largely disconnected from the stream channel network. Surficial erosion was evident at locations in the Upper Pontbren catchment, generally corresponding to those identified as sensitive by local farmers during interviews (Figure 2.12). However, while many agricultural ditches did appear to be morphologically active and could act as sediment sources (Figure 2.13a), those within the conifer plantation in the headwaters of the Nant Pen-y-cwm were deemed unlikely to be significant. The majority have silted up and/or been colonised by vegetation (Figure 2.13b) and only a limited number feed directly into the Nant Pen-y-cwm. Most drain into an artificial pond, set back from the main stream. Those ditches that are connected enter the Nant Pen-y-cwm via a flat area of marshland, where vegetation blockages and heavily reduced flow velocities are likely to restrict the transfer of all but the smallest sediment particles. Sediment production by the plantation site may have been greater in the past but there is no obvious morphological evidence (e.g. scour/depositional features downstream of ditch outfalls) to support this hypothesis. The low gradients (<0.03) of ditches in the network are likely to have limited erosion during and following site preparation (*c.f.* Newson, 1980a).

More recent changes in land use and land management associated with the Pontbren Rural Care Project could also have implications for erosion and sediment transfer. Following reports from local farmers of tree shelterbelts "intercepting"

Figure 2.11 Land surrounding the upper reaches of the Nant Melin-y-grûg.

(a) (b)

Figure 2.12 (a) Livestock feeding area alongside Nant Pen-y-cwm and (b) trampled ground in improved pasture in Upper Pontbren subcatchment (Winter 2005).

(a) (b)

Figure 2.13 Contrasting (a) agricultural and (b) forestry ditches in the Upper Pontbren subcatchment.

overland flow as it moved downslope across fields, a study by Carroll *et al*. (2004a) measured infiltration rates along transects running from six grazed pastures with stocking densities of approximately 2 to 3 LSU ha^{-1} (LSU = livestock units; 1 sheep equivalent to 0.15 LSU) into neighbouring planted woodland areas (formerly improved grassland). While infiltration rates in the grazed pastures were found to be minimal, they were up to 60 times greater within the shelterbelts. The findings raised the possibility that surface runoff could be reduced and, thus, limit a potential mechanism of erosion and sediment transfer. Geomorphological activity within downstream channel networks may also be influenced, both directly through the potential stabilisation of stream banks due to stock exclusion and vegetation growth, and indirectly if the apparent hydrological effects are transferred to streams in the form of reduced peak flows.

2.4.4 Research approach

The evidence and geomorphological indicators outlined in Section 2.4.3 offer support to the hypothesis that agricultural intensification may have increased erosion and sediment transfer within the Pontbren study area, but also raise the possibility that changes in land use and land management instigated as part of the Pontbren Rural Care Project could help to limit or reduce its impact. The site therefore represents an ideal location to assess the likely extent of risks associated with enhanced geomorphological activity and investigate the utility of strategic land management to control resultant problems.

The following experiments and data analyses were designed to generate the geomorphological process knowledge necessary to fulfil the objectives stated in Section 1.2. Geomorphological effects of land use changes and land management practices associated with upland agriculture are explored through a system approach (*c.f.* Vandenberghe and Vanacker, 2008), in which the wide range of interrelated processes that control responses to external drivers is acknowledged and research pursued through multi-disciplinary cooperation. To this end, interpretation is supported by emerging results from an affiliated FRMRC research project at the site into the effects of land use and land management on flood runoff generation (Wheater *et al*., 2008). The study provided hydrological data (precipitation, drain flow, overland flow, ditch flow and stream flow) from sites under different land covers and management regimes, and insights into changes in river flow regimes under different historical and potential future land use scenarios. Table 2.3 documents these data sets, along with those collected by the author through field experiments. Data collection methodologies and procedures for deriving secondary data sets from the information documented in Table 2.3 are described in subsequent chapters.

Data set (units)	Instrumentation	Location	Sampling frequency	Investigator
Rainfall (mm)	Storage rain gauge	Bowl	Monthly	Imperial College London
Rainfall intensity (mm h^{-1})	Tipping bucket rain gauge (0.2 mm)	Bowl	10 min	Imperial College London
Air temperature (° C)	Automatic weather station	Bowl	10 min & daily average	Imperial College London
Soil temperature (° C)	Automatic weather station	Bowl	10 min & daily average	Imperial College London
Soil pore water pressure (cm H_2O)	Tensiometer array	Bowl	10 min	Imperial College London
Soil moisture content (ϑ cm^3 cm^{-3})	Neutron probe (via access tubes)	Bowl	Bi-weekly	Imperial College London
Overland flow (m^3 s^{-1})	V-notch box weir and pressure transducer	Bowl	5 min	Imperial College London
Drain flow (m^3 s^{-1})	V-notch box weir and pressure transducer	Bowl	5 min	Imperial College London
Turbidity of overland flow and drain flow (FTU)	Turbidity sensor	Bowl	5 min	Henshaw (this study)
Volume of sediment transported via overland flow and drain flow (m^3)	V-notch box weir and ruler	Bowl	End of experimental programme	Henshaw (this study)
Particle size of sediment transported via overland flow and drain flow (mm)	Laser particle size analyser	Bowl	End of experimental programme	Henshaw (this study)

Moisture content of sediment transported via overland flow and drain flow (%)	Oven and electronic balance	Bowl	End of experimental programme	Henshaw (this study)
Organic content of sediment transported via overland flow and drain flow (%)	Oven and electronic balance	Bowl	End of experimental programme	Henshaw (this study)
Dry bulk density of sediment transported via overland flow and drain flow (g cm^{-3})	Oven, measuring cylinder and electronic balance	Bowl	End of experimental programme	Henshaw (this study)
Bank erosion rate (mm yr^{-1})	Erosion pins	Stream banks	Seasonal	Henshaw (this study)
Bank erosion extent (m^2)	Measuring tapes	Stream banks	Seasonal	Henshaw (this study)
Particle size of bank material (mm)	Gravelometer and sieves	Stream banks	End of experimental programme	Henshaw (this study)
Bulk density of bank material (t m^{-3})	Hand balance	Stream banks	End of experimental programme	Henshaw (this study)
Bank angle (degrees)	Clinometer	Stream banks	End of experimental programme	Henshaw (this study)
Bank aspect (degrees)	Compass	Stream banks	End of experimental programme	Henshaw (this study)
Slope (m m^{-1})	Total station	Stream channels and ditches	Start of experimental programme	Henshaw (this study)

Width (m)	Total station	Stream channels and ditches	Start of experimental programme	Henshaw (this study)
Bed material particle size (mm)	Gravelometer and sieves	Stream channels and ditches	Start of experimental programme	Henshaw (this study)
Discharge (m^3 s^{-1})	Acoustic doppler velocity meter	Stream channels and ditches	15 min	Imperial College London
Bedload output (t)	Bedload trap	Stream channels and ditches	Event	Henshaw (this study)
Bedload particle size (mm)	Gravelometer and sieves	Stream channels and ditches	Event	Henshaw (this study)
Turbidity (FTU)	Turbidity sensor	Stream channels	15 min	Henshaw (this study)
Suspended sediment concentration (mg l^{-1})	Automatic water sampler	Stream channels	Event	Henshaw (this study)

Table 2.3 Primary data sets used in study.

3 DYNAMICS AND CONTROLS OF SOIL EROSION IN A GRAZED, AGRICULTURALLY IMPROVED UPLAND PASTURE AND THE TRANSFER OF MOBILISED SEDIMENT TO STREAM CHANNELS

3.1 Introduction

Soil erosion can severely reduce the productivity of agricultural land (Lal, 2001) and is believed to be responsible for estimated economic losses of approximately £700 million per year in England and Wales alone (Evans, 1996). However, it is increasingly acknowledged that the delivery of eroded sediment to watercourses may represent an even greater problem (Walling and Collins, 2005). Elevated rates of sediment supply from catchment surface sources due to anthropogenic activities can reduce the conveyance capacity of river channels, thus increasing flood risk and restricting navigation (Verstraeten and Poesen, 2000). Similarly, excessive sediment loads may pose a risk to public water supply (Butcher *et al*., 1993). An elevated sediment load can also have significant environmental impacts due to its effects on water temperature (Owens *et al*., 2005), light penetration through the water column (Bilotta *et al*., 2007), and aquatic habitats such as gravel beds that are used by fish for spawning (Ryan, 1991; Newcombe and Jenson, 1996; Soulsby, 2001). Suspended sediment particles can clog aquatic vegetation (Wood and Armitage, 1997; 1999), affect the health and reproductive capabilities of fish and invertebrates (Newcombe and MacDonald, 1991; Petticrew and Rex, 2006), and play an important role as carriers in the transfer of nutrients (e.g. phosphorus) and contaminants (e.g. pathogens, metals, radionuclides, pesticides, etc) that can reduce water quality (Förstner, 1987; Kronvang, 1990; Harrod, 1994; Rowan, 1995; Walling *et al*., 1997;

Haygarth *et al*., 1998; Kretzschmar *et al*., 1999; Heathwaite and Dils, 2000; Warren *et al*., 2003; Deeks *et al*., 2005; Heathwaite *et al*., 2005).

As discussed in Chapter 2, soil erosion associated with increased livestock grazing in the British uplands is widely accepted to be a serious issue (e.g. McHugh *et al*., 2002) and there is growing evidence that the amount of fine sediment in upland watercourses has increased substantially over recent decades simultaneously with agricultural intensification (Van der Post *et al*., 1997; Hatfield and Maher, 2008). The results of sediment tracing experiments using environmental radionuclides indicate that large amounts of this sediment originates from grazed upland pastures and could therefore represent a serious risk to water quality in upland streams, rivers and lakes. For example, Collins *et al*. (1997b) found that 90% and 84% of suspended sediment sampled in the Rivers Rhiw and Vyrnwy in mid-Wales respectively was derived from eroding pasture sources, while Walling *et al* (1999) calculated that between 60-85% of all fine material transported by the Swale, Ure, Nidd and Wharfe in North Yorkshire originated from uncultivated land such as pasture and moorland in their upstream catchments. A severe lack of comprehensive data on water quality in the British uplands (Stevens *et al*., 2008) makes it difficult to gauge the extent of the threat posed, but studies in lowland grassland environments have shown that significant quantities of sediment and associated nutrients and contaminants can be supplied to watercourses (e.g. Heathwaite *et al*., 1991; Heathwaite and Dils, 2000; Preedy *et al*., 2001), and indicators such as the rapid decline in salmonid populations (e.g. Harrod and Theurer, 2002) suggest that it could be a major issue. While upland waterbodies are unlikely to receive as much pollution as lowland streams, the documented sensitivity of the receiving environment must also be taken into account when assessing the level of risk, as even if soil erosion rates are low by world standards, the transfer of sediment to watercourses could be a major problem in terms of water quality (Bilotta *et al*., 2007).

Bilotta *et al*. (2007) and Haygarth *et al*. (2007) suggest that this apparent oversight may stem from traditionally-held views of pastures as being resistant to erosion due to the retarding effects of their relatively dense and complete vegetation cover on raindrop impact and surface runoff, which restrict the detachment of soil particles and limits their transport away from the point of origin. Nevertheless, action is now underway to address the issue through the implementation of improved land management practices and catchment sensitive farming (e.g. Defra, 2008) to help reduce the delivery of fine sediment to watercourses in upland areas. Vegetated buffer strips have been suggested as one possible control measure following their success in other types of farming, where reductions in hillslope sediment production of between 70-90% have been achieved (e.g. Wilson, 1967; Neibling and Alberts, 1979; Dillaha *et al*., 1987; Magette *et al*., 1987, 1989; Haan *et al*., 1994; Van Dijk *et al*., 1996; Karssies and Prosser, 1999; Le Bissonnais *et al*., 2004). They consist of longitudinal bands of rough vegetation that intercept runoff flowing across the land surface and so prevent it from entering streams directly. Buffer strips tend to increase the infiltration capacity of the soil (e.g. Muscutt *et al*., 1992) and hydraulic roughness (e.g. Neibling and Alberts, 1979), thus reducing flow velocities and enhancing the potential for sediment deposition (Barfield *et al*., 1979; Neibling and Alberts, 1979; Hayes and Hairston, 1983; Dillaha *et al*., 1987).

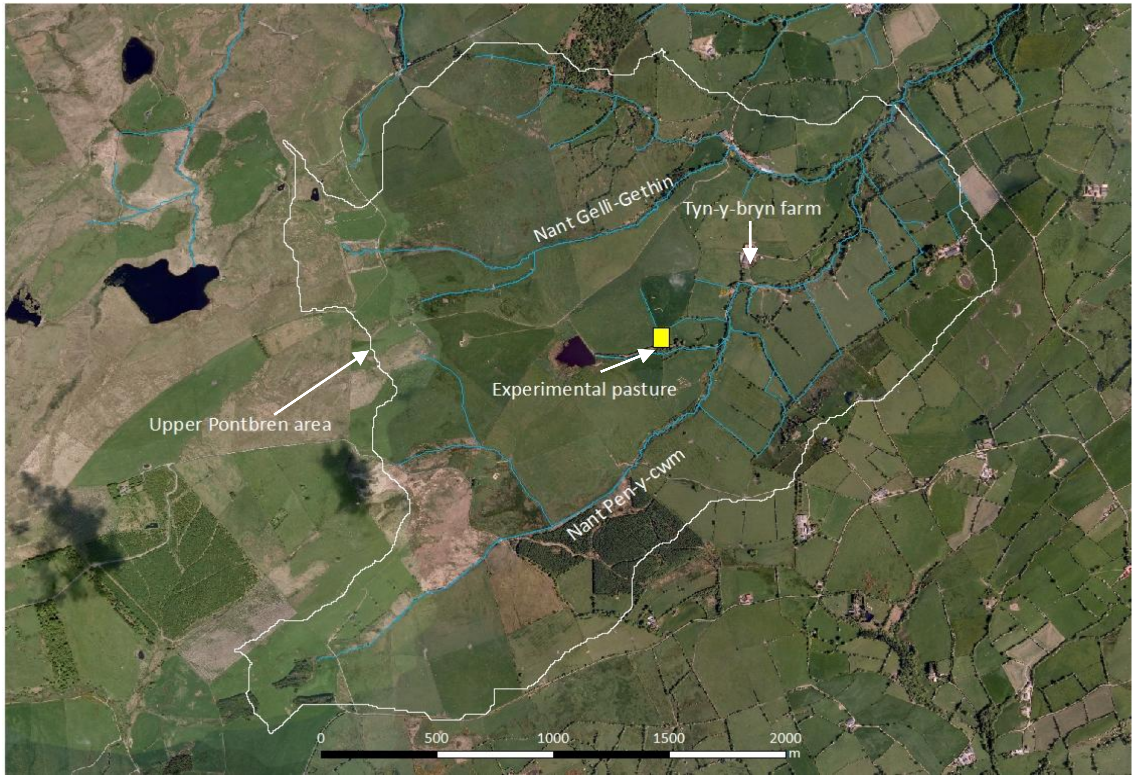
The restoration of woodlands and hedgerows undertaken as part of the Pontbren Rural Care Project could, therefore, have benefits for water quality by intercepting sediment before it is able to enter the local channel network (*c.f.* Carroll *et al*., 2004a). However, if management of diffuse sediment-related pollution is to be effective, not only do sediment sources need to be identified but also the pathways and processes which govern transport in that system need to be understood. While surface erosion often represents the dominant source of fine sediment within British river catchments, there are a variety of routes through which sediment may enter watercourses (Taylor *et al*., 2008). While features such as buffer strips are likely to be effective in controlling sediment transfer across the land surface, they are unlikely to restrict movement via subsurface routes such as soil pipes, macropores and artificial field drains (e.g. Schwab *et al*., 1977; Bottcher *et al*., 1981). However, sub-surface routes have been identified as important and efficient pathways in lowland agricultural systems, contributing large quantities of sediment directly into river systems (Russell *et al*., 2001; Walling *et al*., 2002; Foster *et al*., 2003; Chapman *et al*., 2005). The extensive amount of drainage work undertaken in the British uplands following the end of World War II could, therefore, have increased the degree of connectivity between grazed pastures and watercourses.

This chapter describes a field experiment undertaken between November 2006 and June 2008 in an attempt to resolve some of these issues. The work aimed to quantify the amount and calibre of sediment supplied from a grazed, agriculturally-improved upland pasture to the local channel network at Pontbren, and to explore the processes and pathways which control its production and transport.

3.2 Field site

The investigation was conducted within a grazed pasture on Tyn-y-bryn farm in the Nant Pen-y-cwm subcatchment at Pontbren (52°38.4’N, 3°24.7’W; Figure 3.1). The

(a)



(b)

Figure 3.1 Location of the experimental pasture at Tyn-y-bryn farm in the Upper Pontbren area (a) and view of the site looking upslope from its southern boundary (b). Aerial photography provided by University of Wales Aberystwyth.

site, known as “the Bowl”, comprises a 0.52 ha, gently sloping, natural depression that ranges in elevation from 317 m AOD in its north-western corner down to approximately 305 m AOD along its southern boundary. Runoff from the pasture is collected in a ditch that runs between its lower boundary and a neighbouring farm track, before emptying into a small semi-natural tributary of the Nant Pen-y-cwm (although officially unnamed, the stream is referred to here as the Nant Pant Powsi after the small valley it occupies). The site is representative of large parts of the Upper Pontbren area in that it has been drained and reseeded with improved grass mixtures to increase its livestock grazing capacity and is now used exclusively for sheep grazing. Visual analysis of aerial photographs suggests that the Bowl is underlain by two main field drains spaced 35-40 m apart, each of which collects water from a series of smaller lateral feeder drains spaced 8-10 m apart. However, although field inspections indicate that the drains may be constructed from clay tiles, the exact layout, specification and history of drainage at the site is unknown.

The majority of the Bowl is occupied by Cegin series soil, aside from a thin band of Sannan series soil which runs across its northern edge (Hollis, 2005). The two soil series, belonging to the Cegin association, are widespread over Silurian and Ordovician sedimentary rocks throughout Wales (Rudeforth *et al*., 1984) and together cover over 37% of the Upper Pontbren area. Cegin soils are classified as slightly stony clay loams and characterised by a slightly stony, clay loam A horizon which persists to a depth of 0-20 cm, overlying a slowly permeable clay loam B horizon which is slightly or moderately stony (Thompson, 1982; Wheater *et al*., 2008). Differences in the percentage sand/silt/clay composition of soil samples taken from both soil horizons in the Bowl are presented in Table 3.1, showing an increase in the amount of clay with depth below the surface. The relatively impermeable nature of the subsoils tends to result in waterlogging for long periods during the growing season and, even with artificial drainage, they can remain wet throughout the whole of winter (Thompson, 1982; Rudeforth *et al*., 1984). The upper horizons of Cegin association soils are known to be vulnerable to poaching by livestock for this reason (Rudeforth *et al*., 1984).

Soil horizon	% sand	% silt	% clay
A	13.3	45.7	42.0
B	14.3	32.0	53.7

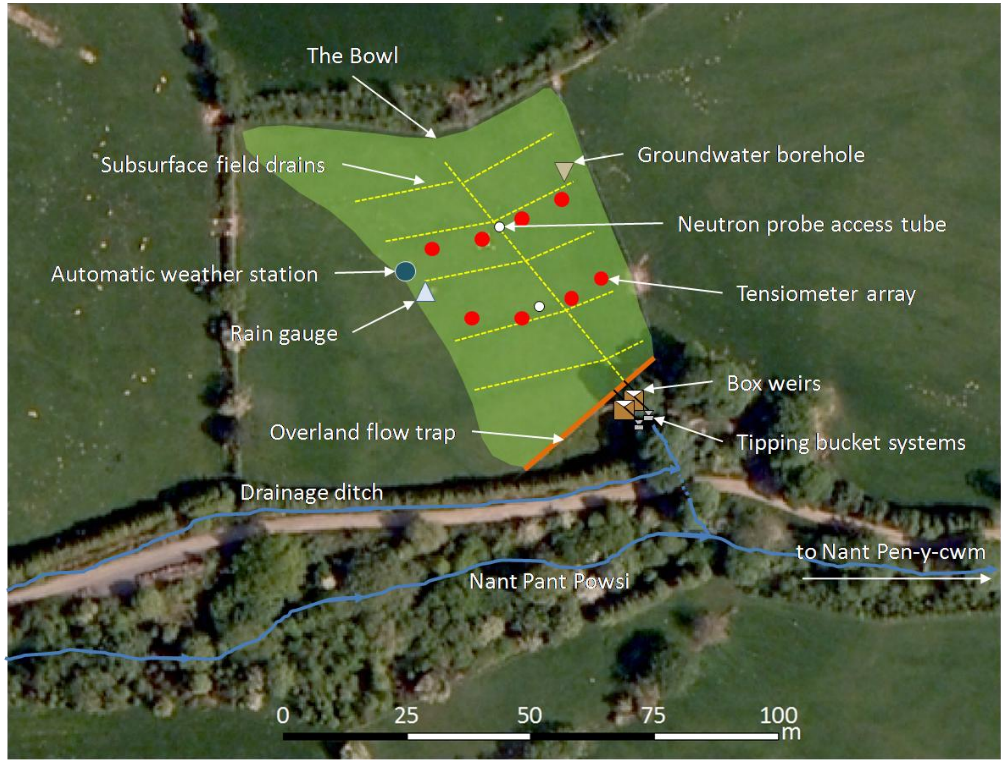
Table 3.1 Differences in the percentage sand/silt/clay content of Cegin soil horizons sampled in the Bowl (data provided by Imogen Solloway, pers. comm.).

3.3 Data collection

3.3.1 Experimental infrastructure and hydrometeorological data

A suite of scientific equipment and supporting infrastructure (Figure 3.2a) has been maintained at the site since 2005 by Imperial College London and CEH Bangor to help improve conceptual understanding of runoff generation within grazed, agriculturally-improved upland pastures (Marshall *et al*., 2009; Jackson *et al*., 2008). Overland flow from a 0.44 ha zero-order hollow (*c.f.* Dietrich *et al*., 1987) within the pasture is intercepted by a plastic gutter at its downslope boundary (Figure 3.2b). The collecting trough is protected from livestock disturbance by a wooden canopy. Runoff from the underlying field drain network, hereafter referred to as drain flow, is also isolated at a drain outlet in the south-eastern corner of the Bowl. It is

(a)



(b)

(c)

Figure 3.2 (a) Layout of hydrometeorological equipment and supporting infrastructure at experimental pasture on Tyn-y-bryn farm; (b) overland flow trap (beneath wooden boards along downslope edge of the Bowl); (c) box weir/tipping bucket runoff monitoring system. Aerial photography provided by University of Wales Aberystwyth.

estimated (based on the layout of upslope feeder drains identified in aerial photographs) that the drain outlet has a contributing surface area of approximately 0.36 ha. Runoff from both sources is measured using a combination of v-notch box weirs (equipped with pressure transducers) and individual tipping bucket systems to ensure accuracy during periods of both high- and low-flow (Marshall *et al.*, 2009; Figure 3.2c). Data loggers record 5 minute-averaged discharge values from the box weirs and the number of tips performed every 10 minutes by the tipping bucket systems. Cross-slope transects of tensiometer arrays monitor changes in soil pore water potential, ψ, (cm H_2O) at depths of 10 cm, 30 cm and 50 cm below the surface of the Bowl every 10 minutes. Access tubes installed adjacent to the tensiometer arrays facilitate the measurement of changes in volumetric soil moisture content, ϑ, (cm^3 cm^{-3}) using neutron probes, and the groundwater elevation beneath the pasture is determined every 30 minutes at an instrumented borehole. An automatic weather station and tipping bucket rain gauge provide a variety of meteorological information, including values of rainfall intensity, air and soil temperature, and relative humidity at 10 minute temporal resolution. Hydrometeorological data collected at the site between June 2006 and June 2008 were made available for use in this study (Miles Marshall, pers. comm.).

3.3.2 Event-scale sediment yield measurement

Sediment export from the Bowl was measured indirectly on a quasi-continuous basis between October 2006 and June 2008 using Partech IR100C turbidity sensors mounted in the outflow pipes connecting the overland flow trap and field drain outlet to the box weirs (Figure 3.3a). The technique exploits the tendency of water turbidity (defined as the degree to which light is scattered and/or absorbed rather

(a) (b) (c)

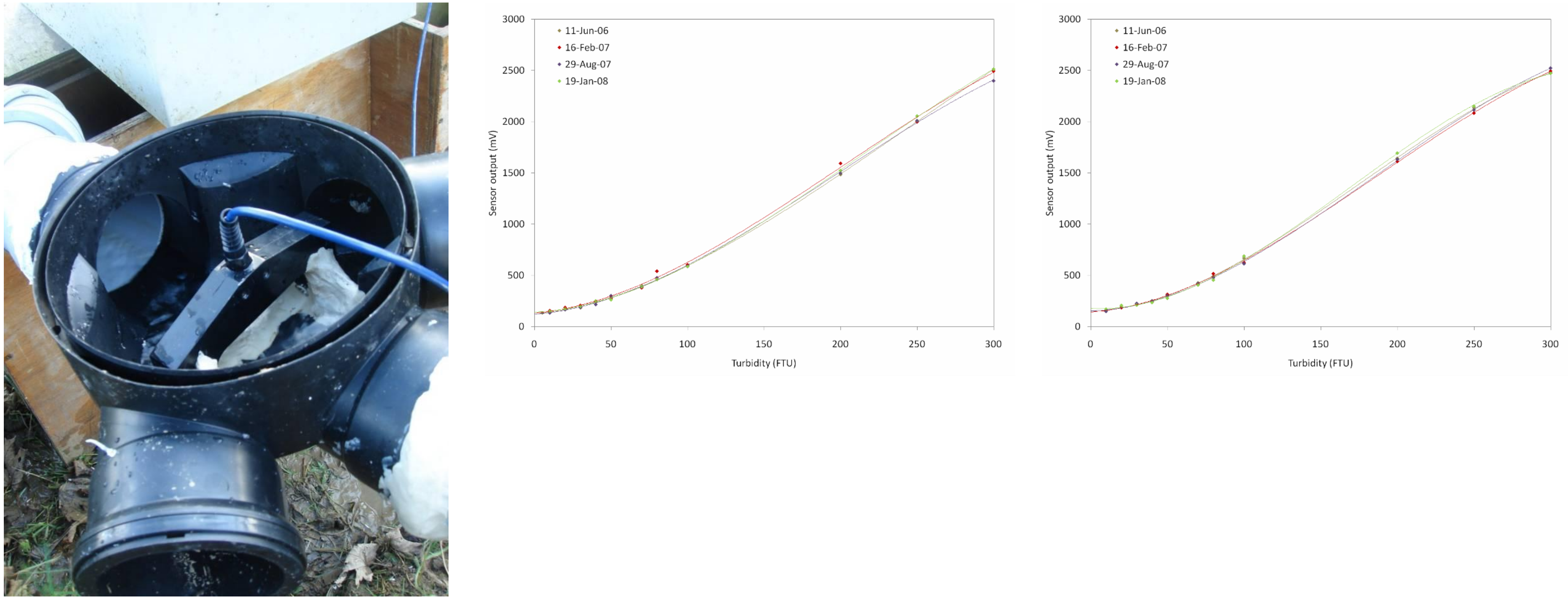


Figure 3.3 Partech IR100C turbidity probe mounted in outflow pipe from the field drain system beneath the Bowl (a); and changes in response through time of sensors mounted in the surface (b) and drain (c) outflow pipes.

than travelling through a water body) to vary proportionally with changes in suspended sediment concentration (Gippel, 1995), and has been used to investigate erosion and sediment transport in a wide range of environments (e.g. Krause and Ohm, 1984; Gilvear and Petts, 1985; Clifford *et al*., 1995a; Brasington and Richards, 2000). The approach offers two significant advantages over time-integrated manual or flow-triggered water sampling programmes. First, it prevents sediment transport events being missed or poorly represented (Gippel, 1995; Webb *et al*., 1997) and, second, it allows fluctuations in transport rates to be studied at temporal scales that permit process inference (Finlayson, 1985; Clifford and French, 1996).

The IR100C sensor quantifies turbidity by measuring the reduction in intensity of pulsed infrared light (wavelength = 950 nm) as it travels through the water column from an emitter to a paired receiver. The receiver adjusts the strength of an internal current loop signal from 0-5 mA according to the level of attenuance, and the response can be converted to a 0-2.5 V output for data logging purposes using a 500 Ω resistor. The sensors deployed at the site were scanned at 30 second intervals and 5 minute-averaged voltage outputs were recorded on a Campbell Scientific CR10x data logger, thus mirroring the frequency of discharge measurements obtained at the box weirs.

Although models in the Partech IR range have good anti-biofouling properties (Clifford *et al*., 1995b), lens cleaning was undertaken on a weekly basis and voltage outputs from the sensors were calibrated against reference solutions of known turbidities approximately every six months to account for any drift in response (*c.f.* Vanous *et al*., 1982). These calibrations were performed *in-situ* at the field site using laboratory-prepared dilutions of Formazin (a commonly used reference material that combines neutral buoyancy with constant particle size; Wass *et al*., 1997). The relationship between turbidity and output (mV) from Partech IR sensors tends to follow a distinctly sigmoidal trend (*c.f.* Clifford *et al*., 1995b) and was, therefore, defined by fitting third-order polynomial regression curves to the calibration data (Figure 3.3b and c). Equations derived from the curves were used to convert the continuous voltage output record for the entire monitoring period into equivalent Formazin Turbidity Unit (FTU) values.

Site-specific relationships between turbidity and suspended sediment concentration are typically modelled using values derived from water samples collected over a range of flow conditions (e.g. Wass *et al*., 1997; Old *et al*., 2003; Minella *et al*., 2008). However, the design of the runoff measurement system at the site and the level of interference that would be generated by event-based water sampling prohibited this approach. Instead, turbidity (FTU) was calibrated against suspended sediment concentration using laboratory-prepared reference solutions containing known quantities of sediment that was deposited in the box weirs over the course of the monitoring period (*c.f.* van den Elsen *et al*., 2003). The resulting linear regression models were used to convert turbidity values obtained during the experiment into equivalent suspended sediment concentrations (Figure 3.4). It should be noted that temporal variation in the size of transported sediment particles due to changes in flow/sediment supply conditions can affect the relationship between turbidity and suspended sediment concentration (Foster *et al*., 1992; Clifford *et al*., 1995b). While particle size variation is unlikely to have been a significant factor in this experiment (see later discussion), reported suspended sediment concentrations should, therefore, not be viewed as absolute and in this study attention is focussed on *relative* changes during runoff events.

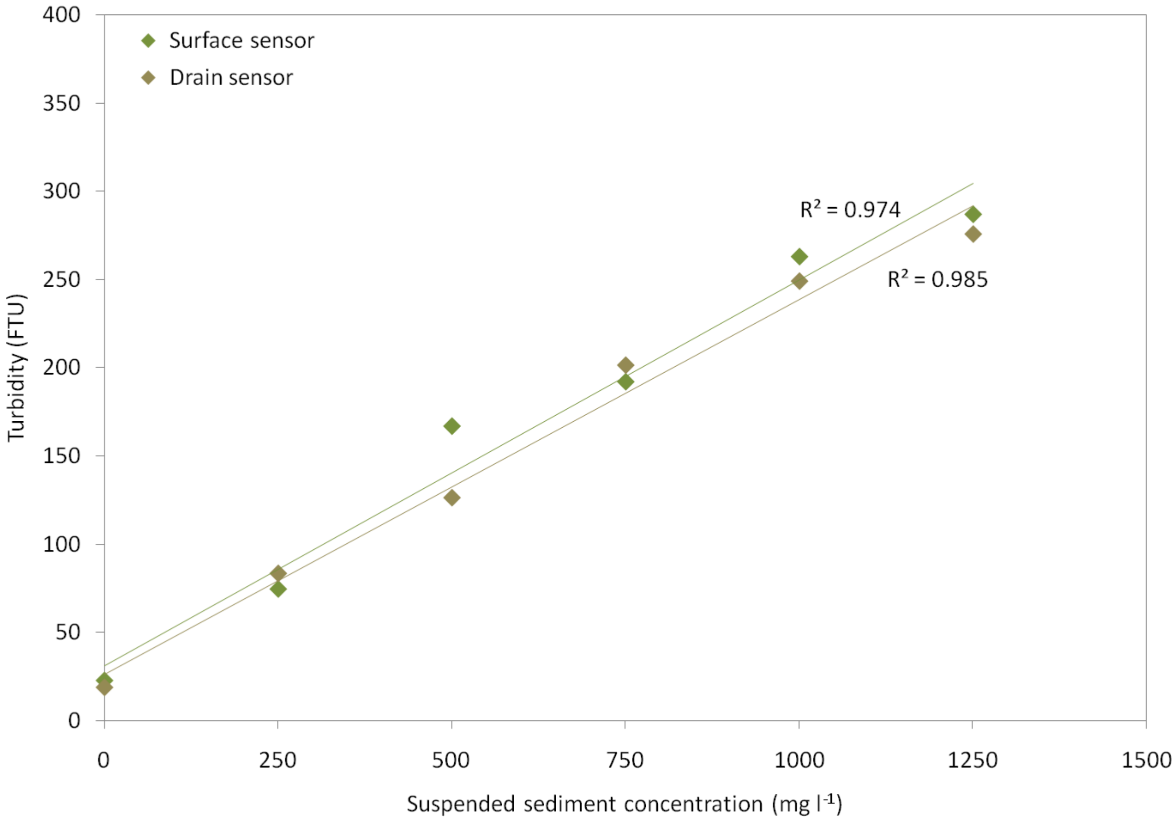


Figure 3.4 Relationship between suspended sediment concentration and turbidity defined using material deposited in the weir boxes downstream of the overland flow trap and field drain outlet.

3.3.3 Long-term sediment yield measurement

Sediment yields can be estimated from calibrated turbidity data sets by integrating derived suspended sediment concentrations with simultaneous discharge measurements (e.g. Wass and Leeks, 1999). However, the turbidity records from both sensors at the site contained periodic breaks due to obscuration of the lenses by organic material, small stones and/or animal activity, and they were therefore unsuitable data sources for long-term sediment yield assessment. As an alternative, sediment deposited in the box weirs between their installation (11 April 2006) and the end of the monitoring period (5 June 2008) was used to estimate annualised sediment export values from the Bowl (*c.f.* Verstraeten and Poesen, 2000; Figure 3.5), thus allowing the relative significance of surface and subsurface sediment delivery pathways to be evaluated.

The volume of accumulated sediment in each box weir was calculated as the product of its depth (measured using a ruler after overlying water had been carefully decanted) and the known floor area of the rectangular structure. The sediment was then excavated and sub-samples removed for laboratory analysis (following Verstraeten and Poesen, 2001). Moisture content (%) values were calculated by comparing the volume of samples before and after oven-drying (105 °C for 24 hours). Dry bulk density (g cm^{-3}) was then computed by dividing the dried sediment mass of samples by their volume, and mean values of the two parameters were subsequently calculated for each box weir in order to estimate their respective total dry sediment contents (kg) from the original wet volume measurements. Annual sediment exports (kg yr^{-1}) from the surface of the Bowl and its underlying field drain network were calculated by dividing the estimated total mass of dry sediment (kg) from the corresponding box weir downstream by the length of the monitoring

Figure 3.5 Removal of sediment deposited in the box weirs at the experimental pasture (05 June 2008).

period (2.15 years). Corresponding sediment yields (kg ha^{-1} yr^{-1}) were calculated based on the contributing areas defined in Section 3.3.1 (see later discussion on appropriateness of expressing drain sediment yield as function of area).

The accuracy of sediment yields calculated using the method described above are likely to be strongly influenced by the trapping efficiency of the box weirs as well as the competence of the runoff collection system in supplying sediment. While visual observations over the course of the monitoring period indicated that all sediment supplied to the overland flow trap or exported from the field drain outlet was transferred to the box weirs without deposition in the intervening pipe system, the proportion of sediment retained there was difficult to quantify directly. Particle size information on collected sediment was derived by laser diffractometry using a Beckman Coulter LS100Q. The results were used to assess the depositional conditions within the structures and evaluate potential impacts that could result from supply to watercourses. Mean organic content (%) values were also derived for each box weir through loss on ignition analysis (550 °C for 4 hours) performed on samples that had been used to calculate dry bulk density.

3.4 Results and discussion

3.4.1 Meteorological characteristics of the field site during the experimental monitoring period

Annual rainfall at the site (based on two years of data from the tipping bucket raingauge) was just over 1440 mm, being generated largely by frontal systems, although convectional thunderstorms did contribute large bursts on occasions, particularly during summer months. One such event, on 27 August 2006, generated a rainfall intensity of 31.2 mm h^{-1} during a 10-minute period, the maximum value recorded at the Bowl during the course of the study. However, such rates are unusual, with over 95% of rainfall recorded during the study falling at rates of less than 10 mm h^{-1}. Figure 3.6 highlights temporal differences in monthly rainfall throughout the study period. The chart shows that rainfall exhibits strong seasonal variation at Pontbren, with a large proportion (>40%) concentrated during the winter months (December-February). The largest monthly total was recorded in January 2008 (274.0 mm). The distribution of wet days of varying magnitudes is shown in Figure 3.7.

While winter rainfall totals were broadly similar during the first and second 12 months of the study period (646 mm: 584 mm), large differences in summer (June-August) rainfall totals were observed. Less than 9% of the total rainfall measured in the first half of the study period fell during summer 2006, causing streams in the Pontbren area to dry up completely (Figure 3.8), The period was the second warmest in England and Wales since records began in 1914 and rainfall during June and July was 43% and 27% of the long-term monthly averages, respectively (Meteorological Office, 2006). This was strongly contrasted by a particularly wet summer in 2007, during which approximately 28% of the total rainfall recorded in the last 12 months of monitoring fell. Monthly rainfall totals in June and July were the highest experienced in England and Wales since 1860 and 1888, respectively and the combined total for the two consecutive months was without recorded precedent (Marsh and Hannaford, 2008). Raingauge data from the Bowl indicate that 378 mm of rain fell in June and July at Pontbren, nearly five times more than during the corresponding period in 2006.

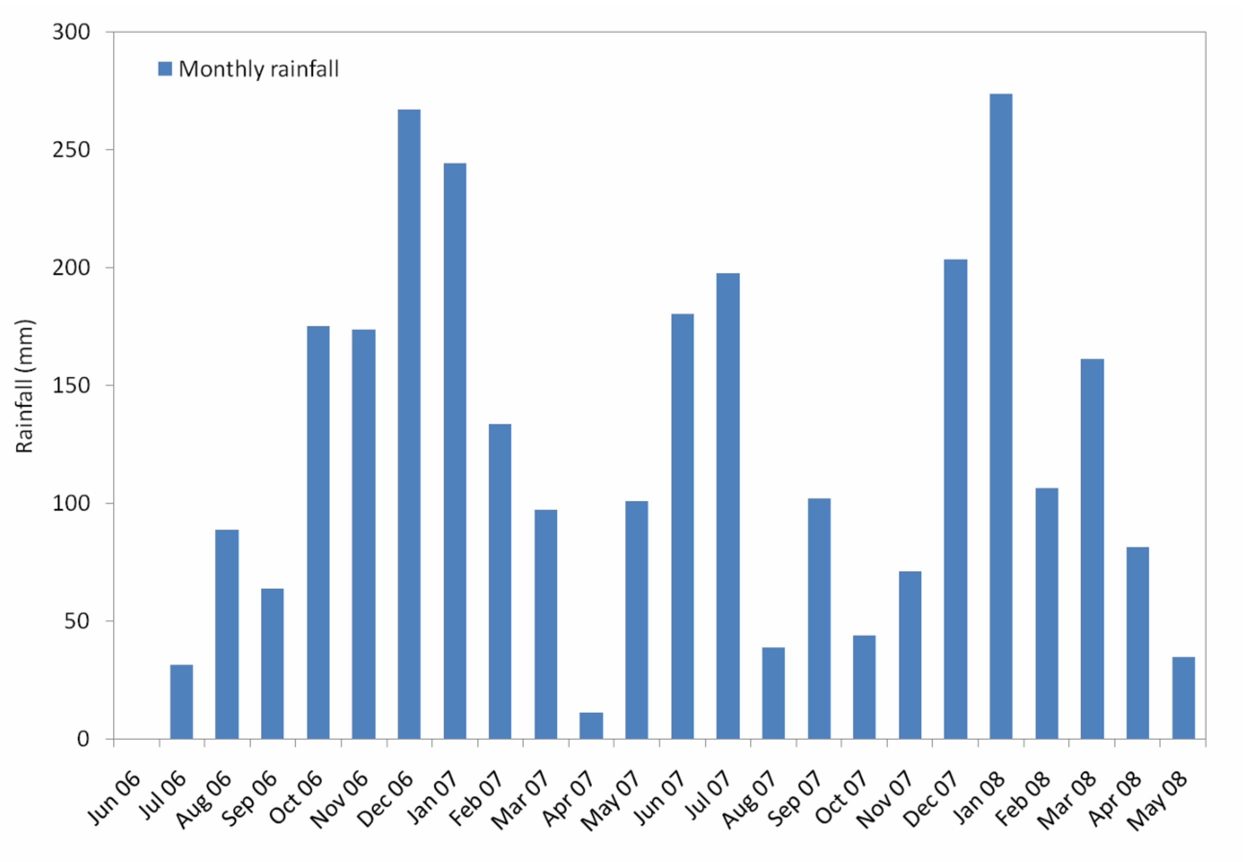


Figure 3.6 Monthly rainfall totals recorded by tipping bucket rain gauge at the Bowl (note: some data missing during June 2006).

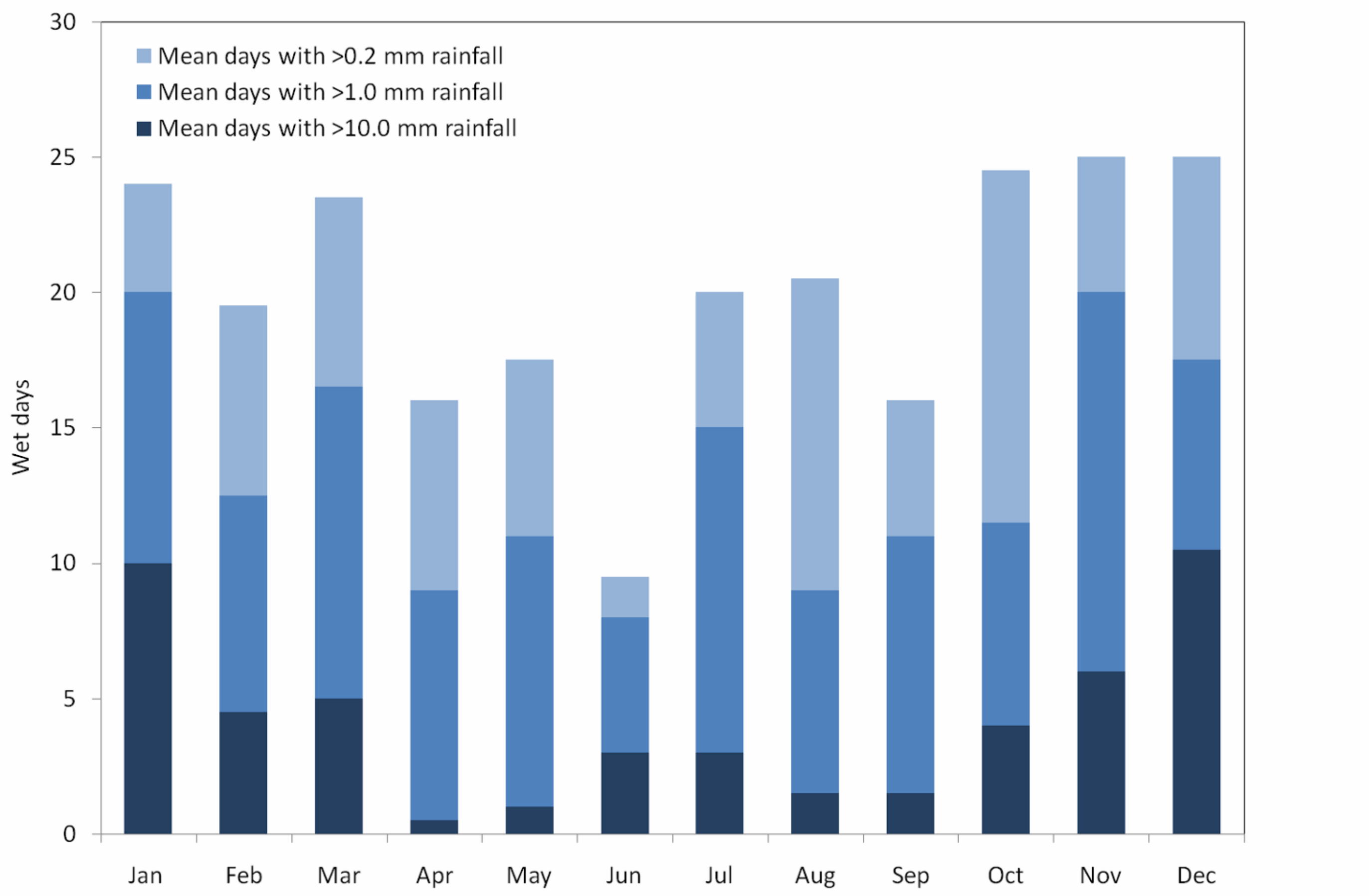


Figure 3.7 Annual distribution of wet days of varying magnitudes observed during the experimental monitoring at the Bowl.

Figure 3.8 Streambed of the Nant Pen-y-cwm exposed during dry weather in June and July 2006.

Figure 3.9 describes annual variation in mean maximum daily temperature, mean minimum daily temperature and number of air frost days recorded by the automatic weather station at the Bowl. The data again show strong seasonal variability, with frost and low temperatures concentrated during winter and spring (March-May) months. Air temperatures during these periods fall below 0 °C on approximately 52% and 37% of days respectively. Mean annual temperature (7.25 °C) and mean annual number of frost days (73.5) compare closely with averages for upland areas of mid-Wales (Meteorological Office, 2008).

3.4.2 Runoff characteristics of the field site

Field observations have verified the occurrence of widespread surface runoff in agriculturally improved pastures at Pontbren during and following periods of heavy rainfall (see Chapter 2; Figure 3.10). This is supported by data from the Bowl, which indicate that substantial volumes of overland flow can be generated and, although more common in winter and spring, surface runoff has been recorded throughout the year. Figure 3.11 compares overland flow and drain flow from the isolated areas of the site between June 2006 and June 2008. The data indicate that, while peak flows during the period tended to be dominated by drain flow, overland flow often formed a significant component of the total runoff and even exceeded the drain flow rate on a number of occasions. Similar phenomena have been recorded at other (smaller) monitoring sites within the study area (Wheater *et al*., 2008), suggesting that the runoff characteristics observed at the Bowl are representative of the wider landscape at Pontbren. For example, up to 74% of rainfall was captured by overland flow traps (as opposed to infiltrating into the soil) at grazed manipulation plot sites during December 2007 and January 2008 (Wheater *et al*., 2008).

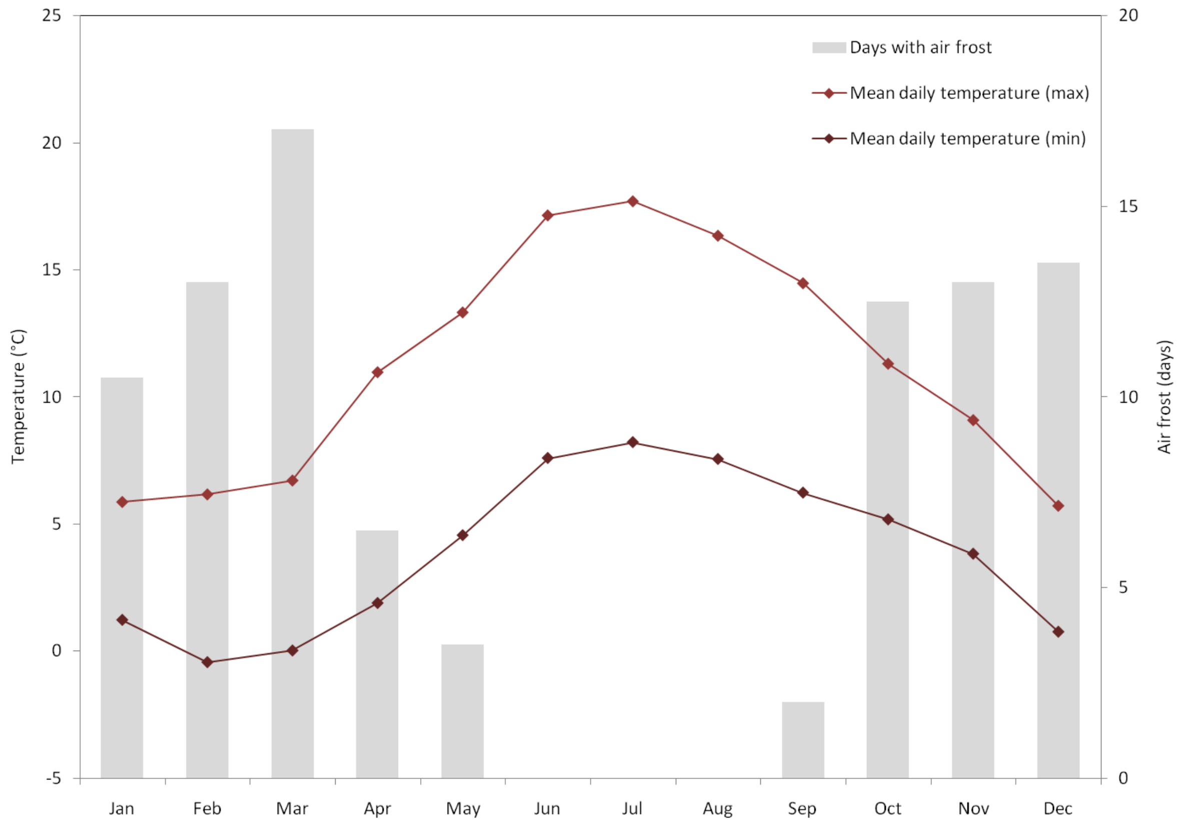


Figure 3.9 Annual variation in mean maximum daily temperature, mean minimum daily temperature and number of air frost days recorded by the automatic weather station at the Bowl.

