IMPACTS OF UPLAND LAND MANAGEMENT ON FLOOD RISK: MULTI-SCALE MODELLING METHODOLOGY AND RESULTS FROM THE PONTBREN EXPERIMENT

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Summary

Recent UK floods have renewed speculation about the linkage between agricultural land management and flooding. Available data to quantify effects of agricultural intensification have been limited, small scale, and mainly focused on the lowlands and arable agriculture. There is a need to quantify impacts for upland areas, which are source areas for runoff generation, and to develop methods to extrapolate from small scale observations to predict catchment-scale response. With assistance from a cooperative of Welsh farmers, and support from the EPSRC Flood Risk Management Research Consortium, a multi-scale experimental programme has been established at Pontbren, in mid-Wales, an area of intensive sheep production. The data have been used to support development of a multi-scale modelling methodology to assess impacts of agricultural intensification and the potential for mitigation of flood risk through land use management. This report provides details of the experimental results, the modelling methodology, and the simulated impact of land management interventions at Pontbren, at both field and catchment scales.

Data are available from statistically-replicated experimental plots under different land management treatments, from instrumented field and hillslope sites, including tree shelter belts, and from first and second order catchments. Measurements include rainfall and climate variables, soil moisture, soil water pressure and soil hydraulic properties at multiple depths and locations, tree interception, overland flow and drainflow, groundwater levels, and streamflow from multiple locations. Detailed, fine resolution, physics-based models have been developed to represent soil and runoff processes, and conditioned using experimental data. The response of these detailed models is used to develop and calibrate simpler ‘meta-models’ to represent individual hydrological elements – in this case mainly individual fields, with their associated field drainage. These meta-model elements are then combined in a distributed catchment-scale model.

Hillslope-scale data, from an under-drained, agriculturally 'improved' pasture, show that field drain flow is a dominant runoff process. However, depending on antecedent moisture conditions, overland flow may exceed drain flow rates and can be an important contributor to peak flow runoff at the hillslope-scale. Flow, soil tension data and tracer tests confirm the importance of macropores and presence of perched water tables under ‘normal’ wet conditions (following the unusually dry summer of 2006 the heavy clay soils cracked, and hydrological response was significantly different until the soils rewetted). Comparisons of soil hydraulic properties show significant increases in hydraulic conductivity and saturated moisture content of soil under trees compared to adjacent improved pasture. Comparisons of pasture runoff with that from within a 10 year-old tree shelterbelt show significantly reduced overland flow due to the presence of trees and/or absence of sheep.

Detailed field-scale simulations are presented to demonstrate the dominant runoff processes under intensive sheep production, and impacts of the use of tree shelter belts in improving soil structure and reducing peak runoff intensities. Catchment-scale simulations show the effects of improved and unimproved grassland, and the potential effects of land management interventions, including farm ponds, and tree shelter belts and buffer strips. Results indicate that careful placement of such interventions can significantly reduce the magnitude of peak runoff at the field and small catchment scale. Simulations carried out within a framework of uncertainty analysis suggest that, for frequent events, the median effect of introducing optimally placed tree shelter belts to the current land use is to reduce peak flow by 29%; introducing full woodland cover would reduce flows by 50%. Considering an extreme event (the Carlisle January 2005 rainfall), the corresponding median effects are a 5% and 36% reduction.

It is concluded that the methodology developed has the potential to represent and quantify catchment-scale effects of upland management; continuing research is extending the work to a wider range of upland environments and land use types, with the aim of providing generic simulation tools that can be used to provide strategic policy guidance.

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1. Introduction

1.1 BACKGROUND

Recent Government policy on flood risk management, in particular DEFRA's Making Space for Water (MSW), recognises that water management must be seen in a broad perspective, and is inextricably linked to land management. If effects of land management are significant in influencing hydrological response at the catchment scale, that is clearly important in terms of flood risk assessment, but also raises the possibility that appropriate land management interventions might be adopted to reduce downstream flood risk. There is therefore an urgent need for guidance concerning the hydrological impacts of land management to inform agricultural policy.

The floods that affected England and Wales during 2000/2001 reinforced growing concern that changing agricultural practices in the UK may have increased the risk of flooding (Wheater, 2006). Land use and management as a source of flooding was one of the key priority areas of short term need identified by the EPSRC in establishing the Flood Risk Management Research Consortium, and, previously, by the DEFRA/EA R&D programme (Calver and Wheater, 2002; Wheater, 2002), following extensive consultation. The role of land use management in enhancing and/or ameliorating UK flood risk was seen as an unanswered question, a view reinforced by a major review, commissioned by DEFRA (O'Connell et al., 2004).

This is not an issue solely confined to the UK; similar concerns have been raised elsewhere across northern Europe (Evrard et al., 2007; Pinter et al., 2006; Bronstert et al., 2002; Pfister et al., 2004; Savenije, 1995). It is thought that agricultural intensification may cause higher flood peaks in streams and rivers due to its impact on runoff processes. For example, degradation of soil structure can lead to reduction in soil infiltration rates and available storage capacities, increasing rapid runoff in the form of overland flow (Heathwaite et al., 1990; Bronstert et al., 2002; Holman et al., 2003; Carroll et al., 2004b; O'Connell et al., 2004). This may increase the risk of flooding (Holman et al., 2003; Stevens et al., 2002), as reported both in the UK and across Northern Europe, particularly on intensively farmed soils (Boardman et al., 1995; Burt 2001).

Although the risk of flooding is concentrated in lowland regions, the management of catchment headwaters, with their generally higher precipitation rates and flashier response, is of particular interest for flood runoff generation. At the outset of the FRMRC programme, it was recognised that while some information on local scale effects of agricultural intensification was available, this was focussed on the lowlands, and arable agriculture. There was an important lack of quantitative information on the impacts of agricultural intensification on runoff from upland catchments.

There are also major uncertainties concerning the propagation of local scale effects to the larger scales of river catchments. Although studies have illustrated how modern management practices can cause an increase in local surface runoff (e.g. Heathwaite et al., 1990), there is little evidence that local scale changes in runoff generation propagate downstream to create impacts at the larger catchment scale. This does not imply that effects do not exist but the few studies in which evidence has been sought have not produced conclusive findings (O'Connell et al., 2004, 2007). It was also recognised that there was a major methodological gap; new modelling methods were required to predict impacts of land use change at catchment scale for flood risk assessment.

Hence, in FRMRC1, the land use management Research Priority Area (RPA2) has focussed on the quantification of the impacts of upland land use management, and the development of modelling methods that can be used to simulate the catchment-scale effects of local scale changes. A major multi-scale experimental and modelling programme has been established in the Severn catchment, at Pontbren, Wales, and this report summarizes the findings from the experimental programme, the development of new modelling methods, and the associated predictions of catchment scale impact of land use and land management change.

More generally, Making Space for Water recognises that a holistic approach to flood risk assessment is required, which should include assessment of morphological change, and include socio-economic change, and stakeholder engagement. And flood risk management must be consistent with a portfolio of policies, including the EU Water Framework Directive, and embrace concepts of environmental sustainability.

A strength of the FRMRC programme is the integration of multi-disciplinary expertise. Hence links were established between RPA2 and RPA8 (Morphology and Habitats), and joint research undertaken to quantify sediment yields associated with different land management and associated stream morphological dynamics. Links were also established with RPA7 (Stakeholder and Policy), and stakeholder research has included evaluation of social, policy and economic controls on land use management, as well as facilitating dialogue between the stakeholder community and the modelling team. There has been close liaison throughout with RPA9 (Risk and Uncertainty), and the work has also linked with elements of the programme in Broad Scale Modelling (RPA5). The Pontbren experiment has thus drawn together researchers from different disciplines and institutions, and established a multi-disciplinary perspective, consistent with the broad aims of MSW.

1.2 AIMS AND OBJECTIVES

Gaining a better understanding of how changes in upland land management can alter the risk of flooding at catchment scale is a key objective of the UK Flood Risk Management Research Consortium (FRMRC; Pender, 2006). The strategic aims of the Land Use Management programme are therefore:

- To develop scientific understanding of the local scale effects of agricultural land management practice on flooding and of their catchment scale impacts.
- To develop modelling tools to represent impacts of land use management at local and catchment scale.
- To provide policy guidance on land management strategies to mitigate flood risk.