Figure 3.10 Overland flow across the surface of the Bowl during rainfall event (08 March 2007).

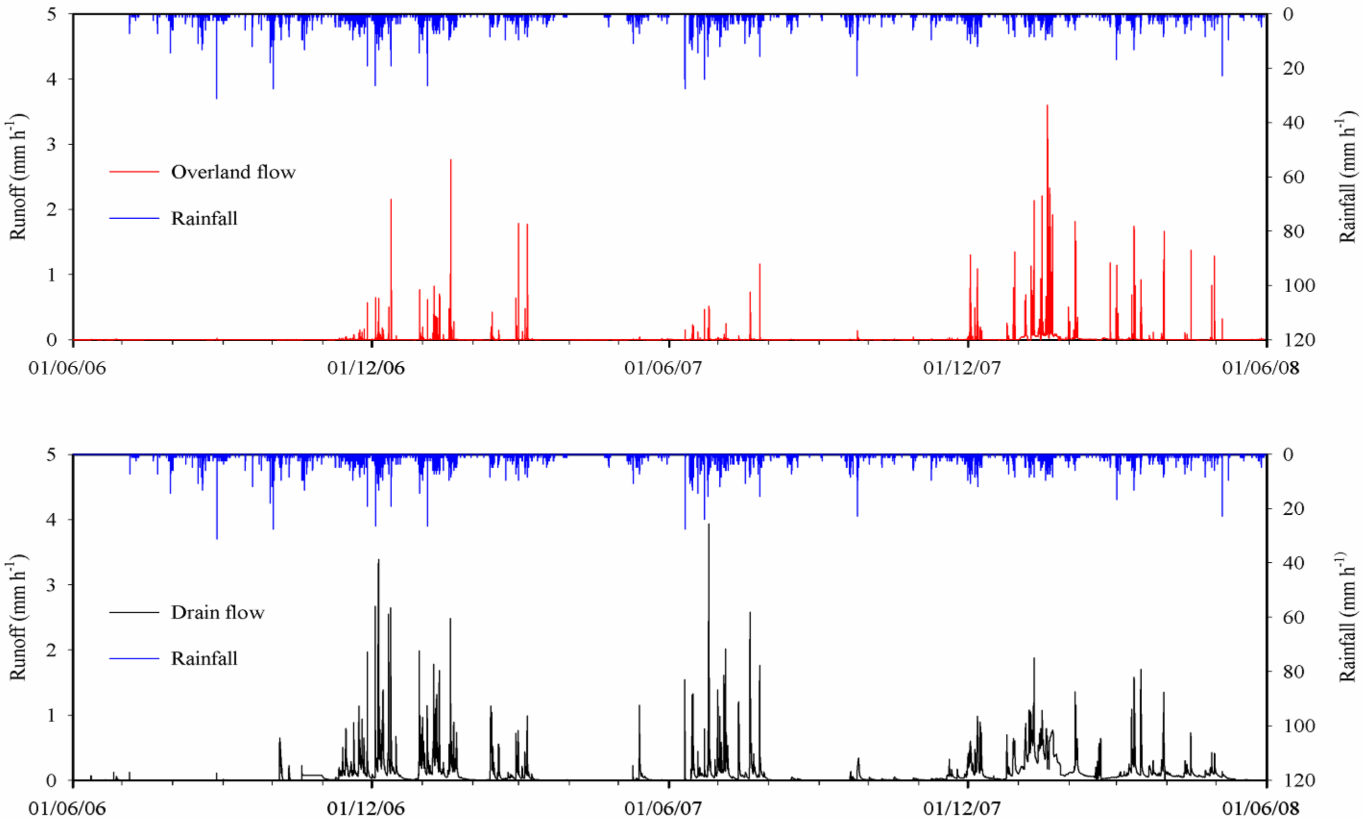


Figure 3.11 Overland flow and drain flow measured at the Bowl experimental hillslope (June 2006-June 2008).

Temporal variability in the incidence and relative magnitude of overland flow and drain flow was considerable during the study period (Figure 3.12). Overland flow occurred more frequently and in greater volumes during winter 2007/08 compared to winter 2006/07. Less than 6% of the total runoff from the Bowl in December 2006 came directly from the ground surface, compared with approximately 16% in December 2007. This was despite there being higher total rainfall (267 mm versus 203 mm) and more of wet days (30: 20) in December 2006. There was also a strong contrast between summer 2006 and summer 2007. Overland flow and drain flow volumes were extremely low between June and October 2006, while large amounts of runoff from both sources were recorded during June and July 2007.

Antecedent climatic conditions are believed to have exerted a strong influence on runoff mechanisms during the study period and may explain the variability encountered at the Bowl (Marshall *et al.*, 2009). Groundwater elevation measurements within the Bowl show that levels are usually fairly unresponsive to rainfall (Figure 3.13). The apparent buffering of groundwater response from the upper layers of the soil profile is believed to reflect the restricted permeability of soils in the Pontbren area (Marshall *et al.*, 2009). Saturated hydraulic conductivity (K_{sat}) tests have shown that water movement down through the soil profile is generally extremely slow, particularly through the B horizon (median K_{sat} = 0.018 m d^{-1}, n = 18), and pore water pressure records from tensiometers at experimental sites indicate that saturated near-surface conditions prevail throughout much of the year despite underdrainage (Wheater *et al.*, 2008). These conditions facilitate the rapid generation of large volumes of overland flow during rainfall events, as observed during winter 2007/08. While the wider lateral influence, and therefore

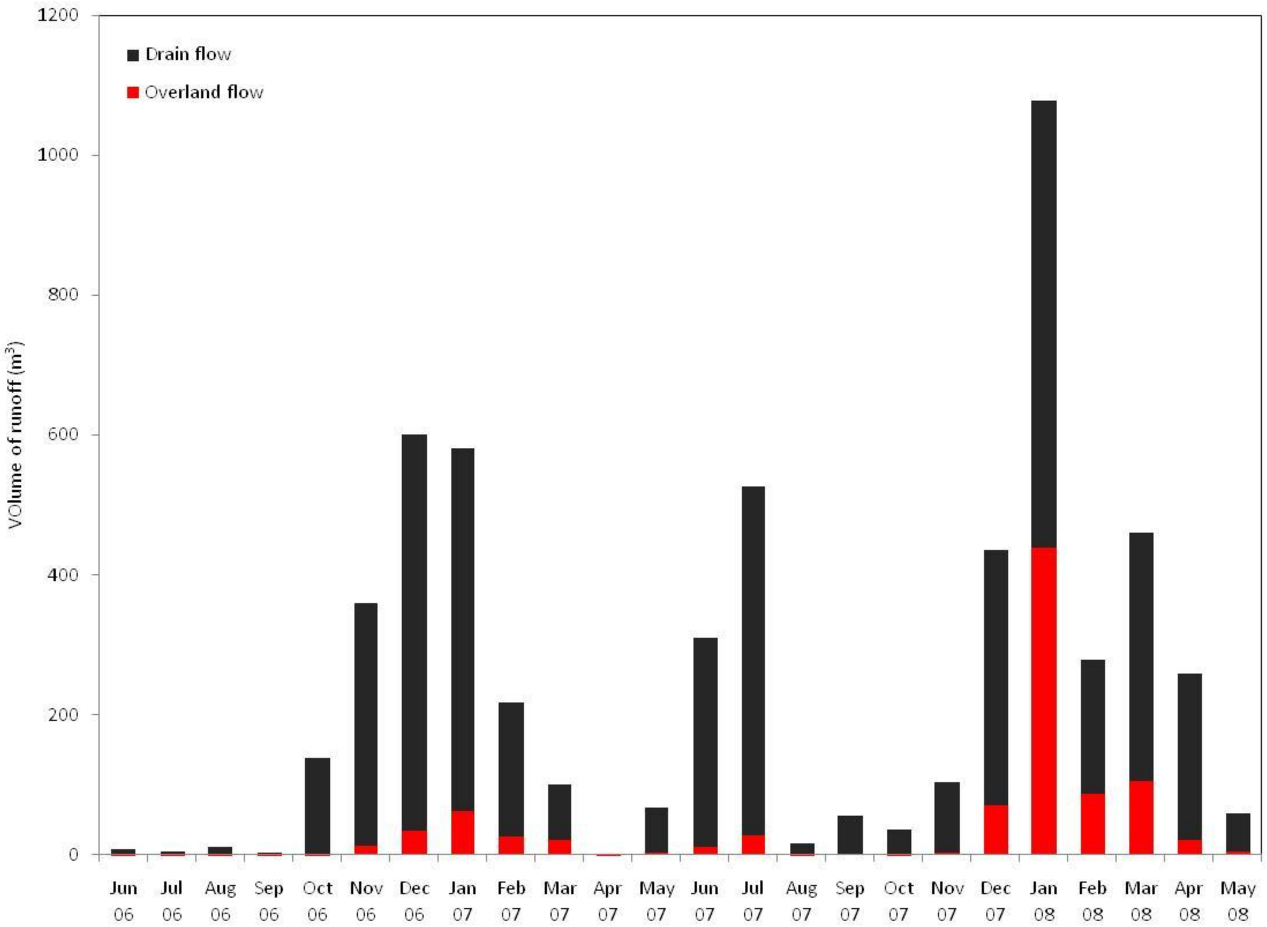


Figure 3.12 Temporal changes in the volumes of overland flow and drain flow recorded at the Bowl during the monitoring period.

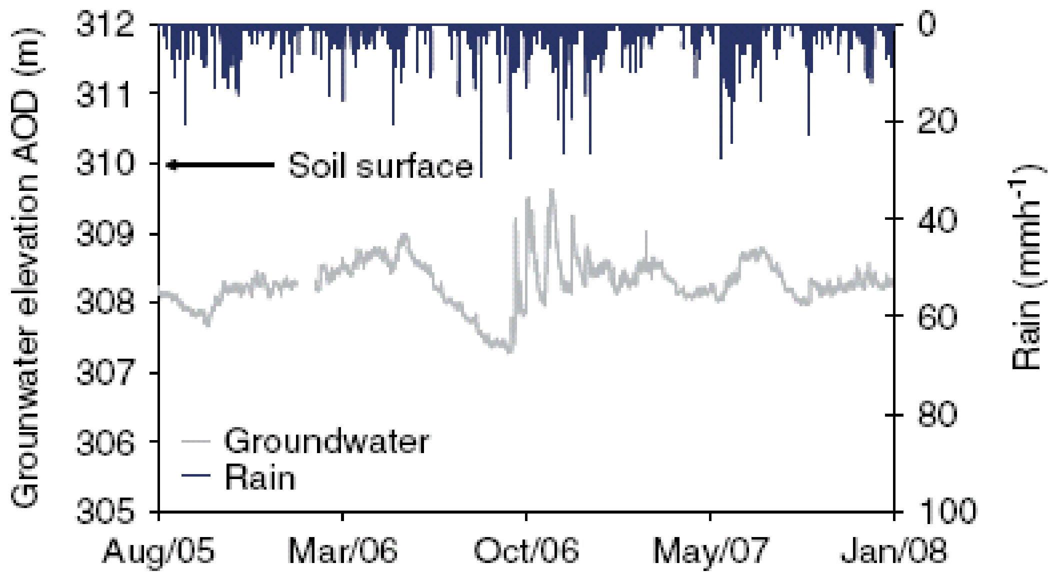


Figure 3.13 Groundwater elevations beneath the Bowl (August 2005-January 2008). Source: Marshall *et al*. (2009); p.473.

effectiveness, of field drains at Pontbren is questionable, dye tracing experiments by Francis (2005) show that preferential flow pathways can exist directly above drains in the area. Dye solution was detected at a drain outflow within two hours of application at the soil surface, indicating an effective hydraulic conductivity of approximately 9 m d^{-1} (Francis, 2005). This estimated rate of water movement through the soil above the drains is almost three times that of the mean K_{sat} in the A horizon, and 500 times that of the B horizon in similar soils not directly above drains (Wheater *et al*., 2008). The results are attributed to the presence of permeable backfill above drains, allowing water to move rapidly through the soil profile and into the drainage system.

Groundwater levels became very responsive to surface rainfall between October 2006 and January 2007, suggesting that a change in the hydraulic properties of the overlying soil occurred during the period. Marshall *et al*. (2009) propose that the hot and dry weather of summer 2006 could be responsible. MORECS (UK Meteorological Office Rainfall and Evaporation Calculation System) data for the Pontbren area indicated the presence of a large soil moisture deficit during summer 2006 and large surface cracks developed due to desiccation in soils at the experimental monitoring sites (Marshall *et al*., 2009). Surface cracks have been observed in similar soils under drought conditions (Newson and Robinson, 1983) and are known to act as preferential pathways for flow (e.g. Bouma, 1981). Marshall *et al*. (2009) suggest that the features may have enabled water to penetrate the relatively impermeable subsoil more easily and thus reduce the amount of overland flow in winter 2006/07.

Marshall *et al*. (2009) highlight changes in bulk hydraulic conductivity following the hot, dry summer of 2006 by comparing overland flow, drain flow and soil pore water pressure at depths of 10 cm, 30 cm and 50 cm in the Bowl during three separate runoff events in January, June, and December 2007. Overland flow accounted for over 50% of the total runoff recorded during the first event (Figure 3.14a). The presence of positive pore water pressures at 10 cm below the soil surface suggests that saturated conditions persisted throughout the event (Figure 3.14b), providing an explanation for the large volumes of surface runoff. Substantial amounts of drain flow were also recorded and peak flow rates for the two runoff sources occurred simultaneously, suggesting that water was able to move rapidly down through the soil profile. Significantly less overland flow was recorded during the event in June 2007 despite similar rainfall intensities to the event in January (Figure 3.14c). Negative pore water pressures in the upper soil profile at 10 cm indicate that the soil was not completely saturated prior to the event and thus able to absorb more water (Figure 3.14d). Drain flow peaked 30 minutes after overland flow, and this lag feature was even greater in the final event in December 2007 (Figure 3.14e). Near-saturated surface soil conditions (Figure 3.14f) resulted in the generation of large volumes of overland flow, which peaked 230 minutes before drain flow. The increase in lag times between peak overland flow and drain flow indicate a substantial decrease in the overall permeability of the soil between winter 2006/07 and 2007/08. Wheater *et al*. (2008) suggest that the change in response could have been caused by the closure of cracks and macropores as the soil reverted to its pre-drought state under wetter conditions.

It should be noted that the hydrological response of drained soils at Pontbren may be atypical of the region. Research by Newson and Robinson (1983) concluded that under drainage could substantially reduce moisture levels in soils similar to those found in the Pontbren area. However, there are a number of site-specific differences

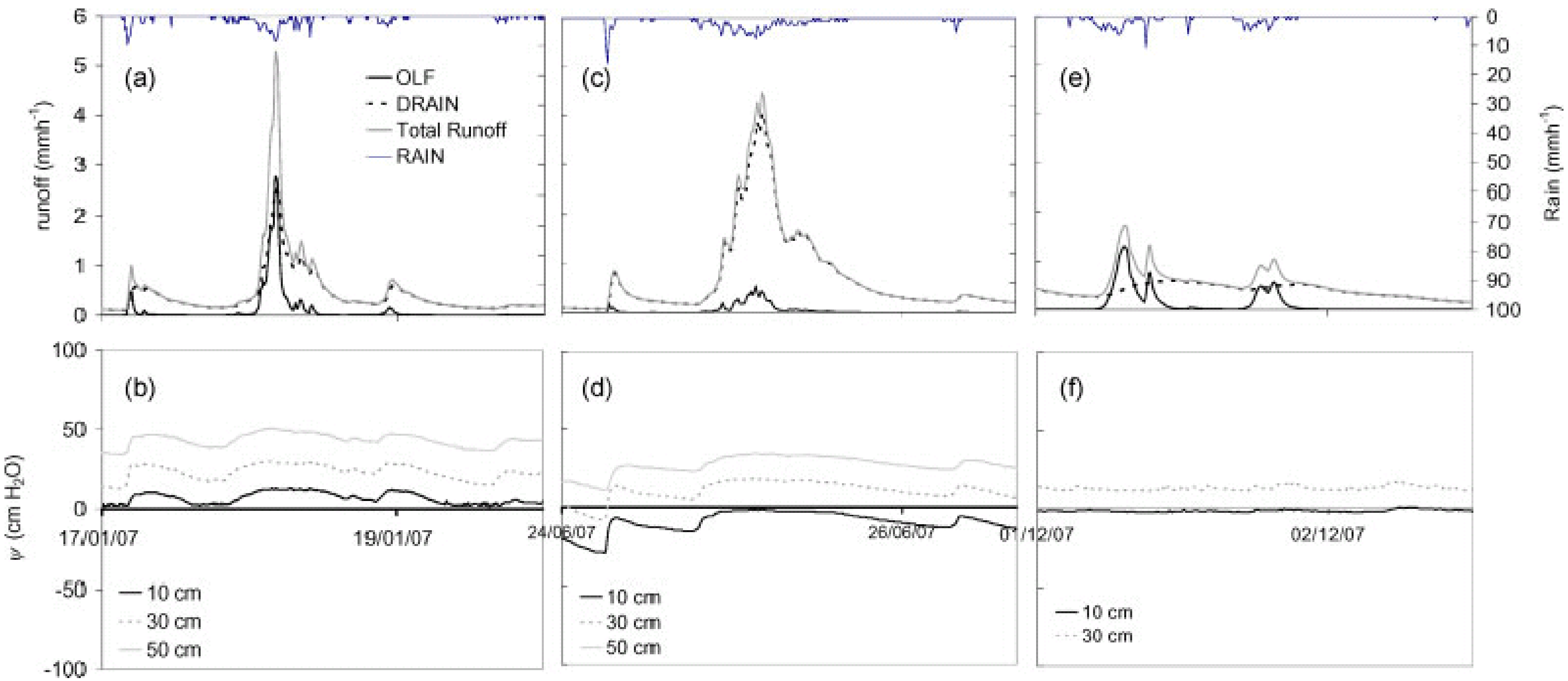


Figure 3.14 Runoff and soil pore water pressure responses at the Bowl during events in January (a and b), June (c and d), and December 2007 (e and f). Source: Marshall *et al*. (2009); p.471.

that may explain the comparative ineffectiveness of the field drains at Pontbren. For example, at the site investigated in the Newson and Robinson (1983) study that is most similar to the Bowl in terms of soil type and field drain arrangement, mean annual rainfall was substantially lower and the ground had been generously subsoiled. Interpretation of results from the study was also complicated by a severe drought in 1976 (Newson, 1980d) and, as highlighted by the data from Pontbren, this may have had significant effects on the hydraulic properties of the soils studied. It is also possible that observations at Pontbren reflect a long-term decline in drain efficiency that would not have been detected by the Newson and Robinson (1983) study, which explored effects up to one year after drainage installation. For example, drainage pipes in peaty soils at Pontbren are known to have been damaged through sagging in response to fluctuations in soil moisture conditions (D. Jenkins, pers. comm.).

3.4.3 Event-scale sediment yield dynamics

Data from the turbidity sensor mounted on the outflow pipe of the overland flow trap at the Bowl indicate that surface runoff mobilises fine sediment on the hillslope but that this is not the sole control of sediment yield. Suspended sediment concentrations in surface runoff were generally very low, with a mean of 23.0 ± 1.5 mg l^{-1} (error margins equal to standard error of mean), although they often exceeded 500 mg l^{-1} during rainfall events that generated substantial volumes of overland flow. A strong positive correlation (r = 0.57, $p < 0.001$) was evident between suspended sediment concentration and overland flow rate, although visual examination of the relationship between the two variables suggests that it is actually nonlinear (Figure 3.15). Suspended sediment concentrations were low and relatively

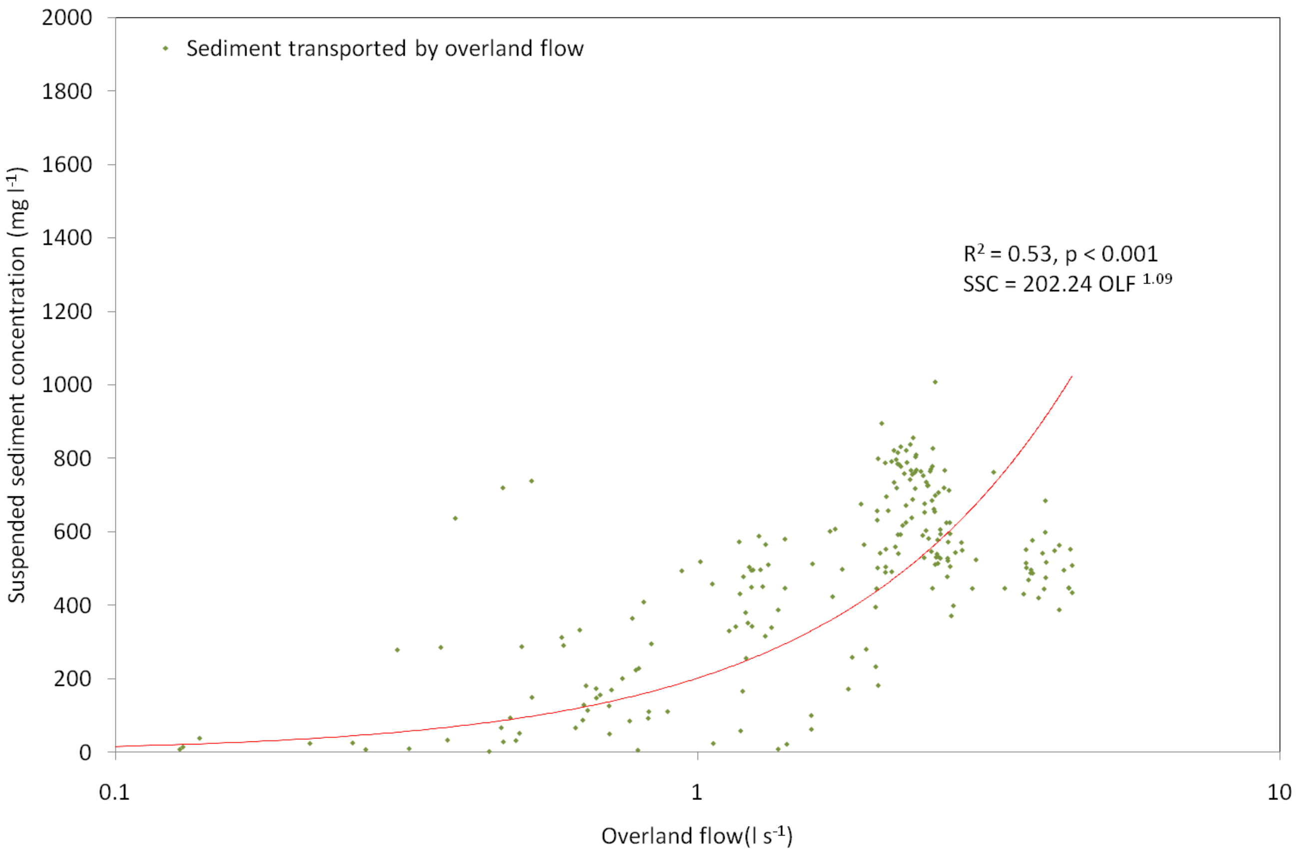


Figure 3.15 Relationship between discharge and suspended sediment concentration in overland flow from the Bowl.

consistent in flows up to approximately 0.5 l s^{-1}, before increasing once an apparent threshold discharge was exceeded. However, the relationship displayed considerable scatter, suggesting other controls may also be important.

Changes in rainfall intensity could help to explain some of the variation and did correlate positively with suspended sediment concentrations in overland flow (Figure 3.16). However, the association was relatively weak with considerable scatter. Analysis of sequential overland flow and suspended sediment concentration data provides a more satisfactory explanation for some of the observed scatter in the overland flow rate-turbidity relationship. Figure 3.17a shows the time series of rainfall intensity, overland flow rate and suspended sediment concentration in overland flow for an event on 7 January 2007. The charts show that a very close relationship exists between changes in rainfall intensity and ensuing overland flow generation during the event, and that suspended sediment concentration varies accordingly. This is clearly demonstrated in Figure 3.17b, which shows how suspended sediment concentration and overland flow rate interact as the event progresses. Although there is evidence of slight clockwise hysteresis, with suspended sediment concentrations being slightly higher on the rising limb of the event hydrograph compared to the falling limb, the two variables can be considered to be broadly in phase. This contrasts strongly with the event described in Figure 3.18 from 9-10 January 2008, which shows much stronger hysteresis.

These differences are demonstrated clearly in Figure 3.19, which describes two consecutive overland flow events of similar magnitudes that were generated by similar rainfall intensities on 10-11 January 2007. Suspended sediment

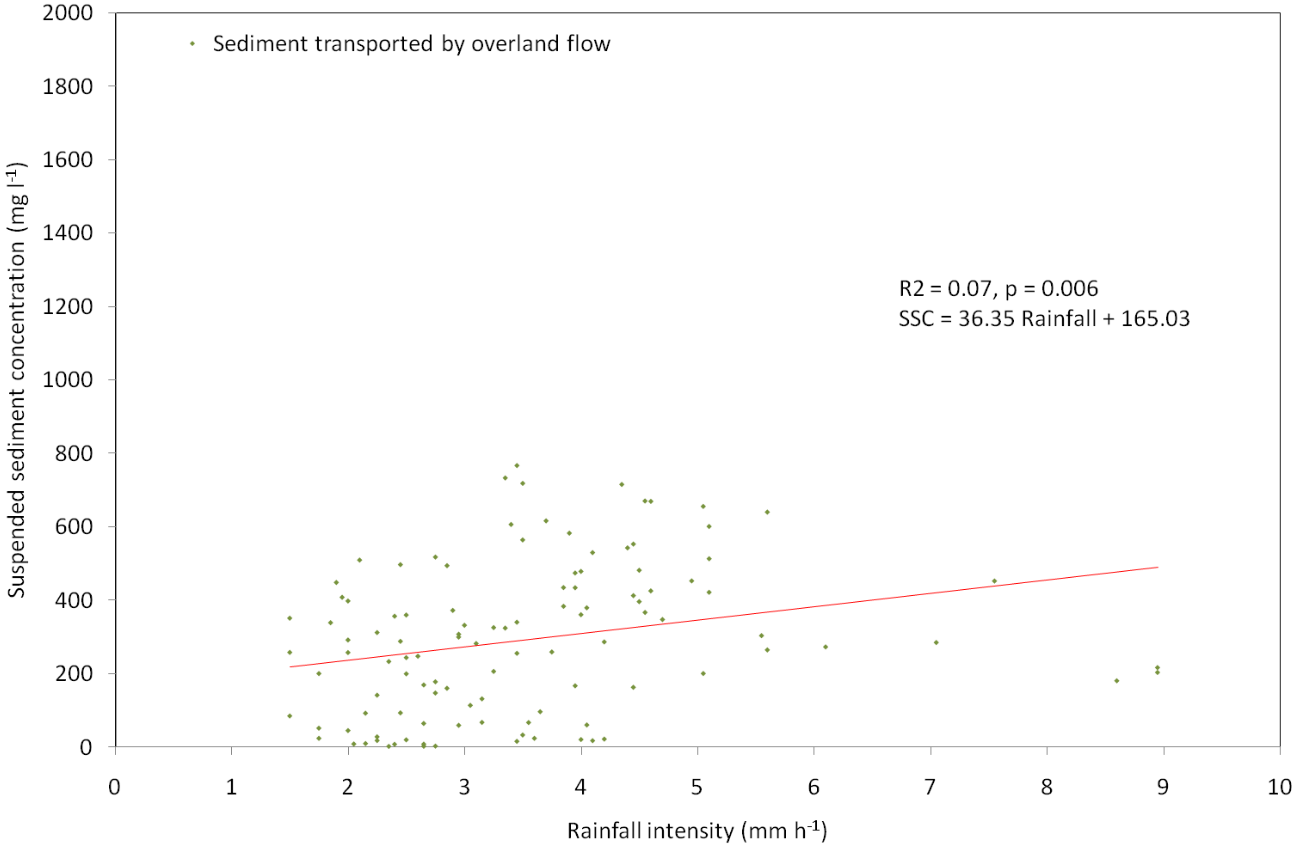
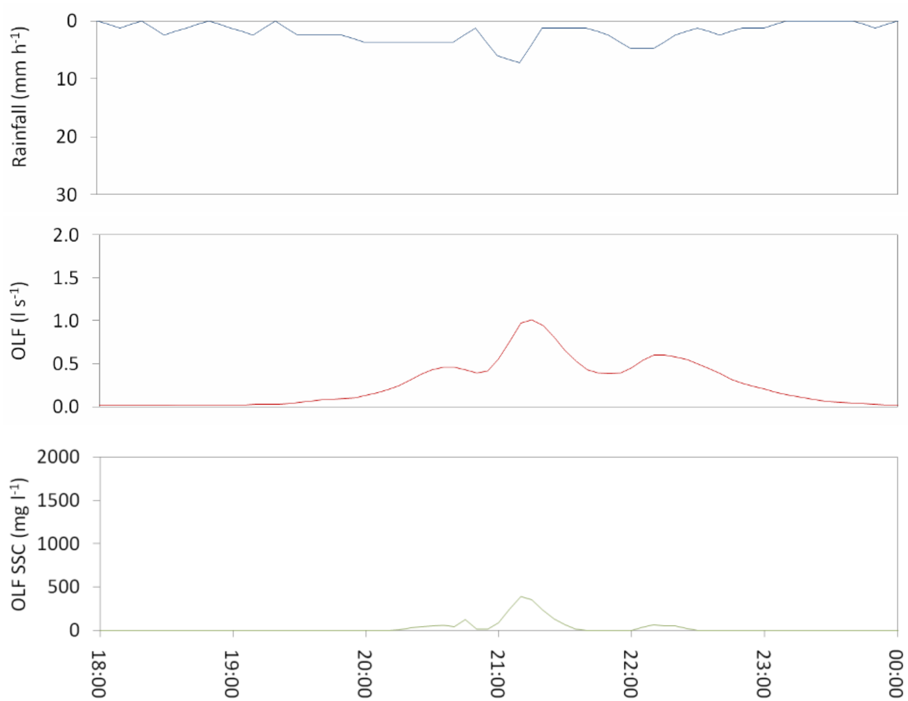


Figure 3.16 Relationship between rainfall intensity and suspended sediment concentration in overland flow from the Bowl.

(a)



(b)

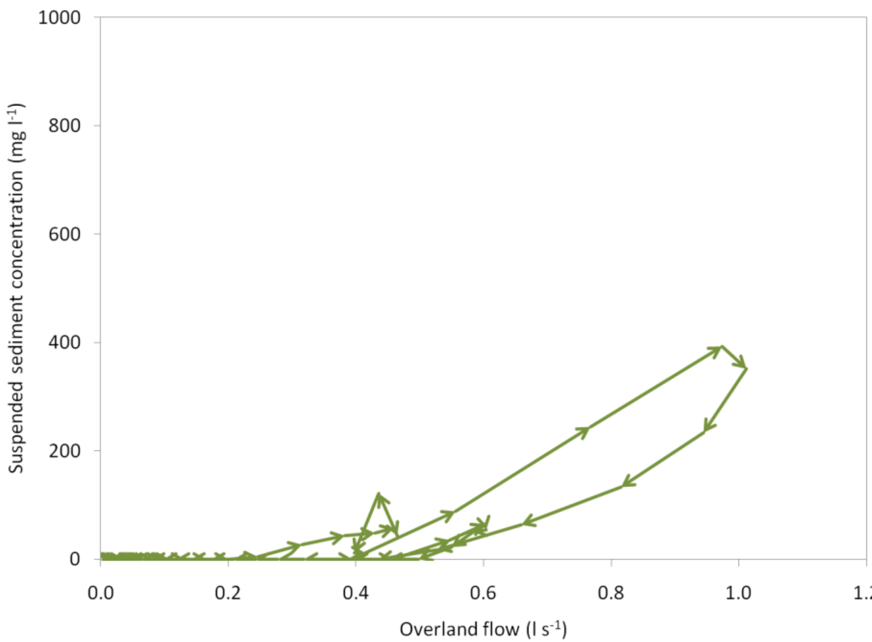


Figure 3.17 Time series of rainfall, overland flow rate and suspended sediment concentration in overland flow (a); and hysteresis plot of overland flow rate against suspended sediment concentration in overland flow (b) for event on 07 January 2007.

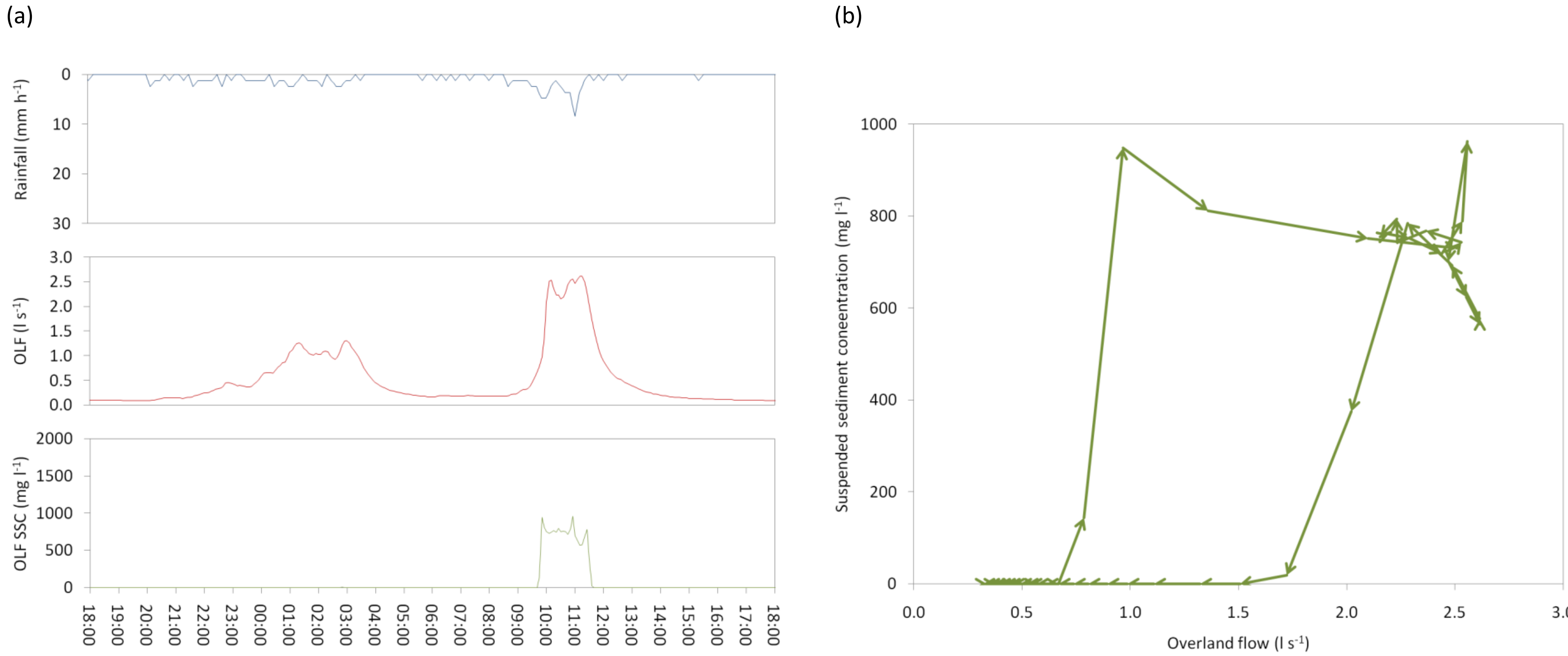


Figure 3.18 Time series of rainfall, overland flow rate and suspended sediment concentration in overland flow (a); and hysteresis plot of overland flow rate against suspended sediment concentration in overland flow (b) for event on 09-10 January 2008.

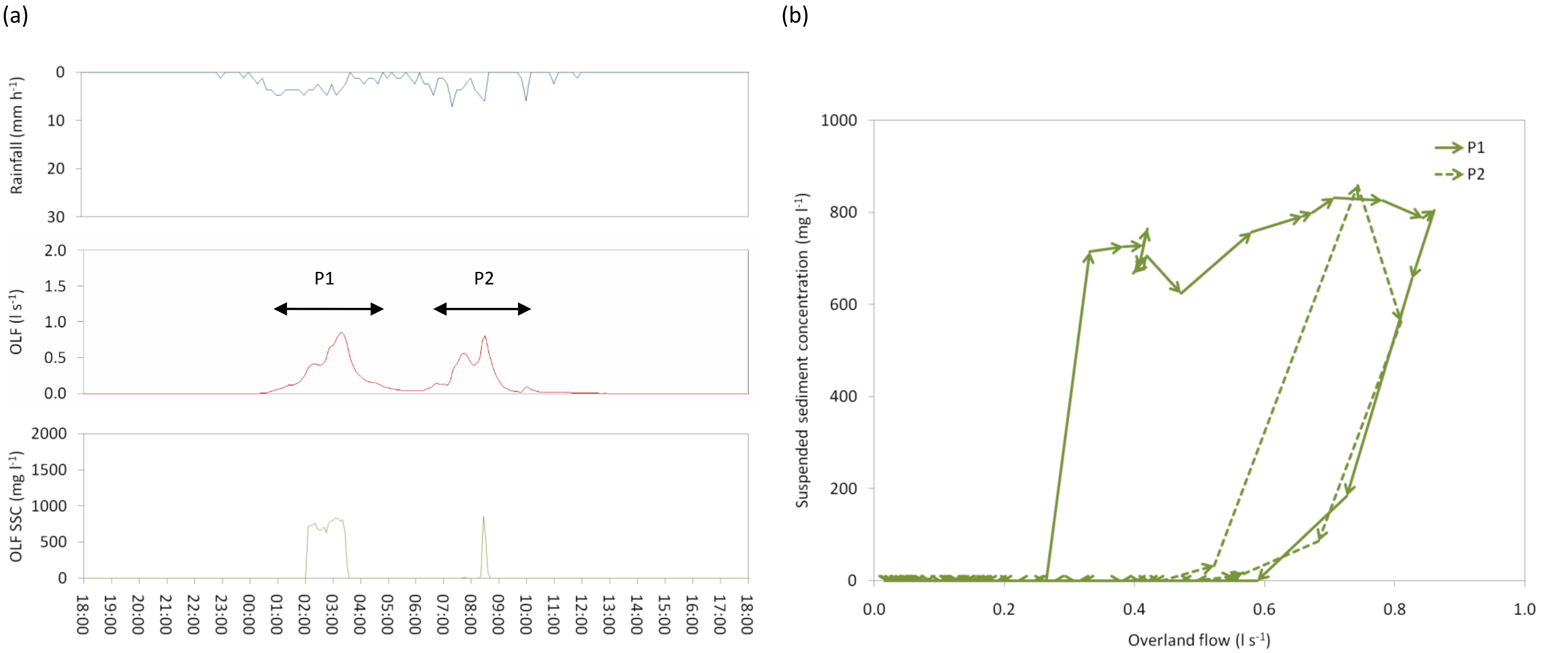


Figure 3.19 Time series of rainfall, overland flow rate and suspended sediment concentration in overland flow (a); and hysteresis plot of overland flow rate against suspended sediment concentration in overland flow (b) for event on 10-11 January 2007.

concentrations increased much earlier in the event (and therefore at lower overland flow rates) during P1 compared to P2, resulting in a larger degree of hysteresis. Similar characteristics have been reported in numerous studies of suspended sediment dynamics in a variety of fluvial systems (e.g. Walling, 1974; Clifford *et al*., 1995a; Brasington and Richards, 2000; Lenzi and Marchi, 2000) and are commonly believed to result from the flushing (and subsequent exhaustion) of available sediment during the initial stages of events. The differences may reflect either a disparity in the availability of sediment at the start of the event or exhaustion of material following the event peak (*c.f.* Walling and Webb, 1978). The findings indicate that transportable sediment (particles within the size range capable of mobilisation under the prevailing flow conditions) was more abundant and/or easily entrained during P1 in comparison to P2. Preconditioning of the soil (*c.f.* Wade and Kirkbride, 1998) by subaerial processes (e.g. freeze-thaw) and/or livestock activity prior to the onset of the event may offer possible explanations for greater sediment availability.

Field drains beneath the Bowl also acted as a source of fine sediment during the study period and could represent an important component of the sediment transfer system in the Upper Pontbren subcatchment. Comparison of simultaneously-measured turbidity data revealed that sediment concentrations were higher in drain flow than overland flow (Wilcoxon signed-rank test, $p < 0.001$), reaching a maximum value of 1564.7 mg l^{-1}, which though high is still within the range expected from published data from drainage systems in lowland environments (e.g. Chapman *et al*., 2005). In contrast to the association between overland flow rate and suspended sediment concentration, suspended sediment concentrations in drain flow showed no relationship with drain flow rate (Figure 3.20). This contradicts findings by

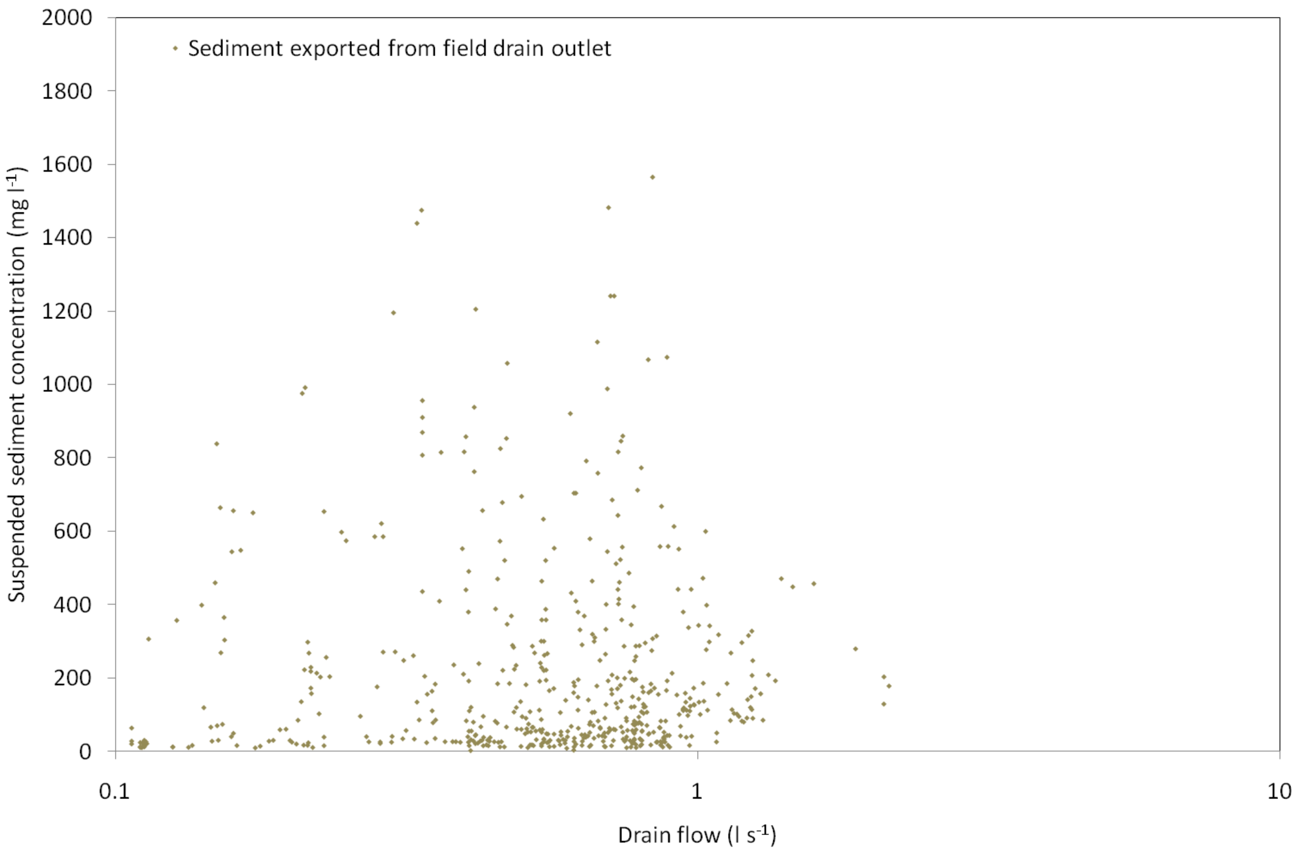


Figure 3.20 Relationship between discharge and suspended sediment concentration in drain flow from the Bowl.

Chapman *et al*. (2005), who found a positive relationship between the two variables. However, their study used aggregated monthly flow data and suspended sediment yields and it is unlikely to properly represent the true complexity of suspended sediment dynamics during runoff events from field drains. Chapman *et al*. (2005) do, however, show that macropores are likely to be an important component of sediment supply to field drains systems. Their data show that drain-derived sediment often originates from the upper layers of the soil profile and its supply efficiency varies with the degree of soil cracking due to changes in soil moisture levels (Chapman *et al*., 2005). Although suspended sediment concentration in runoff from the field drain system at the Bowl does not have clear relationships with either overland flow rate (Figure 3.21) or rainfall intensity (Figure 3.22), as would perhaps be expected if transported material was surface generated, hysteresis plots of suspended sediment concentration in drain flow against overland flow offer some clues to the origin of drain-derived sediment at the field site.

Figure 3.23 shows the relationship between rainfall intensity, overland flow rate, drain flow rate, and suspended sediment concentration in drain flow for an event on 4 January 2008. While little obvious connection can be seen between changes in drain flow rate and suspended sediment concentration, the hysteresis plot reveals a strong initial flushing of sediment as overland flow begins to be generated. It is speculated that this could represent a burst of sediment into the field drain system as water begins to move down through the soil profile during the early stages of events. Sediment is likely to enter the drainage system at pipe junctions, cracks or where filters surrounding the pipes have failed and sediment supply maybe be aided by animal activity. Moles are reported to exploit such areas in order to gain access to drain water during dry periods (R. Jukes, pers. comm.). The soil above field drains

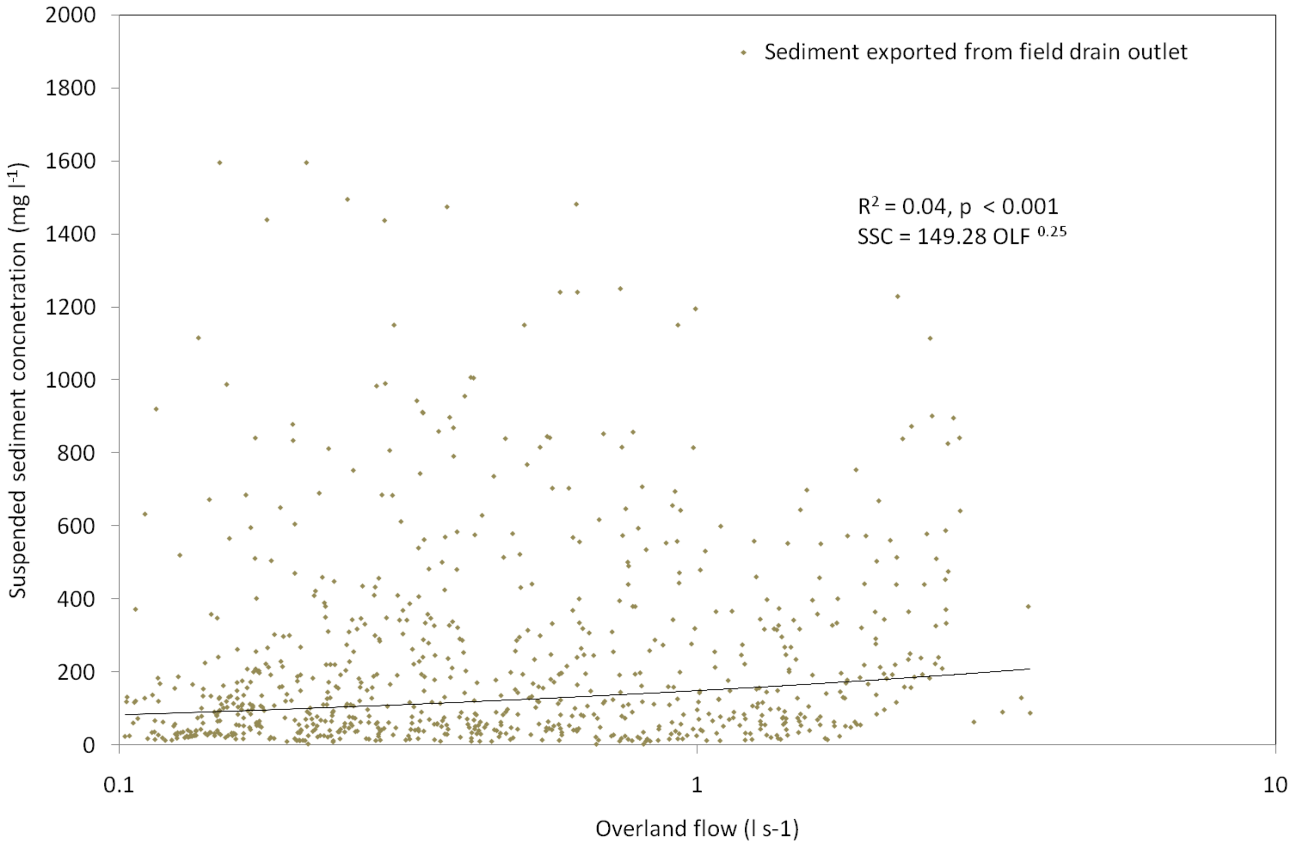


Figure 3.21 Relationship between overland flow rate and suspended sediment concentration in drain flow from the Bowl.