As noted above, a multi-scale experimental and modelling programme has been set up at the Pontbren catchment, mid-Wales. The experimental programme was based on experimental plots, in which land use and land management are being manipulated, and detailed monitoring of hillslope and catchment-scale response to support modelling at those scales. The programme was designed to:

- Quantify local scale impacts of upland land management, including grazing, woodland and riparian buffer strips on soil structure, flood runoff generation and geomorphology.
- Develop multi-scale data to support analysis of the scale-dependence of model parameters.
- Support subsequent extension of the analysis of impacts to the Upper Severn catchment.
- Support analysis of land management policy recommendations for flood mitigation.

In parallel, the modelling research aimed to:

- Derive plot scale physical properties and uncertainty bounds for alternative land use management treatments.
- Derive effective properties and uncertainty bounds at hillslope scale.
- Develop a multi-scale modelling methodology.
- Apply the modelling methodology at 1st order catchment scale to investigate effective properties and catchment-scale impacts of alternative land use management practices.

1.3 PONTBREN AND THE PONTBREN CO-OPERATIVE

This research emerged from, and builds on the Pontbren project, which is a ‘grass-roots’ initiative involving 10 hill farms and over 1000 ha of agriculturally improved pasture and woodland in the upper Severn catchment. Crucially, it was the farmers’ experience and concerns for the impacts of agricultural intensification that led to pilot studies at the site (Carroll et al., 2004a) and hence to the FRMRC research. The Pontbren project provides landowner support for land access, land management manipulation experiments and for socio-economic analysis. Their direct involvement has been invaluable in providing information on site response and the history of land management, and is also seen as an important issue in the promotion of policy guidance to the agricultural community.

Pontbren is also a focus of Welsh Assembly research on sustainable agriculture, and forms part of the Upper Severn, which is a CHASM element of the UK National Infrastructure for Catchment Hydrology Experiments (NICHE). The Severn is a focus for concerns over impacts of land use management on flooding, and is an Environment Agency Catchment Flood Management Programme pilot area.

1.4 STRUCTURE OF REPORT

The present understanding of the impacts of upland agricultural land use in the UK is introduced in Section 2. Sections 3-5 describe the experimental programme; Section 3 describes the study site, Section 4 the field experiment, and Section 5 the experimental results. Sections 6-8 present the modelling research, and in Section 9 a reflection on this work is provided, with specific recommendations for future work. Conclusions are presented in Section 10, together with a brief summary of relevant research in Phase 2 of the FRMRC programme.

2. Review of impacts of upland land management on flood risk

2.1 CHANGES TO UPLAND LAND MANAGEMENT IN THE UK

The drive for increased productivity in farming in the 20th century, particularly since World War II, has brought about major changes in the UK agricultural landscape (O'Connell et al., 2007). Prior to World War II, key characteristics were small fields with dense hedgerows and natural meandering rivers. Since World War II, changes include: loss of hedgerows and increase in field size, installation of land drains connecting hilltop to river channel, and channelized rivers with no riparian zone. This has been accompanied by changing patterns of agricultural land use and intensity of production. Concerns for changes to runoff processes associated with lowland production have centred on changing land use, for example from pasture to cereal cropping, and changes to soil structure, associated with changes to land management practices and their timing. Here we focus on upland land use and land management.

Upland land use in the UK is dominated by grassland production, mainly for sheep, and to a lesser extent forestry, mainly conifer tree plantations for timber production. In terms of grassland production for sheep, this can be based on improved, semi-improved, or unimproved pasture (open moorland). Sheep numbers in Great Britain have increased substantially, from 19.7 million in 1950 to 30.2 million in 1980, peaking in 1990 at 40.2 million as a result of economic incentives in the form of farm support payments based on the number of stock (Fuller and Gough, 1999).