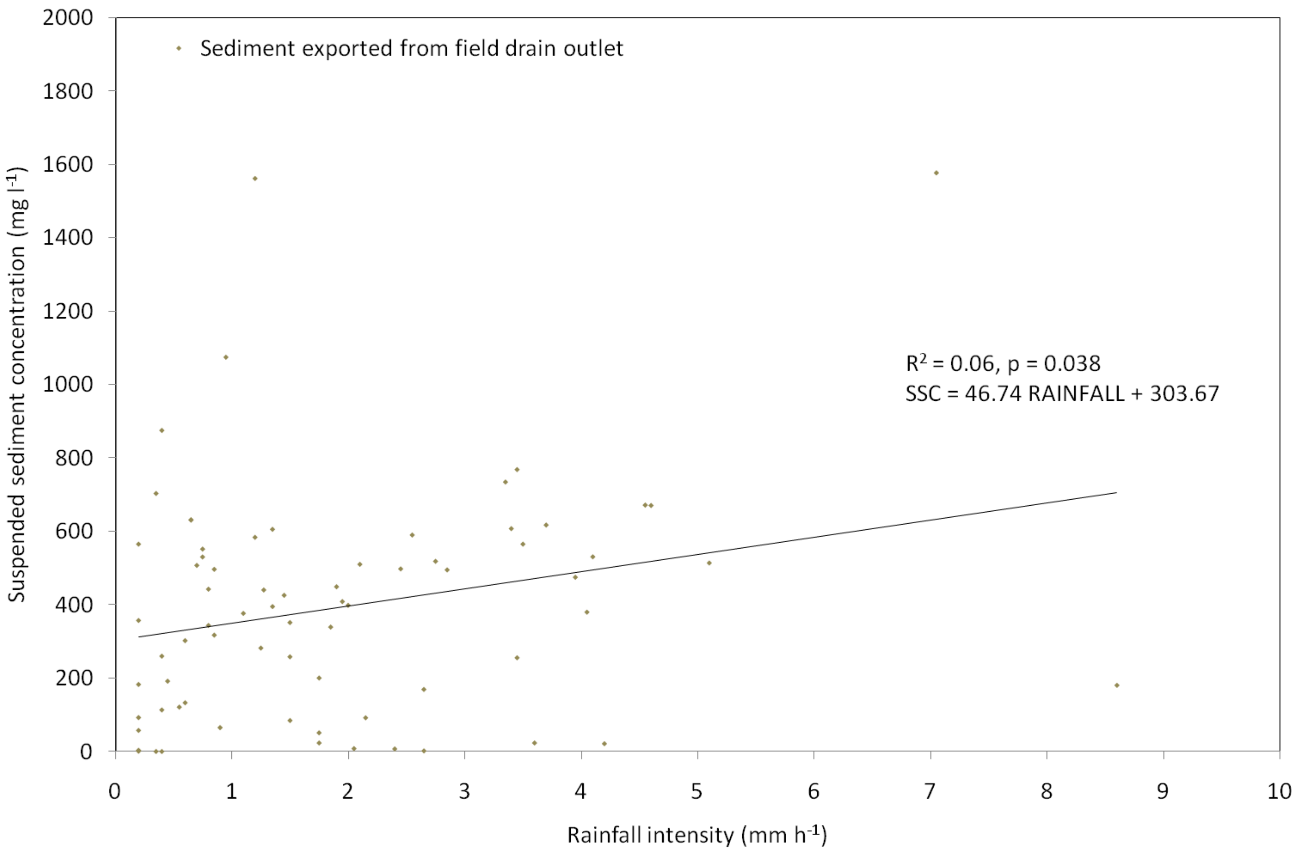
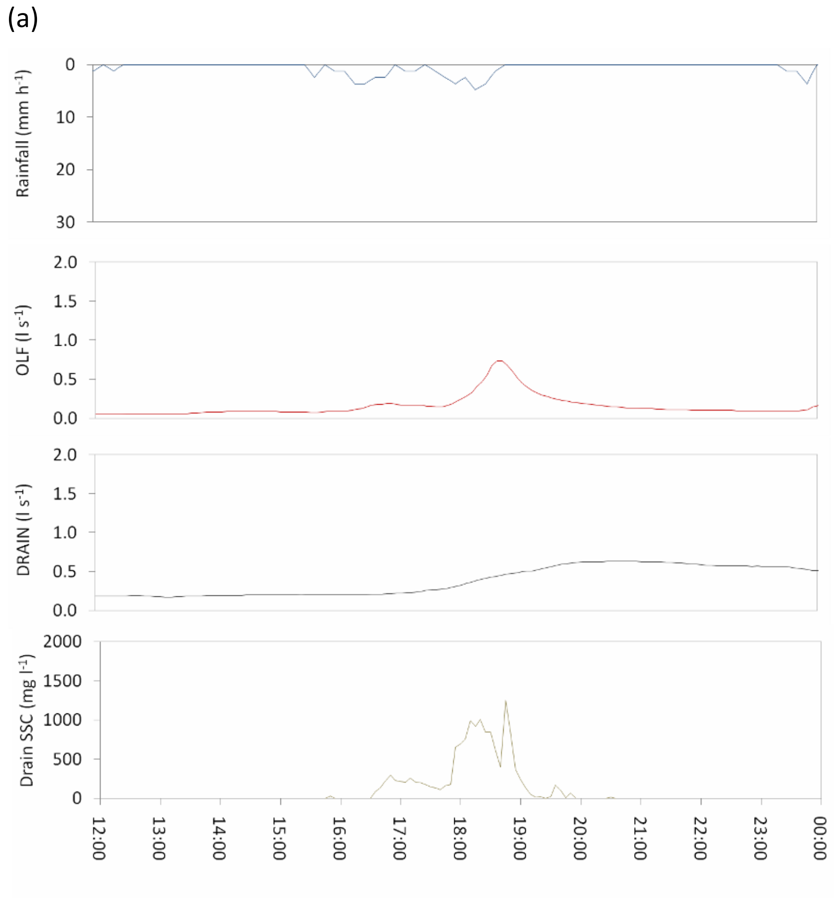


Figure 3.22 Relationship between rainfall intensity and suspended sediment concentration in drain flow from the Bowl.



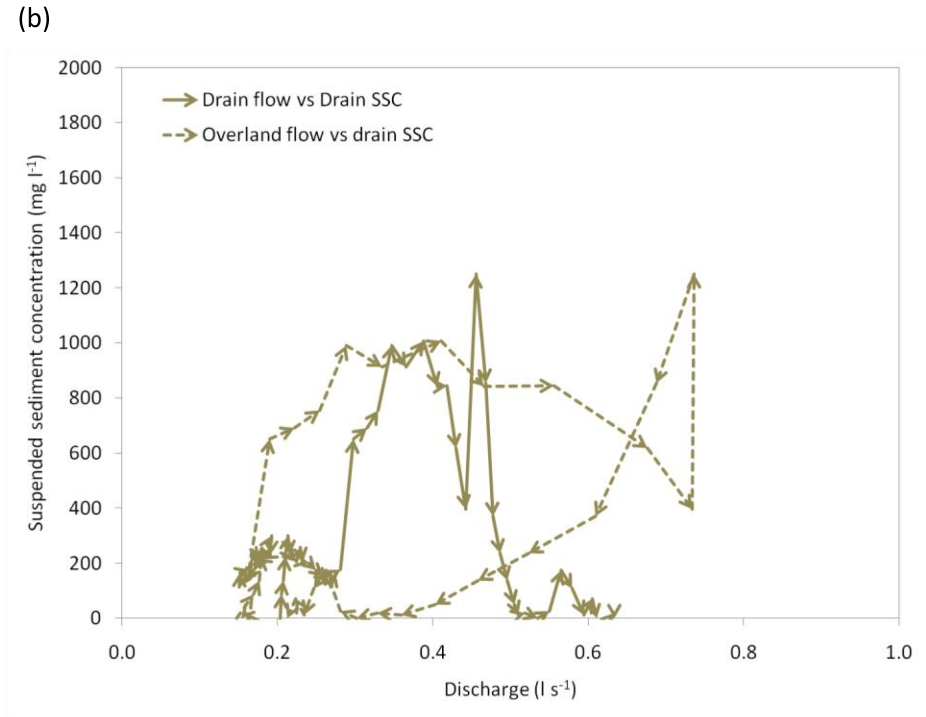


Figure 3.23 Time series of rainfall, overland flow rate, drain flow rate and suspended sediment concentration in drain flow (a); and hysteresis plot of drain flow rate and overland flow rate against suspended sediment concentration in drain flow (b) for event on 04 January 2008.

tends to be more friable than the surrounding clay as a result of disturbance during excavation, facilitating the construction of burrows, which may provide preferential flow routes for water and effectively extend the drainage network up into the soil matrix above. Field observations of surface slumping at such locations offers support for this hypothesis.

3.4.4 Long-term sediment yields

The properties of sediment recovered from the box weirs downstream of the overland flow trap and field drain outlet at the Bowl are presented in Table 3.2. Strong similarities in the mean organic content of sediment derived via both surface and subsurface pathways may indicate a common point of origin at the soil surface. However, it is plausible that worms and root material may constitute some of the organics found in the field drain box weir.

	Bowl surface	Bowl drain system
Wet volume (m^3)	0.082	0.125
Mean moisture content (%)	31.8	36.0
Dry bulk density (g cm^{-3})	0.81	0.78
Organic content (%)	14.9	15.0

Table 3.2 Properties of sediment deposited in the box weir at the Bowl between installation in April 2006 and emptying in June 2008.

The data were used to estimate sediment yields from both sources and the results are presented in Table 3.3. Surface yield values are significantly lower than those identified by Boardman (1986) as the upper limit of tolerable losses (0.5 t ha^{-1} yr^{-1}) and compare well with those reported from undisturbed upland environments in other areas of the UK (e.g. James and Alexander, 1998). The results suggest that the good vegetation cover maintained within the Bowl helps to prevent excessive levels of soil erosion, thus limiting supply to watercourses despite the common occurrence of overland flow. This, in part, reflects the recent efforts of local farmers to prevent erosion through proactive and reactive land management. The contribution of fine sediment generated by surface runoff to catchment-scale sediment yield is further dependent on hydrological connectivity to the channel network (Figure 3.24). While the bowl site is well connected, this is clearly not the case more generally due to topographic and vegetation controls on overland flow in the wider catchment.

Sediment production	Bowl surface	Bowl drain system
Total sediment exported from April 06-June 08 (kg)	45.2	62.7
Annualised sediment export (kg yr^{-1})	21.0	29.1
Sediment yield (kg ha^{-1} yr^{-1})	47.7	80.9

Table 3.3 Estimated sediment yield parameters from the surface of the Bowl and the underlying field drain system.

However, the amount of sediment supplied to the channel network via the field drain system beneath the Bowl is substantially larger than that input via surface pathways. Although the estimated drain yields are lower than the majority of those reported in the literature (see Table 3.4), they may nevertheless be of considerable significance within the Upper Pontbren area due to the great extent of grassland improvement undertaken in the past. Many of these underdrainage systems are

Figure 3.24 Overland flow from a grazed, agriculturally-improved pasture at Tyn-y-bryn farm entering the Nant Pen-y-cwm during heavy rainfall in January 2008.

Location	**Land use**	**Study**	**Suspended sediment yield (kg ha^{-1} a^{-1})**
UK (Bowl drain system, Pontbren)	Improved grassland	This study	80.9
UK (Foxbridge drain, Rosemaund)	Arable	Chapman *et al*. (2005)	964-978
UK (Moorfield drain, Rosemaund)	Arable	Chapman *et al*. (2005)	70-626
UK (Longlands drain, Rosemaund)	Arable	Chapman *et al*. (2005)	270-516
UK (New Cliftonville drain, Pistern Hill)	Arable	Chapman *et al*. (2005)	980
Canada (Central Experimental Farm, Ottowa)	Arable	Culley and Bolton (1983)	407
Denmark (Gelbæk Stream catchment)	Arable	Kronvang *et al*. (1997)	19.4–21.3
Finland (Sjökulla experimental site)	Arable	Paasonen-Kivekäs and Koivusalo (2005)	1508

Table 3.4 Table of published sediment yield values from monitored agricultural field drains in the UK and abroad.

directly connected to the channel network via agricultural ditches or natural streams, and may even generate further sediment at this point in the system by causing erosion beneath the outflow point (Figure 3.25).

The accuracy of the yields presented here is dependent on the trapping efficiency of the box weirs and, while the relative yield values from the two sources are assumed to be the same thanks to the identical design of the apparatus used, absolute yield values may underestimate true yields if the sediment trapping efficiency of the devices is significantly lower than 100%. While total sediment retention is highly unlikely, particle size analysis undertaken on samples from both box weirs indicates that the baffle plates ensured that even very fine material was deposited within the structures (Figure 3.26). The median diameter of particles trapped from both sources was below 6 μm, comparing well with those values reported in previous studies of sediment sourced from grassland and drain runoff (Laubel *et al*., 1999; Chapman *et al*., 2001; 2005).

The applicability of expressing drain sediment yields as a function of perceived contributing area may also be questioned in light of the previously discussed results from event-scale suspended sediment concentration monitoring. Data from the Bowl suggest that drain-derived sediment may be eroded from more discrete sources than previously believed and better represented by a drain condition or network position index rather than the contributing drainage area.

Figure 3.25 Local scour beneath a drain outflow on the lower Nant Melin-y-grûg.

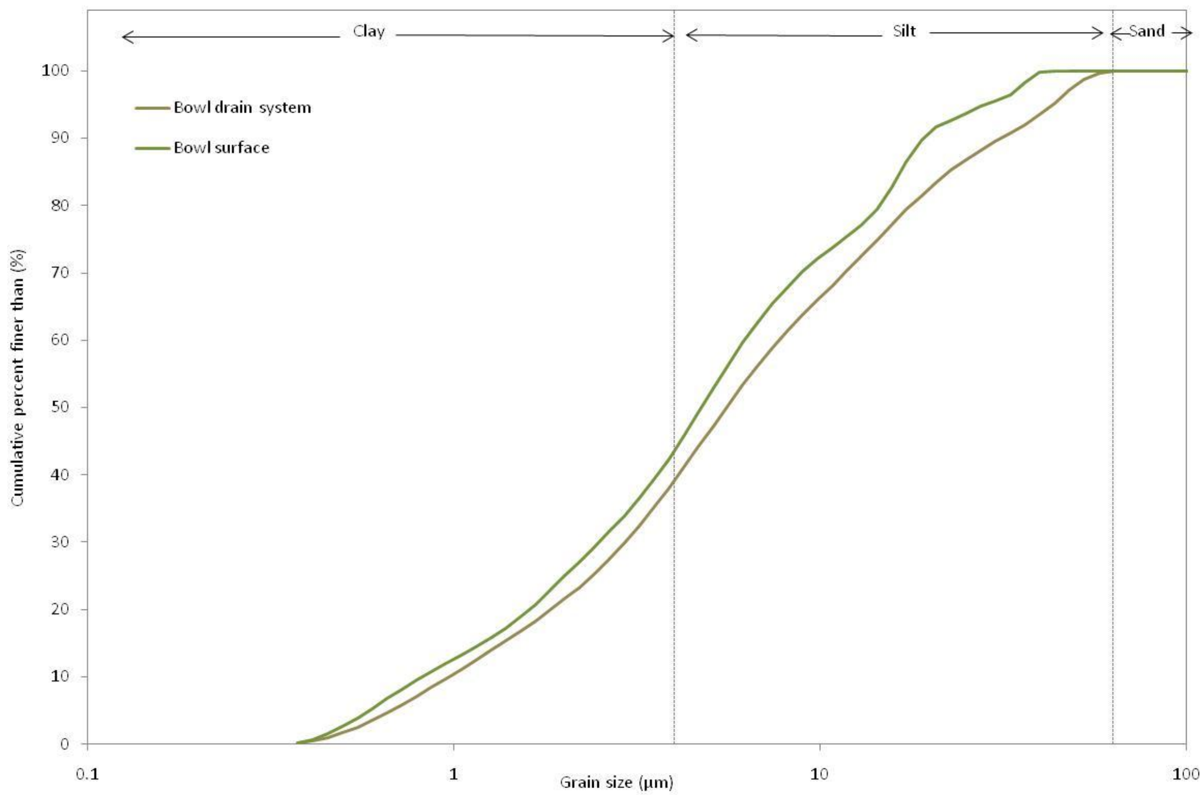


Figure 3.26 Particle size distributions of sediment recovered from the box weirs that collected runoff from the surface of the Bowl and the underlying field drain system.

3.5 Summary

The data and analyses presented in this chapter from the field experiment conducted at the Bowl between summer 2006 and summer 2008 has revealed a number of important insights into the processes and pathways that control the production and transfer of sediment from grazed, agriculturally-improved pastures to upland watercourses. Sediment transfer via surface pathways is largely controlled by the extent and magnitude of overland flow across the surface of pastures but antecedent conditions and preparatory factors are also important in generating sediment and supply limitation can occur. Limited sediment transfer connectivity between pastures and the permanent drainage network calls into question the significance of surface runoff as a delivery route at the catchment scale. Consequently, the direct effectiveness of buffer strips of restored woodland in reducing catchment sediment yields at Pontbren is likely to be limited. However, it should be recognised that buffer strips serve multiple functions and it clear that they have other hydrological, environmental and water quality benefits.

Agricultural field drains may represent a much more important delivery route at the landscape scale due to their direct connectivity with the channel network. Field drains at the Bowl generated more sediment than was supplied via overland flow during the monitoring period and are also much more challenging to manage. Sediment export from field drains does not appear to be a simply function of drain flow as previously believed but, instead, results from a complex array of factors that are likely to include the degree of cracking and macropore development within soils, the extent of overland flow generation, the layout and condition of the drainage system in question and the activities of animals within the soil itself. Such factors are likely to be further complicated in the future due to increases in soil moisture deficits and the intensity of rainfall predicted for many parts of the UK including mid-Wales as a result of climate change (Thorne *et al*., 2007).

Analyses of runoff and sediment yield data presented in this chapter highlight the importance of antecedent conditions as controls of runoff and sediment transfer from agriculturally improved pastures to stream channels. Breaks in the high-frequency turbidity sensor records from the Bowl (see Section 3.3.3) prevented a more detailed investigation into the role of factors such as prevailing soil moisture conditions in controlling sediment yields and transfer routes. However, if the technical problems encountered during this study could be resolved, such effects may be able to be clarified numerically by analysing detailed hydrological data from instruments installed at the Bowl by Imperial College London and CEH Bangor. This could form the basis of further research at the site.

4 DYNAMICS AND CONTROLS OF SEDIMENT SUPPLY FROM ERODING CHANNEL BANKS TO STREAM CHANNELS IN THE UPPER PONTBREN SUBCATCHMENT

4.1 Introduction

Material generated through the erosion of channel banks can constitute a major proportion of the total amount of sediment supplied to rivers. For example, on the basis of data from 48 British catchments recently compiled by Walling and Collins (2005), approximately 20% of sediment transported *via* suspension is typically derived from eroding bank sources, although this contribution can vary widely between and along rivers (Lawler *et al*., 1999; Taylor *et al*., 2008). While bank erosion is a natural channel adjustment process that can help to maintain high biological diversity in riparian and floodplain areas (e.g. Salo *et al*., 1986), accelerated rates of lateral adjustment can present serious problems for river engineers, land owners and environmental managers through the loss of agricultural land, damage to structures, and resultant sedimentation downstream that can threaten aquatic habitats and elevate flood risk by reducing channel capacities (Lawler *et al*., 1997).

Anthropogenic activities have the potential to directly and/or indirectly influence bank erosion rates (and thus sediment supply) through their effects on a number of important environmental controls including the magnitude of peak flows (e.g. Knighton, 1973), antecedent bank moisture (e.g. Hooke, 1979; Simon *et al*., 1999), freeze-thaw activity (e.g. Hill, 1973; Lawler, 1986; Stott, 1997b; Prosser *et al*., 2000; Yumoto *et al*., 2006), desiccation (e.g. Oxley, 1974; Thorne and Lewin, 1979; Lawler, 1992; Prosser *et* *al*., 2000), vegetation cover (e.g. Smith, 1976; Thorne *et al*., 1981; Masterman, 1994), and the presence of large woody debris in channels (e.g. Davis and Gregory, 1994). For example, Stott (1999) and Stott *et al*. (2001) reported a statistically significant increase in bank erosion rates following the clearfelling of conifer trees from riparian areas in a commercial forest plantation in mid-Wales. This change was attributed to the increased exposure of stream banks to the effects of freeze-thaw cycles following harvesting, which tend to occur less frequently and are less intense under the protective cover of trees (Stott, 1997b; 1999; Stott *et al*., 2001). Livestock grazing in riparian areas has also been shown to affect bank erosion rates. Trimble (1994) and Trimble and Mendel (1995) found that grazed banks eroded between three to six times faster than ungrazed banks as a result of the direct loosening of material and removal of vegetation though trampling and feeding.

Field reconnaissance conducted at the outset of this project indicated that strong geomorphological contrasts exist between streams in the Upper Pontbren and Upper Melin-y-grûg subcatchments at Pontbren (see Chapter 2). While the banks of the upper Nant Melin-y-grûg are well-vegetated and display little evidence of geomorphological activity, the widespread occurrence of exposed tree roots, large woody debris and slumped deposits of material at the base of banks along the Nant Pen-y-cwm and Nant Gelli-Gethin suggest that lateral erosion may be an important sediment supply mechanism to both of these streams. The following chapter describes field experiments and data analyses undertaken to quantify the amount and calibre of sediment supplied to streams from eroding channel banks in the Upper Pontbren subcatchment, and to determine the processes and factors that control sediment production from bank sources. The results are used to evaluate the potential influence of land use and land management on bank erosion in the Pontbren study area.

4.2 Methodology

4.2.1 Measurement of bank erosion and estimation of sediment supply from bank sources in the Upper Pontbren subcatchment

Spatial and temporal variations in bank erosion rates in the Upper Pontbren subcatchment were investigated using a network of erosion pins deployed between May 2006 and June 2008. Erosion pins are metal rods which are inserted into eroding banks at right angles to the bank face. The distance between the bank face and the tip of the erosion pin is measured following installation to provide a reference datum against which subsequent erosion (or accretion) can be assessed by repeat surveys. The technique has been used extensively in studies of bank and hillslope erosion (e.g. Wolman, 1959; Haigh, 1977; Thorne and Lewin, 1979; Thorne and Tovey, 1981; Murgatroyd and Ternan, 1983; Lawler, 1986; Stott, 1997b; 1999; Couper and Maddock, 2001) as its relatively low implementation cost permits a large spatial coverage to be achieved, thus enabling process inference (Lawler, 1993). While the use of erosion pins has been linked with disturbance and reinforcement of bank material which may lead to erroneous erosion rates (Thorne, 1981), and the temporal resolution of measurements can be improved through the use of more sophisticated devices such as photo-electric erosion pins (Lawler, 1991), the approach was found to be the most appropriate for this study given the scale and purpose of the investigation and financial constraints.

The erosion pins used at Pontbren consisted of 5 mm diameter galvanised steel rods that were cut into 0.5 m lengths and sharpened at one end to aid insertion into the bank face, thus minimising disturbance during installation (*c.f.* Couper and Maddock, 2001). A total of 110 pins were deployed at 24, randomly selected sites in the Upper Pontbren subcatchment that were identified as actively eroding on the basis of field observations made during spring 2006 (Figure 4.1). The pins were arranged in vertical rows from the bank base to the bank top (150 mm spacing; *c.f.* Stott, 1997b) but spatial variation in bank height meant that the number of pins installed at individual sites varied, ranging between three and nine, with a modal value of four. An assessment of the vertical variation in bank erosion rates at each monitoring site was deemed to be crucial as observations of bank morphology throughout the Upper Pontbren area indicated that the dominant erosion mechanism was *via* cantilever failure. Under this model, hydraulic forces are concentrated at the bank toe, or 'basal endpoint' (c.f. Carson and Kirkby, 1972; Lawler *et al*., 1997a), leading to the undercutting and eventual collapse of overlying bank material (Figure 4.2). Part of each pin (typically between 50-100 mm) was left exposed and the sites were sprayed with non-toxic luminous marker paint to aid relocation (Figure 4.3). The distance of pin protrusion from the bank surface (mm) was measured using callipers every three months (mean measurement interval = 92 days) between 29 May 2006 and 06 June 2008. The time-periods covered by the erosion surveys are defined in Table 4.1. A total of approximately 1000 individual pin measurements were made during the study and pin measurement accuracy is assumed to be ±0.5 mm on the basis of assessments carried out by Stott (1999) and Couper and Maddock (2001).

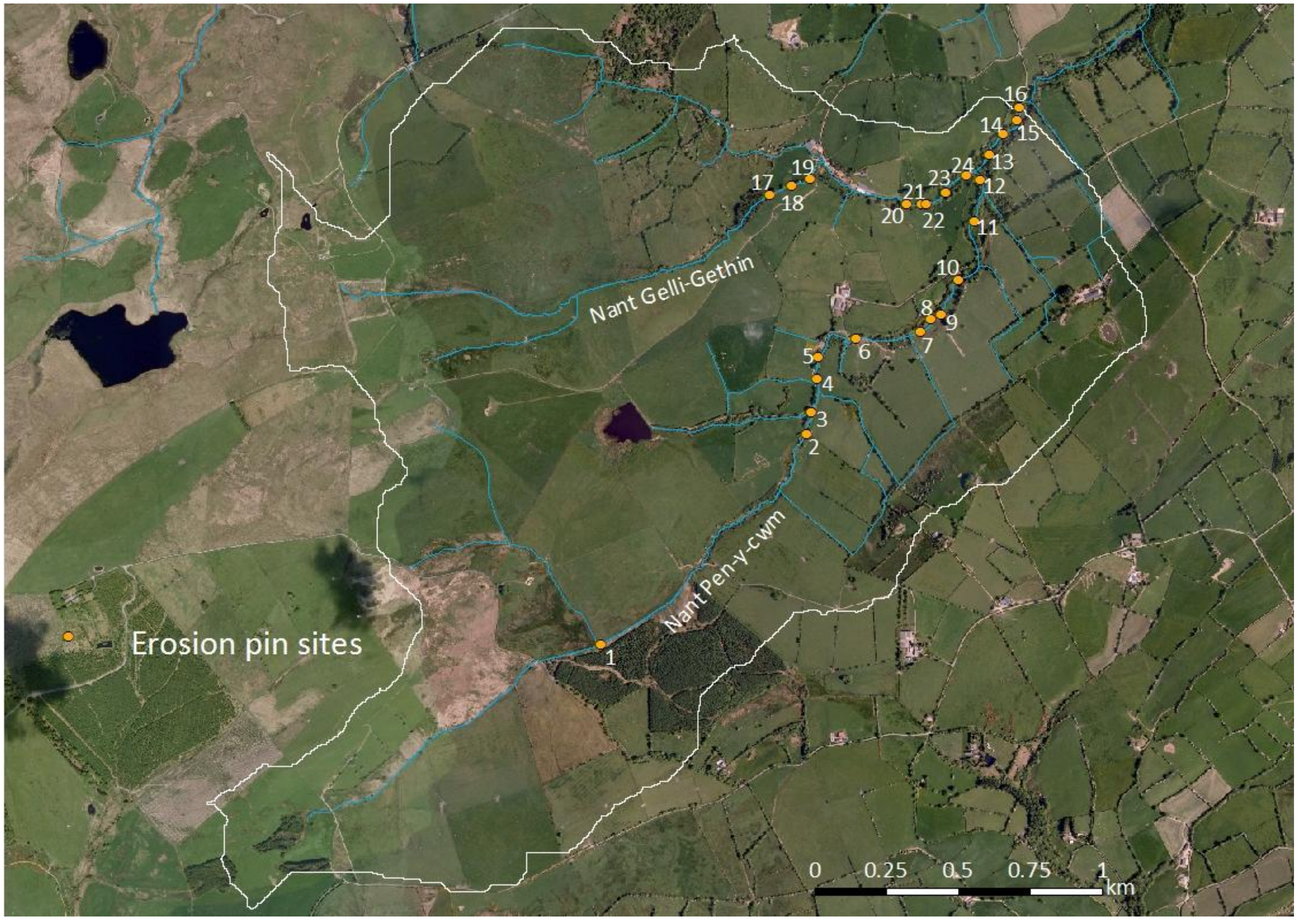
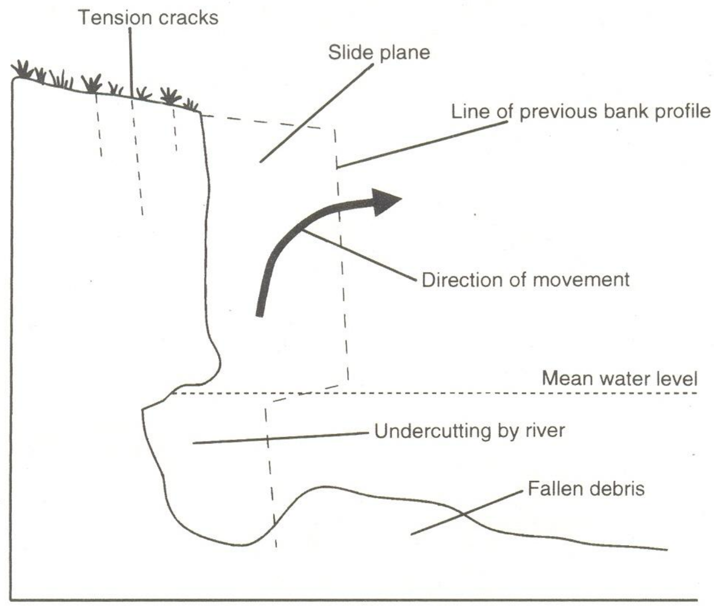


Figure 4.1 Erosion pin monitoring sites in the Upper Pontbren subcatchment.

Box 3.4 *Characteristic features of cantilever failures*



Source: Judith Dunderdale

Cantilever failure: undercutting by the river causes overhanging blocks of soil: the blocks fail by toppling outwards. Failure planes develop along vertical tension cracks at the top of the slope. Common where banks are formed from a cohesive upper layer on top of a "weak" lower layer which is easily eroded by scour. Often associated with boatwash.

Go to Box 4.1 ➛

Figure 4.2 Characteristic morphological features of bank erosion *via* cantilever failure (from Environment Agency, 1999, p.30).

Figure 4.3 Bank erosion monitoring site 17 (Pines) on the Nant Gelli-Gethin.

Period	Start and end date
Summer 2006	29 May 2006 - 06 September 2006
Autumn 2006	06 September 2006 - 01 December 2006
Winter 2006/7	01 December 2006 - 09 March 2007
Spring 2007	09 March 2007 - 04 June 2007
Summer 2007	04 June 2007 - 31 August 2007
Autumn 2007	31 August 2007 - 30 November 2007
Winter 2007/8	30 November 2007 - 29 February 2008
Spring 2008	29 February 2008 - 06 June 2008

Table 4.1 Bank erosion monitoring periods.

An assessment of the spatial extent of bank erosion in the Upper Pontbren subcatchment was carried out at the same time as each erosion pin survey. The area of individual bank sections that were visually determined to be eroding was calculated from field measurements of section heights and lengths obtained manually using 30 m tape measures (*c.f.* Evans and Warburton, 2005). These were then summed to estimate the total bank area in the subcatchment subject to erosion during the survey period ($AREA_{ero}$). This value was combined with the mean erosion value (E_{mean}) for the survey period to generate a volumetric input of sediment from bank sources to streams in the Upper Pontbren subcatchment (VOL_{bs}). E_{mean} was calculated by summing all values of the change in pin exposure and dividing by the total number of pins. Any negative erosion pin measurement values (*c.f.* Couper *et al*., 2002) were included in the calculation of E_{mean} in order to account for the fact that eroded sediment can be redeposited on the bank face/toe as opposed to being delivered directly into a stream channel.

VOL_{bs} was converted to a weight-based bank sediment yield (Q_{bs}) using a bulk density value for the local bank material (*b*) of 1.463 t m^{-3}. Bank material bulk density can be calculated using a number of methods including the use of open-ended cans to obtain plugs of sediment of known volumes that can be subsequently dried and weighed (*c.f.* Bull, 1997; Stott, 1997b), or by deploying polyurethane foam to determine the volume of an excavated bulk sample from its associated bank cavity (*c.f.* Brye *et al*., 2004). However, the presence of large cobbles and boulders in the till banks common at Pontbren made both of these methods unfeasible. Instead, following Mount (2000), a large sample of material (0.7 m^3) was excavated according to premeasured dimensions from the bank upstream of erosion pin site 5 (Tyn-y-bryn middle) and weighed in the field using buckets and hand balances. The representativeness of the bulk density value for bank material across the entire monitored area is unknown as the potential for widespread disturbance to riparian areas caused by multiple measurements prevented further samples being collected. It should also acknowledged that, although bulk density sampling was undertaken during a dry period during June 2008, the value represents a wet (as opposed to a dry) bulk density and sediment yields calculated using it may, therefore, be overestimations compared to other data based on dry bulk densities. Nevertheless, the calculated values are similar to those obtained by other researchers in similar upland environments (e.g. Bull, 1997; Stott, 1997b; Mount, 2000).

The calculated sediment supply to stream channels from eroding bank sources in the Upper Pontbren subcatchment for each survey period can be summarised as follows:

$$Q_{bs} = \mathrm{E}_{mean} \cdot \mathrm{AREA}_{ero} \cdot b$$

where, Q_{bs} is expressed in t, E_{mean} in m, $AREA_{ero}$ in m^2, and b in t m^{-3}.

4.2.2 Exploration of temporal and spatial variation in bank erosion rates in relation to hydrometeorological variables and site-specific parameters

Various hydrological indices designed to represent the potential for bank erosion *via* hydraulic action were generated using discharge data from a gauging station (SF7) operated by Imperial College London/CEH Bangor, located on the Nant Pont-bren-down at the downstream extent of the Upper Pontbren subcatchment (Figure 4.4). These included Q_{max} (the maximum discharge value recorded during the erosion survey period) and Q_{mean} (the average discharge calculated from all recorded values during the erosion survey period). Streamflow data from streams throughout the Pontbren study area are collected using bed-mounted acoustic doppler velocity meters that calculate discharge as a product of flow depth and velocity integrated over predefined cross-sections (McIntyre and Marshall, 2006). Measurements are conducted every minute and 15-minute averaged values logged. The discharge outputs from the devices are calibrated against values measured in the field using standard flow gauging techniques (McIntyre and Marshall, 2006). Missing data values due to sensor damage/obscuration are infilled using linear regression models developed between the affected sensor and the nearest upstream/downstream gauge during periods when both gauges were fully functional ($r^2 = 0.84$-0.95).

Other indices representing the intensity of various subaerial erosion processes (raindrop impact, freeze-thaw activity, and desiccation) and changes in antecedent bank moisture were produced using meteorological data provided by Imperial College London/CEH Bangor. These included RAIN_{max} (the maximum daily rainfall total measured by the tipping bucket raingauge deployed at the Bowl – see Chapter 3), RAIN_{mean} (the average daily rainfall recorded during the erosion survey period), DRY_{day} (the number of days on which no rainfall i.e. less than 0.2 mm was recorded at the Bowl during the erosion survey period, expressed relative to the period length), DRY_{con} (the number of consecutive days without measurable rainfall during the erosion survey period),

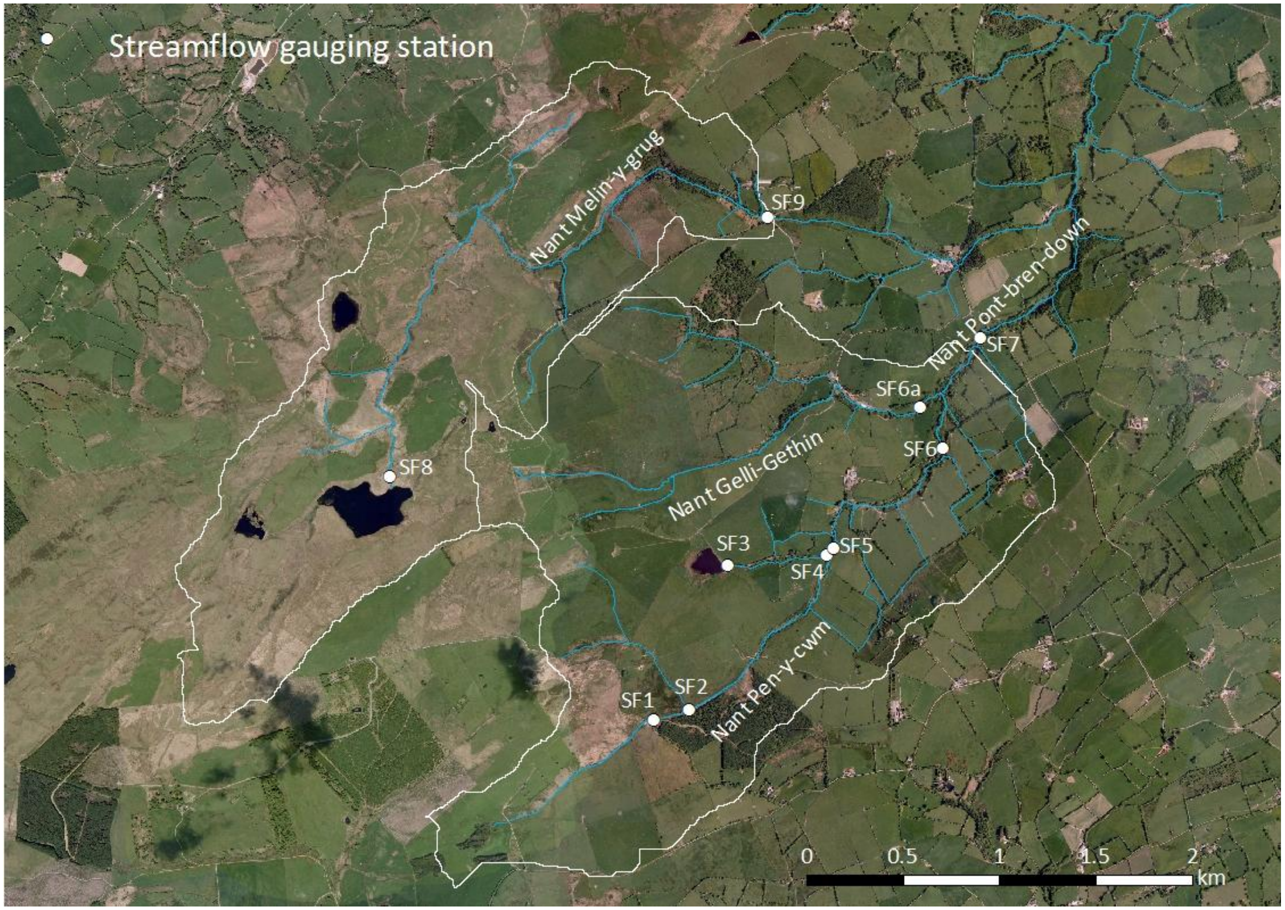


Figure 4.4 Streamflow gauging stations operated by Imperial College London/CEH Bangor in the Pontbren study area.

$TEMPR_{max}$ (the maximum daily temperature range recorded by the AWS at the Bowl during the erosion survey period), $TEMPR_{mean}$ (the average daily temperature range recorded during the erosion survey period), $FROST_{day}$ (the number of days on which air temperatures fell below 0 °C during the erosion survey period, expressed relative to the period length), and $FROST_{tot}$ (the cumulative total length of time that air temperatures were below 0 °C during the erosion survey period, expressed relative to the period length).

Temporal variation in the intensity and areal extent of bank erosion identified through the erosion pin surveys was examined statistically with respect to changes in the hydrometeorological variables represented by the indices described above (*c.f.* Hooke, 1979; Lawler, 1986; Stott, 1997b; Couper and Maddock, 2001). The association between the various indices and a number of bank erosion descriptors was examined through bivariate analysis. These included ER_{mean} (the average change in pin exposure divided by the length of time covered by the survey period); ER_{max} (the maximum rate of erosion recorded at any erosion pin location during the erosion survey period); ER_{high} (the 90^{th} percentile of all erosion rate values recorded during the survey period – which represents an 'upper' erosion rate estimate that is less affected by outliers than ER_{max}); POS% (the percentage of pins at which positive erosion rates were recorded during the erosion survey period); and NEG% (the percentage of pins at which negative erosion values were recorded). Negative erosion pin readings can provide useful insights into the redistribution of eroded material on bank faces as well as indicating the occurrence of loosening of bank material in relation to freeze-thaw action and desiccation (Couper *et al*., 2002). Bank erosion indices were calculated not only for all pins in the Upper

Pontbren subcatchment, but also using erosion pins located solely in the upper and lower sections of banks to determine whether the importance of different processes varied according to elevation. The elevations of erosion pins at each monitoring site were normalised according to a scale between 0 (bank toe) and 1 (bank top), and each of the aforementioned indices recalculated using pins from the lower third of the bank (indices prefixed by L, e.g. LER_{mean}) and the upper third of the bank (indices prefixed by U, e.g. UER_{mean}).

The relationship between a variety of site-specific parameters and measured erosion rates was also examined through bivariate analyses and significance testing (*c.f.* Laubel *et al*., 2003). Parameters explored included the percentage silt-clay and gravel content of the bank, the aspect of the site, the distance between the site and the stream gauge at the downstream end of the Upper Pontbren subcatchment (SF7), the bank angle, and whether the site was accessible by livestock. The parameters were selected on the basis of previous investigations which have demonstrated their importance as controls of bank erosion rates (e.g. Lawler *et al*., 1997; Lawler *et al*., 1999; Couper, 2003; Laubel *et al*., 2003; Zaimes *et al*., 2006). The silt-clay and gravel contents (%) at each site were derived from grain size distributions measured in the field using a modified version of the Wolman (1954) sampling technique. Following the end of bank erosion monitoring in summer 2008, the intermediate diameter of 100 particles at each bank site was measured using a gravelometer (*c.f.* Hey and Thorne, 1983), with particles selected on the basis of a 10 x 10 regular grid marked out using string and pegs. All particles finer than 2 mm were collectively recorded as fines, and the size distribution of this finer fraction determined by sieve analysis performed on small bulk samples removed from the bank using a trowel. The fine end of the grain size distribution was then combined with the coarser main portion using techniques described in Bunte and Abt (2001). While bulk sampling may have been a more scientifically sound method of sampling bank grain size distributions, the very large sample sizes required according to criteria set by Church *et al*. (1987) on the basis of the largest clasts present in the till banks common at Pontbren made that approach impractical. Aspect and bank angles (to the nearest 5 °) were determined in the field using a compass and clinometer respectively, while the longitudinal distance between the site and SF7 was determined from field-recorded GPS positions and high resolution aerial photographs in ArcGIS 9.2. Livestock accessibility was assessed in the field and through consultation with local farmers.

As site-specific parameters remained, or were assumed to remain, constant for the duration of the monitoring period, annualised erosion rates were required for each site in order to examine associations. In order to generate such values, the annual erosion rate at every individual pin location (ER_{pin}) was calculated by summing the values of all positive measurements recorded at the location and dividing by the length of the monitoring period. The mean annual erosion rate for each monitoring site (ER_{site}) was then calculated as:

$$ER_{site} = \frac{1}{N}\sum_{i=1}^{N} ER_{pin_i}$$

where, N = number of pins deployed at the site.

4.3 Results

Table 4.2 shows temporal variation in bank erosion descriptors calculated using data from all erosion pin locations in the Upper Pontbren subcatchment. Lateral activity was commonly observed throughout the year, with measurable differences in pin exposure (positive or negative) occurring at over 95% of pin locations during all of the survey periods monitored. While the majority of values were of a positive nature (indicating erosion of the bank face), around 20 to 40% of readings were negative (indicating deposition on the bank face) Mean erosion rates varied considerably through time, ranging from 7 ± 2 mm yr^{-1} (error value represents standard error of the mean) in Summer 2006 to a maximum of 86 ± 15 mm yr^{-1} during Winter 2006/7. However, the highest individual erosion rates were recorded during Winter 2007/8, when a rate of 1280 mm yr^{-1} was recorded at a pin at Site 22 on the Nant Gelli-Gethin. When examined on a seasonal basis (Figure 4.5), mean bank erosion rates were higher during winter than at all other times of the year (Wilcoxon signed-rank tests, $p < 0.001$), but there were no significant differences between any other seasons (Wilcoxon signed-rank tests, $p = 0.179 < 0.895$). Nevertheless, there were significant year-on-year differences with mean bank erosion rates in both Summer 2007 and Spring 2008 being higher than during the corresponding periods in the preceding year (Wilcoxon signed-rank tests, $p < 0.001$).

Table 4.3 shows temporal variation in mean erosion values and the area of actively eroding banks in the Upper Pontbren subcatchment during the study period, along with calculated values of the volume, weight, and proportion of the total amount of sediment supplied to stream channels from bank sources. The data indicate that not

Bank erosion index	Summer 2006	Autumn 2006	Winter 2006/7	Spring 2007	Summer 2007	Autumn 2007	Winter 2007/8	Spring 2008
ER_{mean} (mm yr^{-1})	7 ± 2	11 ± 2	86 ± 15	4 ± 2	32 ± 9	11 ± 3	66 ± 24	21 ± 6
ER_{max} (mm yr^{-1})	142	102	890	143	672	201	1280	454
ER_{high} (mm yr^{-1})	18	43	202	17	88	28	245	41
%POS (%)	58.2	62.7	74.5	54.5	68.2	65.5	62.7	71.8
%NEG (%)	36.4	34.5	20.9	40.9	30.9	30.0	35.5	25.5

Table 4.2 Temporal variation in bank erosion indices generated using data from all erosion pin locations in the Upper Pontbren subcatchment. Error values represent the standard error of mean.

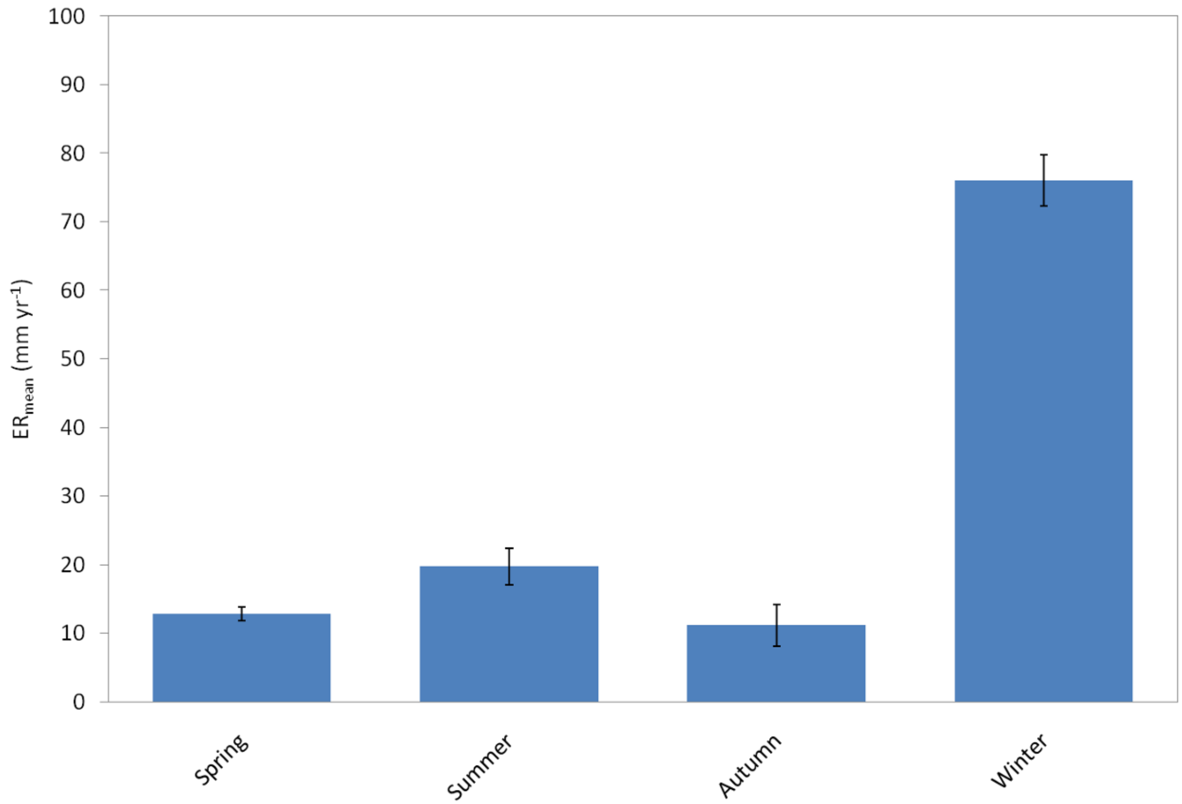


Figure 4.5 Mean seasonal bank erosion rates in Upper Pontbren subcatchment.

	Summer 2006	Autumn 2006	Winter 2006/7	Spring 2007	Summer 2007	Autumn 2007	Winter 2007/8	Spring 2008	Total
E_{mean} (mm)	2 ± 1	3 ± 1	23 ± 4	1 ± 1	8 ± 2	3 ± 1	17 ± 6	6 ± 2	-
$AREA_{ero}$ (m^2)	378.7	399.3	474.8	474.3	394.6	382.9	410.4	419.9	-
VOL_{bs} (m^3)	0.8	1.0	10.9	0.5	3.0	1.1	6.8	2.4	26.5
Q_{bs} (t)	1.13	1.51	15.98	0.69	4.45	1.59	9.95	3.54	38.83
% of total	2.9	3.9	41.1	1.8	11.4	4.1	25.6	9.1	100

Table 4.3 Temporal variation in mean erosion, area of eroding banks, volume of sediment supplied to channels and weight of sediment supplied to channels in the Upper Pontbren subcatchment. Error values signify the standard error of the mean.

only was bank erosion most intense during winter in terms of the amount of lateral adjustment, but the spatial extent of erosion was also greater. As a result, the amount (volume and weight) of sediment supplied to stream channels from eroding bank sources was accentuated further during this part of the year. For example, approximately 16 t of material was generated during Winter 2006/7 compared to less than 1 t during Spring 2007. In total, over 38 t of material was supplied to stream channels in the Upper Pontbren subcatchment from eroding bank sources over the entire study period, with winter inputs accounting for over 65% of the total amount. Particle size data obtained from each monitoring site (Figure 4.6) was used to estimate the relative amounts of silt-clay, sand and gravel within the eroded material (Table 4.4). The data show that the majority of material supplied to stream channels from eroding bank sources consists of sand and gravel-sized particles.