Sheep population expansion has been most dramatic in northern England, south-west England, and much of Wales. These are regions containing large upland areas, generally deemed unsuitable for commercial arable production. In Wales, 72 % of agricultural land was estimated to be under grassland production in 2005, almost exclusively to support sheep farming. A large proportion of the UK sheep flock is located on designated Less Favoured Areas (LFAs), consisting of upland and hilly areas (Sansom, 1999). In 1995 it was estimated that 88 % of the Welsh sheep flock was to be found in these LFAs, whereas historically, sheep would have been more common on the lowlands with their less harsh climate, and only taken to the uplands during summer months (Sansom, 1999). Associated with this increase in sheep numbers has been the increase in the amount of improved pasture in upland areas, created from open moorland (unimproved pasture) by draining, ploughing, and reseeding with rye grass (*Lolium* spp.). This 'improvement' was also financially supported by government and EEC incentives (James and Alexander, 1998).

2.2 LOCAL (PLOT/FIELD SCALE) EFFECTS OF UPLAND LAND MANAGEMENT CHANGE

The grazing of livestock has been shown to have an effect on the physical properties of the soil. Decreases in soil infiltration rate, porosity, and hydraulic conductivity, along with increases in soil bulk density, have been reported to occur with increasing stocking densities (Rauzi and Smith, 1972; Langlands and Bennett, 1972; Gifford and Hawkins, 1978; Willatt and Pullar, 1983; Greenwood et al., 1997; Nguyen et al., 1998). The reduction in soil infiltration rate, hydraulic conductivity, and porosity suggest that, depending on precipitation rates, these sites will be more prone to overland flow. Enhanced runoff rates at the plot scale have been demonstrated as a result of grazing and increased stocking densities (Heathwaite et al., 1989, 1990; James and Alexander 1998; Nguyen et al., 1998; Elliot et al., 2002). It is thought that the reduction in biomass or height of vegetation, as a direct effect of grazing or when moorland is converted into improved pasture, leads to a corresponding reduction in rooting depth and soil porosity (Sansom, 1999). It is also likely that the reduction in vegetation height, caused by the grazing animals and the change from moorland species, e.g. heather (*Calluna vulgaris*) and bilberry (*Vaccinium* spp.) may exacerbate surface runoff due to a reduction in interception and infiltration rates (Sansom, 1999; Orr and Carling, 2006)

The under-drainage of clay soils to improve production is a common agricultural practice and the UK is one of the most extensively under-drained countries in Europe. Much of this drainage occurred between the 1940s and the 1980s, encouraged by government grants and free advice (Robinson and Armstrong, 1988). Drains were typically installed in 'grid-iron' or 'herringbone' patterns to a depth of between 0.85 and 1.4 m and at a spacing of between 12 and 40 m, depending on the permeability of the soil and the level of water table control (Armstrong and Harris, 1996). In the UK, very impermeable soils will often have a secondary treatment such as 'subsoiling' or 'moling', however this is not commonly practiced in upland areas under grassland production. In upland areas, underdrainage is generally installed to reduce surface water occurrence as a result of impermeable subsoil and for spring water alleviation (Robinson and Armstrong, 1988) and, in the case of moorland, to improve vegetation suitability for grazing (Holden et al., 2004). We note that in Wales the Wilcocks soil series (one of the dominant soil series at Pontbren) was considered to require drainage to intercept water moving downhill laterally above impermeable subsurface layers (Robinson and Armstrong, 1988). Although the cessation of grants in 1984 has meant that there has been little new land being drained, some of the existing drainage is still maintained (Armstrong and Harris, 1996).

In terms of runoff, the installation of field drains will generally cause a reduction in surface and near surface runoff due to a lowering of the water table and an increase in the available storage capacity of the soil. Runoff from undrained land may be faster or slower depending on the nature of the soil and its management (Armstrong and Harris, 1996), as well as the temporal patterns and intensity of rainfall. Reid and Parkinson (1984) illustrated how runoff response from drained fields varied seasonally depending on antecedent moisture conditions. A reduction in time to peak and increase in magnitude in peak flows has been reported in relation to installation of field drains in a 16 km^2 clay catchment in N.E. England (Robinson et al., 1985).