Examination of the vertical distribution of erosion on banks in the Upper Pontbren subcatchment revealed strong differences between the lower and upper bank regions. Overall, mean erosion rates were significantly higher at pin locations in the lower third of monitored banks compared to those in the upper third (Mann-Whitney U test, $p < 0.01$), but this varied seasonally (Figure 4.7a and b). For example, while mean lower bank erosion rates during Winter 2006, Summer 2007 and Autumn 2007 were significantly greater than mean upper bank erosion rates (Mann Whitney U tests, $p = 0.01-0.04$), no significant differences were observed during any other erosion survey periods during the study. Between-site variation was also large (Figure 4.8), with values of ER_{site} (± standard error of mean) ranging from 3 ± 0 mm yr^{-1} at Site 18 on the Nant

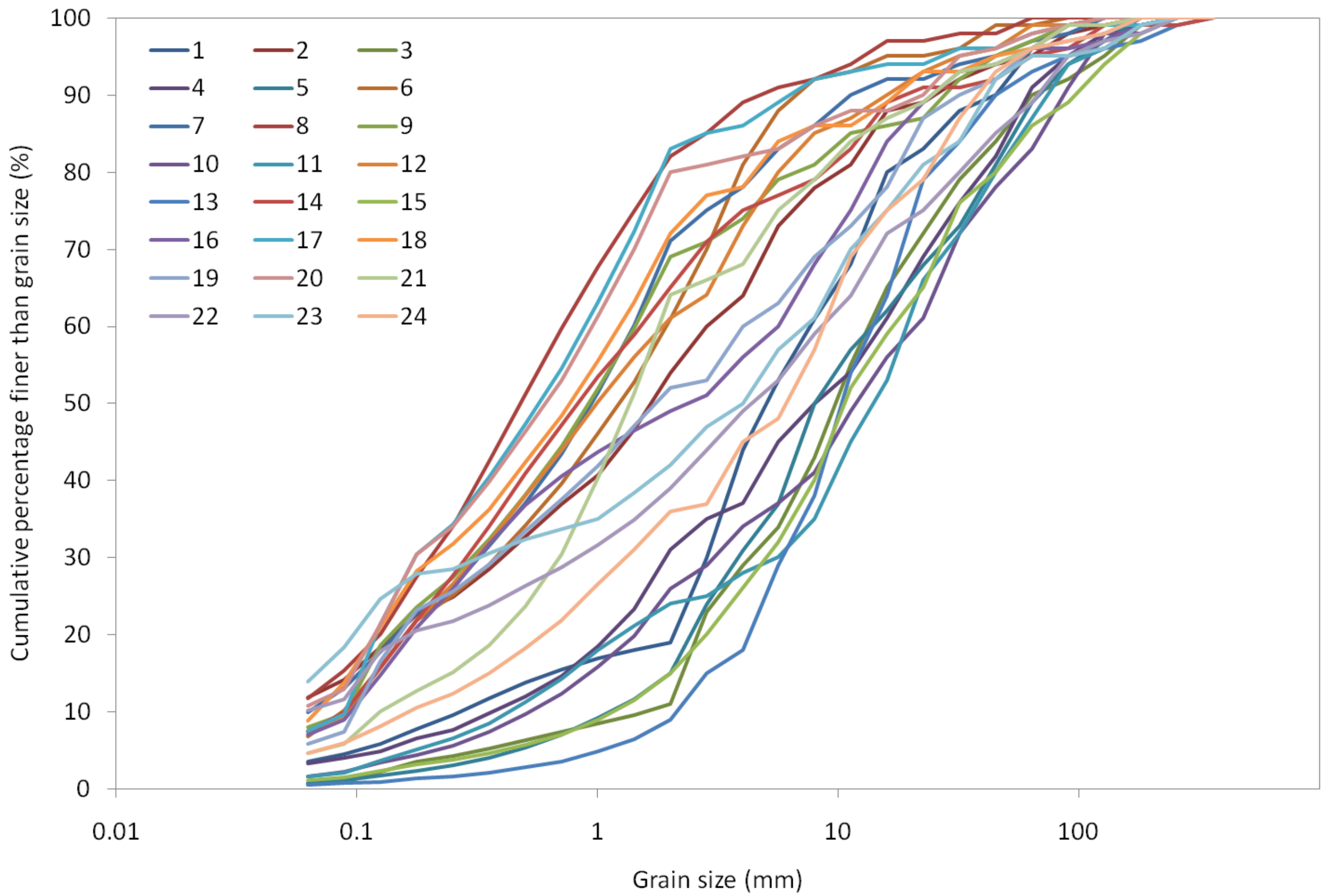


Figure 4.6 Grain size distributions for bank material at all bank erosion monitoring sites.

	Q_{bs} (t)								
Size fraction	**Summer 2006**	**Autumn 2006**	**Winter 2006/7**	**Spring 2007**	**Summer 2007**	**Autumn 2007**	**Winter 2007/8**	**Spring 2008**	**Total**
Silt-Clay (<0.063 mm)	0.07	0.09	1.00	0.04	0.28	0.10	0.62	0.22	2.42
Sand (0.063-2 mm)	0.46	0.62	6.53	0.28	1.82	0.65	4.06	1.45	15.86
Gravel (>2 mm)	0.60	0.80	8.45	0.36	2.35	0.84	5.27	1.87	20.55

Table 4.4 Temporal variation in the amount of silt-clay, sand and gravel supplied to stream channels in the Upper Pontbren subcatchment.

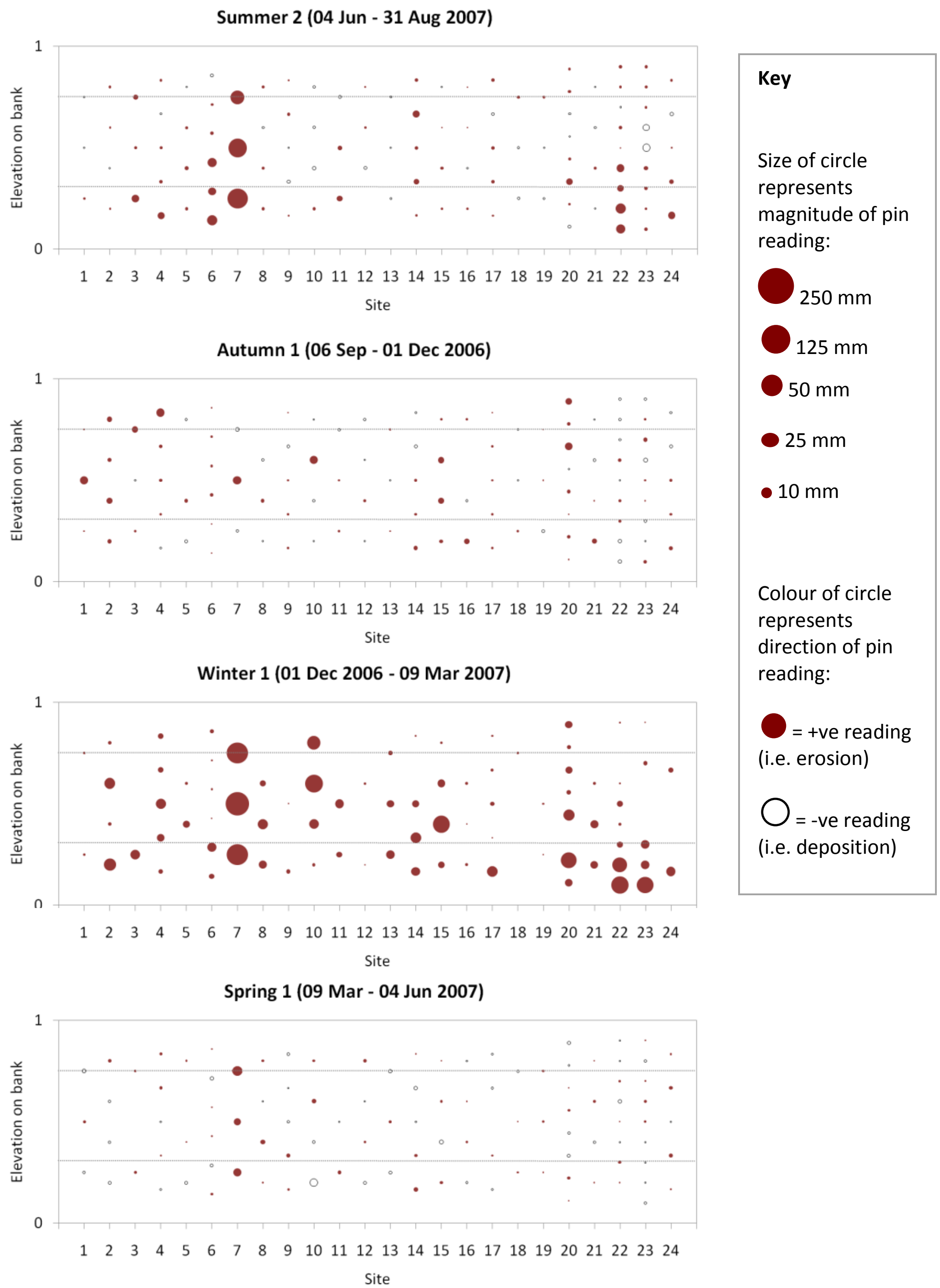


Figure 4.7 (a) Vertical distribution of bank erosion at mainstream sites during first year of monitoring.

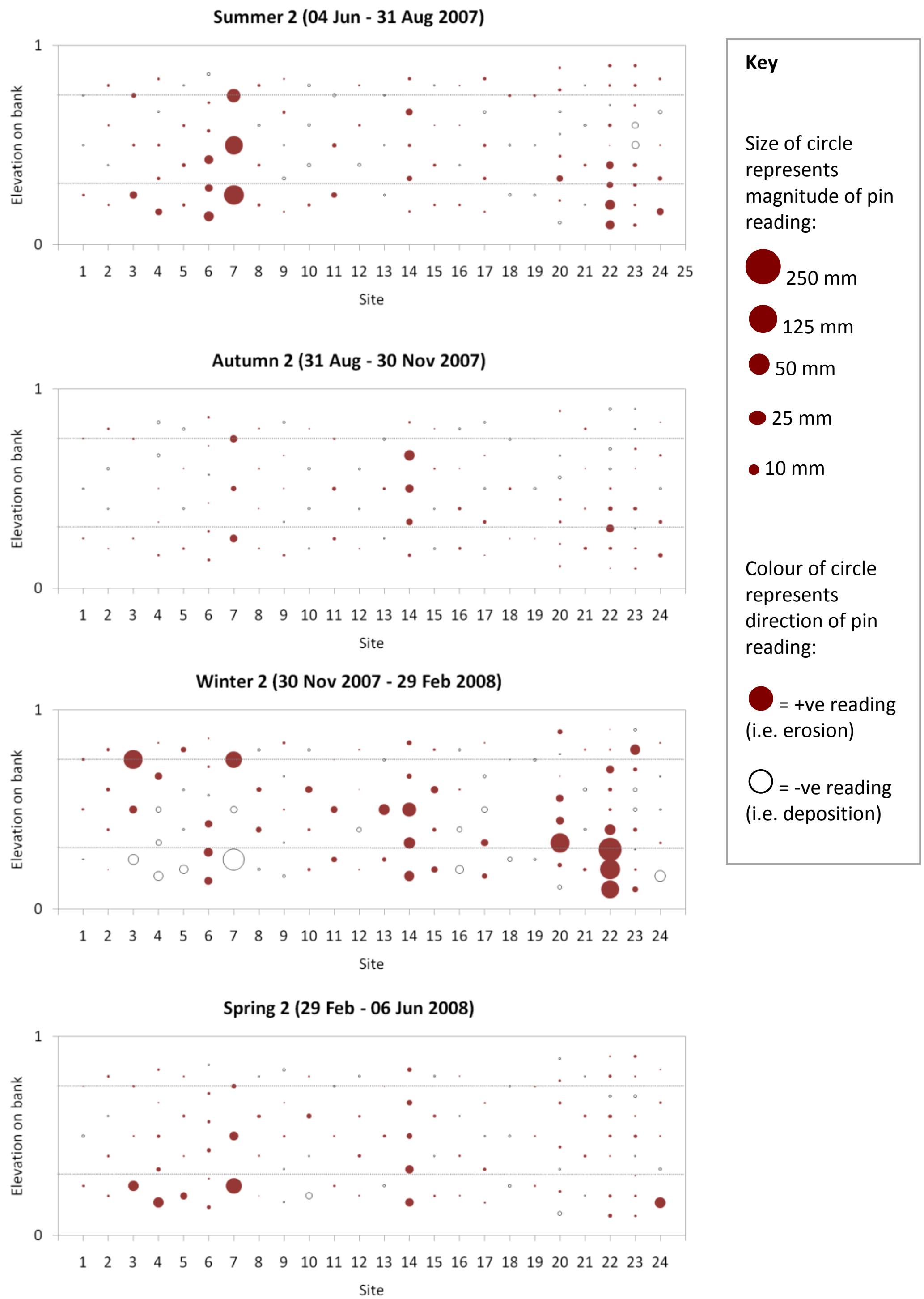


Figure 4.7 (b) Vertical distribution of bank erosion at mainstream sites during second year of monitoring.

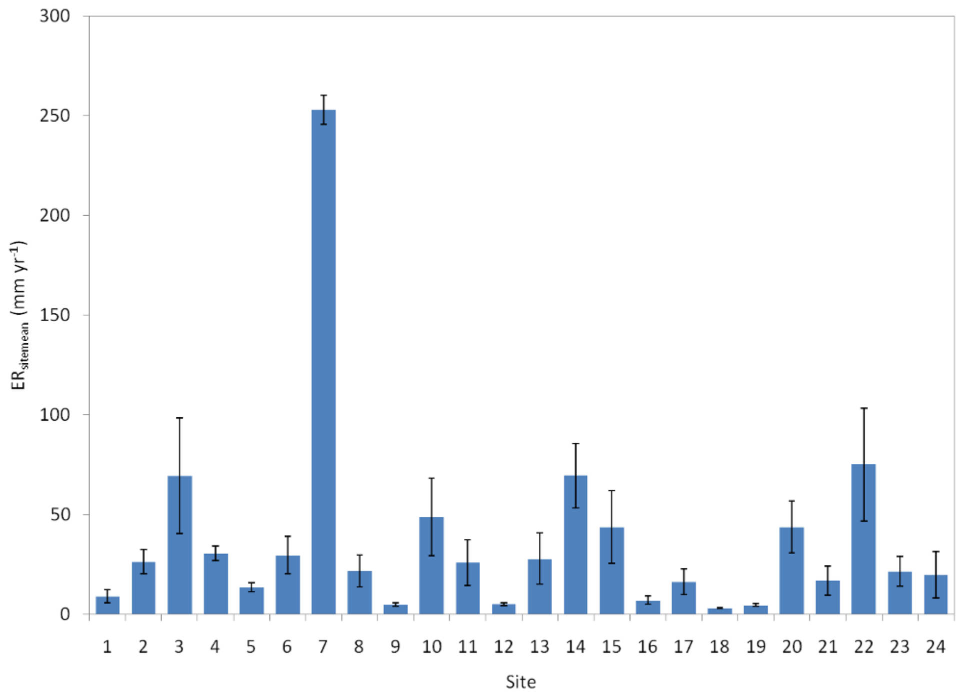


Figure 4.8 Between-site variation in mean bank erosion rates in the Upper Pontbren subcatchment. Error bars represent the standard error of mean.

Gelli-Gethin (Gorge 1 Upper) to 253 ± 7 mm yr^{-1} at Site 7 on the Nant Pen-y-cwm (Hillslope Upper).

The relationships between various descriptors of bank erosion and potential hydrometeorological controls are shown in Figures 4.9-4.12. The data show that strong, curvilinear relationships exist between indices representing streamflow (Q_{max} and Q_{mean}) and bank erosion intensity (ER_{mean}, ER_{max}, ER_{high}). Indices representing raindrop impact and/or antecedent bank moisture ($RAIN_{max}$, $RAIN_{mean}$) also appear to have a strong influence on erosion intensity, although this may reflect a degree of collinearity between rainfall and streamflow (see later discussion). However, no obvious relationships between indices designed to represent subaerial erosion processes (DRY_{day}, DRY_{con}, $TEMPR_{max}$, $TEMPR_{mean}$, $FROST_{day}$, $FROST_{tot}$) and the intensity of bank erosion are evident in the data, with each graph displaying considerable scatter. Plots of the various hydrometeorological controls against descriptors representing the areal extent of bank erosion (%POS) also revealed few clear patterns. However, positive relationships between indices designed to represent the potential for desiccation (DRY_{day} and DRY_{con}) and the frequency of negative erosion pin readings i.e. accretion (%NEG) are noticeable. The strength and statistical significance of these relationships was explored through the calculation of Pearson product-moment correlation coefficients between the various hydrometeorological variables and bank erosion indices (Table 4.5). ER_{mean}, ER_{max} and ER_{high} were log-transformed prior to analysis to satisfy assumptions of normality. Q_{max}, Q_{mean} and $RAIN_{mean}$ were all found to be significantly correlated with the indices which describe the intensity of bank erosion ($p < 0.05$). Some significant negative relationships were evident between temperature

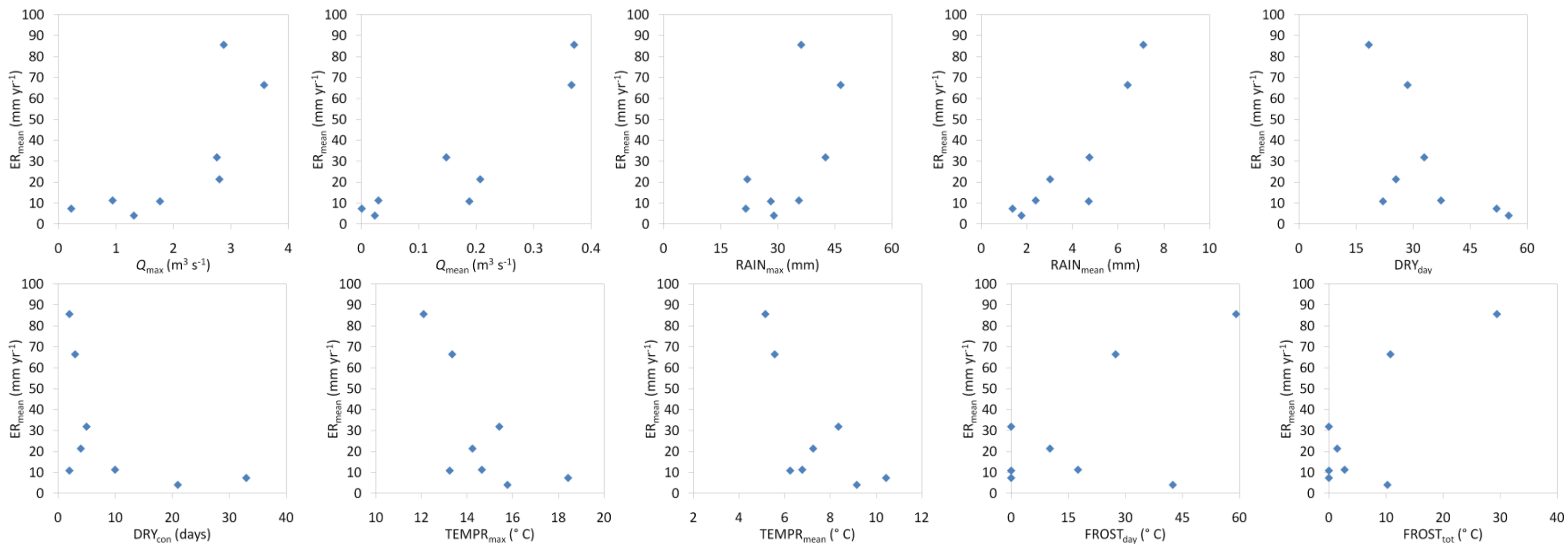


Figure 4.9 Relationships between hydrometeorological indices and ER_{mean}.

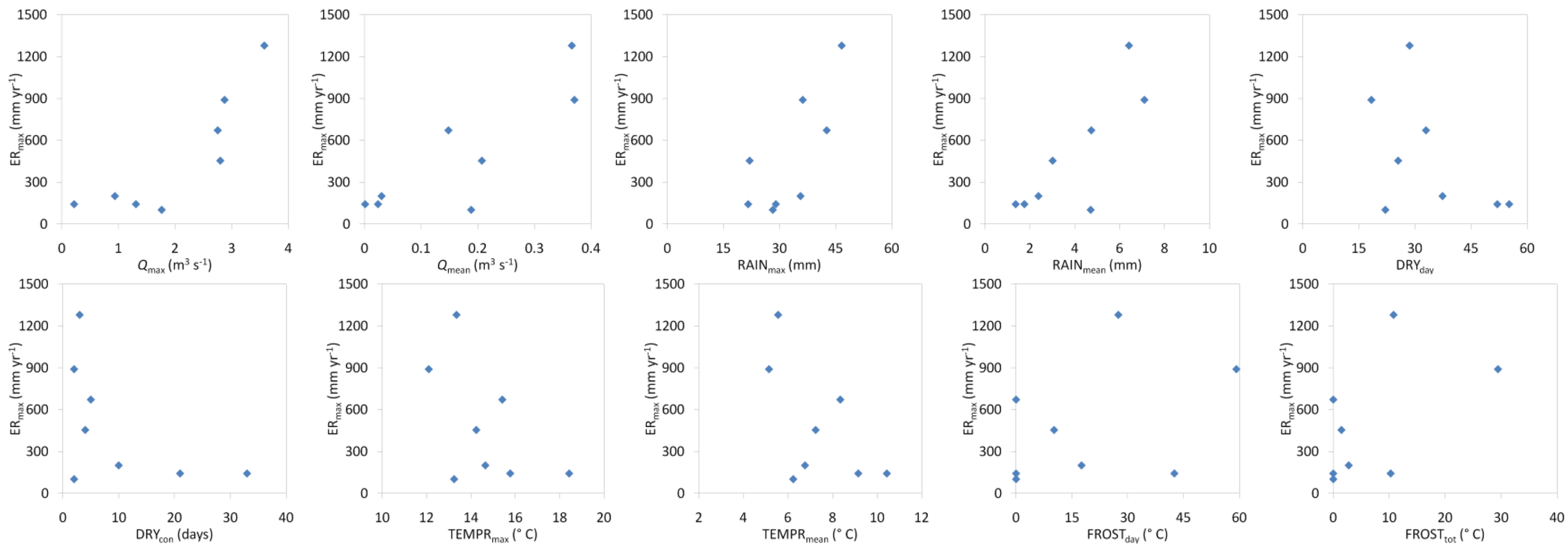


Figure 4.10 Relationships between hydrometeorological indices and ER$_{max}$.

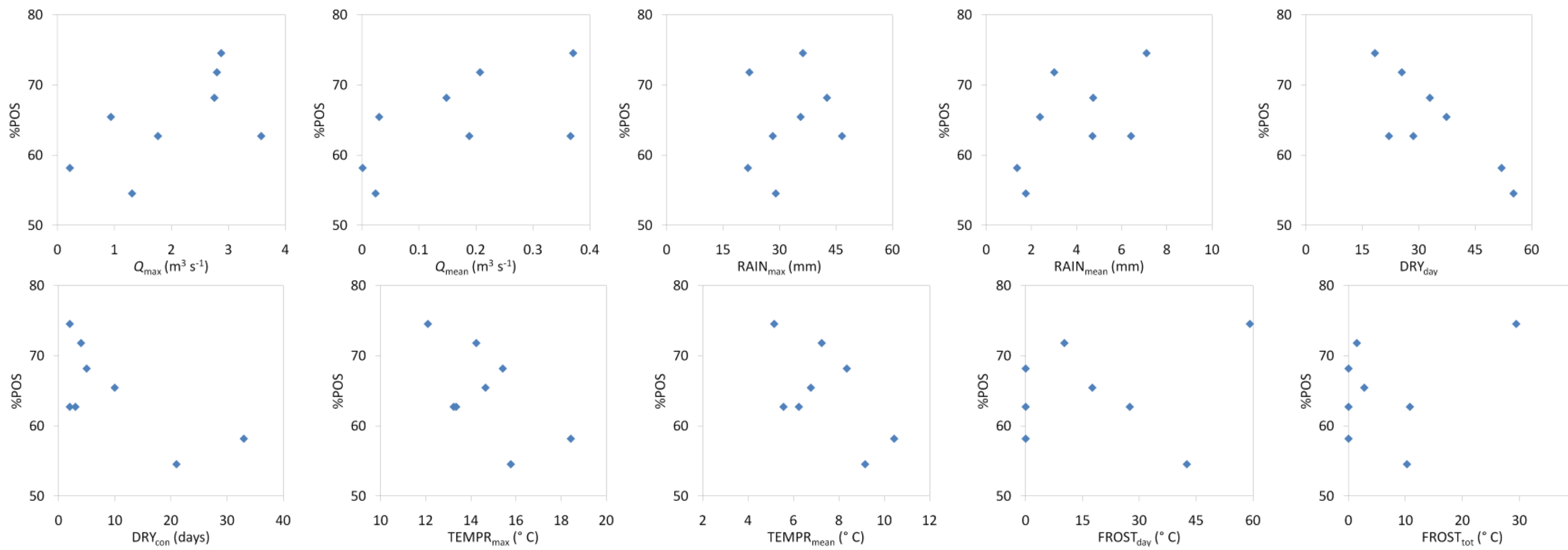


Figure 4.11 Relationships between hydrometeorological indices and %POS.

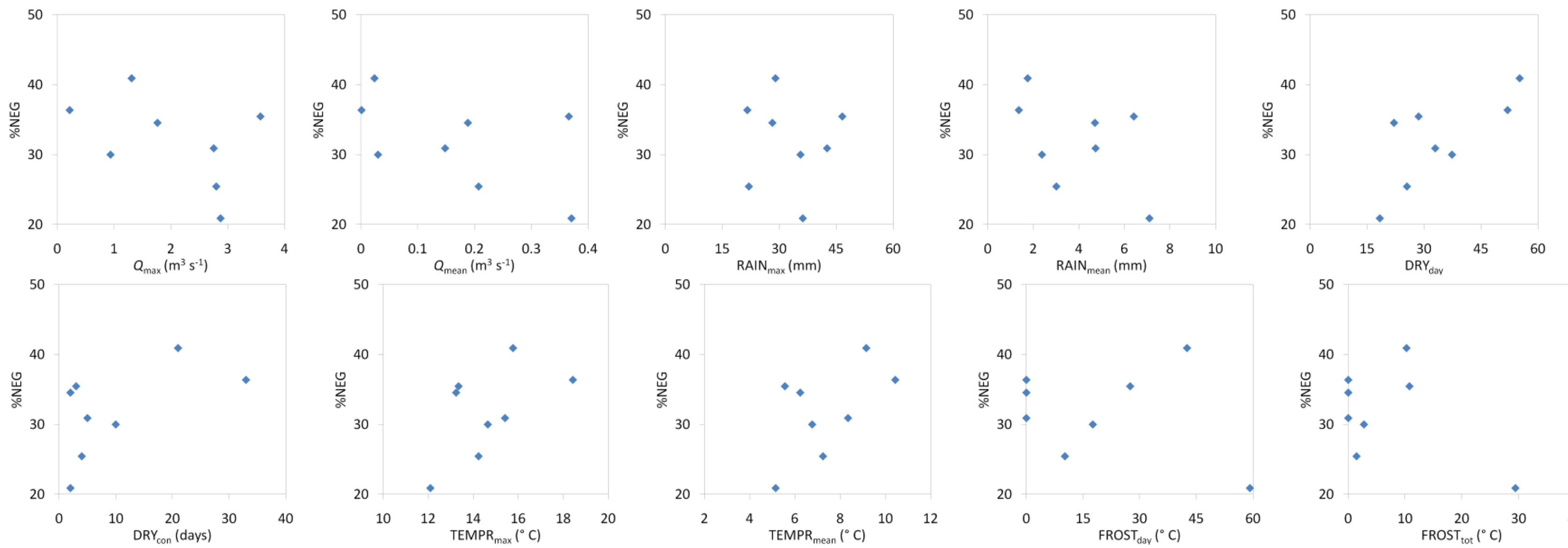


Figure 4.12 Relationships between hydrometeorological indices and %NEG.

	Bank erosion index				
Hydrometeorological variable	**(L)ER_{mean}**	**(L)ER_{max}**	**(L)ER_{high}**	**%POS**	**%NEG**
Q_{max}	0.843**	0.861**	0.870**	0.591	-0.444
Q_{mean}	0.907**	0.786*	0.934**	0.614	-0.534
$RAIN_{max}$	0.645	0.688	0.748*	0.202	-0.070
$RAIN_{mean}$	0.902**	0.737*	0.960**	0.580	-0.478
DRY_{days}	-0.768*	-0.517	-0.731*	-0.812*	0.719*
DRY_{con}	-0.703	-0.556	-0.718*	-0.702	0.554
$TEMPR_{max}$	-0.678	-0.489	-0.720*	-0.614	0.539
$TEMPR_{mean}$	-0.721*	-0.515	-0.750*	-0.608	0.549
$FROST_{days}$	0.326	0.367	0.367	0.163	-0.256
$FROST_{tot}$	0.552	0.499	0.571	0.360	-0.440

Table 4.5 Pearson product-moment correlation coefficients between bank erosion indices and hydrometeorological variables. * Correlation is signifcant at the 0.05 level. ** Correlation is significant at the 0.01 level.

range/desiccation indices and bank erosion intensity indicators, although this may reflect collinearity between certain hydrometeorological variables (see later discussion). The association between %NEG and dry weather conditions also proved significant at the 0.05 level.

The dominance of streamflow-related variables as apparent controls of bank erosion rates in the Upper Pontbren subcatchment was maintained even when trends were examined at different elevations on streambanks in the study area. Tables 4.6 and 4.7 compared Pearson product-moment correlation coefficients between the selected hydrometeorological variables and recalculated bank erosion descriptors for the lower and upper bank areas, respectively. The highest correlations at both levels are found with streamflow and rainfall variables, although the association between bank erosion intensity and the occurrence of frost is stronger in the upper bank region than when considered using the full erosion pin data set (the relationship between $FROST_{tot}$ and log-transformed UER_{high} is significant at the 0.05 level).

The influence of various site-specific factors (Table 4.8) on mean erosion rates at each monitoring site (ER_{site}) was found to be negligible (Figure 4.13). No statistically significant relationship was observed between ERsite and the percentage silt-clay or gravel content, bank angle, position within the drainage network or aspect of the bank. There was also no significant difference in site-averaged erosion rates between sites where livestock access was permitted and those where fencing had been erected (Mann-Whitney U test, $p = 0.583$).

Hydrometeorological variable	Bank erosion index (L)LERmean	(L)LERmax	(L)LERhigh	L%POS	L%NEG
Q_{max}	0.766*	0.854**	0.913**	0.292	-0.184
Q_{mean}	0.780*	0.737*	0.899**	0.303	-0.190
$RAIN_{max}$	0.532	0.644	0.505	0.247	-0.133
$RAIN_{mean}$	0.758*	0.668	0.813*	0.382	-0.262
DRY_{days}	-0.741*	-0.465	-0.732*	-0.589	0.480
DRY_{con}	-0.660	-0.517	-0.691	-0.561	0.408
$TEMPR_{max}$	-0.568	-0.423	-0.643	-0.502	0.331
$TEMPR_{mean}$	-0.617	-0.439	-0.637	-0.501	0.333
$FROST_{days}$	0.210	0.323	0.337	0.247	-0.173
$FROST_{tot}$	0.434	0.437	0.521	0.361	-0.298

Table 4.6 Pearson product-moment correlation coefficients between bank erosion indices calculated using data from the lower third of the bank and hydrometeorological variables. * Correlation is signifcant at the 0.05 level. ** Correlation is significant at the 0.01 level.

	Bank erosion index				
Hydrometeorological variable	**(L)UERmean**	**(L)UERmax**	**(L)UERhigh**	**U%POS**	**U%NEG**
Q_{max}	0.837**	0.557	0.821*	0.881*	-0.744*
Q_{mean}	0.881**	0.611	0.955**	0.634	-0.693
$RAIN_{max}$	0.847**	0.877**	0.609	0.540	-0.437
$RAIN_{mean}$	0.927**	0.751*	0.928**	0.492	-0.547
DRY_{days}	-0.658	-0.316	-0.667	-0.441	0.534
DRY_{con}	-0.723*	-0.401	-0.617	-0.610	0.540
$TEMPR_{max}$	-0.748*	-0.487	-0.737*	-0.434	0.513
$TEMPR_{mean}$	-0.788*	-0.524	-0.748*	-0.426	0.560
$FROST_{days}$	0.444	0.609	0.577	0.106	-0.408
$FROST_{tot}$	0.583	0.705	0.751*	0.115	-0.481

Table 4.7 Pearson product-moment correlation coefficients between bank erosion indices calculated using data from the upper third of the bank and hydrometeorological variables. * Correlation is signifcant at the 0.05 level. ** Correlation is significant at the 0.01 level.

Site	Name	Stream	No. erosion pins	Bank angle (°)	Aspect	Silt-clay content (%)	Gravel content (%)	Stock access (Y/N)
1	Cors-y-carreg	Nant Pen-y-cwm	3	85	SE	3.6	81.0	N
2	Tyn y bryn upper	Nant Pen-y-cwm	4	95	W	11.9	46.0	N
3	Nant Pant Powsi confluence	Nant Pen-y-cwm	3	95	ESE	0.7	89.0	N
4	Tyn y bryn middle	Nant Pen-y-cwm	5	105	W	3.3	69.0	N
5	Tyn y bryn lower	Nant Pen-y-cwm	4	85	E	0.8	85.0	N
6	Low bridge	Nant Pen-y-cwm	6	90	SSW	6.9	39.0	Y
7	Hillslope upper	Nant Pen-y-cwm	3	70	N	9.9	29.0	Y
8	Hillslope middle	Nant Pen-y-cwm	4	85	SSE	11.8	18.0	Y
9	Hillslope lower	Nant Pen-y-cwm	5	70	NNW	8.0	31.0	Y
10	Dell	Nant Pen-y-cwm	4	90	S	1.6	74.0	N
11	Stones	Nant Pen-y-cwm	3	90	NNW	1.6	76.0	Y
12	Gelli Gethin confluence	Nant Pen-y-cwm	4	90	E	7.5	39.0	N
13	Fence post	Nant Pen-y-cwm	3	90	W	0.6	91.0	N
14	Barbed wire crossing	Nant Pen-y-cwm	5	95	NW	7.4	35.0	N
15	Fallen tree	Nant Pen-y-cwm	4	90	E	1.1	85.0	N
16	PBD bedload traps	Nant Pen-y-cwm	4	90	S	7.0	51.0	N
17	Pines	Nant Gelli-Gethin	5	85	WNW	7.5	17.0	Y
18	Gorge 1 upper	Nant Gelli-Gethin	3	90	E	8.8	28.0	Y
19	Gorge 1 lower	Nant Gelli-Gethin	3	85	SE	5.8	48.0	Y
20	Gorge 2 entrance	Nant Gelli-Gethin	8	55	NE	10.8	20.0	Y
21	Gorge 2 roots	Nant Gelli-Gethin	4	85	S	4.6	36.0	Y
22	Gorge 2 middle	Nant Gelli-Gethin	9	70	N	10.2	61.0	Y
23	Gorge 2 lower	Nant Gelli-Gethin	9	80	N	13.9	58.0	Y
24	Pen-y-cwm confluence	Nant Gelli-Gethin	5	90	N	4.6	64.0	N

Table 4.8 Characteristics of bank erosion monitoring sites in the Upper Pontbren subcatchment.

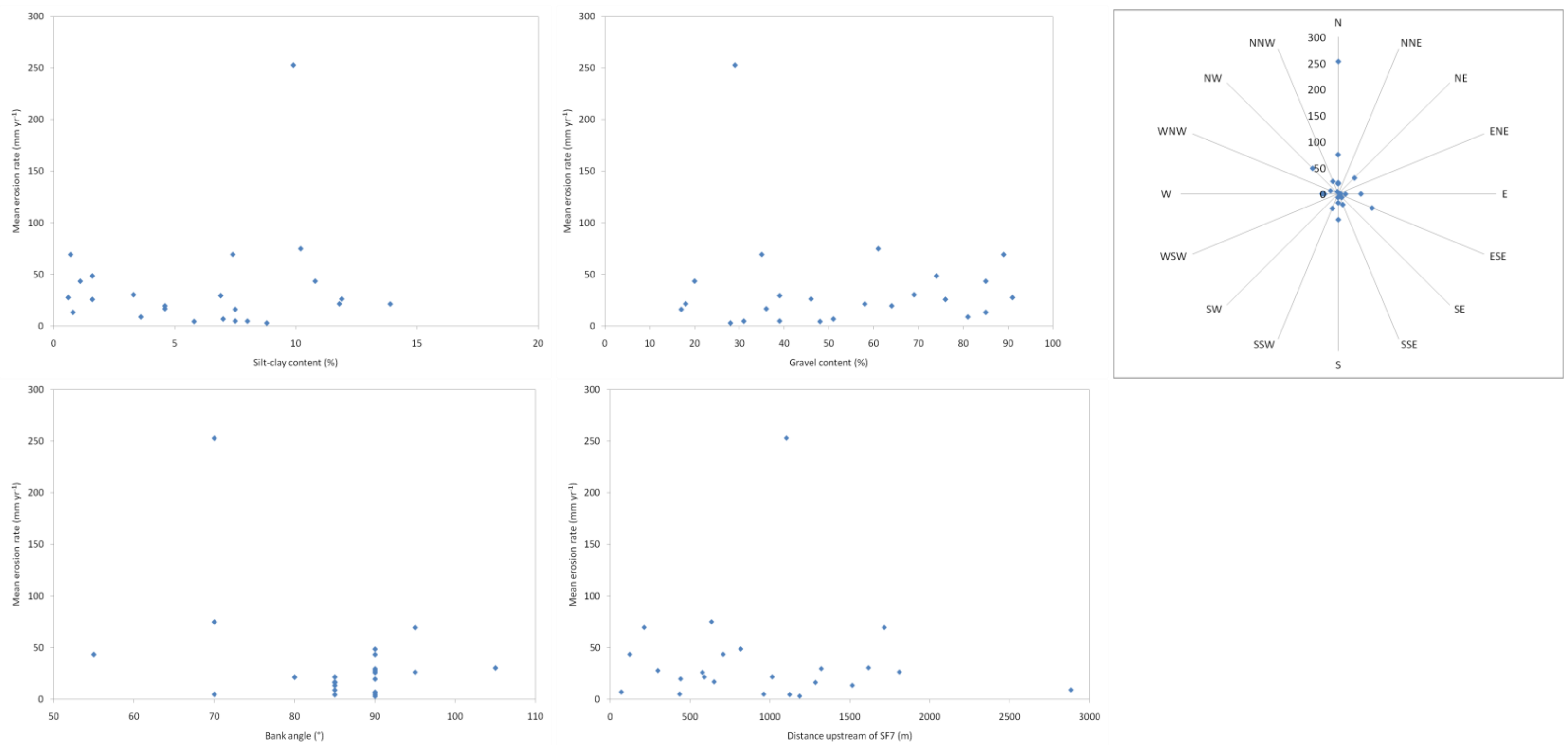


Figure 4.13 Relationships between site-averaged erosion rates and site-specific parameters.

4.4 Discussion

Mean annual bank erosion rates observed in the Upper Pontbren subcatchment are broadly consistent with those measured by other researchers in similar-sized, headwater catchments in the UK (Table 4.9) and follow a similar seasonal pattern to that reported elsewhere in which the highest rates of erosion occur during winter (*c.f.* Lawler, 1986; Stott, 1997b). The results of surveys of the spatial extent of erosion also show a clear seasonal trend, with larger areas of banks judged to display signs of erosion during winter and spring compared to summer and autumn. This is likely to reflect seasonal changes in soil moisture content, soil fabric and the degree of vegetation cover/reinforcement through the year and results in an accentuation of the amount of sediment supplied to stream channels from eroding bank sources during the wetter, colder months. Increased vegetation cover during summer and autumn periods may help to limit erosion rates by reducing velocities and shear stresses at the bank face (Lawler *et al*., 1997).

When expressed as a function of catchment area, the mean annual yield of sediment from channel banks (3.4 t km^{-2} yr^{-1}) is higher than those reported by Stott (1997b) in similar upland catchments in Scotland under forested and moorland land uses (1.9 t km^{-2} yr^{-1} and 2.8 t km^{-2} yr^{-1}, respectively). The amount of sediment produced on an annual basis from bank sources is also likely to be much greater than that supplied to channels from the surface of improved pastures in the Upper Pontbren subcatchment. If sediment yield figures derived from experiments conducted from the Bowl are assumed to be representative, the amount of sediment supplied to the channel network from the surface of all improved pastures in the Upper Pontbren subject can be calculated by

Study	**Location**	**Catchment area (km^2)**	**Bank erosion rate ($mm\ yr^{-1}$)**
Hill (1973)	Crawfordsburn and Clady Rivers, Northern Ireland	3-4	5-67
Lewin *et al*. (1974)	Maesnant, mid-Wales	0.5	30
Gardiner (1983)	River Lagan, County Down, Northern Ireland	20	76-140
Murgatroyd and Ternan (1983)	Narrator Brook, Dartmoor	4.8	0.7-5.2
Stott (1997b)	Monachyle and Kirkton Glens, Scotland	6.9-7.7	47-59
Stott *et al*. (2001)	Various streams, Plynlimon, mid-Wales	< 3.1	17-96
This study	Upper Pontbren subcatchment, mid-Wales	< 5.7	36

Table 4.9 Published bank erosion rates from other British headwater catchments.

multiplying the Bowl's sediment yield by the total area of improved grassland. Upscaling *via* this method produces a theoretical yield of approximately 21.9 t yr^{-1} from improved pasture sources, which is actually slightly higher than the measured yield from eroding channel banks (19.4 t yr^{-1}). However, as discussed in Chapter 3, the delivery of pasture-derived material to the channel network is limited by factors such as lack of hydrological connectivity between surface source areas and streams, the presence of buffer strips and topographic obstructions. Hence, the scientific integrity of the estimated value is dubious as the aforementioned factors are certain to reduce the delivery ratio for surface sources in comparison to that for channel banks, which is close to unity. Nevertheless, the comparison is useful as it illustrates that even under a 'best case scenario' in terms of pasture surface-channel network connectivity, bank sources would still be highly significant in this system and, in reality, are therefore likely to dominate the sediment budget. It should also be noted that the size of sediment particles supplied to channels from the two different sources differs significantly. While surface-derived material tends to be very fine (D_{50} < 6 µm), the majority of sediment generated from eroding banks ranges from sand-sized material up to boulders. In fact, only 6 % (2.4 t) of bank-derived sediment generated during the study period was within the silt-clay particle size range. These results further illustrate the importance of bank erosion as a sediment supply mechanism in Welsh upland streams, particularly with respect to sediment coarser than sand (*c.f.* Lewin *et al*., 1974; Grimshaw and Lewin, 1980; Bull, 1997; Stott *et al*., 2001).

Examination of the relationships between various hydrometeorological variables and bank erosion indices suggests that hydraulic action is the primary cause of lateral adjustment in the Upper Pontbren subcatchment, supporting the results of a study of erosion processes acting on massive till banks along the Crawfordsburn River in Northern Ireland (Hill, 1973). Curvilinear relationships between Q_{max}/Q_{mean} and bank erosion intensity are evident, and examination of vertical variation in erosion rates at individual monitoring sites illustrates the concentration of erosion in the lower bank region (Figure 4.14). The sequential profiles show how banks tend to be undercut at their bases through time before the over-steepened or over-hanging, upper bank portion above eventually collapses. Similar sequences have been observed in composite banks consisted of non-cohesive gravels overlain by cohesive alluvium (Thorne and Tovey, 1981). It should be noted that erosion rates may be further accentuated during wet periods due to changes in structural properties relating to bank moisture levels (e.g. Wolman, 1959; Knighton, 1973; Hooke, 1979). However, clear interpretation of the role of antecedent bank moisture conditions is difficult as there is strong collinearity evident between all streamflow and rainfall indices ($r > 0.8$).

The pre-eminence of fluvial processes as controls of bank erosion in the Upper Pontbren subcatchment is clear, questioning the assertion by Lawler (1992) that subaerial processes can dominate in the upper reaches of rivers where stream power tends to be relatively low. Results from other studies of bank erosion processes in British headwater streams have demonstrated the significance of frost and subsequent needle-ice formation in mobilising material from bank faces (e.g. Lawler, 1986; Lawler, 1993; Branson *et al*., 1996; Stott, 1997b; Yumoto *et al*., 2006). However, no clear relationship between freeze-thaw activity and bank erosion was evident in the Pontbren erosion pin data. This may reflect the composition of the bank material in the area; Hill (1973) found

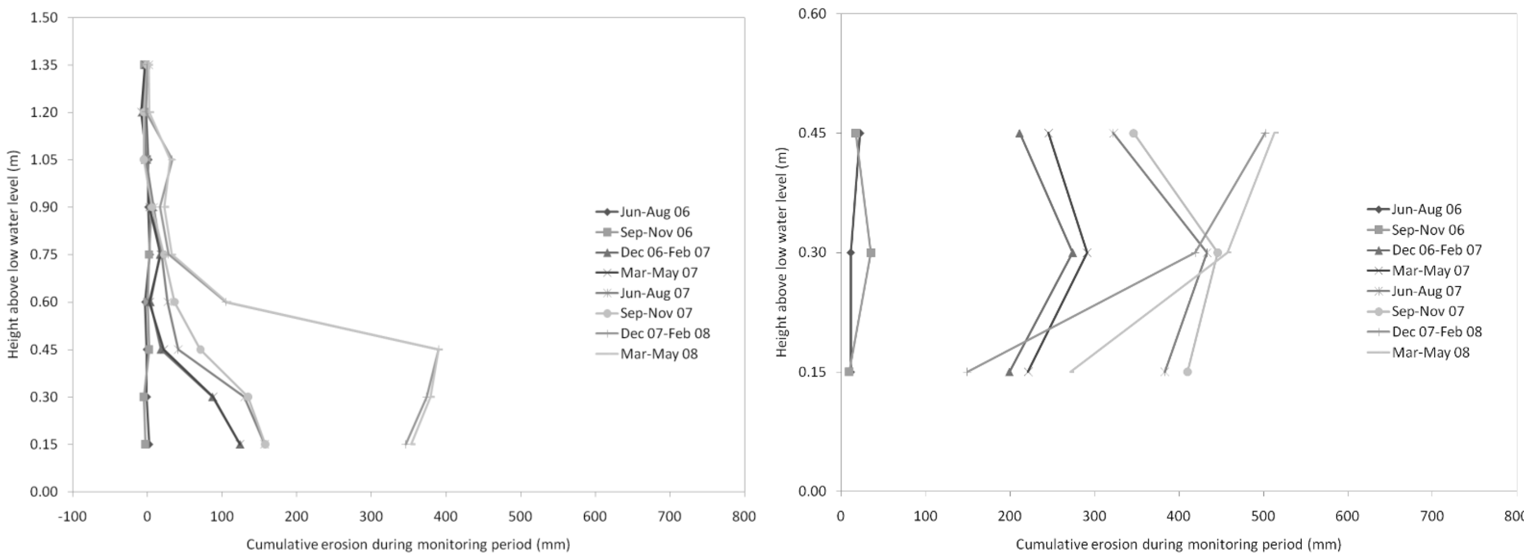


Figure 4.14 Sequential profiles showing cumulative bank erosion at monitoring sites in the Upper Pontbren subcatchment.

that freeze-thaw cycles were of much greater importance in controlling erosion from till banks consisting of fine clays than those made of coarser material. Couper (2003) has also demonstrated that banks with high silt-clay contents have a higher susceptibility to subaerial erosion. It is also possible that the temporal frequency of bank erosion measurements was insufficient to capture the effects of subaerial erosion processes as smaller episodes of retreat are likely to be hidden by much larger, fluvially-controlled events.

There is some evidence, however, that desiccation may cause significant bank erosion in the Upper Pontbren subcatchment. While no clear trends exist between descriptors of bank erosion intensity and variables designed to represent desiccation (DRY_{day}, DRY_{con}), there is a statistically significant, positive relationship between dryness and the number of negative erosion pin readings. Couper *et al*. (2002) have shown the occurrence of such phenomena to be linked with the loosening and peeling of the soil surface due to heating, a process also observed by Oxley (1974) and Lawler (1992). A study by Gittens (2005) at Pontbren showed that stones embedded in the till in the upper sections of banks along the Nant Pen-y-cwm tended to loosen and fall out during dry, hot summer periods possibly as a result of the contraction of surrounding fine clay material due to heating (*c.f.* Thorne and Lewin, 1979; Thorne and Osman, 1988). This may help to explain the occurrence of bank erosion (albeit minimal) during Summer 2006 despite an almost total absence of significant streamflow (see Chapter 3).

The considerable variation in bank erosion rates observed between monitoring sites could not be explained by site-specific physical factors such as bank material composition, bank angle, aspect or longitudinal position in the catchment channel network, despite such factors being shown to be important in previous studies (e.g. Lawler *et al*., 1997; Lawler *et al*., 1999; Couper, 2003; Laubel *et al*., 2003). The influence of grazing management practices on bank erosion in the study area is also debatable on the basis of data collected during this study as no significant difference was evident between grazed and fenced sites (*c.f.* Zaimes *et al*., 2006). This may, in part, stem from the morphology of the banks studied in that they tended to be very steep and would, therefore, be unlikely to be subjected to direct hoof impacts. It could also reflect the type of livestock which graze the Upper Pontbren area. The majority of studies into links between riparian erosion and livestock grazing to date have focussed on the impact of cattle (e.g. Platts, 1991), which are known to preferentially congregate around watercourses. Sheep, however, tend to avoid riparian areas (*c.f.* May and Davis, 1982; Platts, 1982) and are therefore likely to cause less disturbance to streambanks. It should be noted, however, that livestock exclusion conducted as part of the Pontbren Rural Care Project may have helped to reduce bank erosion in areas that used to be openly grazed by cattle at Tyn-y-bryn farm (Figure 4.15).