The drainage of soils rich in organic matter may have both short and long-term effects. Lowering the water table in peatlands will increase the amount of available storage capacity in the short term but will also increase organic matter decomposition rates, resulting in a subsequent decrease in available storage as the organic matter content decreases (Holden et al., 2004) and hence potentially an increase in flood peaks in the long term. There is anecdotal evidence from the Pontbren catchment that the Wilcocks soil series, with its peaty surface layer, may have in recent years retreated up the hillside, being replaced by the Cegin series which lacks this organic rich surface layer and its associated soil water storage capacity. This has been (anecdotally) attributed to agricultural intensification activities, such as the installation of field drains and increase in stocking densities.

2.3 RUNOFF PROCESSES AND LAND MANAGEMENT CHANGE

The processes that deliver stormflow to streams will vary, depending directly on topography, soil properties, and rainfall characteristics, and indirectly on climate, vegetation and land use (Anderson and Burt, 1978; Dunne, 1978). Theories of runoff production are well developed, based on recognition of the hillslope as the key hydrological element for runoff production. Recognition of the important role of subsurface flow at hillslope scale led to concepts such as the variable source area (Dunne and Black, 1970), in which lateral subsurface flows generate dynamic areas of near-stream saturation and runoff production. Subsequent work has recognised the importance of preferential flow paths. Macropores and naturally occurring soil pipes, in association with transient perched water tables, have been demonstrated to be important contributors to streamflow in upland catchments in the UK (Chappell et al., 1990; Kirkby 1991; Muscutt et al., 1993; Jones, 2004; Wheater et al. 1991, 1993).

However, for upland areas where, as at Pontbren, there is extensive field drainage, the concept of the hillslope as the basic element of runoff generation has to be modified. After drainage, runoff processes will depend on the field drain network and its connectivity to the stream. Since drainage is generally associated with a well-developed system of ditches, which accept drain flows and overland flow, it is the drain and ditch system that define the hydrological response units.

In impermeable catchments, with hard rock geology, it is generally thought that groundwater does not play an important role in streamflow generation. However, hydrochemical data from the Plynlimon catchments in mid-Wales have illustrated the importance of groundwater in streamflow generation in a catchment previously thought impermeable (Neal, et al., 1997; Haria and Shand 2004: Shand et al., 2005; Haria and Shand; 2006). Nevertheless, where extensive drainage is installed, it is likely that soils are of low permeability, and that interaction between storm runoff response and groundwater is limited. Groundwater at Pontbren is discussed in Section 3, but we can note that while localised groundwater occurs, and is exploited by the farmers for water supply, and some drains have been installed to intercept seeps, the evidence is that groundwater response is disconnected from surface water response and that groundwater plays a very limited role in streamflow generation.

2.4 CATCHMENT-SCALE EFFECTS OF UPLAND LAND MANAGEMENT CHANGE

To date, catchment-scale hydrological studies in upland UK have mainly focused on the impact of afforestation. The drive for self sufficiency in food production during the last century was discussed above; similar concerns regarding timber resulted in large swathes of upland moorland in the UK being converted into plantation forestry. Catchment studies, most notably the Plynlimon experiments, partly located in the Upper Severn catchment in Wales, were undertaken initially in response to concerns about the effects that such land use might have on water yields, as raised by Law in 1956. Subsequently there have been concerns over the impact of forestry on flood events. The widely held view, based on extensive studies worldwide, is that mature forests will in general significantly reduce peak flows due to increased evaporation losses, particularly due to interception, and the increased water storage capacity of soils under trees (Robinson and Dupeyrat, 2005). However, afforestation of the UK uplands was historically associated with extensive drainage, and in an important study of the Coalburn catchment, it was shown that moorland drainage, undertaken to support afforestation, played a key role in *increasing* peak flows. However, as the life cycle of the plantation proceeded, the increased influence of the growing trees became more important and peak flows subsequently reduced, particularly for smaller events (Robinson et al., 1991; Robinson, 1998; Robinson et al., 2003).

In 2005 it was estimated that plantation forestry occupied less that 7 % of the land cover, compared to more than 50 % of total land cover being under grassland production in the UK. There is therefore a need for catchment studies to investigate this important land use. Studies have demonstrated that intensive grazing of animals will have an impact on runoff at the plot scale, but, despite the extensive use of grassland for livestock production in upland UK, relatively little is known about its impacts on river flows. Increased peak flows and flood events in rivers have been associated with increases in stocking densities (Sansom 1999; Meyles et al., 2006) but it has been difficult to isolate the impact of land use change from that of climate change and general variability of response at the catchment scale (Sullivan et al., 2004; Orr and Carling; 2006). The drainage of moorlands has also been associated with a reported increase in flood frequency (Lane, 2001). However, studies into the impact of peat and hill drainage present conflicting results (Robinson 1990; Holden et al., 2004). A current Defra-funded project to investigate evidence of land use change in catchment-scale response (project FD2120) has yet to report, but we understand (K. Beven, pers. comm.) that results are again inconclusive – uncertainties in data, compounded by climatic variability and complex patterns of land use change, preclude simple analysis of catchment scale effects.

As well as the direct impact that land use change may have on flood peaks, associated with runoff production, there are also potential indirect effects resulting from the impact on catchment sediment dynamics. Increased probability of flooding because of channel aggradation, with reduction in conveyance capacity and higher water levels, as a result of increases in sediment delivery associated with upstream changes in land use has been illustrated in the USA (Stover and Montgomery, 2001). Initial results from a study currently taking place in the Pontbren catchment has shown significantly higher bedload yields in subcatchments where extensive areas of land have been artificially improved to support intensive grazing, compared to ones dominated by unimproved pasture (Henshaw and

Thorne, in review). This is associated with local-scale channel degradation, but clearly there is the potential for downstream aggradation.

In summary, relatively little is known about the impacts of upland agricultural land use on flood generation (O'Connell et al., 2004). In spite of this, policy makers are looking to land use management as one means of managing flood risk (Archer, 2007). In the comprehensive review of studies into the impacts of rural land management on flood generation, O'Connell et al. (2004) highlighted: 1) the complexity of the local scale impacts; 2) the very limited amount of evidence of catchment scale impacts; and 3) the inadequacies of available data sources and modelling studies. Among their recommendations, they called for field trials of flood mitigation measures and the establishment of a solid research base towards establishing best practice. This provided strong motivation for the development of the experimental resource at Pontbren.

3. Study area

This chapter describes the Pontbren study area.

3.1 LOCATION AND CLIMATE

Pontbren is located in the headwaters of the Upper Severn, Powys, in mid-Wales (Latitude 52.65°, Longitude -3.41°) (Figure 3-1). Because of its proximity to the west coast of the UK mainland, the climate is strongly influenced by oceanic weather patterns, characterised by warm moist conditions. The average annual precipitation measured at the Pontbren rain gauge site **HT** (see location on Figure 4-1) for the period April 2005 – January 2008 was 1670 mm.

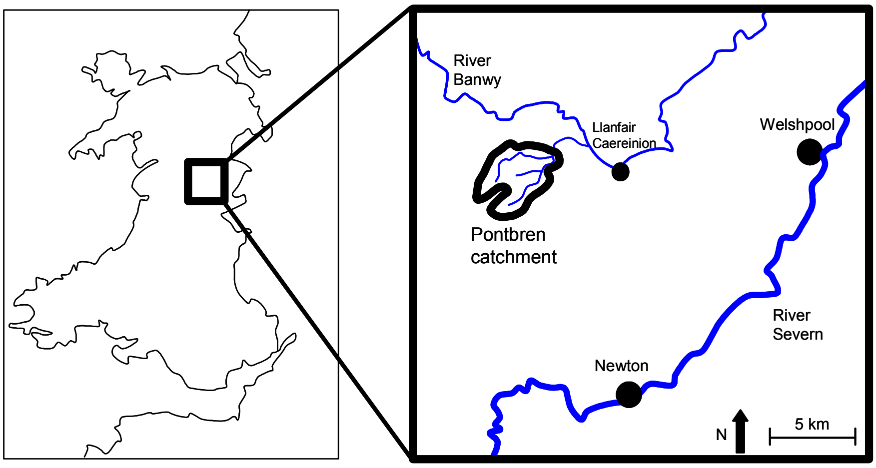


Figure 3-1. Pontbren study site location.