It is suggested that the wide range of bank erosion rates observed at sites in the Upper Pontbren subcatchment may, in part, result from the widespread occurrence of in-channel obstructions such as large woody debris and large deposits of coarse material on the beds of the Nant Pen-y-cwm and Nant Gelli-Gethin. Both streams display strong evidence of geomorphological disturbance (see Chapter 2) and it is conceivable that the lateral adjustment observed during this study could represent an ongoing response to a large flood event or events in the past (*c.f.* Newson, 1980b). However, the relative

Figure 4.15 Localised bank erosion evident around cattle watering area on Nant Pen-y-cwm (Source: David Jenkins, Coed Cymru).

absence of any significant bank erosion in the upper reaches of the Nant Melin-y-grûg in comparison to streams in the Upper Pontbren subcatchment also raises the possibility that historical changes in land use could also have had a significant influence and this hypothesis is supported by hydrological data collected as part of the wider FRMRC research programme in the study area. For example, Figure 4.16 compares normalised hydrographs of total runoff from the Bowl (overland flow and drain flow combined; see Chapter 3) with runoff measured in the Nant Pen-y-cwm and Nant Melin-y-grûg between June 2006 and June 2008. Data from gauging stations SF6 and SF9 are presented on the basis of their similar upstream drainage areas (317 ha and 406 ha, respectively; Figure 4.4). The graphs indicate a striking similarity in the shape of runoff hydrographs from the Bowl and the Nant Pen-y-cwm, albeit with reduced normalised peak flows in the stream compared to those from the hillslope. However, while the runoff response of the Nant Melin-y-grûg is also flashy in character, normalised peak flows are considerably lower than in the Nant Pen-y-cwm and there is greater attenuation on the receding limb of events.

A combination of physiographical and anthropogenic factors may explain the difference in hydrological response between the two subcatchments. The upper reaches of the Nant Melin-y-grûg drain a marshy upland basin dominated by peaty, Wilcocks association soils (mainly Hiraethog, Wilcocks, and Crowdy series) and three shallow lakes: Llyn Newydd (1.4 ha), Llyn Hir (7.9 ha), and Llyn y Grinwydden (2.2 ha) (Figure 4.17). Wheater *et al*. (2008) attempted to isolate the effect of the lakes on peak flow attenuation using data from a gauging station installed at the outflow from Llyn Hir in November 2006 (SF8). The relatively short transmission time between the two gauging

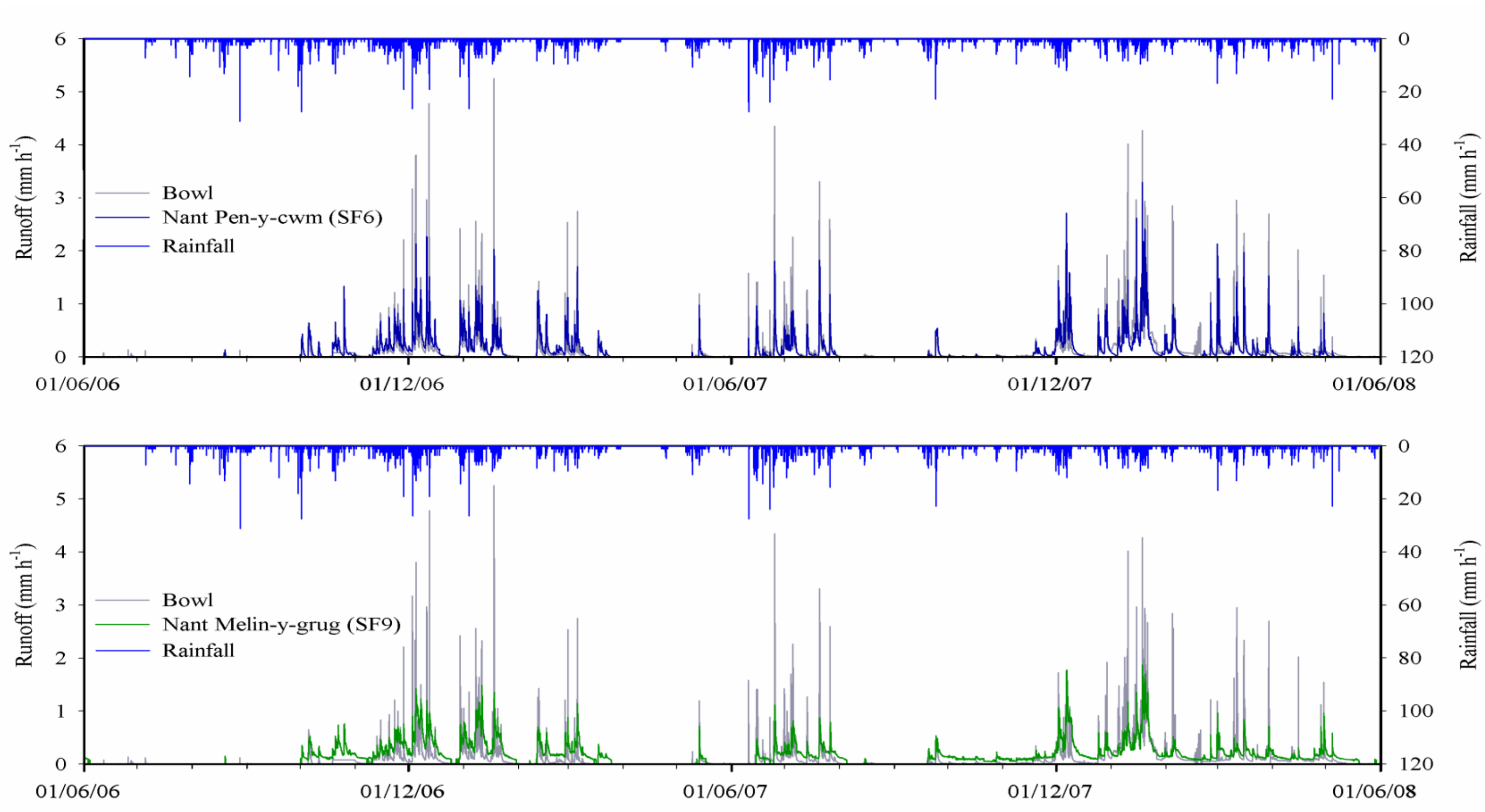


Figure 4.16 Hydrological responses of the Bowl experimental hillslope, the Nant Pen-y-cwm (SF6) and the Nant Melin-y-grûg (SF9).

Figure 4.17 Shallow lakes and peat bog in the headwaters of the Nant Melin-y-grûg: Llyn Newydd (foreground) and Llyn Hir (background).

stations on the Nant Melin-y-grûg permitted discharge values recorded at SF8 to be simply subtracted from SF9 to generate runoff data for the intervening area of land (Wheater *et al*., 2008). The procedure effectively removed Llyn Hir, Llyn Newydd and the moorland upstream of SF8, reducing the Upper Melin-y-grûg area to approximately 292 ha. The land use composition of the revised subcatchment remained similar to the original (heath/moorland/rough pasture = 77.4%, permanent/improved grassland = 16.6%) and although Llyn y Grinwydden remained within the new area, it is not considered to be significant given its similarity in size and position in the drainage network to the artificial lake in the Upper Pontbren area.

Flow duration curves for simultaneous discharge measurements at SF6, SF9, and SF9-SF8 were compared to determine the effect of the lakes (and upstream moorland) on flood peaks (Wheater *et al*., 2008). The analysis was originally performed using data collected between November 2006 and January 2007. Figure 4.18 shows updated flow duration curves for the subcatchments that incorporate additional data up to June 2008. While the removal of land upstream of SF8 did result in an increase in peak flow rate, normalised peak discharges for the revised subcatchment (SF9-SF8) were still appreciably lower than those recorded at SF6 on the Nant Pen-y-cwm. The results suggest that while the lakes (and/or surrounding moorland) at the source of the Nant Melin-y-grûg do play an important role in dampening the hydrological response of the subcatchment, peak normalised flows at SF9 remain lower than in the Nant Pen-y-cwm even when they are excluded. Other possible physiographical causes could include differences in catchment gradient or soil types. However, on the basis of these parameters alone, the slightly steeper terrain and wetter soils of the Upper Melin-y-grûg

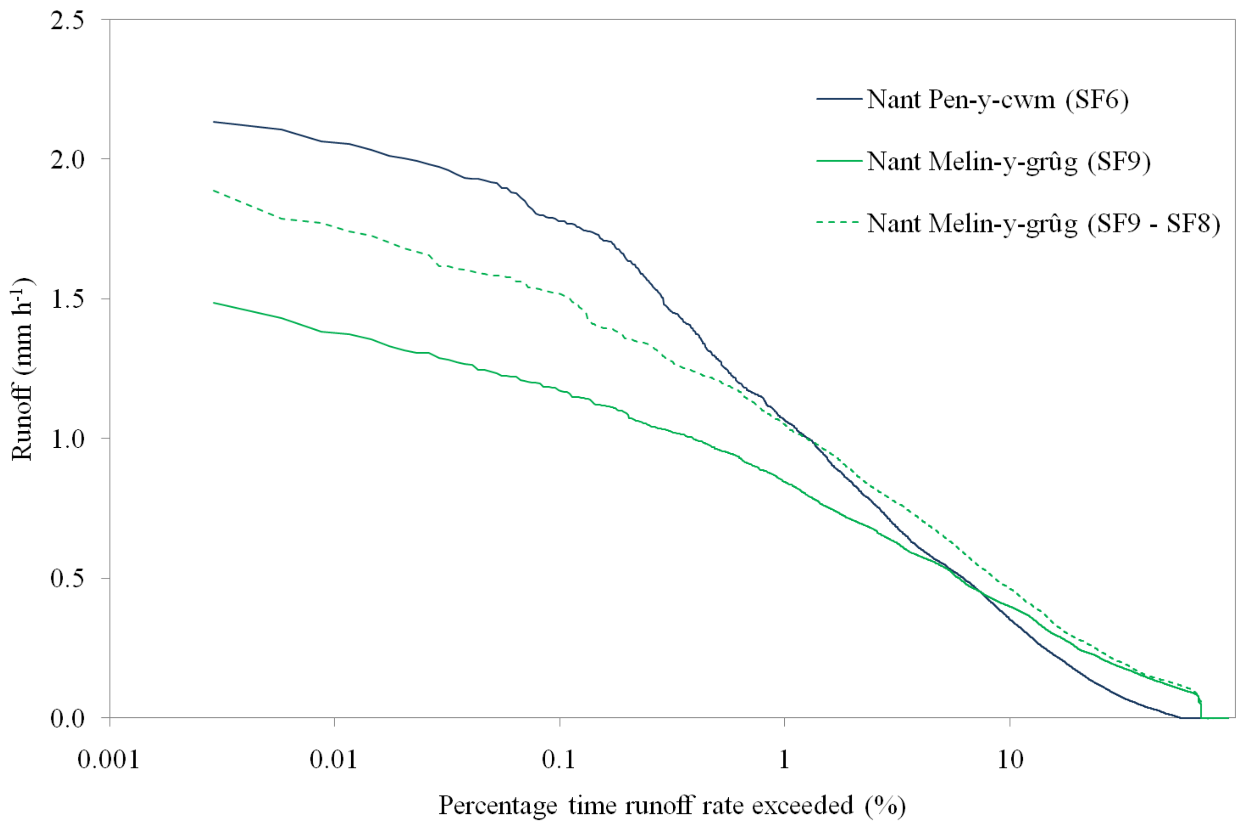


Figure 4.18 Flow duration curves of streams in the Upper Pontbren and Upper Melin-y-grûg subcatchments.

area would be expected to generate a more flashy response than the Upper Pontbren subcatchment (*c.f.* Burt, 1995; Evans *et al*., 1999; Holden and Burt, 2002; Holden and Burt, 2003) rather than the less flashy response actually observed.

Historical changes in land use and land management may, therefore, provide a plausible explanation for the higher normalised peak flows observed in the Nant Pen-y-cwm subcatchment. An evaluation of the structural properties of soils in the study area was undertaken during the NSRI survey in 2005 using a methodology employed by Holman *et al*. (2003) to evaluate levels of soil degradation under different cropping/land management regimes in a number of UK catchments (including the Upper River Severn). A summary of the features used to classify the level of soil degradation and resultant hydrological implications is provided in Table 4.10. Over 30% of sampling locations classified as improved grassland (n = 34) exhibited high levels of degradation, with a further 65% deemed to be moderately degraded (Palmer, 2005). However, no features associated with severe or high levels of degradation were observed at unimproved grassland sampling locations (n = 6) and only one third were moderately degraded. There is also anecdotal evidence that recent agricultural intensification has coincided with a reduction in the organic content of surface soil layers in the Upper Pontbren area (R. Palmer, pers. comm.). These observations suggest that infiltration rates and soil moisture storage capacities are likely to be lower in soils under improved pastures compared to those beneath areas of unimproved grassland, and this may contribute to enhanced runoff. Soil characterisation and detailed analysis of local-scale hydrological responses at unimproved grassland sites will be undertaken to clarify these effects as

Degradation class	Description of hydrological implications	Soil degradation features
Severe (S)	Soil degradation generates sufficient enhanced runoff to cause widespread erosion that is not confined to wheelings.	Extensive rill erosion on slopes, depositional fans on footslopes and level ground. Plus most characteristics of High degradation.
High (H)	Soil degradation generates enhanced runoff across whole fields where slopes allow.	Extensively poached surface or wheelings 5cm or deeper; damage to topsoil or immediate subsurface structure (apedal or weak coarse angular blocky structure); changes to vertical wetness gradient.
Moderate (M)	Soil degradation generates localised areas of enhanced runoff where slopes allow.	Slight poaching (locally severe); weak subsurface structure/compaction.
Low (L)	Insignificant enhanced runoff generation.	Few signs of enhanced runoff mechanisms present, but can show signs of localised poaching and standing water as long as the whole profile maintains a good soil structure.

Table 4.10 Soil degradation classification scheme used in NSRI survey (2005).

part of a second phase of FRMRC research that commenced in January 2008 and will run until January 2010 (M. Marshall, pers. comm.).

The installation and expansion of drainage systems to facilitate agricultural development in the Upper Pontbren subcatchment may also be a significant factor that contributes to higher peak runoff values in the Nant Pen-y-cwm (Wheater *et al*., 2008). As the previous chapter highlights, underdrainage in the area appears to be broadly ineffective at reducing soil water levels and saturation-excess overland flow generation is common. However, field drains can have a significant local influence on hydraulic conductivity and encourage the rapid transfer of water down through the soil profile. The majority of improved pastures in the study area are bordered by open ditches that receive runoff *via* both mechanisms and provide an efficient pathway between fields and the natural stream channel network. Higher levels of agricultural development in the Upper Pontbren subcatchment have resulted in a greater drainage density in comparison to the upper reaches of the Nant Melin-y-grûg (2.9 km^{-1}: 2.0 km^{-1}) and the difference may help to explain the contrasting hydrological responses observed in streams draining the two areas.

It should be noted that agricultural development may not be the only anthropogenic influence on the hydrological response of the Nant Pen-y-cwm. As discussed in Section 2.4.2, a plantation of coniferous trees was established in the headwaters of the stream in 1988 and the site may have affected flows at different stages of development. Commercial afforestation in upland areas is usually preceded by the creation of a network of open drains to improve soil conditions. The associated increase in drainage density and provision of efficient flow routes for surface water during storms can lead to increased flood peaks and shorter response times in years immediately following land preparation (Archer and Newson, 2002). For example, Robinson (1989) reported an increase in average storm hydrograph peaks of approximately 20% and a reduction in lag times of about 25% in the Coalburn catchment, Cumbria, and similar results were observed in another experimental catchment at Llanbrynmair in Wales. However, water yields and flood peaks in small catchments tend to decline through time as trees mature, interception losses increase, and drains become increasingly colonised by grasses and mosses (Robinson *et al*., 1998; Fahey *et al*., 2004).

The lack of long-term discharge records at Pontbren makes it difficult to evaluate the impact of the conifer plantation on flows, but it is plausible that flood peaks could have been increased as a result of site preparation. However, a number of factors suggest that any increases would have been limited in magnitude. The site occupies less than 4% of the total Upper Pontbren area (and less than 6% of the land upstream of gauging station SF6 on the Nant Pen-y-cwm). This is significantly less than the total planted area at either Coalburn or Llanbrynmair (over 90% and 70%, respectively) and it is therefore doubtful that any effects at Pontbren would have been as dramatic as the ones observed at those sites. The design of the plantation's drainage system, in which a large proportion of ditches drain into an artificial pond, is in any case likely to delay flow reaching the Nant Pen-y-cwm. Historical maps also indicate that a number of the fields which had occupied the site prior to the plantation's establishment had been agriculturally improved and may have already exhibited an accelerated runoff response.

Runoff hydrographs from gauging stations on the Nant Pen-y-cwm upstream of the site do not exhibit any obvious difference in shape to those from downstream and it is therefore unlikely that the contrasting present-day hydrological responses of the Nant Pen-y-cwm and Nant Melin-y-grûg can be attributed to the existence of the conifer plantation. A new gauging station (SF6a) was installed on the Nant Gelli-Gethin in summer 2008 to help to validate this conclusion and, although yet to be fully calibrated at the time of reporting, early data from the site indicates that the stream exhibits a similar hydrological response to the Nant Pen-y-cwm despite a complete absence of afforestation in the catchment area upstream (M. Marshall, pers. comm.). Increased water use and interception as trees in the plantation have matured, and the widespread growth of vegetation in ditches (Figure 2.13b), may have actually reduced water yields to the Nant Pen-y-cwm in recent years. Indeed, reduced base flows (especially during summer months) have been observed in the Nant Pen-y-cwm (Wheater *et al*., 2008). However, similar hydrological features are apparent in the Nant Gelli-Gethin and small, plantation-free tributaries of the Nant Pen-y-cwm. Increased water use by improved grass swards (e.g. Roberts *et al*., 1990) and a decline in soil moisture storage capacity as a result of changes in soil properties associated with agricultural intensification appear, therefore, to offer an alternative explanation for reduced low flows at Pontbren.

Considerable uncertainty therefore remains around the role of land use as a cause of the different flow regimes of streams in the Upper Melin-y-grûg and Upper Pontbren subcatchments. However, the differences in peak flows do present a potential explanation for the observed differences in bank erosion described in this chapter through their effect on fluvial processes and channel stability. In this context, coarse and fine sediment transport in streams throughout the Pontbren study area are therefore examined in the following two chapters to investigate the influence of peak flows on sediment dynamics and morphological adjustments in the fluvial system.

5 DYNAMICS AND CONTROLS OF BEDLOAD YIELDS FROM HEADWATER SUBCATCHMENTS AT PONTBREN

5.1 Introduction

As discussed in Chapter 2, changes in flow and sediment supply regimes resulting from anthropogenic activities can have significant impacts on sediment yields from river catchments. Evidence presented in Chapters 3 and 4 suggests that agricultural intensification in the Upper Pontbren subcatchment during the second half of the twentieth century may have increased both the potential for sediment transport and the amount of sediment supplied to streams by altering hydrological responses at the local and catchment-scales and improving sediment source-channel connectivity. However, recent changes in land management practices undertaken as part of the Pontbren Rural Care Project could help to limit or reverse some of these effects and may, therefore, also influence sediment yields, with possible implications for flood risk management.

The impacts of land use changes and land management practices on sediment yields from headwater streams in the Pontbren study area are considered in this and the following chapter. Coarse and fine sediment yields are considered separately due to differences in the manner in which different-sized sediment particles are transported and contrasts in the way their yields are measured. This chapter focuses on the transport of coarse sediment particles, which tend to roll, slide or saltate at velocities less than those of the surrounding flow (Knighton, 1998). Material transported *via* these mechanisms is referred to as bedload and typically represents a substantial proportion of the total sediment transported in upland streams (Schmidt and Ergenzinger, 1993). Finer sediment tends to be transported as suspended load, where particles are temporarily carried within the water column by turbulent mixing processes (Knighton, 1998). The finer material constitutes a proportion of the total sediment yield from upland catchments that is similar to or greater than that moving as bedload (Kirby, 1991) and this is considered in Chapter 6.

This chapter describes a programme of bedload transport measurements implemented at sites on headwater streams in the Pontbren study area between June 2006 and June 2008. Spatial and temporal variability in the quantities and sizes of coarse sediment transported at the measurement sites is explored in relation to hydrological and hydraulic controls, and sediment supply factors. The results are used to evaluate the potential significance of differences in the extent of historical agricultural intensification between subcatchments and the implementation of novel land management practices in recent years under the Pontbren Rural Care Project.

5.2 Methodology

5.2.1 Bedload yield and particle size measurement

Bedload transport is temporally discrete and substantial volumes of coarse material are usually only mobilised during high flow conditions. This prohibits the use of devices that require manual operation (e.g. Bathurst *et al*., 1985) in studies where long-term bedload yield data are desired and necessitates the use of alternative methods. Continuous measurements of bedload transport activity can be performed using impact sensors (e.g. Carling *et al*., 2002; Reid *et al*., 2007) but such devices are currently unable to provide information on the size of particles in motion. Other continuously-recording devices such as pressure-pillow (Reid *et al*., 1980) and load cell-based (Sear *et al*., 2000) samplers can collect mobilised material for subsequent analysis. However, sediment traps of this type tend to have limited storage capacities, are expensive to deploy in large numbers, and are vulnerable to damage to their electronic components, which may fail in harsh upland environments.

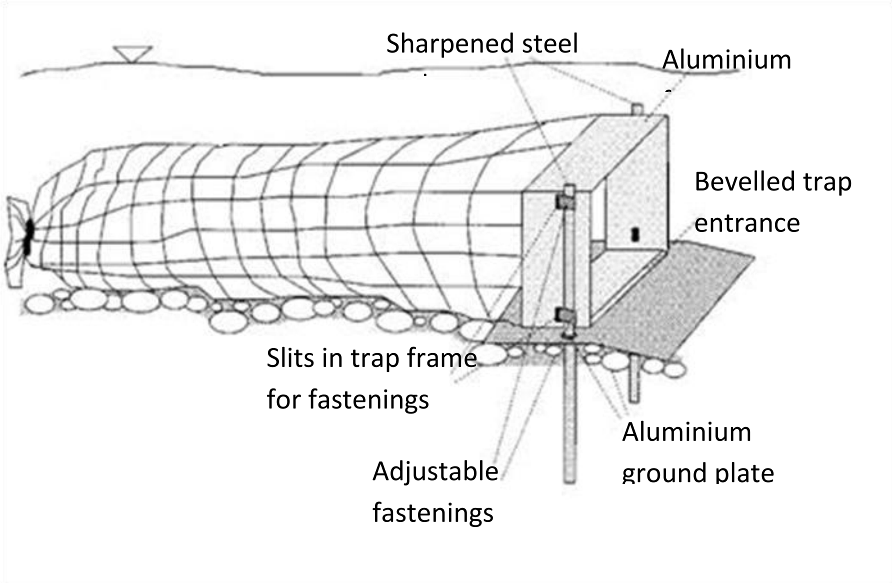
Simple, time-integrated approaches using samplers which have no moving parts provide a cheaper alternative for studies mainly concerned with long-term bedload yields. Pit traps that collect bulk samples of bedload material over individual or multiple, temporally contiguous transport events have been used in upland streams similar to those at Pontbren (e.g. Painter *et al*., 1974; Carling, 1983). However, large concrete installations are relatively expensive (Newson, 1981) and their installation and eventual removal cause substantial disturbance to the streambed environment. Also, while repeat surveys of sediment accumulation at pre-established structures or areas of natural deposition can be used as an alternative method of bedload yield estimation (e.g.Richards and McCaig, 1985; Newson and Leeks, 1987), all forms of open pit trap can have highly variable sampling efficiencies. Fine bedload material can saltate over the top of traps or be remobilised following deposition and thus evade measurement. Stott *et al*. (1986) utilised permeable timber-framed weirs as traps to circumvent some of these problems with conventional pit traps. However, the dams are reported to have become clogged with organic debris at times during the study and it is possible that backwater effects could have affected hydraulic conditions upstream. The total blockage of streams caused by the use of such traps may also have environmental implications if deployed over long periods of time (e.g.

by limiting fish passage). An alternative bedload measurement strategy was therefore employed in this study.

The traps used to sample bedload yields in headwater streams at Pontbren were based on a model developed by Bunte *et al*. (2004) to assess transport rates of gravel- and cobble-sized sediment in remote mountain streams in the USA (Figure 5.1). The trap device is designed to sit on the streambed surface and therefore negates the need for major excavation or excessive environmental disturbance. Bedload particles enter individual traps through a 0.4 m x 0.3 m x 0.1 m aluminium frame and are caught in a net manufactured of high-strength, flexible plastic that trails for approximately 1.5 m downstream. A mesh size of 3.8 mm was selected as a good compromise between permissible retardation of flow through the net and the capability to sample small gravel particles, on the basis of recommendations by Bunte *et al*. (2004). The traps have the capacity to hold up to 250 kg of gravel. However, given a probable decline in sampling efficiency once the trap is over 40% full (Emmett, 1984), the actual operational capacity is more likely to be closer to 100 kg. Accumulations of gravel greater than this could be expected to impede flow and thus reduce the sampling efficiency of the device.

The traps were deployed in rows across streams and secured to steel stakes driven into the streambed using a fencing hammer. An aluminium base plate (0.6 m x 0.4 m) was positioned between each trap and the bed surface to prevent inadvertent particle entrainment around the trap entrance (Bunte *et al*., 2005). The upstream end of the base plate slants downwards at an angle of 10° and was pushed a few centimetres into the bed to ensure that a smooth transition was achieved. The low-friction surface accelerates the near-bed flow velocity by 25-50%, guaranteeing that

(a)



(b)

(c)

Figure 5.1a-c Bedload traps developed for use on headwater streams in the Pontbren study area. Source of diagram in Figure 5.1a: Bunte *et al*. (2004); p. 880.

all particles which move onto the base plate from upstream proceeded into the trap. Measurements to determine whether flow acceleration extends upstream of the ground plate have been inconclusive (Bunte and Swingle, 2004).

Bedload traps were installed at six sites in the Pontbren study area in autumn 2005 (Figure 5.2). However, wire ties originally used to secure the traps to the steel stakes in the bed often snapped during flood events. The traps were, therefore, adjusted to incorporate extra-strong nylon rope fastenings and redeployed in spring 2006.

Bedload yield measurement sites included:

- a drainage ditch at Pant Powsi (PP), located immediately downstream of the Bowl experimental pasture detailed in Chapter 3 (Figure 5.3a).
- the Nant Pen-y-cwm at Cors-y-Carreg (CYC), upstream of where ditches from the conifer plantation enter that stream (Figure 5.3b).
- the Nant Pen-y-cwm at New Bridge (NB), downstream of the conifer plantation and Pant Powsi (PP) (Figure 5.3c).
- the Nant Pen-y-cwm at Sheepfold (SHP), downstream of a heavily incised reach with eroding banks (Figure 5.3d).
- the Nant Pont-bren-down (PBD), downstream of the confluence between the Nant Pen-y-cwm and Nant Gelli-Gethin (Figure 5.3e).
- the Nant Melin-y-grûg at Hirrhos Bridge (HB; Figure 5.3f).

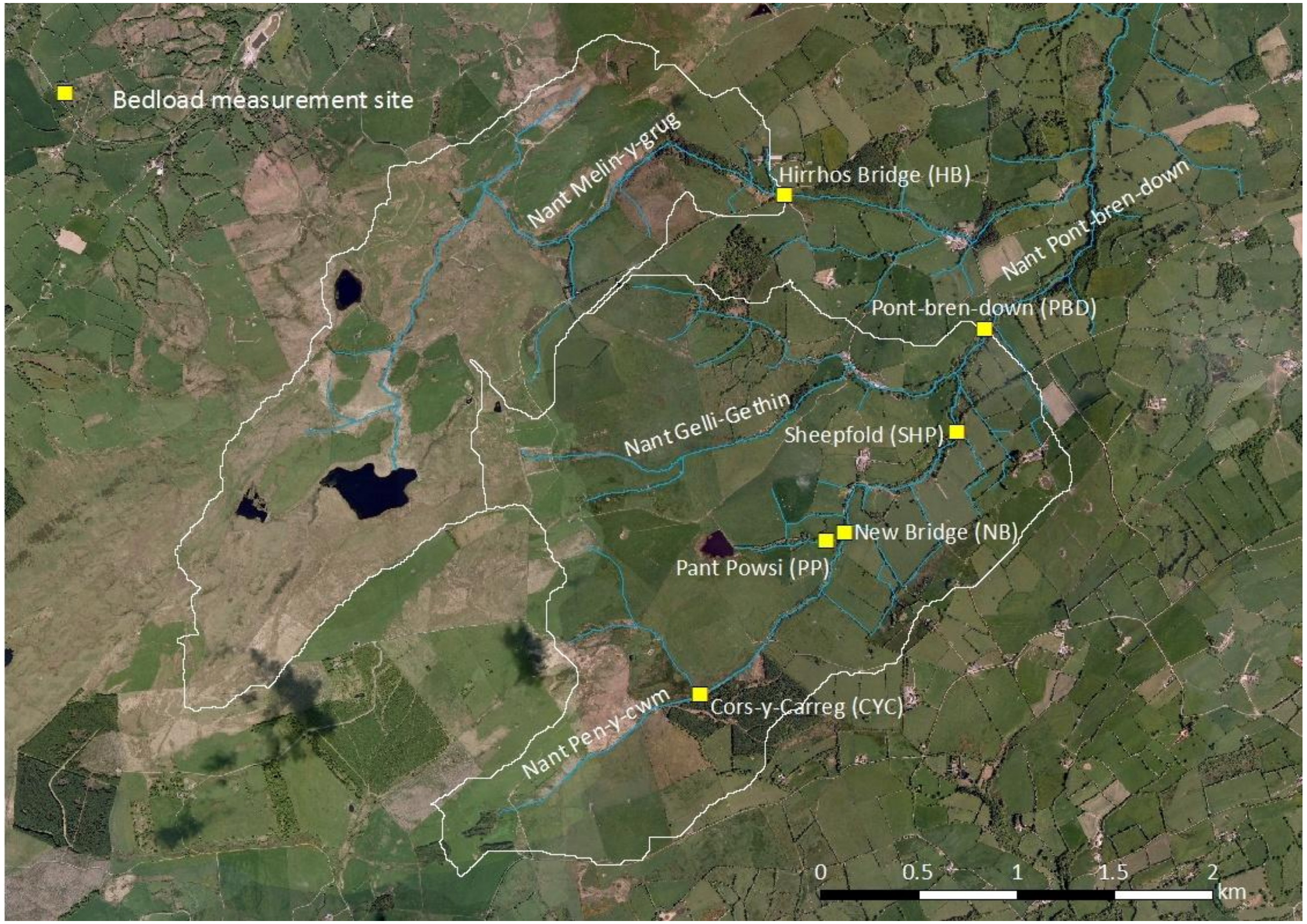


Figure 5.2 Location of bedload yield measurement sites in the Pontbren study area.

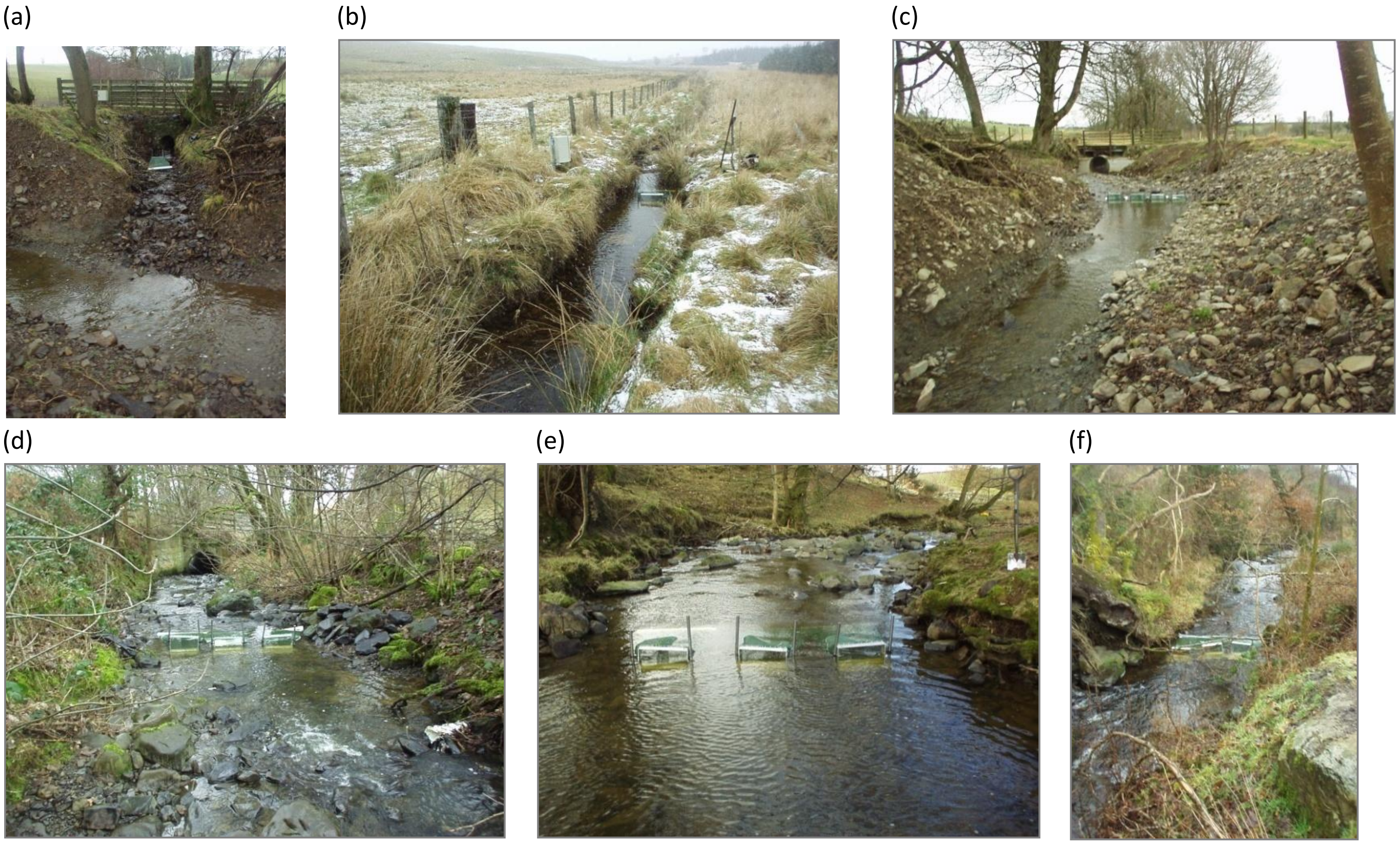


Figure 5.3 Bedload measurement sites at (a) Pant Powsi (PP); (b) Cors-y-Carreg (CYC); (c) New Bridge (NB); (d) Sheepfold (SHP); (e) Pont-bren-down (PBD); and (f) Hirrhos Bridge (HB).

Full site descriptions are provided in Table 5.1. The number of traps deployed at each site ranged from 1-4, ensuring that between 30-50% of the active (unvegetated) cross-sectional streambed width was sampled. Traps were labelled in alphabetical order from left bank to right bank. Higher streambed coverage was not achieved mainly due to the presence of obstacles such as large, embedded boulders, but also to minimise the risk of trap damage and blockages resulting from organic debris. Traps were evenly-spaced where possible and one was placed in the channel thalweg at each site.

Samples of trapped bedload were collected from the traps on a semi-regular (≈1-2 week) basis over the data collection period reported in this thesis (June 2006-June 2008 due to the irregular trapping record during winter 2005/06) and, where possible, after individual high flow events. The interval between trap emptying events (n = 74) varied according to in-stream flow conditions (3-29 days), but had a mode of 6 days. Sampled bedload particles in each trap were separated from any trapped organic material in the field and transferred to labelled containers for transport prior to laboratory analysis. Samples were oven-dried, sieved at half-phi intervals, and the total mass of particles in each size fraction was recorded. The size of particles coarser than 16 mm was determined using a gravelometer (*c.f.* Hey and Thorne, 1983). The mass of size fractions finer than 4 mm was not recorded as the efficiency of the traps to retain sediment finer than the diameter of the net mesh (3.8 mm) is unknown. Bedload particle size percentiles (D_5, D_{16}, D_{25}, D_{50}, D_{75}, D_{84}, and D_{95}) were calculated for each event at each site by linear interpolation between data points on cumulative size distribution curves. Particle size statistics (mean, sorting, skewness, and kurtosis) were calculated graphically using formulae proposed by Folk and Ward (1957).

Bedload measurement site	Stream	No. traps	Gauging station	Improved grassland upstream (%)	Upstream drainage area (km^2)	Elevation (m AOD)	Channel bed slope	Active streambed width (m)	Db_{50} (mm)	Db_{90} (mm)	Sorting (Folk & Ward, 1957)	Skewness (Folk & Ward, 1957)	Kurtosis (Folk & Ward, 1957)
Pant Powsi (PP)	Nant Pant Powsi	1	SF4	100	0.290	253	0.033	0.74	34	74	1.20	-0.14	0.88
Cors-y-Carreg (CYC)	Nant Pen-y-cwm	1	SF2	68	1.292	314	0.025	1.10	5	20	1.77	-0.10	0.72
New Bridge (NB)	Nant Pen-y-cwm	4	SF5	70	2.389	277	0.022	3.48	26	68	1.14	0.01	0.95
Sheepfold (SHP)	Nant Pen-y-cwm	3	SF6	77	3.166	243	0.031	3.06	35	85	1.39	-0.26	0.79
Pont-bren-down (PBD)	Nant Pont-bren-down	3	SF7	80	5.767	212	0.022	3.67	40	102	1.41	-0.27	0.95
Hirrhos Bridge (HB)	Nant Melin-y-grûg	3	SF9	13	4.058	251	0.038	2.91	34	100	1.28	0.11	1.23

Table 5.1 Bedload measurement site information.

For each sampling period, the total mass of bedload transported in each grain size class for the whole cross-section, Q_{bi}, was estimated by allocating representative sections of the active (unvegetated) streambed width to each trap on the basis of field observations over a range of discharges. For example, the following equation describes the calculation of B_i where four bedload traps have been deployed:

$$Q_{bi} = \frac{m_{i1}w_1}{w_i} + \frac{m_{i2}w_2}{w_i} + \frac{m_{i3}w_3}{w_i} + \frac{m_{i4}w_4}{w_i}$$

where, m_{i1} to m_{i4} = total bedload mass in the *i*th size class collected in trap 1-4, w_1 to w_4 = representative sections of streambed width for trap 1-4, and w_i = bedload trap width (0.4 m). Values of Q_{bi} for all size fractions were then summed to calculate the total bedload output for the site, Q_b, during the sampling period. Annual bedload yields at each monitoring site were calculated from these values and expressed as a function of subcatchment area, in units of t km^{-2} yr^{-1}.

5.2.2 Bedload transport dynamics

Relationships between time-integrated bedload yield data and streamflow-based indices designed to represent sediment transport potential were examined to investigate whether hydrological and/or sediment supply factors could explain spatial and temporal variation in coarse sediment transport in the headwater streams at Pontbren. This approach has been adopted in a number of studies of commercial forestry impacts on bedload yields in upland catchments (e.g. Werritty, 1984; Moore and Newson, 1986; Stott, 1997a; Stott *et al.*, 2001), with commonly tested parameters including maximum instantaneous discharge, total discharge above a pre-defined threshold of bedload transport initiation, and duration above the threshold discharge for bedload movement. The strength (or lack) of these relationships has been used to make inferences concerning the availability of sediment for transport. For example, Moore and Newson (1986) found that 60% of the variance in bedload yields in a forested catchment could be explained by a combination of these factors, compared with only 40% in a neighbouring grassland catchment. The difference was believed to reflect the greater importance of supply-limited conditions in the grassland catchment, where sediment capable of transport by the flow events encountered was less abundant due to the absence of ditches, which acted as sediment sources in the forested catchment. This conclusion has been supported more recently by Stott *et al*. (2001), who concluded that bedload yields were significantly lower in the grassland catchment despite it experiencing higher discharges.

However, while discharge is undoubtedly an important control of bedload transport (e.g. Barry *et al*., 2004), other factors such as stream gradient, channel width, bed material size, and the presence of large-scale roughness elements such as bedforms and large woody debris can also have significant effects (e.g. Bathurst *et al*., 1983; Bettess, 1984; Ashworth and Ferguson, 1989; MacFarlane and Wohl, 2003). Unless such factors are accounted for, conclusions regarding the influence of land management on bedload yields from sites where sediment transport potential is estimated on the basis of discharge alone must be treated with caution. For example, while the streams monitored by Stott *et al*. (2001) have similar dimensions and bed sediment characteristics (Billi, 1987), measurement site information provided by Kirby *et al*. (1991) indicate that the local gradient of the forested stream

(0.056) is much steeper than that of the paired grassland stream (0.021). This may contribute to, or provide an alternative explanation of, the higher rates of bedload transport observed in the forested stream.

To avoid this potential obstacle to accurate interpretation, this study uses bedload transport potential indices based on the concept of stream power. The term, initially proposed by Bagnold (1966), is defined as the rate of energy expenditure per unit length of channel and has been used in an increasing number of studies to evaluate bedload transport (Bagnold, 1977; 1980), predict channel adjustment (e.g. Knighton, 1999), and quantify incipient motion (e.g. Ferguson, 2005; Petit *et al*., 2005). Bedload transport equations based on stream power have performed well in comparative tests (e.g. Gomez and Church, 1999; Martin and Church, 2000) and are considered by many sediment transport specialists to be a conceptually attractive approach in that it treats rivers as transporting (and, therefore, work-performing) machines (Ferguson, 2005).

The representation of bedload transport potential using stream power-based indices is also pragmatic as they can be calculated from gross channel properties (width and slope) and discharge records without the need to know specific flow attributes such as velocity and depth (Ferguson, 2005). Expressed relative to stream bed area, specific stream power is defined by:

$$\omega = \frac{\rho g Q s}{w}$$

where, ω = specific stream power (W m^{-2}), ρ = density of water (approx. 1000 kg m^{-3}), g = acceleration due to gravity (9.81 m s^{-2}), Q = discharge (m^3 s^{-1}), s = slope (m m^{-1}), and w = water surface width (m). 15-minute averaged specific stream power values were calculated for each of the bedload monitoring sites by combining the discharge records from the streamflow gauges operated by Imperial College London/CEH Bangor with measured values of stream gradient and channel width. The most appropriate slope value for use in stream power calculations is the energy slope, but channel bed slope was used as an approximation for practical purposes. Bed slope was derived from bed elevations obtained by total station survey 5–10 channel widths upstream and downstream of bedload monitoring locations. The average active channel width over the same length of stream that was used to calculate bed slope was used to represent channel width. This was determined on the basis of field observations over a range of discharge conditions.

The following basic indices were generated for each bedload monitoring period using the calculated specific stream power values:

> ω_{max}: the maximum specific stream power recorded during the monitoring period (W m^{-2});
>
> E_{tot}: the total recorded flow energy (MJ) during the monitoring period, calculated by integrating 15-minute averaged stream power values over time.

Indices based on critical specific stream power values derived using bedload yield and particle size data were also generated in order to account for differences in grain and/or form roughness between sites (*c.f.* Ferguson, 2005; Petit *et al*., 2005). These included:

$E_{transport}$: the total excess energy (MJ) available to perform geomorphic work during the monitoring period, calculated using critical power values based on the power required to mobilise a small amount (1 kg) of bedload material;

$E_{particle}$: the total excess energy (MJ) available to perform geomorphic work during the monitoring period calculated using critical power values based on the power required to mobilise a 4 mm diameter particle (the minimum size recorded by the bedload traps used in this study);

$T_{transport}$: the total time (hours) critical power values required to mobilise a small amount (1 kg) of bedload material are exceeded in the monitoring period;

$T_{particle}$: the total time (hours) critical power values required to mobilise a 4 mm diameter particle are exceeded in the monitoring period.

The procedure and equations used to derive site-specific critical specific stream power values for the indices listed above are described in Section 5.3.2.

5.3 Results and analyses

5.3.1 Spatial and temporal variation in bedload yields from headwater streams in the Pontbren study area

Spatial variation in bedload yields at sampling points in headwater streams in the Pontbren study area was substantial (Table 5.2). Differences exceeding one order of magnitude were recorded between sites in the Upper Pontbren subcatchment, ranging from 0.018 t km^{-2} yr^{-1} at Cors-y-Carreg to 0.491 t km^{-2} yr^{-1} at Pont-bren-down, and yields increased with distance downstream. With the exception of the Cors-y-Carreg site near the source of the Nant Pen-y-cwm, estimated yields were higher at all bedload measurement locations in the Upper Pontbren subcatchment compared to the Upper Melin-y-grûg, suggesting that differences in land use and land management history may have an important influence. Yields at those sites most similar in terms of upstream drainage area in the two subcatchments (Sheepfold on the Nant Pen-y-cwm and Hirrhos Bridge on the Nant Melin-y-grûg) differed by a factor of 12.

Although the contrasts between subcatchments in the study area were large, bedload yield values recorded at Pontbren are relatively low in comparison to published bedload yields from other upland research catchments in the UK (Table 5.3). This could reflect a number of factors including the lack of significant hillslope sediment inputs and relatively gentle stream gradients at Pontbren in comparison to more mountainous, upland research sites, along with the wide variation in land use, climate, topography, and soils encompassed within the existing UK bedload yield data set (Stott, 1997a). Given the importance of high magnitude, low frequency flood events in upland sediment systems (*c.f.* Newson, 1980b), the length of

Bedload measurement site	Stream	Bedload output (t)			Bedload yield (t km^{-2} yr^{-1})		
		2006/07	**2007/08**	**Total**	**2006/07**	**2007/08**	**Mean**
Pant Powsi (PP)	Nant Pant Powsi	0.015	0.051	0.033	0.051	0.176	0.113
Cors-y-Carreg (CYC)	Nant Pen-y-cwm	0.014	0.032	0.046	0.011	0.025	0.018
New Bridge (NB)	Nant Pen-y-cwm	0.133	0.172	0.304	0.056	0.072	0.064
Sheepfold (SHP)	Nant Pen-y-cwm	0.999	1.290	2.290	0.316	0.408	0.362
Pont-bren-down (PBD)	Nant Pont-bren-down	2.833	N/A	N/A	0.491	N/A	N/A
Hirrhos Bridge (HB)	Nant Melin-y-grûg	0.056	0.190	0.245	0.014	0.047	0.030

Table 5.2 Bedload yields from headwater subcatchments in the Pontbren study area. Note: 2007/08 bedload data for Pont-bren-down site missing due to damage sustained by traps during high flow events in summer 2007 and winter 2007/08.

Land use and location	Study	Catchment area (km^2)	Bedload yield ($t\ km^{-2}\ a^{-1}$)	Comments
Improved grassland				
PP, Pontbren	Henshaw (this thesis)	0.29	0.11	Bedload coarser than 4 mm.
CYC, Pontbren		1.29	0.02	Bedload coarser than 4 mm.
NB, Pontbren		2.39	0.06	Bedload coarser than 4 mm.
SHP, Pontbren		3.17	0.36	Bedload coarser than 4 mm.
PBD, Pontbren		5.77	0.49	Bedload coarser than 4 mm.
Moorland/rough pasture				
HB, Pontbren	Henshaw (this thesis)	4.06	0.03	Bedload coarser than 4 mm.
Maesnant, Plynlimon	Lewin *et al*. (1974)	0.54	3.70	
Nant Iago, Plynlimon	Lewin and Wolfenden (1978)	1.02	1.47	Bedload coarser than 2 mm.
Cyff, Plynlimon	Newson (1980a)	3.13	7.80	Figures incorporate large flood event.
	Stott *et al*. (2001)		0.91	
M1-M3, Balquhidder	Stott (1997a)	0.24-0.55	0.90-5.93	Bedload coarser than 2.8 mm.
Mature forest				
Tanllwyth, Plynlimon	Newson (1980a)	0.89	29.05	
	Leeks (1992)		38.40	
	Stott *et al*. (2001)		8.68	
Hore, Plynlimon	Leeks (1992)	3.08	11.80	
K1-K12, Balquhidder	Stott (1997a)	0.16-1.23	0.33-25.26	Bedload coarser than 2.8 mm.

Table 5.3 Published bedload yield data from UK research catchments with different land uses.

monitoring period is also likely to have a strong influence on sediment yield values, with those records which incorporate such events (e.g. Newson, 1980a) likely to be disproportionately influenced for long periods of time after those events. Differences in measurement techniques are also likely to result in substantial differences in calculated bedload yields between studies.

Data from the bedload measurement site on the instrumented agricultural drainage ditch at Pant Powsi indicate that 33 kg of coarse sediment was transferred into the Nant Pen-y-cwm from the source during the monitoring period. Although relatively small in absolute terms, the bedload yield of the ditch is greater than all measurement sites except Sheepfold and Pont-bren-down when normalised by drainage area. Given the spatial extent of drainage undertaken for pasture improvement in the Upper Pontbren subcatchment, it is plausible that agricultural ditches may represent an important source of coarse sediment for the Nant Pen-y-cwm, Nant Gelli-Gethin and Nant Pont-bren-down.

Examination of time-integrated bedload trap data (Figure 5.4a-f) reveals that the incidence of coarse sediment transport varied considerably between measurement sites. Bedload material was recorded in traps at New Bridge and Sheepfold on the Nant Pen-y-cwm on 30% and 34% of site visits, respectively, during the monitoring period, compared to just 12% at Cors-y-Carreg. Bedload transport occurred less frequently in the Nant Melin-y-grûg (trapped material recovered on 19% of visits to Hirrhos Bridge) than at any other site in the Upper Pontbren subcatchment, and coarse sediment was found to have been exported from the instrumented agricultural drainage ditch at Pant Powsi during 24% of the measurement periods. The majority of bedload transport occurred during winter months (December-

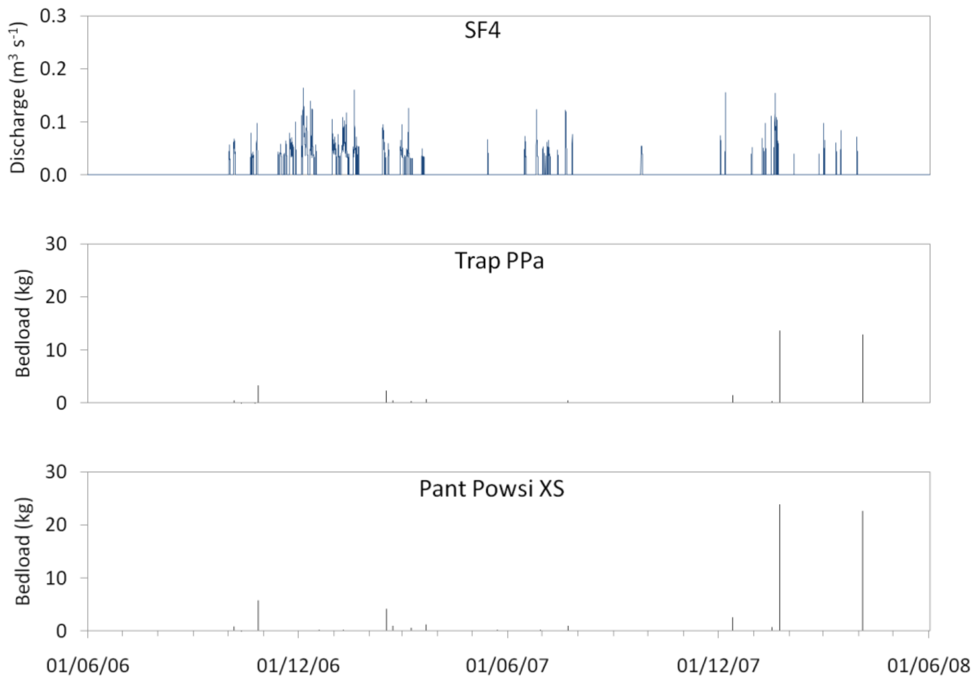


Figure 5.4a Temporal variation in discharge and bedload transport at Pant Powsi bedload measurement site.

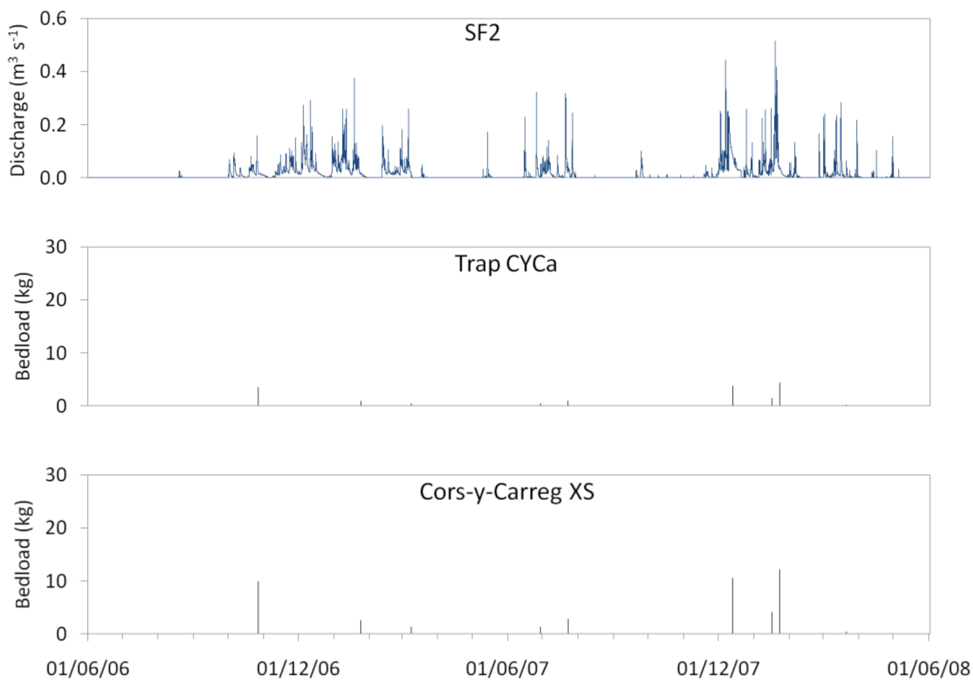


Figure 5.4b Temporal variation in discharge and bedload transport at Cors-y-Carreg bedload measurement site.

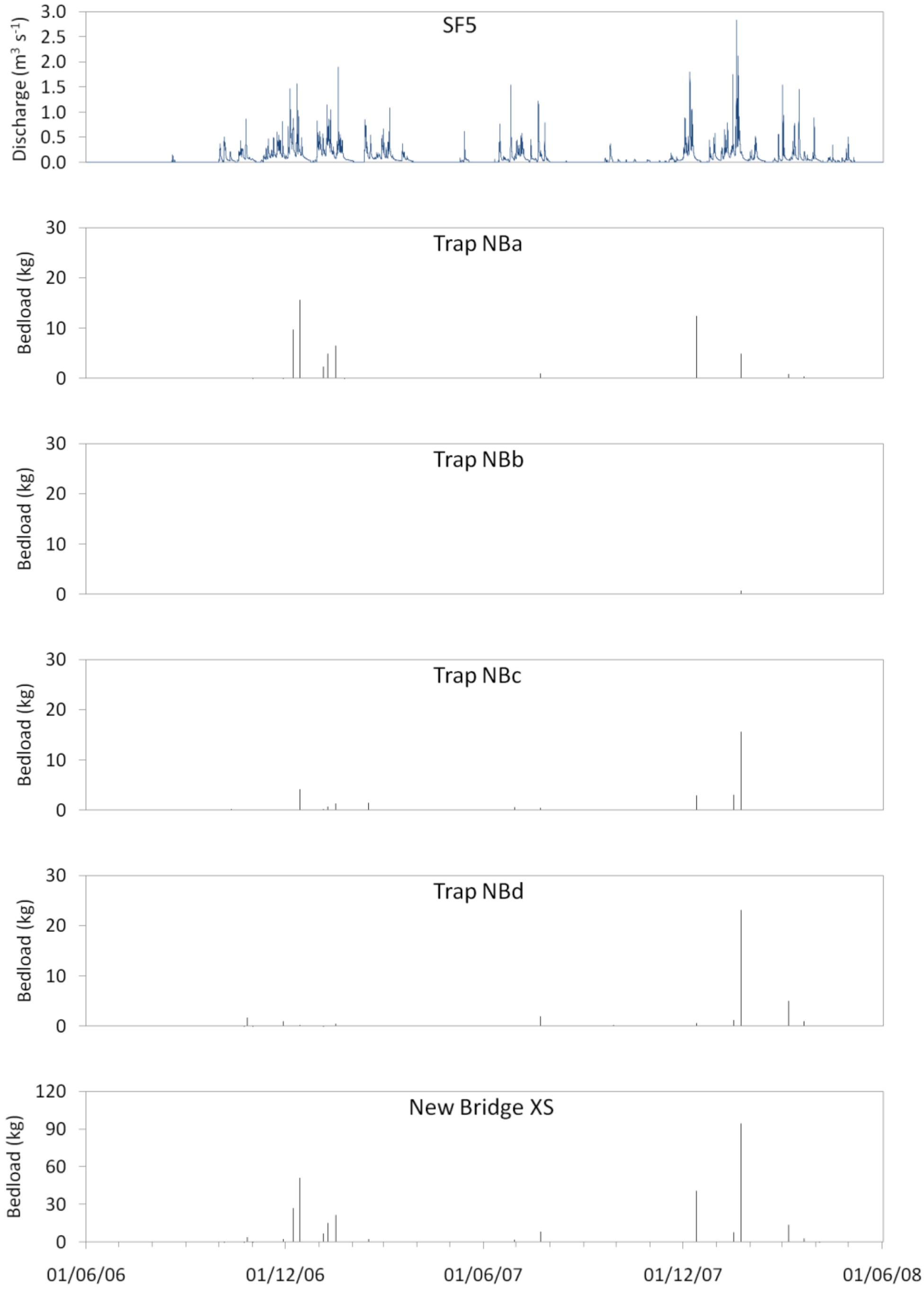


Figure 5.4c Temporal variation in discharge and bedload transport at New Bridge bedload measurement site.

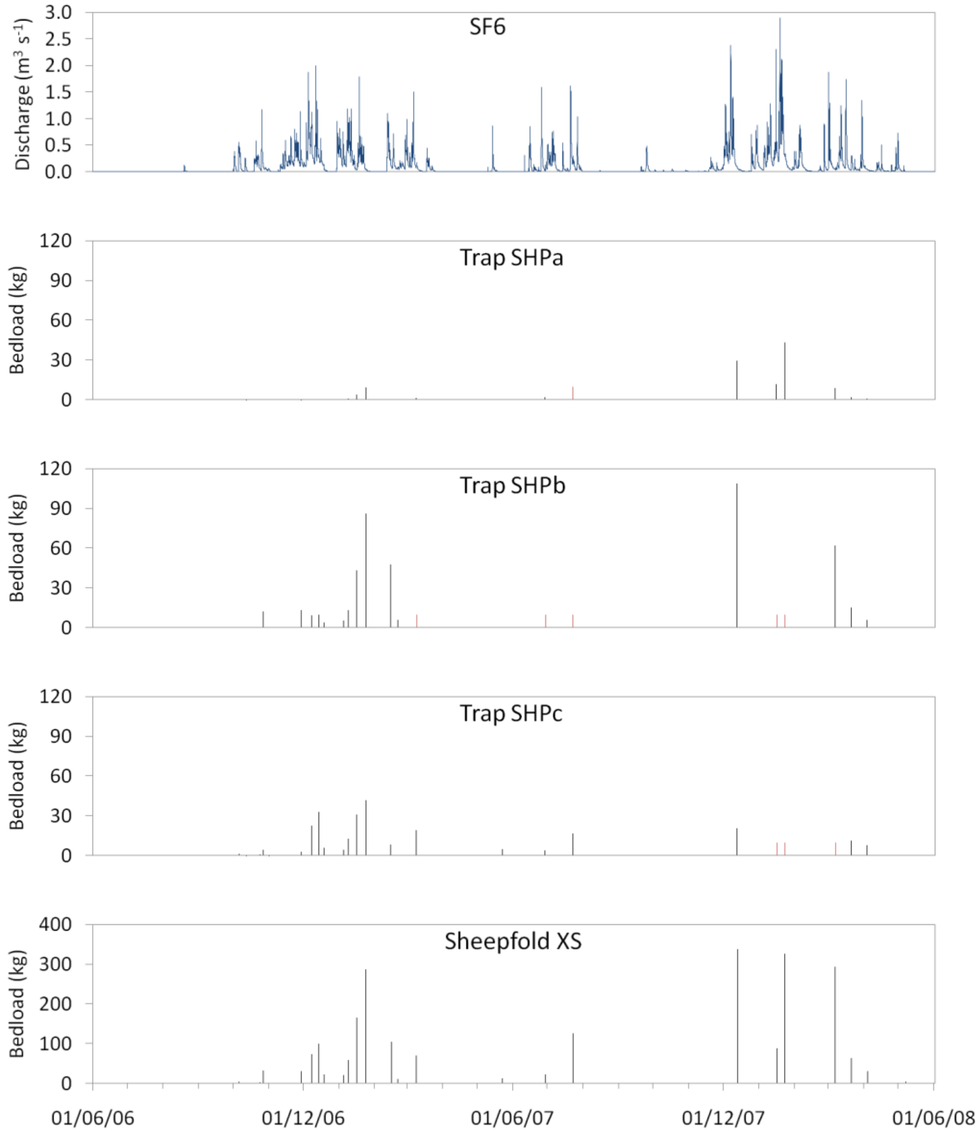


Figure 5.4d Temporal variation in discharge and bedload transport at Sheepfold bedload measurement site. Red lines indicate trap failure.

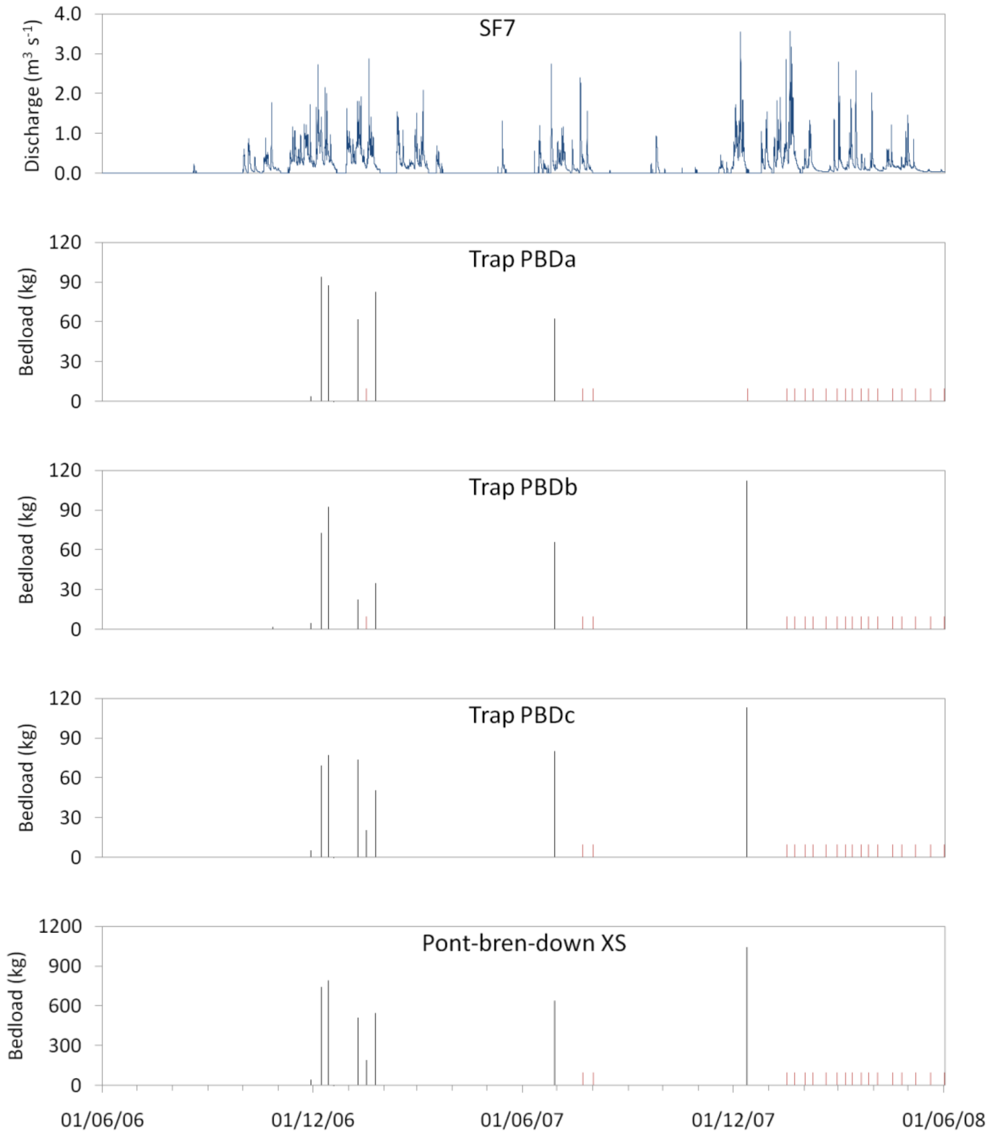


Figure 5.4e Temporal variation in discharge and bedload transport at Pont-bren-down bedload measurement site. Red lines indicate trap failure.

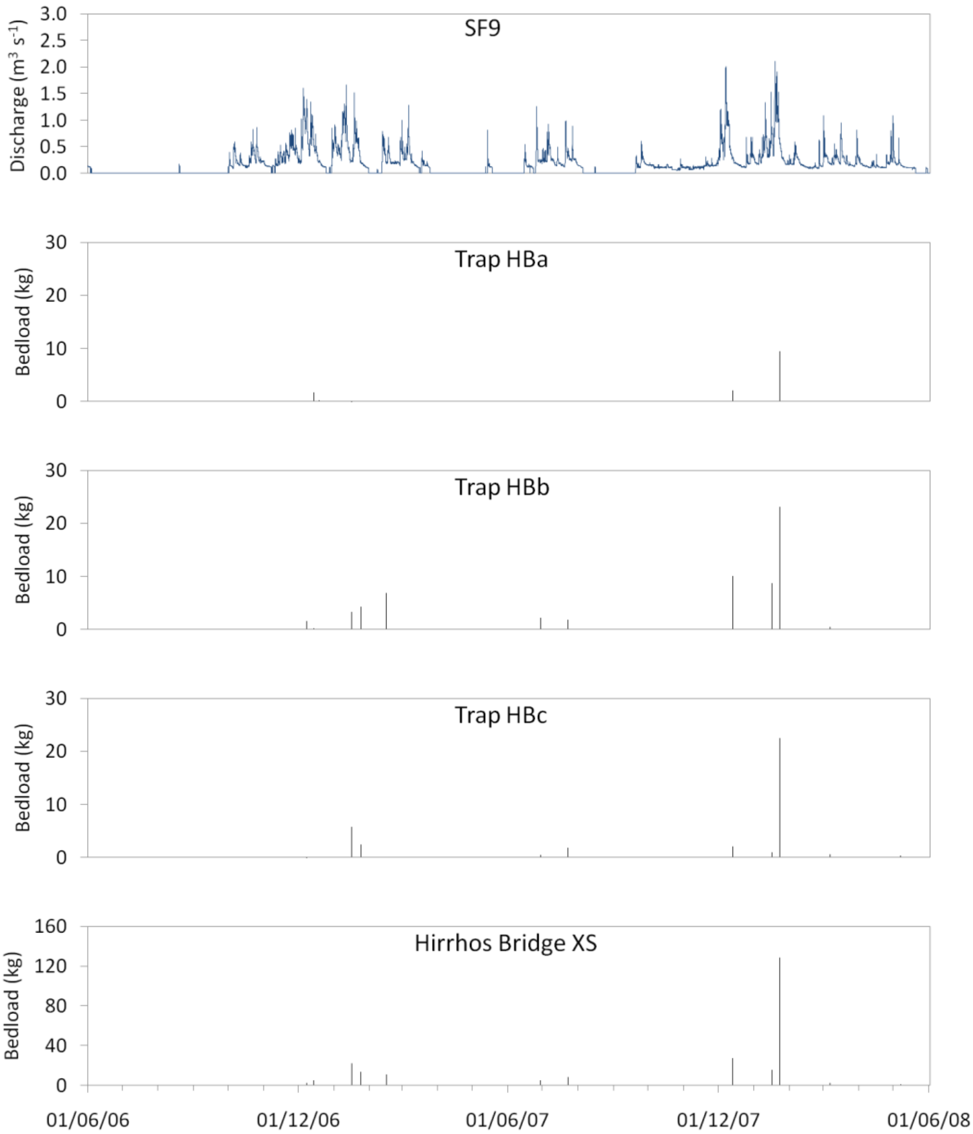


Figure 5.4f Temporal variation in discharge and bedload transport at Hirrhos Bridge bedload measurement site.

February), with coarse sediment trapped during the season accounting for between 51% and 98% of the total yield at each site.

A strong association between flood peaks in the stream discharge records and temporal changes in bedload yields was evident at the majority of measurement sites in the Pontbren study area (Figure 5.4 a-f). The largest estimated cross-sectional bedload yields at each measurement site during any single sampling period ranged from approximately 12 kg at Cors-y-Carreg to 1042 kg at Pont-bren-down, and occurred between either 5-13 December 2007 or 16-23 January 2008. These periods coincided with the two largest flood events recorded during the study on 6 December 2007 (peak discharge at SF7 = 3.568 $m^3 s^{-1}$) and 18 January 2008 (peak discharge at SF7 = 3.577 $m^3 s^{-1}$), and correspondence between substantial levels of bedload transport and other, smaller, high flow events during winter 2006/07 and summer 2007 can be visually identified. These links are explored further in Section 5.3.2.

The bedload trap data also indicate that the level of cross-sectional variation in coarse sediment transport differs widely between measurement sites (Table 5.4). Bedload transport was distributed relatively evenly across the monitored cross-section at Pont-bren-down, with material from traps A-C accounting for 38%, 28%, and 34% of the total sediment collected, respectively. However, this pattern was not observed at other sites where multiple traps were deployed. The majority of sediment trapped at Sheepfold and Hirrhos Bridge (59% and 67%, respectively) was recovered from traps located in the centre of the stream channels. In contrast, the trap nearest to the left bank (trap A) at New Bridge collected substantially more bedload (46%) than the two central traps (traps B and C), which amassed 1% and

Bedload measurement site	Total bedload trapped between 01/06/06 and 31/05/08 (kg)				Percentage of total trapped bedload (%)			
	Trap A	Trap B	Trap C	Trap D	Trap A	Trap B	Trap C	Trap D
Pant Powsi (PP)	37.6	-	-	-	100	-	-	-
Cors-y-Carreg (CYC)	16.6	-	-	-	100	-	-	-
New Bridge (NB)	59.5	0.9	31.1	37.5	46.1	0.7	24.1	29.0
Sheepfold (SHP)	47.3	381.8	216.6	-	7.3	59.1	33.5	-
Pont-bren-down (PBD)	391.9	296.1	357.0	-	37.5	28.3	34.2	-
Hirrhos Bridge (HB)	4.2	39.7	15.3	-	7.1	67.1	25.8	-

Table 5.4 Cross-stream variation in bedload yields at bedload measurement sites in the Pontbren study area.

24% of the total yield at that site, respectively. Such lateral variation has been observed in a number of other studies of bedload transport (e.g. Warburton, 1992; Stott, 2002) and could be caused by local differences in bed shear stresses leading to the occurrence of 'ribbons' of bedload material moving across an otherwise largely immobile bed.

5.3.2 Relationships between specific stream power-based indices of bedload transport potential and bedload yields from headwater streams in the Pontbren study area

Figure 5.5 shows relationships between maximum specific stream power and bedload yield at measurement sites in the Pontbren study area. Power functions fitted to data from the New Bridge, Sheepfold, Pont-bren-down and Hirrhos Bridge sites explained between 50-78% of the observed variance and were all significant to the 1% level, confirming the importance of high flow events in controlling bedload transport. Maximum specific stream powers required to mobilise coarse sediment in the Nant Melin-y-grûg were much greater than those at comparable sites in the Upper Pontbren subcatchment, and data from the Hirrhos Bridge site displayed considerable scatter. No statistically significant relationship was evident between maximum specific stream power and bedload yield at either the instrumented agricultural drainage ditch at Pant Powsi or Cors-y-Carreg in the upper reaches of the Nant Pen-y-cwm. Although ω_{max} proved relatively successful at describing bedload yields at the majority of sites, scatter in the relationships is likely to result from factors such as the occurrence of multiple flood events during individual monitoring periods and does not truly represent the overall power exerted on the bed.

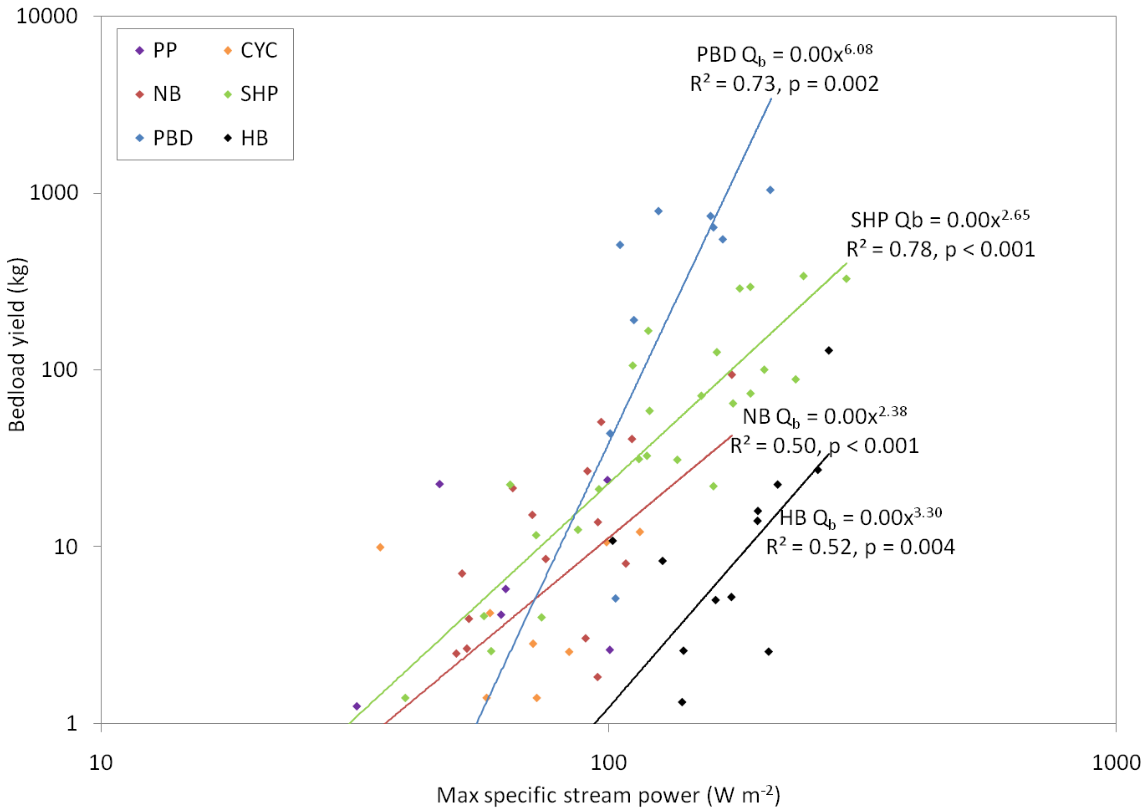


Figure 5.5 Relationship between maximum specific stream power and bedload yield at measurement sites in the Pontbren study area.

Associations between total energy and bedload transport were considerably weaker, explaining between 32-61% of the observed variance in yields at New Bridge, Sheepfold, Pont-bren-down and Hirrhos Bridge, while no significant relationship could again be identified at either Pant Powsi or Cors-y-Carreg (Figure 5.6). As with maximum specific stream power, total energy explained the lowest amount of variance at the Hirrhos Bridge site on the Nant Melin-y-grûg, while the highest R^2 value was generated at Sheepfold on the Nant Pen-y-cwm. However, it should be noted that only a small fraction of the energy expended by a river is used to transport sediment. In fact, most potential and kinetic energy is lost through friction with the bed and in-channel objects such as vegetation and evaporation (Evans et al., 1998), thereby reducing the amount of available excess energy to perform geomorphological work and this may explain the relative weakness of relationships between E_{tot} and bedload yield.

As discussed in Section 5.2.2, additional bedload transport potential indices based on critical specific stream power threshold values ($E_{transport}$, $E_{particle}$, $T_{transport}$, and $T_{particle}$) were calculated to address this issue using bedload yield and size data. Following procedures outlined by Bunte *et al*. (2004), two different specific stream power threshold values were calculated for each bedload measurement site:

(1) the critical power required to mobilise 1 kg of sediment coarser than 4 mm; and

(2) the critical power required to mobilise a particle with a diameter of 4 mm.

Power functions were fitted to bedload yield and maximum specific stream power data from New Bridge, Sheepfold, Pont-bren-down and Hirrhos Bridge (Figure 5.7),

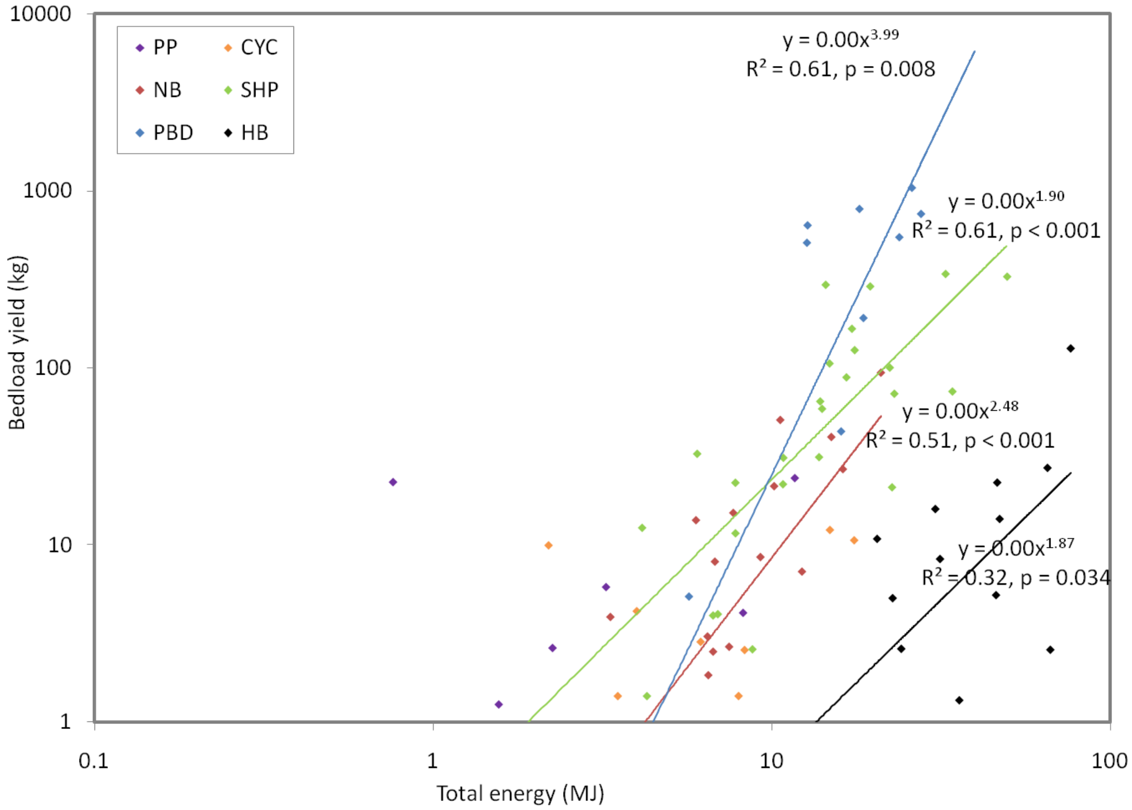


Figure 5.6 Relationship between total energy and bedload yield at measurement sites in the Pontbren study area.

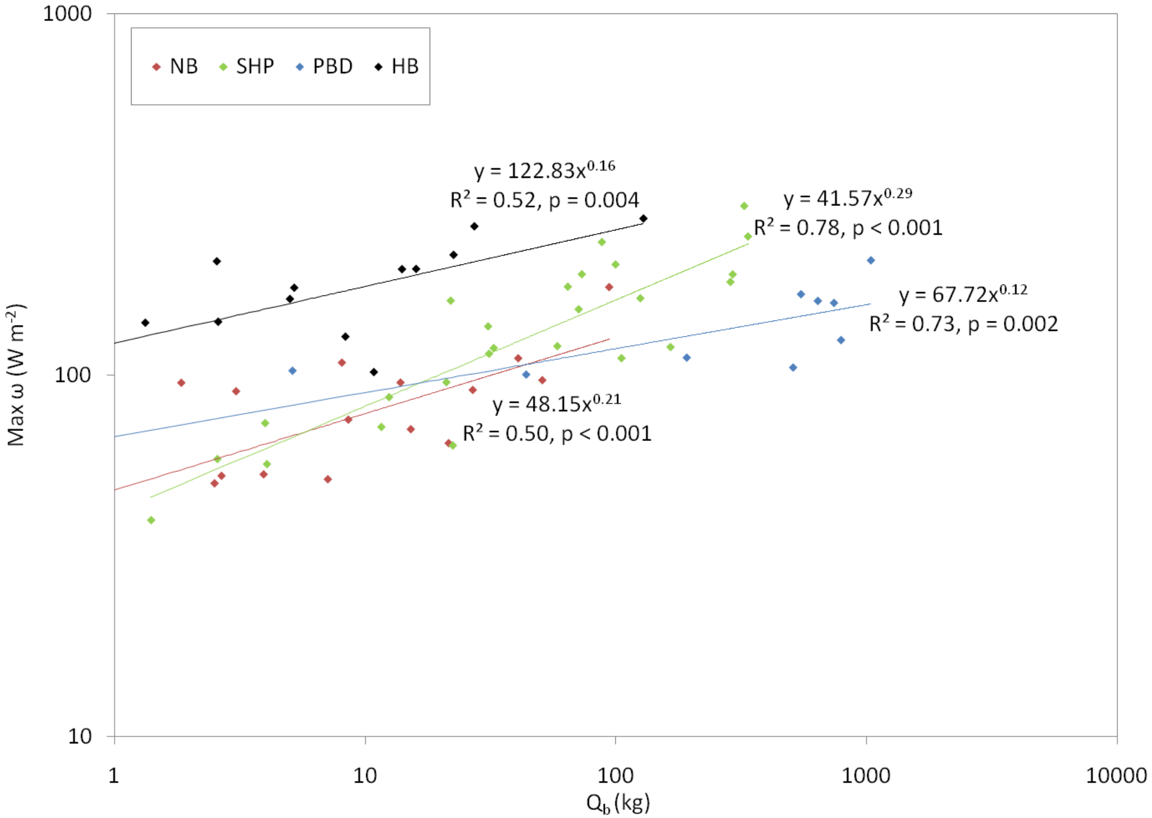


Figure 5.7 Relationships between bedload yield and maximum specific stream power at NB, SHP, PBD and HB measurement sites.

and the resulting equations used to calculate (1). Critical power threshold (2) was estimated using equations describing regression lines fitted through bedload D_{95} data against maximum specific stream power (Figure 5.8).

The critical specific stream power-based indices were much more successful at describing variation in bedload yield data than total energy and, on occasions, out-performed maximum specific stream power as explanatory variables (Figures 5.9-5.12). However, despite their obvious conceptual strength, no single index consistently explained the most variation. For example, a linear function of $T_{transport}$ explained the highest amount of the variance observed at New Bridge, but power functions of $E_{particle}$ accounted for the most bedload yield variation at Sheepfold and Pont-bren-down, respectively. At Hirrhos Bridge on the Nant Melin-y-grûg, a linear function of $E_{transport}$ was most successful. As with both ω_{max} and E_{tot} however, higher values of critical specific stream power-based indices tended to be required in order to transport a given amount of bedload material at Hirrhos Bridge in comparison to sites in the Upper Pontbren subcatchment.

Comparisons between the aggregated totals of the various indices of bedload transport potential calculated for each measurement site and annualised bedload yields also suggest that hydrological/hydraulic factors are not the only controls of catchment sediment outputs (Table 5.5). With the exception of the value calculated on the basis of $T_{particle}$, all representations of total bedload transport potential at New Bridge on the Nant Pen-y-cwm were lower than those at Hirrhos Bridge on the Nant Melin-y-grûg. Despite this, bedload yields at New Bridge were twice as high as those at Hirrhos Bridge. Similarly, total bedload transport potential at Pont-bren-down calculated *via* all methods apart from $T_{particle}$ was similar or only marginally

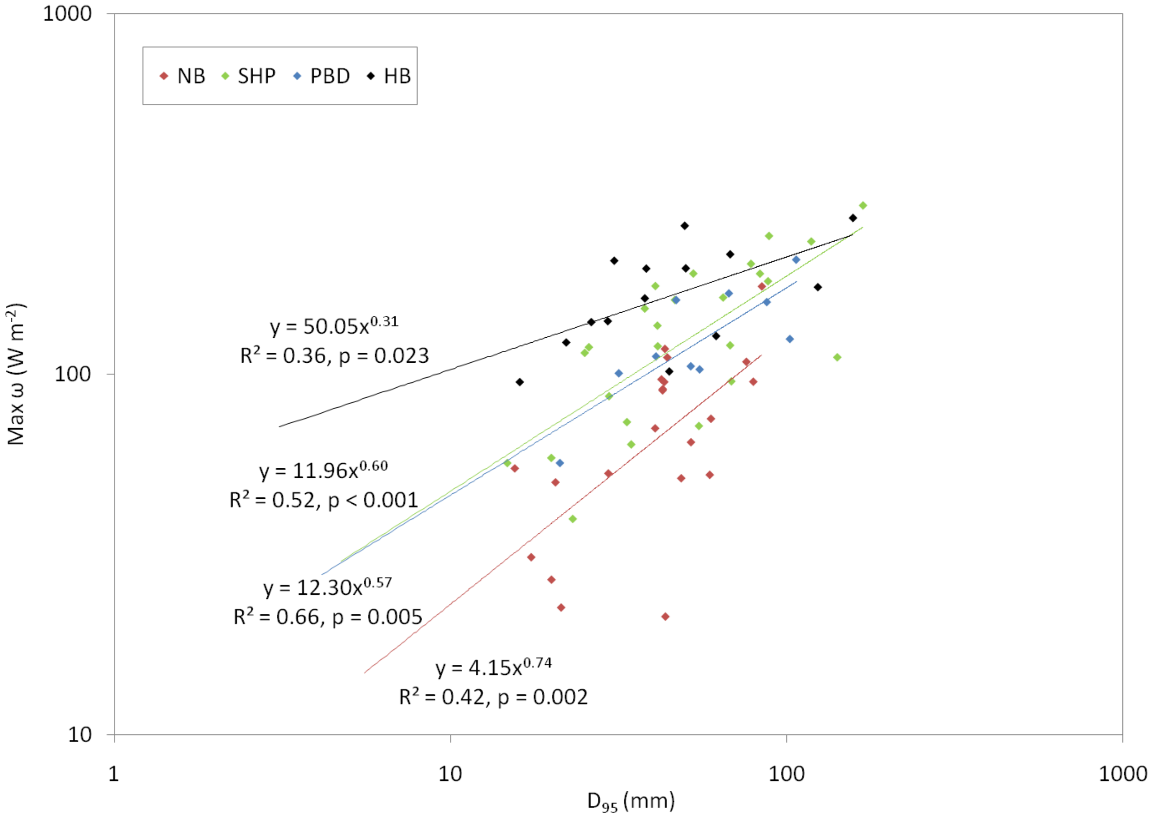


Figure 5.8 Relationships between bedload D_{95} and maximum specific stream power at NB, SHP, PBD and HB measurement sites.

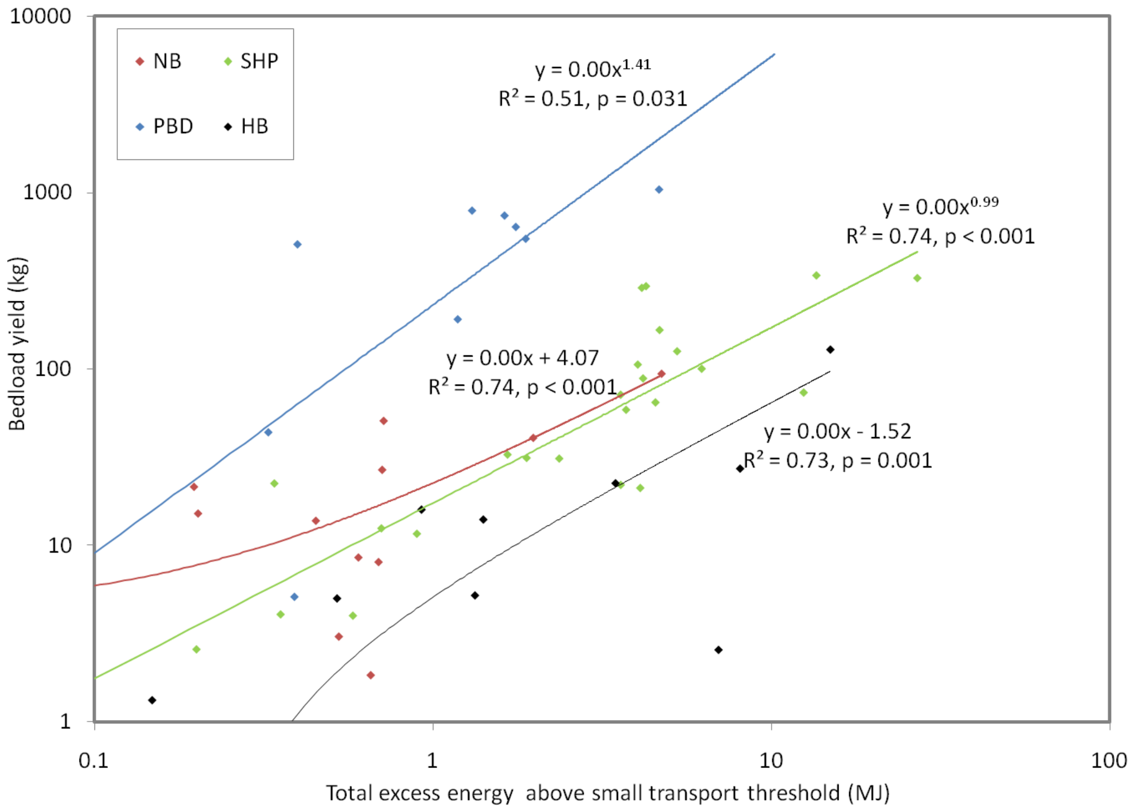


Figure 5.9 Relationships between total excess energy above the small bedload transport power threshold and bedload yield at NB, SHP, PBD and HB.

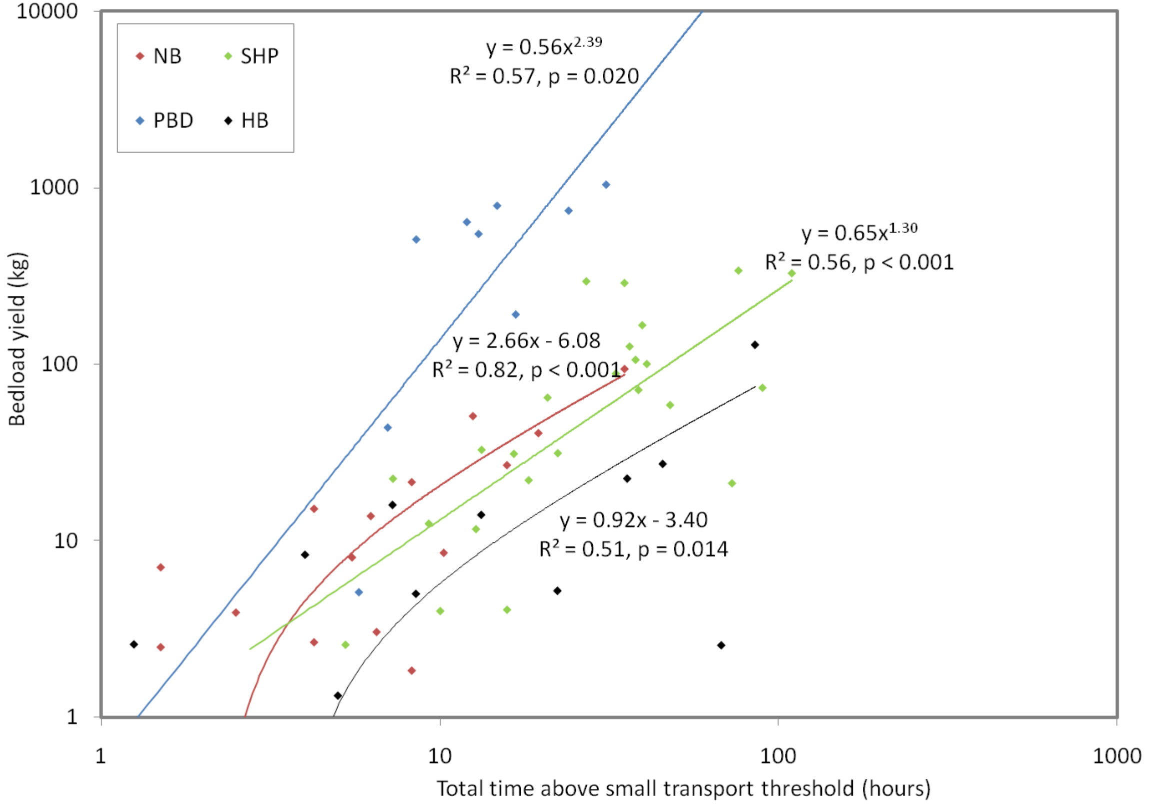


Figure 5.10 Relationships between total time above the small bedload transport power threshold and bedload yield at NB, SHP, PBD and HB.

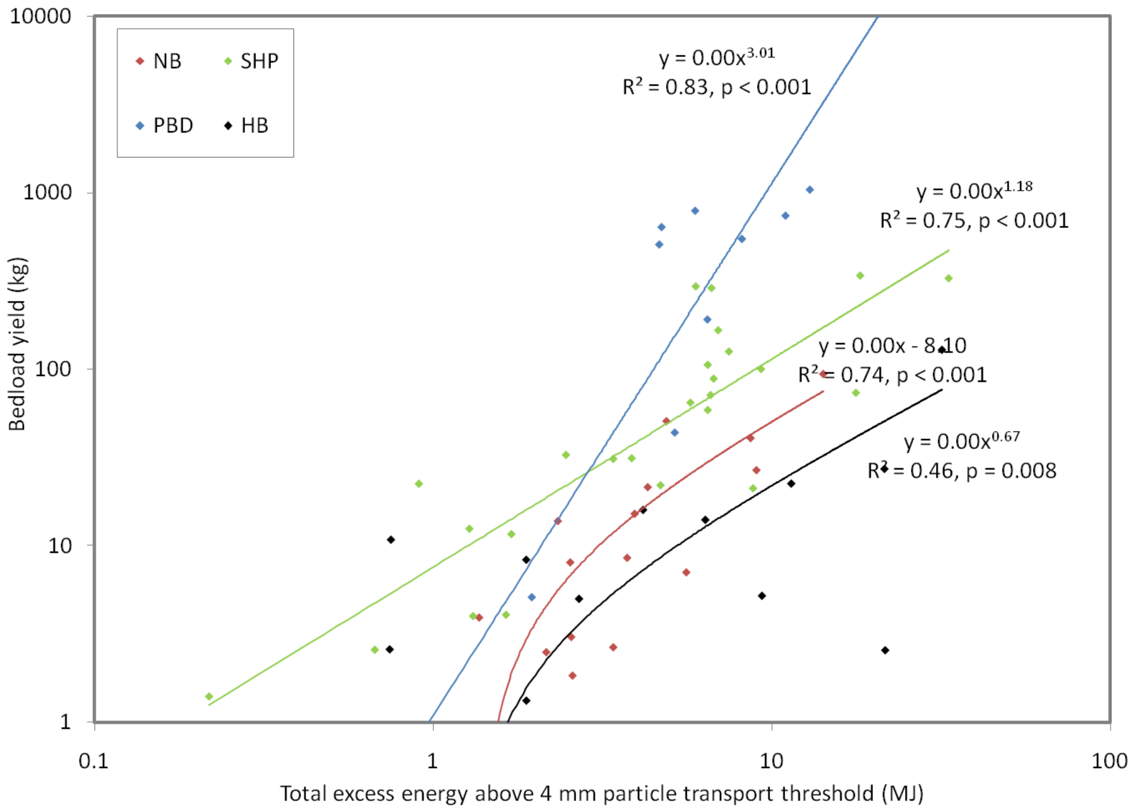


Figure 5.11 Relationships between total excess energy above the 4mm particle transport power threshold and bedload yield at NB, SHP, PBD and HB.

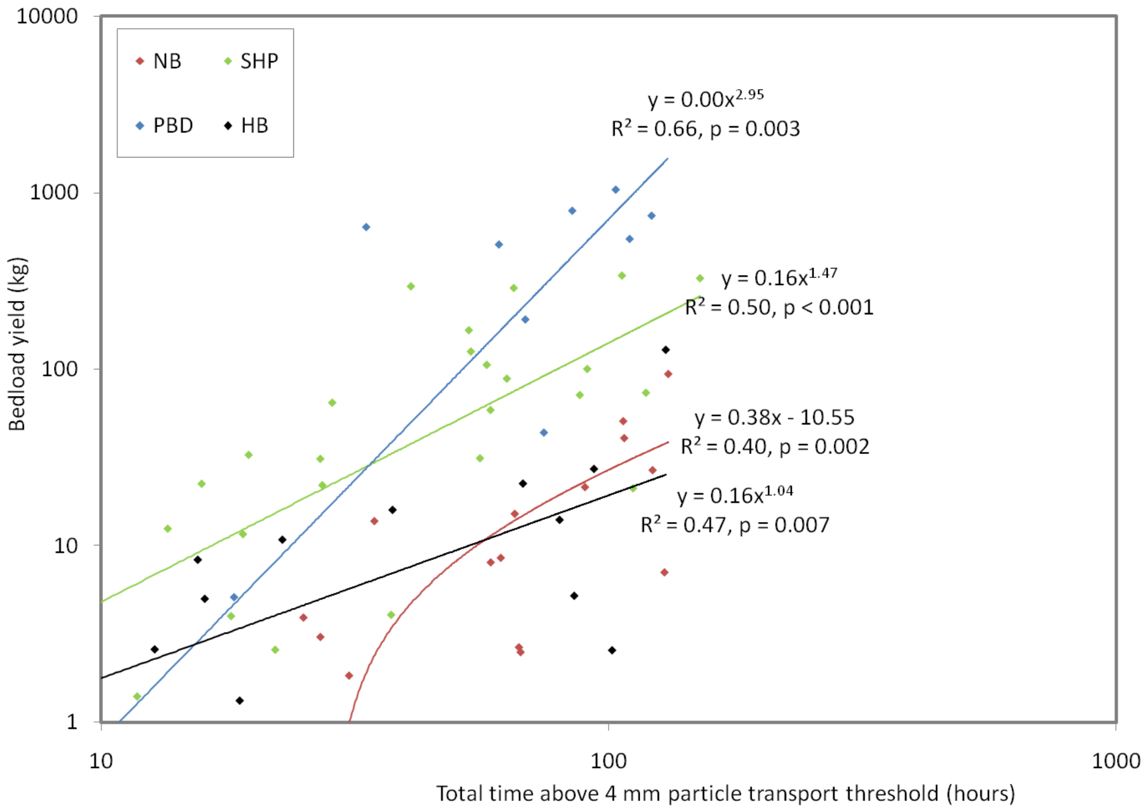


Figure 5.12 Relationships between total time above the 4mm particle transport power threshold and bedload yield at NB, SHP, PBD and HB.

Bedload transport potential index	Bedload measurement site				Ratio between site and HB		
	NB	**SHP**	**PBD**	**HB**	**NB**	**SHP**	**PBD**
E_{tot}: Total energy (MJ)	303	602	621	1423	0.2	0.4	0.4
$E_{transport}$: Total excess energy above small transport threshold (MJ)	13	136	35	40	0.3	3.4	0.9
$E_{particle}$: Total excess energy above 4 mm particle transport threshold (MJ)	106	216	178	141	0.8	1.5	1.3
$T_{transport}$: Total time above small transport threshold (hours)	160	1181	344	331	0.5	3.6	1.0
$T_{particle}$: Total time above 4 mm particle transport threshold (hours)	2172	1995	2114	1046	2.0	1.9	2.0
Bedload yield (t km^{-2} yr^{-1})	0.064	0.362	0.491	0.030	2.1	12.0	16.4

Table 5.5 Comparison of bedload yields and indices of bedload transport potential between NB, SHP, PBD and HB measurement sites.

higher than at Hirrhos Bridge, yet bedload yields differed by a factor of 16. Calculations using indices based on critical specific stream power do suggest that bedload transport potential at Sheepfold on the Nant Pen-y-cwm is likely to be considerably higher than at Hirrhos Bridge. Nevertheless, differences in energy available to perform geomorphological work between the sites (1.5-3.6 times greater at Sheepfold) are much lower than the differences in observed bedload yields (12x greater at Sheepfold).