Figure 3-2 highlights the main streams of the Pontbren catchment along with the adjacent and smaller 'Rhos aflo' catchment. The primary stream in the Pontbren catchment is the Afon Einion, siginificant tributaries of which are: the 2nd order Nant Melin-y-grug; and 3rd order Nant Pont-bren-down which is formed where the Nant Pen-y-Cwm and Nant Gelli-Gethin meet. At the outlet of the Pontbren catchment, the Afon Einion feeds into the Afon Banwy neu Einion, a primary tributary of the River Severn. The drainage areas of the Pontbren and Rhos aflo catchments are approximately 18 km^2 and 4 km^2 respectively.

The Pontbren streams are mostly perennial, however dry river beds have been observed over most of the stream network at some time during the three summers of our experimental observation (2005-2007), and, according to anecdotal evidence from local farmers, such occurrences have increased in frequency in recent years (R. Jukes pers. comm.). Farmers also suggest that since the 1960s significant increases in overland flow and flood flows have occurred, together with associated increases in channel bank erosion. Evidence of channel bank erosion and scour damage to culverts is clearly visible on the main streams and along drainage ditches.

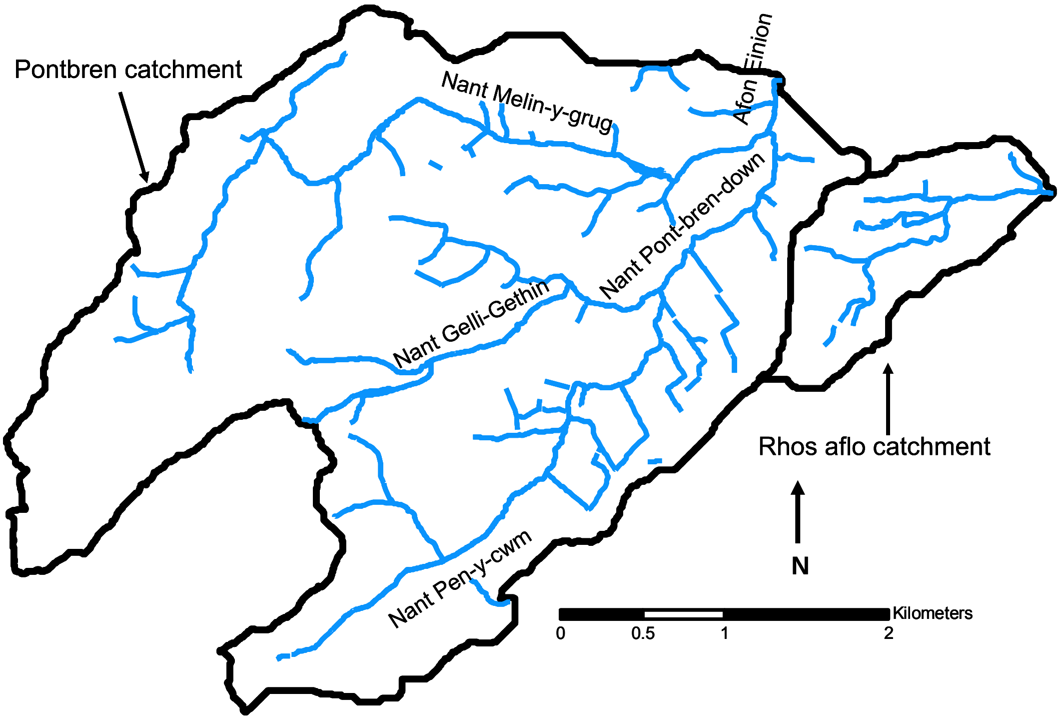


Figure 3-2. Pontbren and Rhos aflo catchment boundaries along with stream networks.