5.3.3 Influence of sediment supply on bedload yields from headwater streams in the Pontbren study area

The limited ability of parameters representing bedload transport potential to explain the observed spatial and temporal variation in bedload yields in the Pontbren study area suggests that differences in sediment supply conditions between sites may also be significant. Bedload yield data from the Pant Powsi measurement site indicates that, when assessed proportionally in terms of the contributing drainage area, agricultural drainage ditches can supply large amounts of coarse sediment to streams and this may contribute to the higher bedload yields observed in the Upper Pontbren subcatchment, where grassland improvement has been much more extensive than in the Upper Melin-y-grûg. The importance of ditches as sources of coarse sediment may actually be even greater than is indicated by the data reported in this thesis. Observations made after the doctoral study period, prior to and following a large flood event in October 2008, revealed that a number of drainage ditches were heavily eroded as knickpoints migrated upstream from the natural stream channels to which they are tributaries. Estimated sediment losses during this single event were at some of these sites estimated to exceed 2 m^3 of material, of which a large proportion consisted of particles coarser than 4 mm, thus greatly surpassing yields from the instrumented ditch at Pant Powsi. Nevertheless, information from local farmers at Pontbren indicates that geomorphological activity varies considerably between ditches, and that slope, vegetation and the maintenance regime of individual ditches are all likely to strongly influence the amount of coarse sediment transferred to stream channels downstream. It is, therefore, unlikely that the presence of agricultural drainage ditches alone can explain the occurrence of higher bedload yields at sites in the Upper Pontbren subcatchment.

In fact, the supply of sediment from eroding banks in the Upper Pontbren subcatchment is likely to represent the source of the majority of the elevated bedload yield observed at the New Bridge, Sheepfold and Pont-bren-down sites. Figure 5.13 compares seasonal variation in bank sediment yields, calculated using data documented in Chapter 4, with bedload outputs at instrumented cross-sections over the same time periods. Calculation of Pearson product-moment correlation coefficients between seasonal bank and stream coarse sediment yields revealed statistically significant associations at New Bridge ($p = 0.002$), Sheepfold ($p < 0.001$) and Pont-bren-down ($p = 0.011$), while no significant relationships were evident at Cors-y-Carreg, Pant Powsi or Hirrhos Bridge. Field reconnaissance revealed the limited extent of active bank erosion upstream of those sites (see Chapter 2); supporting the conclusion that the sediment supply from bank erosion is more limited there. Bedload transport under such conditions is only likely to occur during low-frequency, high-magnitude events; characteristics typical of undisturbed upland streams in the UK (Newson, 1982). Conversely, the majority of banks identified as

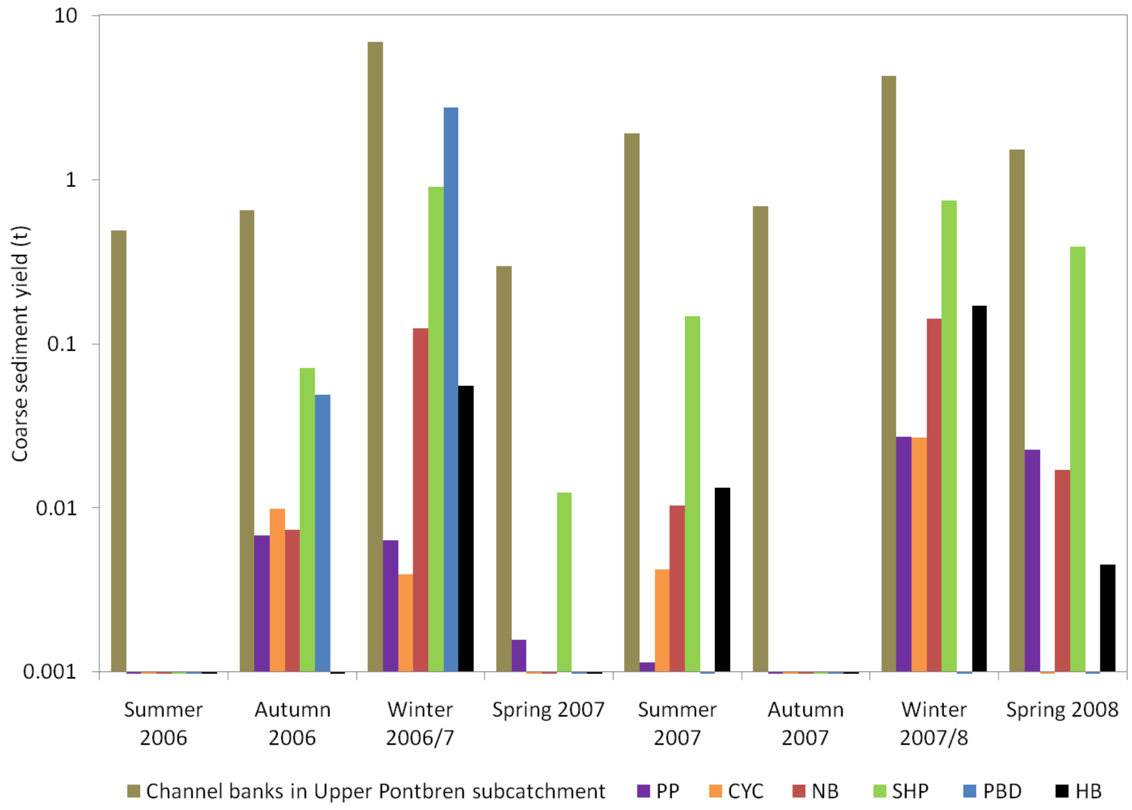


Figure 5.13 Comparison of seasonal variation in sediment supply from eroding bank sources in the Upper Pontbren subcatchment and bedload outputs at stream sediment yield measurement sites. Note: bedload transport data from Pont-bren-down is not reported during Summer 2007, Winter 2007/8 and Spring 2008 due to trap failure.

being geomorphologically active during the study were located in reaches of the Nant Pen-y-cwm immediately upstream of New Bridge and Sheepfold, and along the Nant Gelli-Gethin upstream of Pont-bren-down. The quantity of coarse sediment transferred to streams from these eroding bank sources was considerably larger than the amount exported from the sub-catchment as bedload material, indicating that an abundance of easily-mobilised coarse sediment was available for transport at those sites throughout the study period. This conclusion is supported by the fact that the vast majority of bedload transport observed during the study period could be described as 'Phase 1' type (*c.f.* Jackson and Beschta, 1981), whereby particles pass over the surface of an intact, armoured bed. This is highlighted in Figure 5.14, which shows that bedload particles tended to be finer than those which comprised the bed material, indicating that transport was thus size-selective under all but the most extreme flow conditions at all measurement sites (*c.f.* Ashworth *et al*., 1992; Lisle, 1995; Wathern *et al*., 1995).

5.4 Discussion: the influence of historical land use changes and land management on bedload yields from headwater streams in the Pontbren study area

Data and analyses presented in this chapter indicate that differences in peak flows between streams in the Upper Pontbren and Upper Melin-y-grûg subcatchments cannot, alone, explain the observed spatial and temporal variation in bedload yields, and that disparities in sediment supply conditions between sites are also likely to be highly significant. The supply of greater quantities of coarse sediment to streams in the Upper Pontbren subcatchment compared to the upper reaches of the Nant Melin-y-grûg can, in part, be linked directly to the presence of drainage ditches

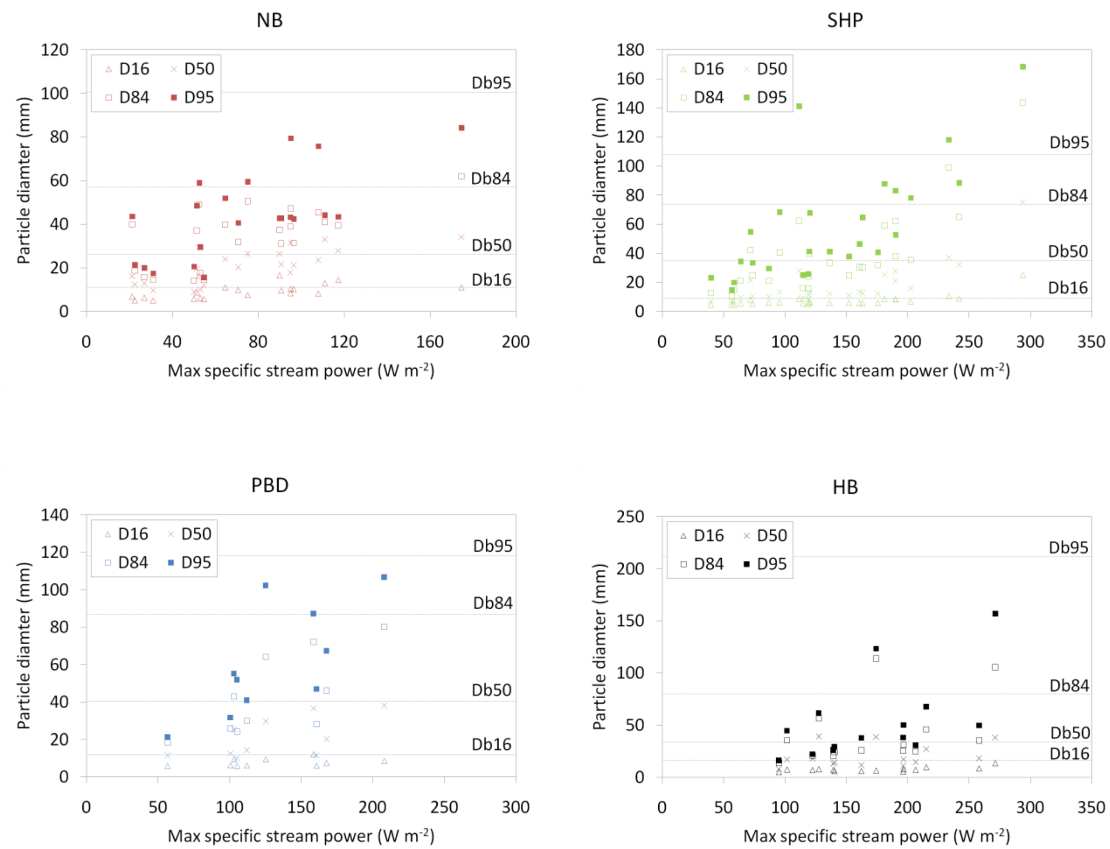


Figure 5.14 Comparison between bedload and bed material particle size percentiles for events of increasing magnitude at NB, SHP, PBD, and HB.

installed to facilitate grassland improvement and, thus, increase livestock grazing and productivity. However, it is believed that the majority of the excess coarse sediment comes from eroding channel banks on the basis of results presented in Chapter 4, and the existence and activity of this sediment source may also be linked to historical changes in land use albeit in an indirect manner through their impacts on catchment hydrology.

Recent hydrological research by Imperial College London/CEH Bangor has shown that the creation of tree shelterbelts and restoration of woodlands and hedgerows as part of the recent Pontbren Rural Care Project has had significant impacts on the properties of underlying soils (Marshall *et al*., 2009; Wheater *et al*., 2008). For example, soil dry bulk densities (ρ_b) were found to be significantly lower in the A horizon of soils within planted areas compared to those at improved grassland sampling sites. Marshall *et al*. (2009) speculate that reduced compaction due to the exclusion of livestock, increased levels of organic matter and/or the decay of old tree roots are contributing to the lower bulk densities observed in soils within shelter belts and restored woodlands. Tests have also confirmed that the mean air capacity (ϑ) of soils in areas planted with trees is significantly higher than in soils under improved grassland, indicating that a greater amount of pore space is likely to be available for infiltrating rain water and/or overland flow (Marshall *et al*., 2009).

Significantly higher saturated hydraulic conductivity values were recorded in the A horizon of soils in tree planted areas (median K_{sat} = 8.34 m d^{-1}, n = 5) compared to those within grazed pastures (median K_{sat} = 3.43 m d^{-1}, n = 13) and the results imply that these factors may allow water to move more freely through the soil (Wheater *et al*., 2008). Staining patterns of dye applied to the ground surface within shelterbelts at Pontbren indicate that water moves preferentially along living roots beneath tree shelterbelts and can be transferred to substantial depths within the soil (Wheater *et al*., 2008). Birch (*Betula* spp.) roots were observed to aid the movement of water from the surface to a depth of 0.45 m, while root systems beneath ash (*Fraxinus excelsior*) trees encourage the transmission of water to a depth of 0.65 m. Interestingly, water appears to favour tree root pathways over other macropores such as cracks and earthworm burrows (Wheater *et al*., 2008).

These findings are supported by data from neutron probes positioned along a transect running through the Half Moon shelterbelt. These data suggest that soils within planted tree areas are drier compared to those beneath grazed pastures, increasing their capacity for soil moisture storage (Wheater *et al*., 2008). Soils downslope of shelterbelts are also drier in comparison to soils on the upslope side (Wheater *et al*., 2008). Overland flow rates have been found to be substantially lower within shelterbelts at Pontbren compared to improved pastures as a result (Marshall *et al*., 2009).

The effect of tree planting on runoff generation within improved pastures has been evaluated through high-resolution simulations using a physically-based hillslope model (Jackson *et al*., 2008). Figure 5.15 shows predicted drain flow, overland flow and total runoff from a 100 m x 100 m improved pasture with a slope of 0.05 (representative of the average slope in the Upper Pontbren subcatchment) under three land use management configurations: no shelterbelt; a 80 m x 15 m cross-slope shelterbelt with a 10 m grazed buffer on three sides; and a 80 m x 15 m down-slope shelterbelt with a 10 m grazed buffer on three sides. The results indicate that shelterbelts can substantially reduce the transfer of runoff from grazed hillslopes to

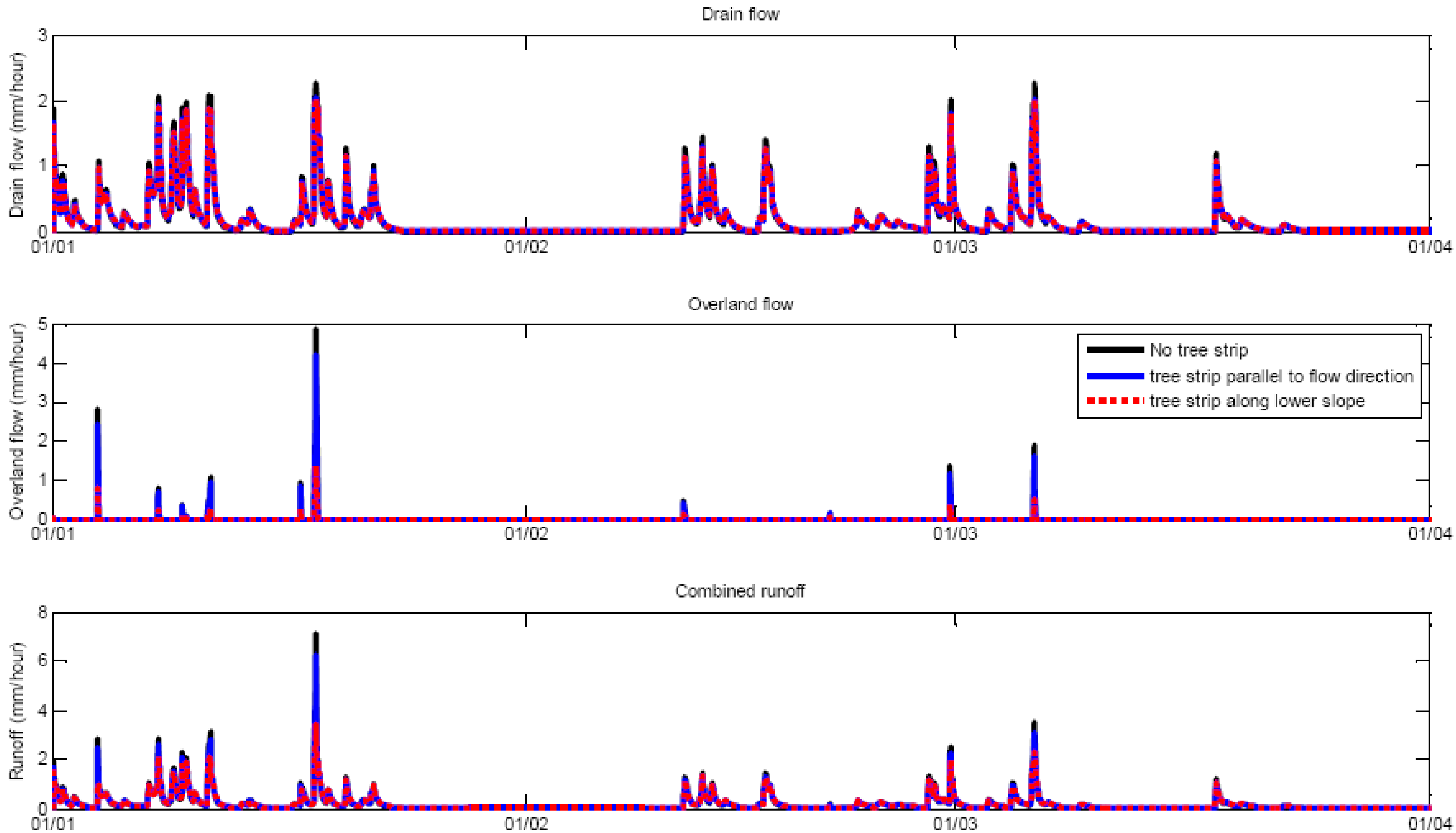


Figure 5.15 Predicted drain flow, overland flow, and combined runoff under different tree shelterbelt/grazed grassland conditions. Source: Wheater *et al*. (2008); p. 108.

the channel network (Jackson *et al*., 2008). While a similar amount of drain flow was generated under all three land use management configurations, the addition of a shelterbelt across the base of the modelled hillslope reduced overland flow by up to 60% and peak total runoff by approximately 40% (Jackson *et al*., 2008). The addition of a shelterbelt positioned in line with the slope in the simulated grazed pasture also reduced overland flow and total runoff peaks but the effects were less beneficial (Jackson *et al*., 2008).

Process information and data sets from detailed modelling exercises at the hillslope scale have been used to develop a second model that is capable of simulating land use and land management changes at the wider catchment scale. Constructed using the semi-distributed rainfall-runoff modelling toolbox (RRMTSD) (Orellana *et al*., in preparation), the model divides catchments into a network of sub-areas for which lumped conceptual rainfall-runoff models are computed (Wheater *et al*., 2008). Fields are used as individual response units at Pontbren as they are usually bounded by ditches and land management tends to be implemented at such scales (Wheater *et al*., 2008). Field types currently represented in the modelling framework are:

- grazed improved grassland; shelterbelt/hedgerow near bottom of slope;
- shelterbelt/hedgerow near top of slope; shelterbelt/hedgerow 90° to contour;
- woodland;
- ungrazed improved grassland;
- grassland with drains removed;

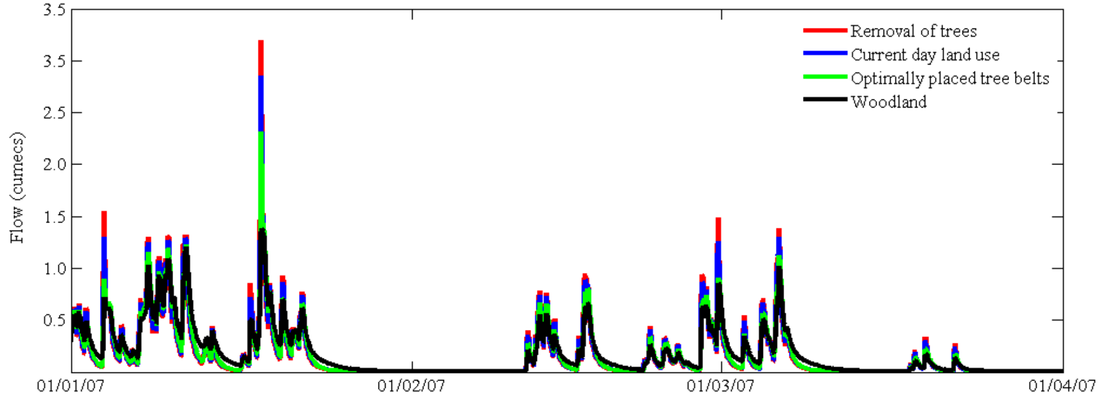
- unimproved grassland/rough grazing; and

- marsh/wetland.

Good correspondence between observed and modelled flows has been observed during testing of the catchment scale model (Wheater *et al*., 2008).

The model has been used to predict the impact of a number of land use management scenarios on flows in streams within the study area (Wheater *et al*., 2008). To date, the effects of woodland and hedgerow restoration undertaken as part of the Pontbren Rural Care Project, planting shelterbelts within all current grazed grassland sites, and covering the entire catchment with woodland have been simulated (Figure 5.16). Results suggest that tree planting in the Upper Pontbren area may have resulted in peak flow reductions of the order of 13% since the height of agricultural intensification in the early 1990s (Wheater *et al*., 2008). A 29% reduction from current conditions could be achieved through optimized placement of shelterbelts within improved pastures, with a maximum reduction of 50% possible through total woodland coverage (Wheater *et al*., 2008).

As part of the research performed to support this thesis, the simulated changes in peak flows reported by Wheater *et al*. (2008) were used to recalculate the potential for bedload transport at measurement sites in the Upper Pontbren subcatchment under the different land use scenarios and compare them to baseline (i.e. observed) conditions (Table 5.6). The results revealed that while the total flow energy increased or decreased proportionally with discharge, disproportionate changes were evident in the total amount of energy available to perform geomorphological



	Change from baseline			
	Time to peak (mins)	Peak flow, lower bound (%)	Peak flow, median (%)	Peak flow, upper bound (%)
Tree removal	0	5.6	12.9	17.6
Optimally placed tree belts	15	-13.4	-29.2	-47.8
Woodland over whole catchment	45	-9.2	-50.2	-68.6

Figure 5.16 Comparison of modelled streamflow data under different land use and land management scenarios. Source of data: Beth Jackson, Imperial College London. Source of table: Wheater *et al*. (2008); p.125.

Bedload transport potential index	Change from baseline under pre-Pontbren Rural Care Project scenario (%)			Change from baseline under optimally-placed shelter belts scenario (%)		
	NB	**SHP**	**PBD**	**NB**	**SHP**	**PBD**
Total energy (MJ)	+13	+13	+13	-29	-29	-29
Total excess energy above small transport threshold (MJ)	+46	+31	+50	-69	-57	-72
Total excess energy above 4 mm particle transport threshold (MJ)	+25	+25	+29	-50	-51	-57
Total time above small transport threshold (hours)	+43	+17	+43	-59	-46	-63
Total time above small transport threshold (hours)	+15	+11	+11	-34	-34	-39

Table 5.6 Changes in bedload transport potential from present-day baseline conditions under different land use and land use management scenarios.

work. For example, in the scenario ‘tree removal’, depending on the bedload transport potential index selected, it is estimated that the amount of energy available to mobilise coarse material under pre-Pontbren Rural Care Project conditions would have been between 15-46% greater at New Bridge, 11-31% greater at Sheepfold, and 11-50% greater at Pont-bren-down than that actually recorded during the monitoring period. These values indicate that the potential for bedload transport is likely to have been much greater in the past and this may have contributed to destabilisation of the channel system through incision and bank erosion that was evident in the Upper Pontbren subcatchment following extensive grassland improvement and consequent increases in stocking densities in the decades following World War Two (*c.f.* Simon and Rinaldi, 2006).

Further, results for the ‘optimally-placed shelterbelt’ scenario suggest that more significant reductions in bedload transport potential than have been observed under the baseline condition could be achieved through the use of well-planned plantings of trees to provide buffer strips. This is the case because the energy available to perform geomorphological work at New Bridge, Sheepfold and Pont-bren-down was predicted to decrease by between 34-69%, 34-57%, and 39-72%, respectively, depending on the index of bedload transport potential selected. While the capability of land management practices implemented under the Pontbren Rural Care Project to reduce the yield of coarse sediment from upland catchments associated with the more extreme flood events remains questionable, the results of analyses perfomed in this research project suggest that the creation and/or restoration of woodland features does have the potential to reduce long-term erosion, limit the annual supply of coarse sediment to the fluvial system and so decrease rates of bedload transport and downstream supply in disturbed fluvial systems.

Taking all of these findings together, it may be concluded that, if such effects could be modelled and predicted spatially and temporally, strategic implementation of land management practices similar to those pioneered by farmers at Pontbren could help to reduce flood risks and threats to people, property and infrastructure associated with coarse sediment transfer in upland Britain.

6 DYNAMICS AND CONTROLS OF SUSPENDED SEDIMENT YIELDS FROM HEADWATER SUBCATCHMENTS AT PONTBREN

6.1 Introduction

This chapter describes the results of an investigation of suspended sediment transport in headwater streams at Pontbren. A similar approach to that adopted in Chapter 5 is utilised, whereby spatial and temporal variation in suspended sediment yields in headwater streams at Pontbren is explored in relation to their transport potentials, sediment sources and supply regimes in an attempt to identify the influence of historical land use changes and land management practices on present-day suspended sediment dynamics. Results and process insights presented in the preceding three chapters of this thesis inform the following analyses of continuous suspended sediment yield data from sites on the Nant Pen-y-cwm and Nant Melin-y-grûg.

6.2 Methodology

6.2.1 Suspended load measurement and sediment yield calculation procedure

Suspended load measurement in upland streams presents a number of problems. Discharges are highly variable, meaning that infrequent routine sampling can miss short-lived, but highly significant, transport events and lead to the underestimation of yields (Gippel, 1995). Suspended material also tends to be too small to be trapped efficiently unless dam structures are present. However, suspended sediment particles tend to absorb and/or scatter light as it passes through water meaning that continuous measurements of turbidity can be used to infer instantaneous suspended sediment concentration (e.g. Clifford *et al*., 1995a). These values can be combined with discharge records to calculate suspended sediment yield. The basic methodology presented here for suspended load measurement in headwater streams at Pontbren is adapted from Wass *et al*. (1997).

Partech IR100c and IR40C turbidity sensors were installed at paired sites on the Nant Pen-y-cwm (Sheepfold) and Nant Melin-y-grûg (Hirrhos Bridge) in spring 2006 (Figure 5.2). The devices quantify the reduction in intensity of infrared light (wavelength = 950 nm) as it passes through the water column between an emitter and a receiver (path length = 40-100 mm), and have manufacturer-quoted suspended sediment concentration detection ranges of 0-200 mg l^{-1} and 0-1500 mg l^{-1} respectively. The use of infrared light by the Partech sensors is preferable to visible light as it requires less power, limits algal growth on lenses, is less responsive to water colouration, and offers greater sensitivity to particles in the size range usually associated with suspended sediment (Wass *et al*., 1997). The sensors produce a 0-5 mA signal which can be converted to a voltage by placing a resistor in the current loop (Clifford *et al*., 1995b). A 500 Ω resistor was used for this application to produce 2.5 V at full-scale deflection. Voltage outputs were sampled every minute and averaged values logged every 15 minutes on a Campbell Scientific CR10X data logger. Dual sensor deployment was utilised at both sites to ensure that turbidity could be measured in high resolution over all anticipated flow conditions and provide insurance against technical failures.

The sensors were mounted on a depth-proportional aluminium boom (after Eads and Lewis, 2002) that was secured to the bed in the centre of the channel at each monitoring site (Figure 6.1). Booms were sited within a culvert at Sheepfold and on a concrete apron at Hirrhos Bridge. Floats attached to the downstream end of each boom raise the sensors off the bed during high flows to ensure possible damage by coarse sediment and organic debris is avoided but that low flow sampling can still be performed (noted as a problem in headwater streams by Kirby, 1991). Perforated aluminium guard plates were also fitted to protect the sensor heads from scratches and bi-weekly lens cleaning undertaken to prevent bio-fouling. Although sampling was only undertaken at one point in the cross-section, it is assumed that suspended sediment is uniformly distributed throughout the flow on account of the high levels of turbulence found in upland streams, particularly during flood events (Bathurst *et al*., 1985).

Voltage outputs from the sensors were calibrated against known values using formazin solution (HMSO, 1984). Standards that ranged between 5-1000 formazin turbidity units (FTU) were used in field calibration exercises. These were prepared by diluting 4000 FTU stock solutions that were prepared according to manufacturer's instructions. For each device, the relationship between the two variables was defined by fitting a third-order polynomial regression curve to the calibration data (Figure 6.2). The equations of the resulting lines were used to convert field voltage measurements from each sensor into standard turbidity values. Data from the IR100C sensors were used to quantify turbidities up to 250 FTU, and values from the IR40C sensors were used for detection higher than 250 FTU on account of their respective sensitivities over different parts of the measurement range.

Water samples collected at monitoring sites over a range of flow conditions were used to calibrate measured turbidity against actual suspended sediment concentration. Sampling was initially undertaken by hand using wide-necked bottles during field visits. However, logistical difficulties associated with measuring suspended sediment concentrations during high flow events necessitated a switch from manual to automatic, stage-triggered sampling using Hach Sigma 900 MAX autosamplers. The intake tubing of the autosamplers was secured to the turbidity sensor mounting boom to ensure that samples were taken from directly around the sensor heads. Recovered samples were vacuum-filtered through pre-weighed Whatman GF/C filters (1.2 μm pore diameter) and oven-dried for 24 hours at 105 °C. The filters were then reweighed and the difference in mass used to calculate the suspended sediment concentration of the sample. Turbidity values measured at the time of sampling were plotted against suspended sediment concentration and used to develop linear regression models for each monitoring site (Figure 6.3). The resulting equations were used to predict 15 minute averaged suspended sediment concentration values for each site using the continuous turbidity records. The suspended sediment concentration values were integrated with stream discharge data from the nearest flow gauge in the Imperial College/CEH Bangor-operated network (SF6 at Sheepfold and SF9 at Hirrhos Bridge) to estimate suspended sediment yield.

6.2.2 Assessment of controls on suspended sediment transport in headwater streams at Pontbren

In order to assess the influence of differences in hydrology and sediment supply between the Upper Pontbren and Upper Melin-y-grûg subcatchments on suspended

(a) (b) (c)

Figure 6.1 (a) Turbidity monitoring equipment, deployed in a culvert at (b) Sheepfold on the Nant Pen-y-cwm and (c) beneath Hirrhos Bridge on the Nant Melin-y-grûg.

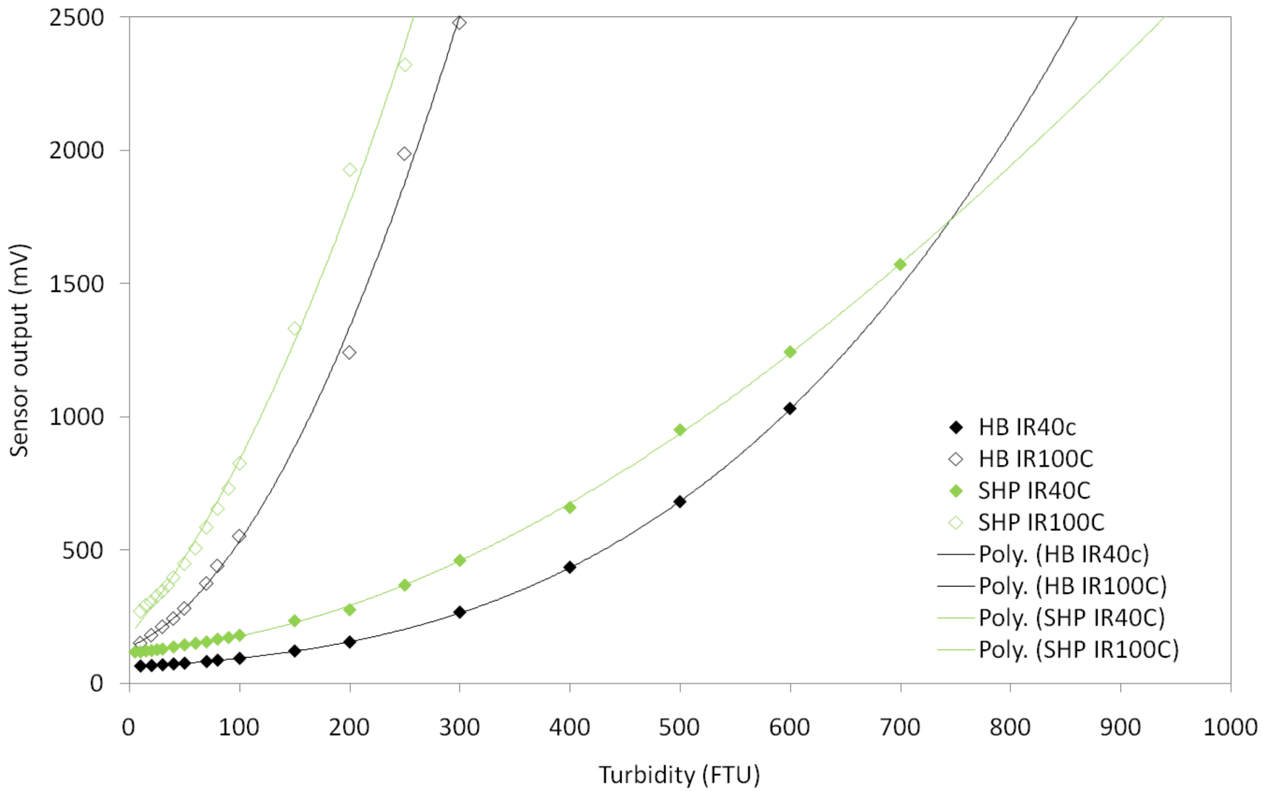


Figure 6.2 Relationship between turbidity and sensor output for probes deployed at Hirrhos Bridge and Sheepfold.

sediment transport in their respective streams, relationships between suspended sediment yields and a number of potential explanatory variables were explored in a number of ways. Sediment transport potential was represented by specific stream power (see Chapter 5), and the total flow energy at each measurement site was calculated by integrating instantaneous power values over the entire monitoring period. Supply factors were explored through interpretation of hysteresis plots and regression analyses using data documented in Chapters 3-5.

6.3 Results and discussion

6.3.1 Suspended sediment transport in the Nant Pen-y-cwm and Nant Melin-y-grûg

The suspended sediment yields of the Nant Pen-y-cwm at Sheepfold and the Nant Melin-y-grûg at Hirrhos Bridge are presented in Table 6.1. The values are based solely on data collected during the first 12 months of turbidity measurement at both sites (June 2006-June 2007) due to damage sustained by the equipment during several large flood events during summer 2007 and winter 2007/8 (see Chapters 3 and 5). Large woody debris washed down the streams during the high flow events caused the mounting booms at both sites to detach from their base plates and snapped cables supplying power to the turbidity probes. Data recorded during these events were lost, and it is believed that a considerable amount of suspended sediment transport may have occurred during a number of subsequent events while repairs and recalibration work was undertaken. The gaps in the data records would have resulted in annual suspended sediment yields being severely underestimated

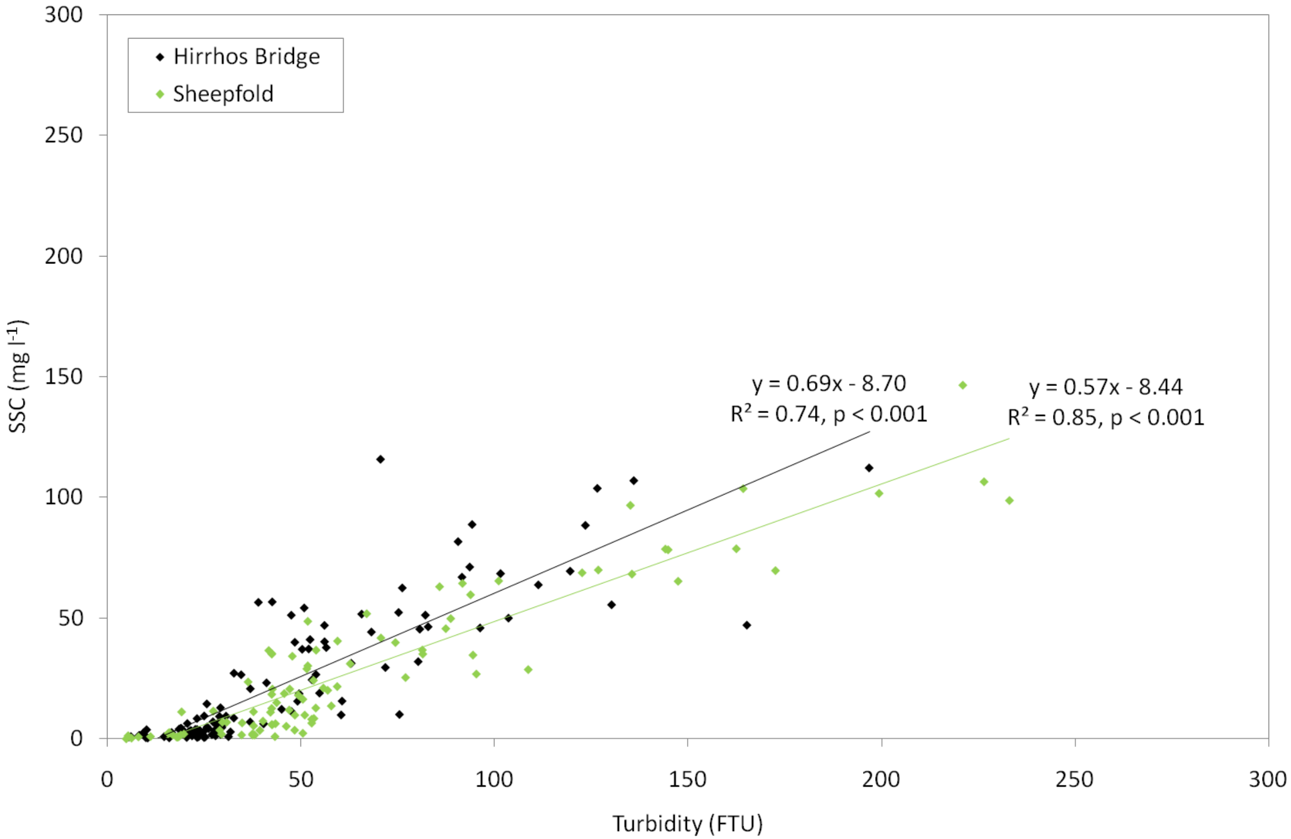


Figure 6.3 Relationship between measured suspended sediment concentration and turbidity at Hirrhos Bridge and Sheepfold sites.

Land use and location	Study	Catchment area (km^2)	Suspended sediment yield ($t\ km^{-2}\ yr^{-1}$)	Comments
Improved grassland				
SHP, Pontbren	Henshaw (this thesis)	3.17	17.31	
Moorland/rough pasture				
MYG, Pontbren	Henshaw (this thesis)	4.06	3.21	
Maesnant, Plynlimon	Lewin *et al*. (1974)	0.54	1.00	
Cyff, Plynlimon	Moore and Newson (1986)	3.13	6.10	
	Leeks and Marks (1997)		5.34	
Coalburn, Cumbria	Robinson and Blyth (1982)	3.10	3.00	
Holmestyes, Yorkshire	Burt (1984) in Soutar (1989)	0.20	3.20	
Caunant Ddu, Llanbrynmair	Francis and Taylor (1989)	0.34	3.70	
Nant Ysguthan, Llanbrynmair		0.14	0.70	
Mature forest				
Tanllwyth, Plynlimon	Moore and Newson (1986)	0.89	12.10	
	Leeks and Marks (1997)		24.26/43.76	Before/after tree felling.
Hore, Plynlimon	Leeks (1992)	3.08	24.40/141.00	Before/after tree felling.
Hafren, Plynlimon	Leeks and Marks (1997)	3.67	19.59	
Severn, Plynlim	Leeks and Marks (1997)	8.70	15.25	

Table 6.1 Suspended sediment yields from Pontbren and other British upland catchments with different land uses.

and values obtained during the second 12 months of monitoring (June 2007-June 2008) were, therefore, excluded from their calculation.

The suspended sediment yield of the Nant Pen-y-cwm (17.31 t km^{-2} yr^{-1}) was over five times greater than that of the Nant Melin-y-grûg (3.21 t km^{-2} yr^{-1}), confirming the existence of a disparity between the Upper Pontbren and Upper Melin-y-grûg subcatchments in terms of both fine and coarse sediment production. While bedload yields measured at Pontbren were low compared to those reported from other upland catchments in the UK (see Chapter 5), suspended sediment yields are more comparable. The yield of the Nant Melin-y-grûg appears typical of an undisturbed moorland catchment. However, the yield of the Nant Pen-y-cwm is of a similar magnitude to those found in afforested catchments, where drainage ditches excavated to ensure ideal growing conditions supply large quantities of fine material to the natural channel network (Stott and Mount, 2004).

Figures 6.4(a) and 6.4(b) show variation in suspended sediment concentrations in relation to changes in discharge at the Sheepfold and Hirrhos Bridge turbidity measurement sites, respectively. Mean suspended sediment concentration values were low in both streams, measuring 19.9 mg l^{-1} in the Nant Pen-y-cwm and 6.6 mg l^{-1} in the Nant Melin-y-grûg. The difference between the two was statistically significant at the 0.1% level (paired sample t-test). However, values ranged considerably, with peak instantaneous concentrations of 396.5 mg l^{-1} and 156.9 mg l^{-1} recorded at Sheepfold and Hirrhos Bridge, respectively. There is good general correspondence in terms of the timing of suspended sediment transport in both streams, with higher concentrations tending to occur on both streams during high flow events. However, the highest concentrations recorded in each stream do not

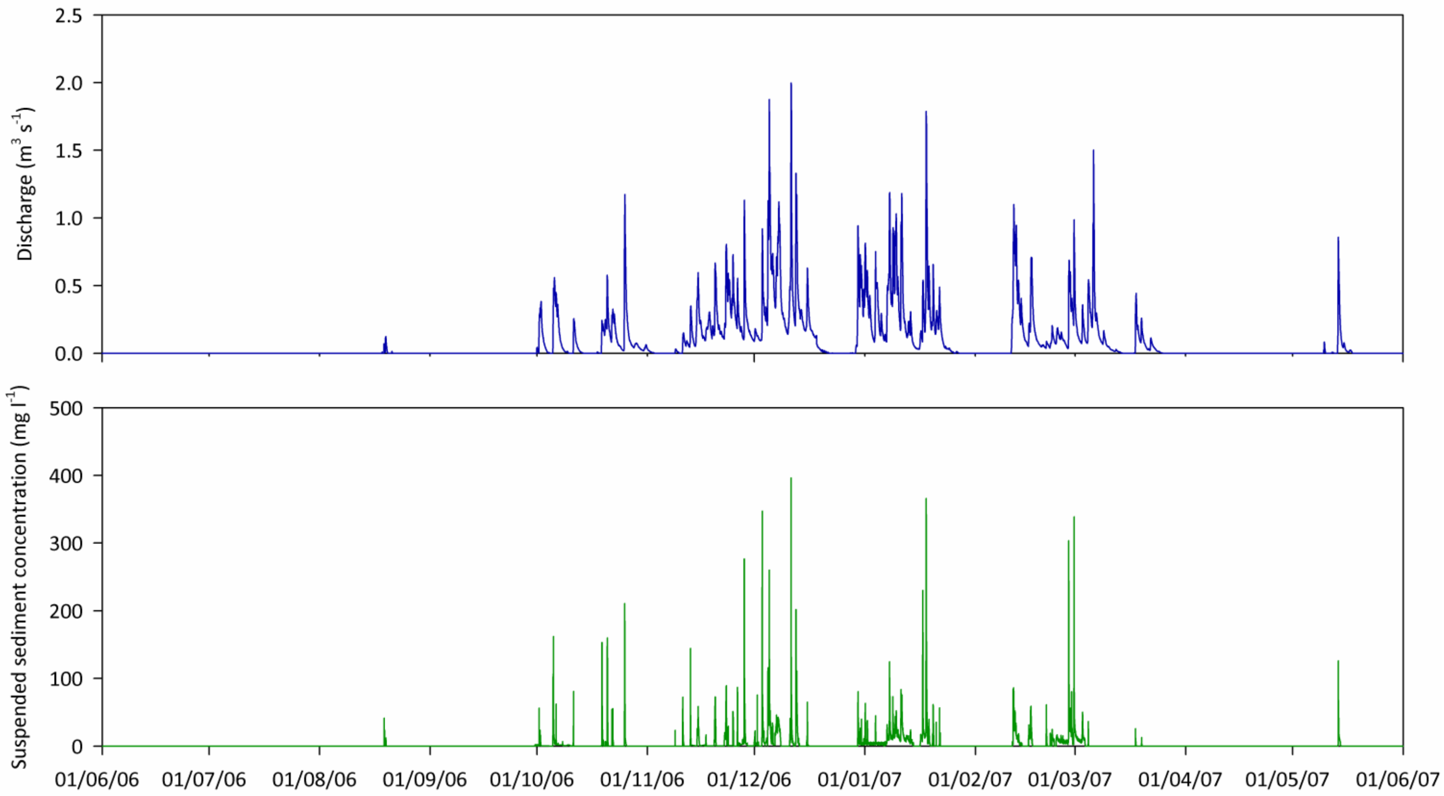


Figure 6.4(a) Temporal variation in discharge and suspended sediment concentration at Sheepfold during the monitoring period.

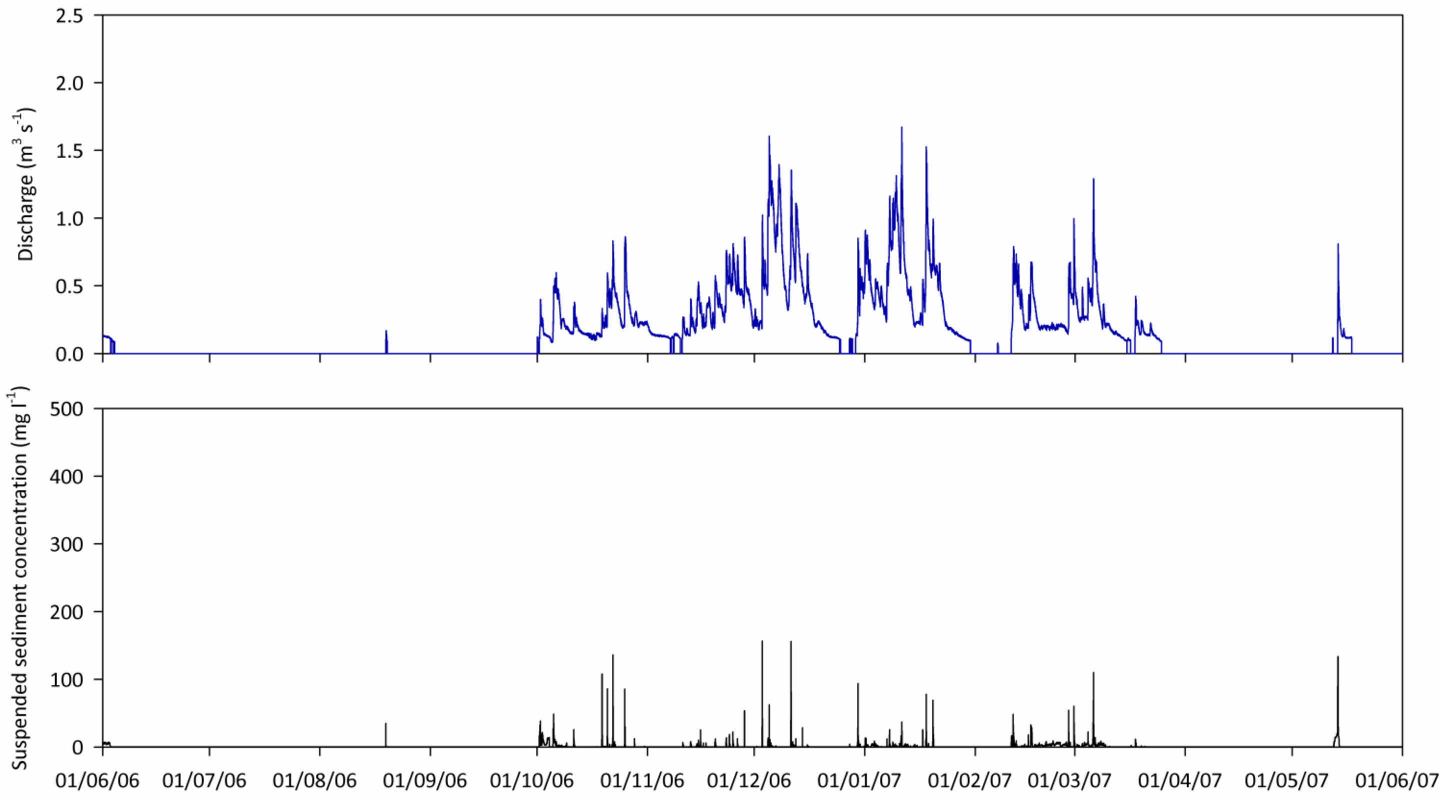


Figure 6.4 (b) Temporal variation in discharge and suspended sediment concentration at Hirrhos Bridge during the monitoring period.

occur during the same events and there is no obvious consistency between the magnitude of a flood event and the concentration of suspended sediment in the flow. Suspended sediment yields from both streams displayed a strong seasonal trend, with the majority of fine material transported during winter (Figure 6.5). The yields of December, January and February accounted for 83% and 70% of the total fine sediment export from the Upper Pontbren and Upper Melin-y-grûg subcatchments, respectively.

6.3.2 Exploring spatial and temporal variation in suspended sediment transport at Pontbren

Relationships between specific stream power and suspended sediment concentration at Sheepfold and Hirrhos Bridge are displayed in Figure 6.6. While regression analyses revealed the existence of a statistically significant positive relationship at both sites ($p < 0.001$), the amount of variance in suspended sediment concentration explained by the variable was very low. The r^2 value for Sheepfold was 0.27, while Hirrhos Bridge had an r^2 of 0.08. This lack of a strong relationship between transport potential and suspended sediment concentration has been reported extensively in the literature and, in combination with the fact that the total flow energy of the Nant Melin-y-grûg at Hirrhos Bridge (626 MJ) was actually much greater than that of the Nant Pen-y-cwm at Sheepfold during the monitoring period (270 MJ), reflects the importance of sediment supply as a control of fine sediment transport (Knighton, 1998). The availability of fine sediment can vary both spatially and temporally, and is often independent of instream conditions, thus leading to considerable amounts of scatter and preventing the definition of simple transport functions (Knighton, 1998).

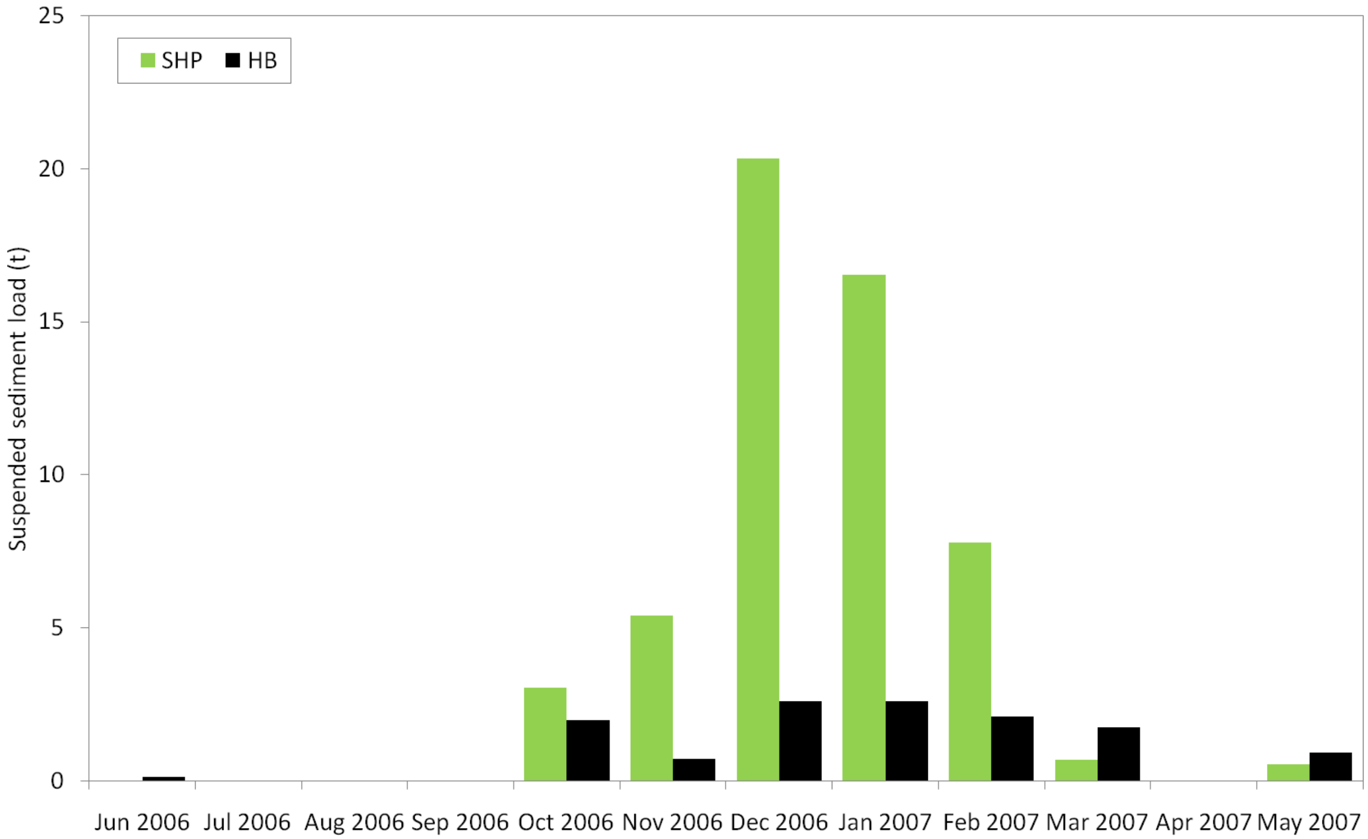
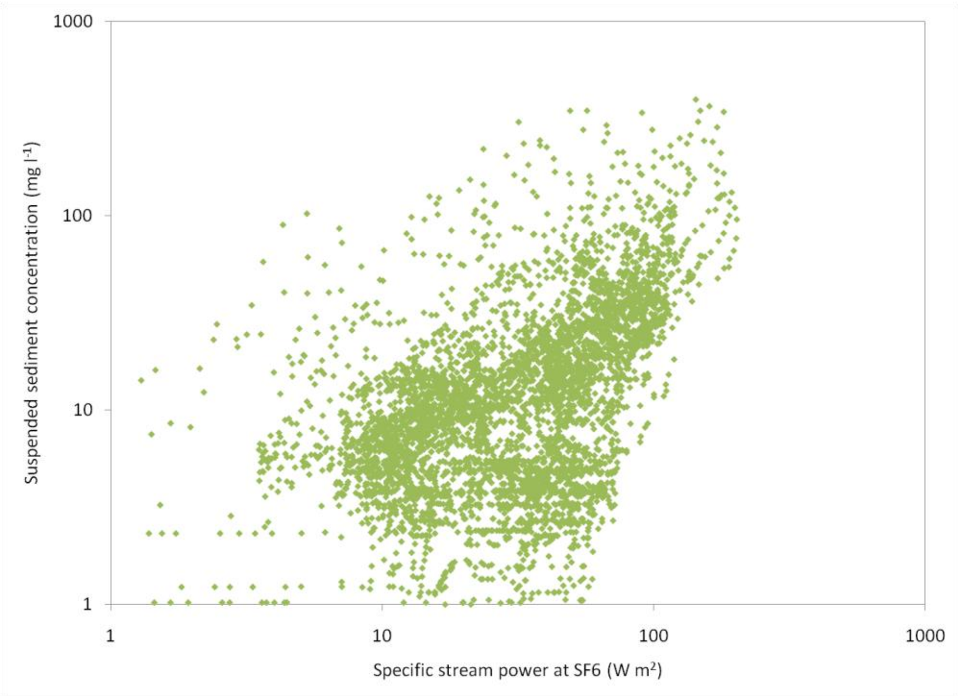


Figure 6.5 Monthly suspended sediment yields measured at Hirrhos Bridge and Sheepfold.

(a)



(b)

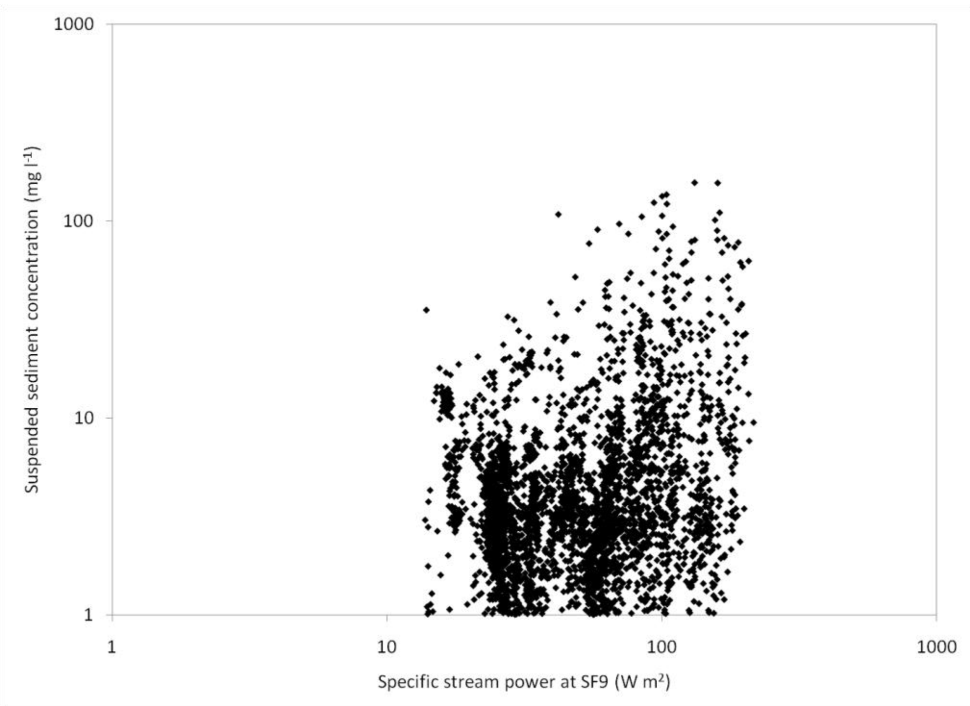
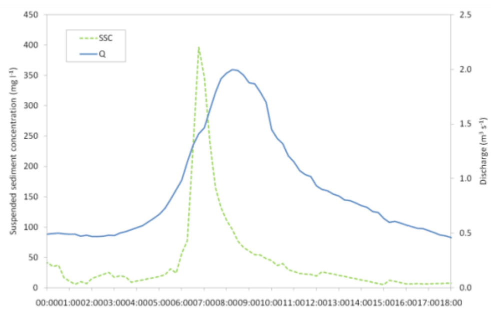


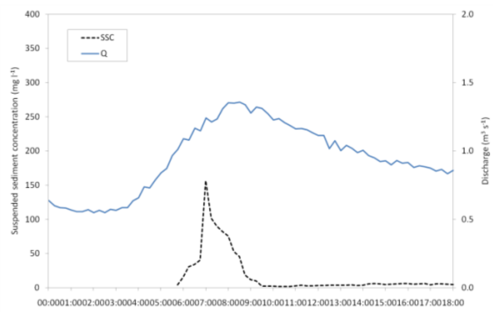
Figure 6.6 Relationship between specific stream power and suspended sediment concentration at (a) Sheepfold and (b) Hirrhos Bridge.

This can be demonstrated by examining suspended sediment concentration and discharge data from individual flood events. Figure 6.7 shows the typical responses of suspended sediment concentrations over the duration of a high flow event in the Nant Pen-y-cwm and Nant Melin-y-grûg. Concentrations are notably higher at Sheepfold compared to Hirrhos Bridge but the manner of response at the two sites is very similar, with suspended sediment concentrations peaking before discharge and greater on the rising limb of the hydrograph in comparison to the falling limb. Hysteresis of this form, referred to as 'clockwise' or 'Type 1' (*c.f.* Williams, 1989), is very common and tends to be observed where there is an abundant source of sediment that becomes progressively depleted during the initial stage an event (Knighton, 1998). It is also noticeable that very little fine sediment is transported on the falling limb of the hydrograph in the Nant Melin-y-grûg in comparison to the Nant Pen-y-cwm.

While the type of hysteresis observed in the Nant Pen-y-cwm was consistent throughout the entire monitoring period, the response of suspended sediment concentrations in the Nant Melin-y-grûg to changes in discharge was more variable. The plot in Figure 6.8 demonstrates the occurrence of 'anticlockwise' or 'Type II' hysteresis (*c.f.* Williams, 1989), where the sediment wave lags behind the water wave to give higher suspended sediment concentrations on the falling limb of an event compared to those at the same discharge on the rising limb. This type of response tends to occur where there is an absence of immediately available sediment and material is derived from sources located a substantial distance away from the point of measurement (Knighton, 1998). It can also be caused by

(a) (b)





(c)

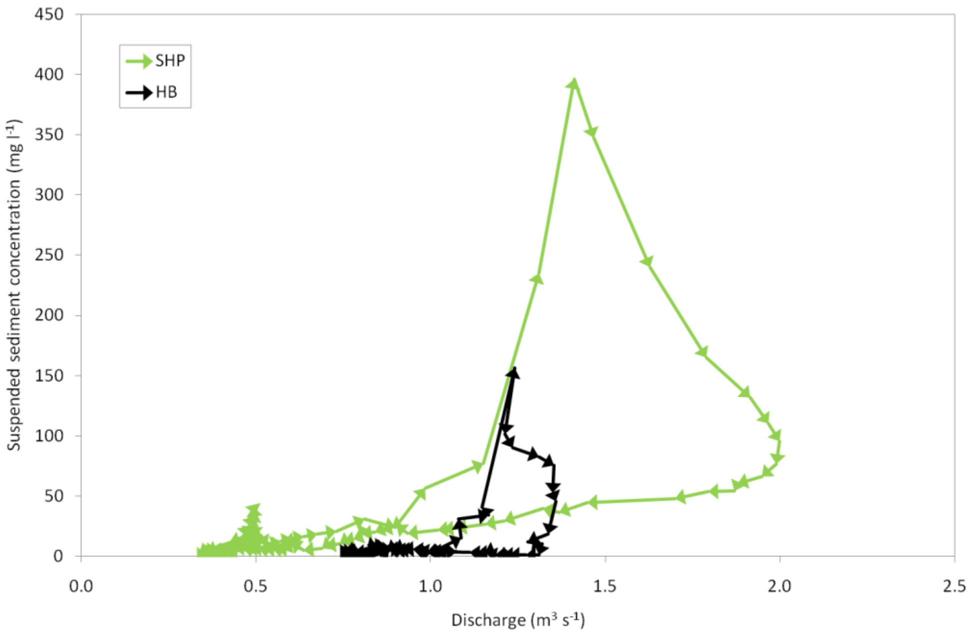
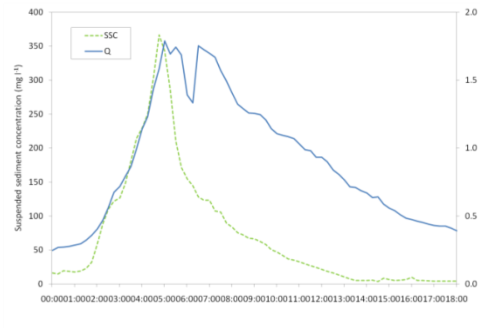
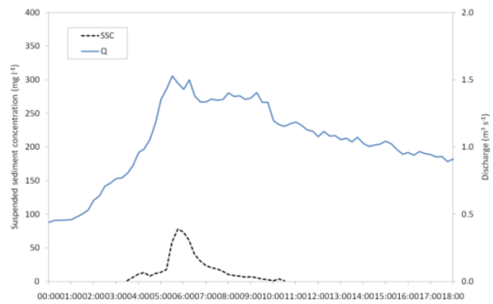


Figure 6.7 Temporal variation in discharge and suspended sediment concentration at (a) Sheepfold and (b) Hirrhos Bridge during high flow event on 11 December 2006 and associated hysteresis plots (c).

(a)



(b)



(c)

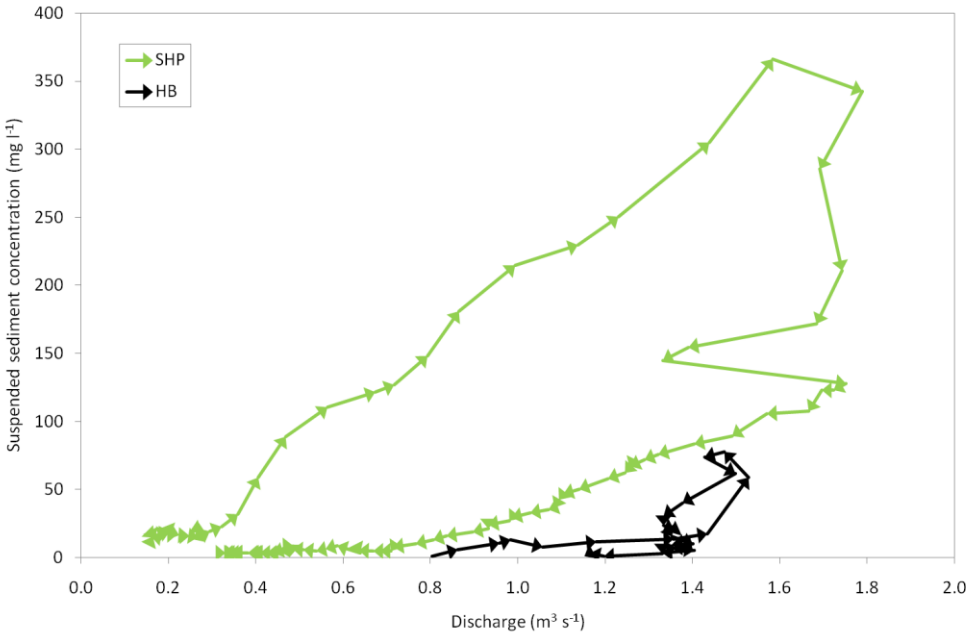


Figure 6.8 Temporal variation in discharge and suspended sediment concentration at (a) Sheepfold and (b) Hirrhos Bridge during high flow event on 18 January 2007 and associated hysteresis plots (c).

geomorphological activity such as the failure of banks resulting from post-flood drawdown (Knighton, 1998). Both of these responses suggest that fine sediment availability is much more restricted in the Upper Melin-y-grûg subcatchment in comparison to the Upper Pontbren area, and that contrasts in land use histories and land management practices could, therefore, have a large influence. It should be noted, however, that the types of responses observed at Hirrhos Bridge were not exclusive to those discussed above. Hysteresis more similar to that typically observed at Sheepfold was encountered during an event on 13 May 2007 (Figure 6.9), indicating that fine sediment availability in both subcatchments may vary temporally.

A number of factors may help to explain the noted differences in fine sediment availability between streams in the Pontbren study area, and support the hypothesis that suspended sediment yields are higher in the Nant Pen-y-cwm compared to the Nant Melin-y-grûg due to the contrasting land use histories of their upstream drainage areas. As demonstrated in Chapter 3, grazed, agriculturally improved pastures are likely to represent important sources of fine sediment in the Upper Pontbren area, particularly due to the associated installation of underdrainage but also as a result of elevated levels of overland flow. The use of a linear function of overland flow intensity instead of specific stream power was found to improve the amount of variance in suspended sediment concentrations in the Nant Pen-y-cwm that could be explained from 27% to 40%, while no significant relationship between the two variables was observed data collected in the Nant Melin-y-grûg (Figure 6.10). Likewise, a linear function of drain flow intensity was found to explain 48% of the variance in suspended sediment concentrations observed at Sheepfold compared to just 17% of those at Hirrhos Bridge (Figure 6.11). Clearly, the strength

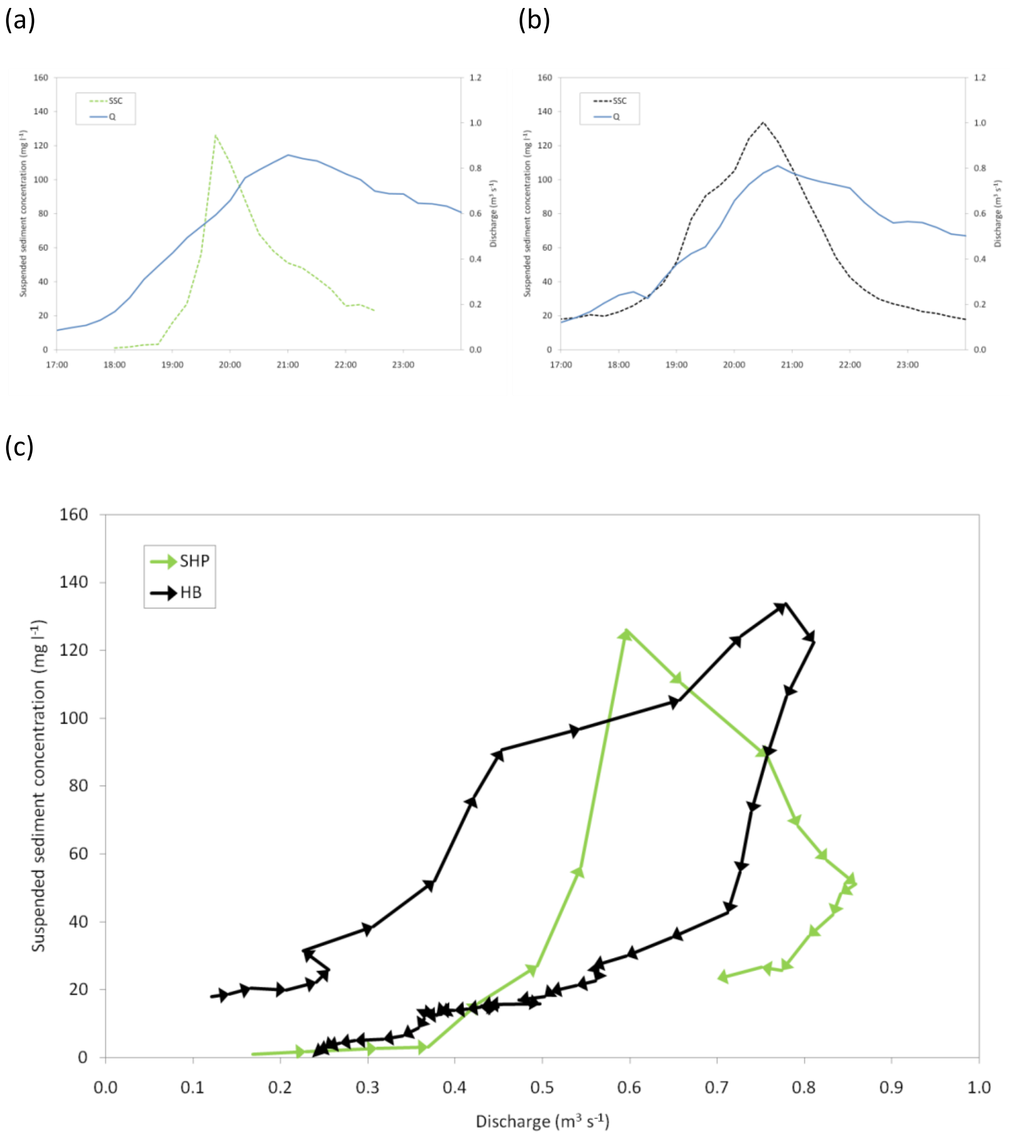
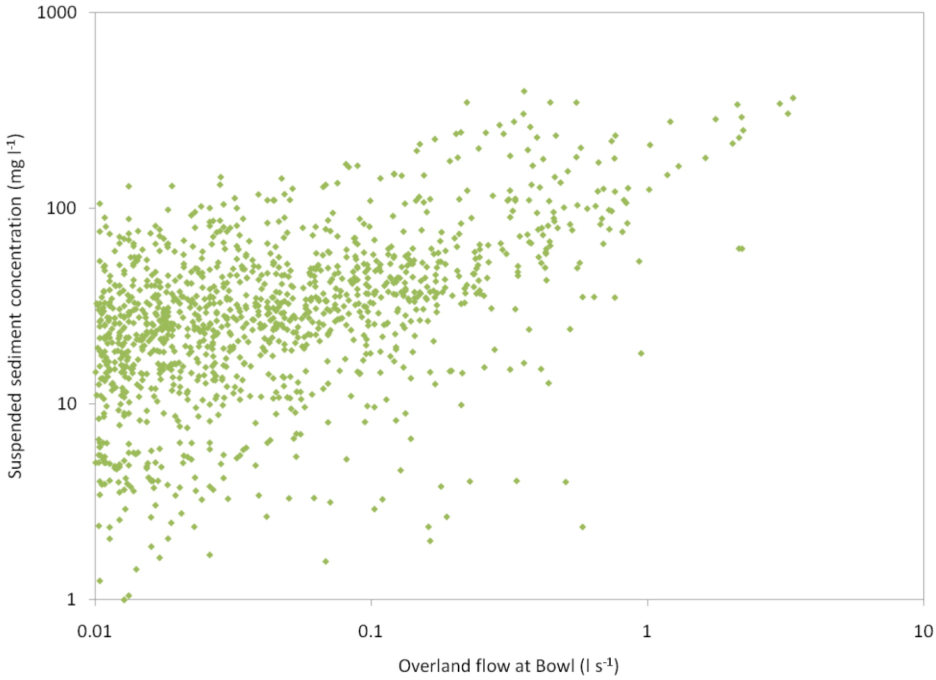


Figure 6.9 Temporal variation in discharge and suspended sediment concentration at (a) Sheepfold and (b) Hirrhos Bridge during high flow event on 13 May 2007 and associated hysteresis plots (c).

(a)



(b)

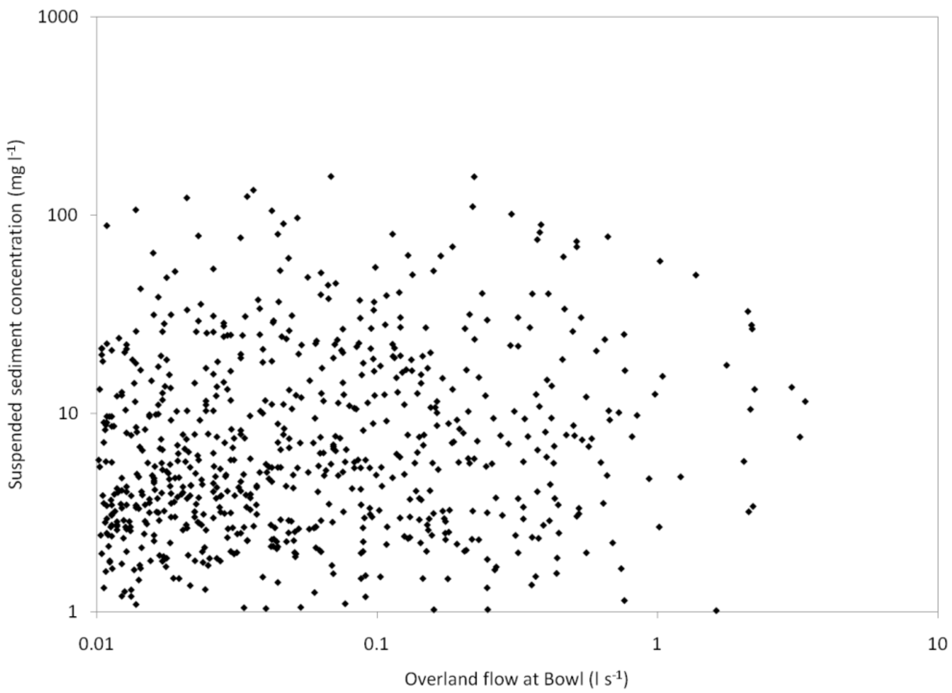
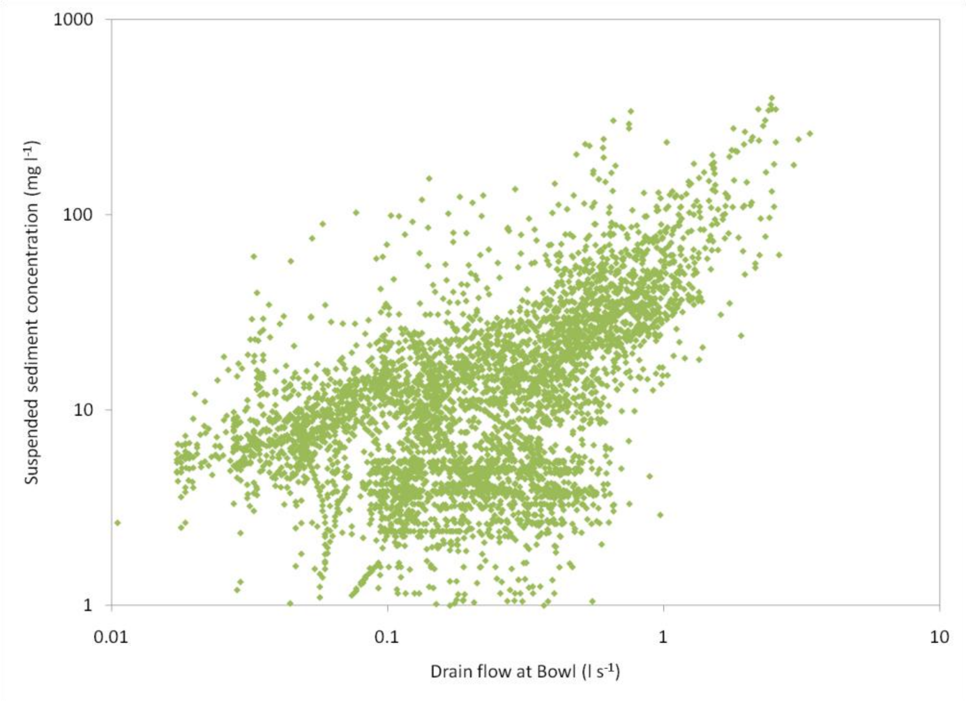


Figure 6.10 Relationship between overland flow intensity recorded at the Bowl and suspended sediment concentration at (a) Sheepfold and (b) Hirrhos Bridge.

(a)



(b)

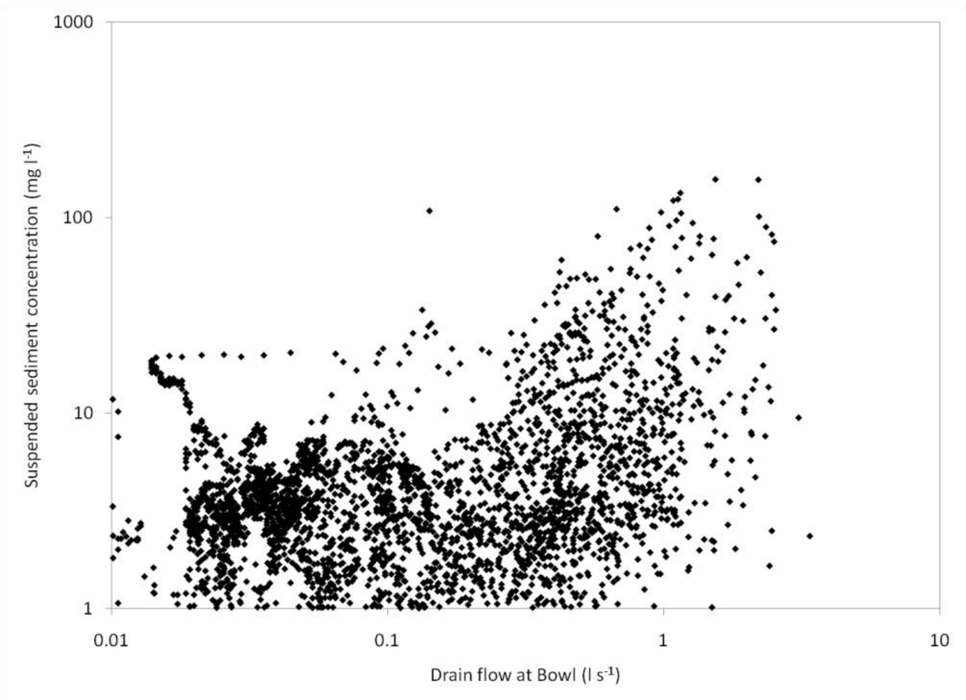


Figure 6.11 Relationship between drain flow intensity recorded at the Bowl and suspended sediment concentration at (a) Sheepfold and (b) Hirrhos Bridge.

of such associations is subject to scatter inherent in the relationships between flow intensity (overland/drain) and sediment yield at the Bowl, and it is unclear how representative the Bowl is of the wider Pontbren area. Lag effects may also be important, as shown in Figure 6.12. Nevertheless, the data do highlight the potential significance of grazed, agriculturally improved pastures as sources of fine sediment in the Upper Pontbren subcatchment and, thus, a link between upland agricultural land management practices and fine sediment yields in headwater streams.

There is also evidence to support the existence of channel network-based sources of fine sediment in the Upper Pontbren subcatchment that are absent in the upper reaches of the Nant Melin-y-grûg. Data presented in Chapter 4 show that eroding channel banks supply large amounts of sediment to the Nant Pen-y-cwm and this could help to explain the higher suspended sediment yields recorded in that stream. Table 6.2 highlights the strong correspondence between temporal variation in the quantity of fine sediment (silt-clay fractions) supplied from eroding banks and the amount of suspended sediment transport at Sheepfold. However, the data also indicate that bank-derived sediment could have accounted for a maximum of just 17% of the total fine sediment yield, and that other sources must have been important as well. Potential other channel network-based sources are likely to include drainage ditches and the streambed itself. Higher levels of bedload transport in the Nant Pen-y-cwm (see Chapter 5) are likely to result in the exposure of underlying fine material to mobilisation by the flow, as evidenced by the significant positive relationship ($p < 0.001$) between time-integrated bedload and suspended sediment yields at Sheepfold displayed in Figure 6.13, but which is absent at Hirrhos Bridge on the Nant Pen-y-cwm.

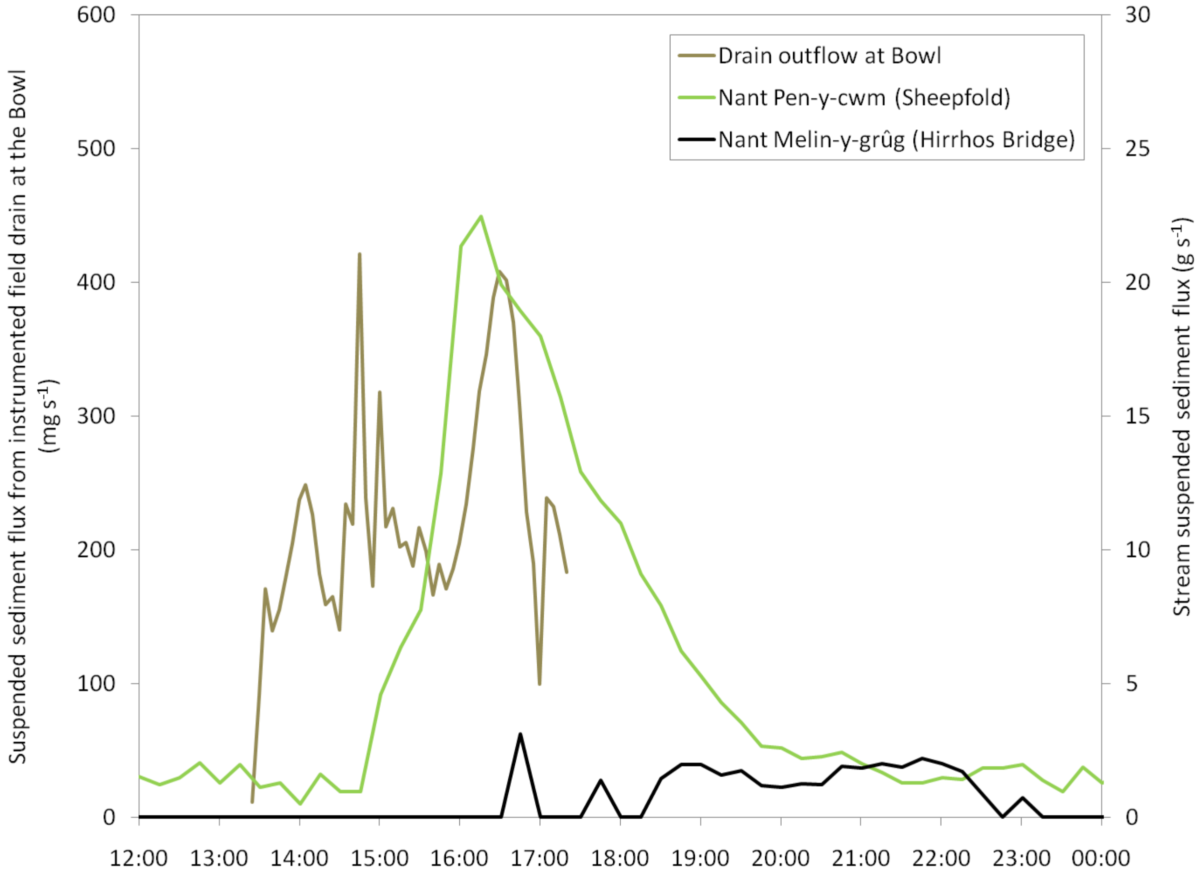
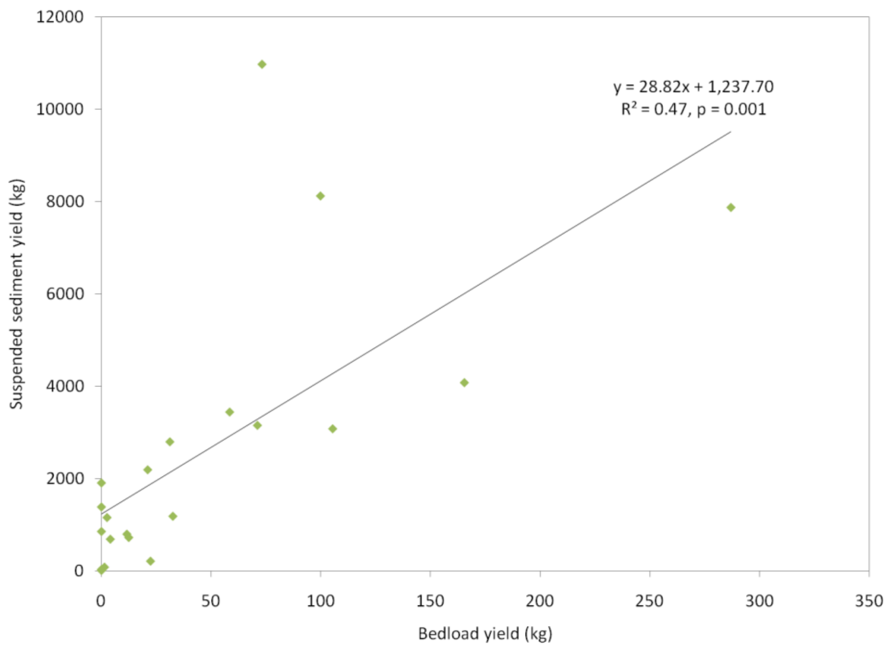


Figure 6.12 Comparison of suspended sediment fluxes from the field drain at the Bowl and in the Nant Pen-y-cwm and Nant Melin-y-grûg.

(a)



(b)

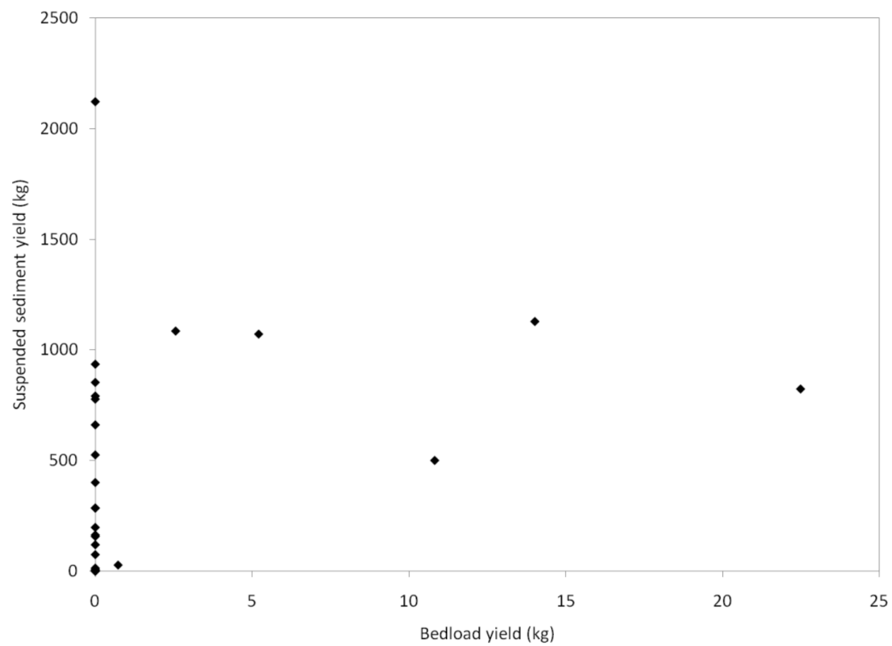


Figure 6.13 Relationship between time-integrated bedload and suspended sediment yields at (a) Sheepfold and (b) Hirrhos Bridge.

		Summer 2006	Autumn 2006	Winter 2006/7	Spring 2007
Silt-clay supplied from eroding channel banks in the Upper Pontbren subcatchment	t	0.53	0.71	7.52	0.32
	%	5.9	7.8	82.8	3.6
Suspended sediment output at Sheepfold on the Nant Pen-y-cwm	t	0.01	8.49	45.22	0.55
	%	0.0	15.6	83.3	1.0

Table 6.2 Comparison of sediment yields from eroding bank sources in the Upper Pontbren subcatchment with suspended sediment yields from the Nant Pen-y-cwm at Sheepfold.

Data and analyses presented in this chapter demonstrate that, as with coarse sediment, fine sediment yields from the Upper Pontbren subcatchment are greater than those from the Upper Melin-y-grûg area and the differences cannot be explained solely through a difference in sediment transport potential. Differences in fine sediment availability between the contrasting systems appear to be a more likely cause of the observed spatial and temporal variation in suspended sediment transport. This may be a direct result of land management practices associated with agricultural intensification, or the legacy of channel network destabilisation caused by hydrological changes potentially associated with the same features (see Chapter 5). The effects of recent woodland and hedgerow planting as part of the Pontbren Rural Care Project is unlikely to have a major direct impact on suspended sediment yields through the direct filtration of fine sediment transported across the land surface (i.e. as normal buffer strips) due to the relative unimportance of this type of source in the study area. However, peak flow reductions associated with the scheme may help to reduce levels of geomorphological activity within the channel network and thus restrict fine sediment export to lowland reaches.

7 CONCLUSIONS

7.1 Conclusions

Research presented in the preceding chapters of this thesis explores the influence of historical land use changes and land management practices associated with British upland agriculture on catchment sediment dynamics. The work was motivated by growing concerns that widespread development in upland areas during the second half of the twentieth century to support intensive livestock grazing may have affected both hydrology and patterns and rates of erosion and sediment transfer, thereby potentially increasing sediment-related flood risks and posing a threat to aquatic and riparian habitats. An extensive programme of field experiments, informed by literature, local knowledge, and results from a parallel FRMRC study into the impacts of land use management on hydrological response at different scales, was conducted at Pontbren in mid-Wales to assess the effects of agricultural intensification on upland catchment sediment dynamics, and whether they could be modified through the adoption of sustainable land management practices pioneered by a farming cooperative in the local area.

Impacts of land use changes and land management practices were evaluated for a number of potential sediment sources and transfer mechanisms. Data collected from an intensively-instrumented, agriculturally-improved grazed pasture was used to demonstrate that such areas supply fine material (silt/clay) to channel networks *via* both surface runoff and subsurface field drains (Chapter 3). The contribution of fine sediment transferred to streams *via* surface runoff to the total sediment yield of the Upper Pontbren subcatchment (where agricultural development has been most widespread) is, nevertheless, unlikely to be substantial as, despite the widespread occurrence of overland flow during rainfall events, soil erosion rates within pastures were found to be very low as a result of proactive and reactive soil erosion management undertaken by local farmers, and supply is ultimately reliant on hydrological connectivity between source and channel. Sediment yields from field drains were found to be significantly higher, however, and are likely to represent a far more important transfer mechanism at the catchment-scale for soil eroded within grazed pastures as a result of their direct connectivity to the channel network.

Large quantities of fine and coarse sediment are also supplied to stream channels in the Upper Pontbren subcatchment from eroding channel banks (Chapter 4). A direct influence of grazing pressure on bank erosion rates could not be detected, with no difference evident between monitoring sites where livestock access was unrestricted and those where fencing has been erected in recent years as part of the Pontbren Rural Care Project. However, anecdotal evidence suggests that grazing by cattle (as opposed to sheep) in riparian areas did cause substantial erosion in the past and that affected areas have since recovered, thus supporting another direct link between land management and sediment dynamics in the study area.

The dominance of fluvial processes as controls of bank erosion rates in the Upper Pontbren subcatchment and the relative absence of any significant lateral adjustment in the upper reaches of the Nant Melin-y-grûg despite similar bank material properties suggests that changes in land use may have affected sediment supply from channel bank sources *via* a more indirect method (Chapter 4). Present-day peak runoff rates are higher in the Nant Pen-y-cwm compared to the Nant

Melin-y-grûg, while hydrological modelling exercises undertaken by Imperial College London suggest that the difference in peak discharges between the two streams during floods was even greater at the height of agricultural intensification in the area, prior to the inception of the Pontbren Rural Care Project. Hydrological changes potentially caused by the installation of drainage systems and the effects of increased livestock numbers on soil hydraulic properties (Chapters 2-4) may have contributed to the documented destabilisation of the channel network in the Upper Pontbren subcatchment. Ongoing geomorphological adjustment to this change in boundary conditions and the input of substantial amounts of large woody debris to channels may be driving present-day sediment supply from this type of source. Coarse sediment availability in the Upper Pontbren subcatchment was further supplemented by material mobilised from agricultural drainage ditches (Chapter 5).

The contrasting availability of coarse and fine sediment from the sources described above in subcatchments of contrasting land use histories at Pontbren was found to be the dominant influence on bedload and suspended sediment yields (Chapters 5 and 6), suggesting that agricultural intensification following World War II had a large impact on sediment dynamics in the study area. However, while suspended sediment yields in streams draining agriculturally-intensified subcatchments at Pontbren are broadly comparable with values obtained during studies of afforestation (a practice widely associated with negative environmental impacts), and bedload yields are over ten times greater compared to those from moorland subcatchments, it is difficult to assess the significance of agricultural intensification in relation to other types of upland land use change, and dangerous to assume agricultural intensification would necessarily produce similar effects in other parts of the British uplands. Site-specific physiographic factors may render particular catchments more sensitive than others, while the interrelationship between climate and land use drivers is also likely to be very important in controlling the occurrence and magnitude of any impacts in upland sediment systems that result from land use changes. Flood events that are capable of instigating major coarse sediment transport and extensive geomorphological adjustments in small upland catchments are rare and, thus, while catchments may be 'sensitised' by changes associated with agricultural intensification (*c.f.* Mackin and Lewin, 2003), it may be some time before impacts become apparent. Dating of lichen from sedimentary deposits has shown that, contrary to popular belief, the incidence and size of geomorphologically effective flood events in small upland river basins in the UK has decreased markedly over the past 50 years, and may be at their lowest level since 1750 (Macklin and Rumsby, 2007). However, anecdotal evidence (Chapter 2) indicates that at least two of these types of events have occurred in the Pontbren area since the mid-twentieth century and, in combination with factors associated with agricultural intensification, may have 'set-up' the present-day geomorphological configuration of the streams investigated in this thesis. Understanding events of this nature invariably involves adopting a forensic approach of the sort followed in this investigation due to their low frequency and the inability of current technology to measure the volumes of sediment transported.

While the capability of land management practices associated with the Pontbren Rural Care Project to reduce sediment supply to stream channels from agriculturally-improved pastures is questionable on the basis of results presented in this thesis, peak flow reductions resulting from woodland and hedgerow planting have been shown to cause substantial reductions in the amount of energy available to mobilise material from channel-network based sources. Given the apparent importance of these sources in the Pontbren system, it is plausible that land use management could be used to reduce coarse and fine sediment export from similar upland catchments. Addressing sediment-related flood risks and river management issues in such a manner echoes the philosophy of many modern water management policies such as Defra's Water Strategy and Making Space for Water, and could assist efforts to satisfy the EU Water Framework Directive's objective of achieving 'good ecological status' in rivers by 2015 (EU, 2000). Tactical land management interventions of this nature could also help to increase the 'resilience' of upland sediment systems to predicted future changes in climate (*c.f.* Raven *et al*., in press). Increased levels of winter rainfall and more extreme events are forecast to occur in the UK over coming decades (e.g. Jenkins *et al*., 2008), and both are likely to increase the magnitude and frequency of flood events in British rivers (Environment Agency, 2009). Such changes are almost certain to increase the potential for erosion and sediment transfer within upland channel networks and, thus, measures that could limit or prevent such effects may be desirable.

Nevertheless, it is important to stress that measures such as woodland planting and hedgerow restoration will only be effective river and flood risk management 'tools' if they are implemented strategically within catchments, and should not be viewed as universally-applicable 'blanket remedies' (*c.f*. Newson, in press). Hydrological and geomorphological process evidence presented in this thesis, other outputs from the Pontbren study (e.g. Jackson *et al*., 2008; Wheater *et al*., 2008; Marshall *et al*., 2009) and published literature (e.g. Lane *et al*., 2006) all indicate that the spatial organisation of land use modifications is a crucial factor in controlling the incidence and size of impacts downstream. Assuming that tree planting in upland areas will always deliver flood risk and river management benefits, irrespective of how and where it is conducted, is, therefore, just as dangerous as expecting agricultural intensification to always have negative impacts. Land use management decision-making should not be based on 'myths' (*c.f.* Calder and Aylward, 2006) of this ilk but, instead, on improved understanding of hydrological and geomorphological connectivity and sensitivity within river catchments.

7.2 Recommendations for further research

The findings presented in this thesis suggest that land use and land management practices could have a large impact on both coarse and fine sediment export from upland catchments by adjusting their hydrological functions and sediment supply regimes. If such effects could be fully understood and predicted, strategic land use management could be utilised to minimise sediment-related flood risks. Further work is now being undertaken as part of a second phase of FRMRC research to predict sediment yields and downstream morphological responses for a range of land use management and climate change scenarios using models from the FRMRC sediment 'toolbox' (Wallerstein *et al*., 2006a), and those developed by Imperial College London to predict changes in hydrological responses at the catchment-scale (Wheater *et al*., 2008). Sediment models include the River Energy Audit Scheme (REAS; Wallerstein *et al*., 2006b), the Sediment Impact Assessment Method (SIAM; (Biedenharn *et al*., 2006) and the Cellular Automaton Evolutionary Slope and River model (CAESAR; Coulthard *et al*., 2002). Experimental data and evidence of historical morphological responses in the Pontbren catchment will be used to validate the modelling approaches. The project aims to deliver:

- A science base and methodology to predict downstream morphological adjustments in response to the hydrological and sediment impacts of future climate and land use changes in upland catchments.

- Rational evaluation of the extent to which these impacts can be reduced through land and river management interventions, and a decision-support tool for selecting appropriate management actions.

- A report detailing the implications of (1) and (2) for future flood risk management strategies in the UK, particularly for flood risk management responses that involve source control and/or catchment-wide storage in upland environments.

In addition to further work relating to links between land use management and sediment dynamics, data collected at during this investigation at Pontbren constitutes a rare and valuable source of information regarding sediment transport in a British upland environment. Catchment-scale experimentation of this kind has been limited in the past and the data could be used to explore a variety of more theoretical topics including bedload and suspended sediment transport prediction, controls of bank stability, and channel network recovery following destabilisation. The combined effects of changes in catchment sediment dynamics and hydrology on instream and riparian habitats in the Pontbren study area is also of interest and pilot studies involving students at the University of Nottingham have been undertaken with a view to more detailed investigations in the future. Such goals have, in part, inspired the extension of research at Pontbren until at least November 2010.

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