3.2 TOPOGRAPHY

The local topography consists of the characteristic undulating hills of mid-Wales. Land is situated between 170 m and 438 m above Ordinance Datum (AOD), Figure 3-3, with higher ground to the west draining to the east. Although these are not 'upland catchments' in a global context, they are considered so in terms of UK agriculture.

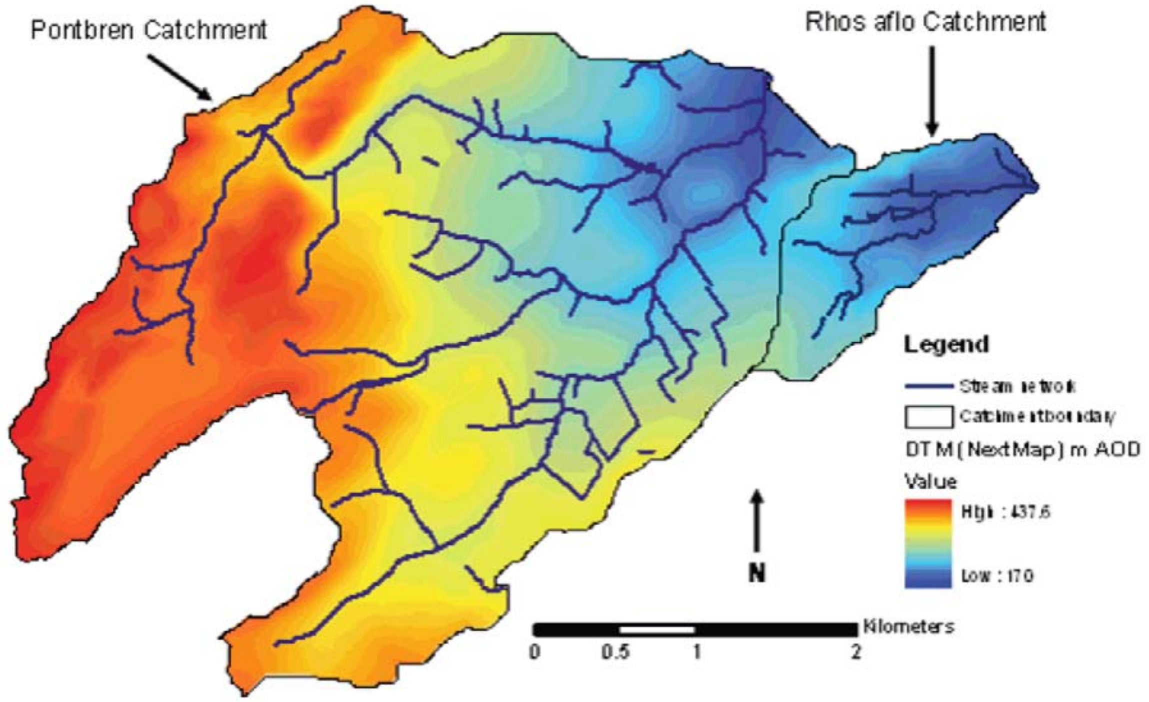


Figure 3-3. Catchment topography

3.3 SOILS

Clay-rich soils dominate the landscape, with peaty surface layers found on the higher ground. Soils tend to be waterlogged for long periods of time due to an impermeable subsurface layer and relatively wet climate (Rudeforth et al., 1984). Figure 3-4 shows a soil map for the Pontbren area produced from a survey carried out by the National Soils Resources Institute (NSRI) in March and April of 2005. The Cegin association is the dominant soil series (37 % of the area under investigation), consisting mainly of cambic stagnogleys with brown earths on the steeper slopes. The 2nd most dominant soil series is the Wilcocks series (25 % of the area under investigation, cambic stagnohumic gley soils), which is found mainly at higher altitudes. Both soil series are widespread in Wales on glacial drift derived from Ordovician and Silurian greywackes, which may explain the frequent occurrence of stones and boulders composed of coarse sandstones (Bird et al., 2003). A description of the soils found at Pontbren is given in Table 3-1.

Figure 3-5 shows a typical soil profile of the Cegin soil series which is classified as a slightly stony clay loam and is characterised by a slightly sloney, clay loam A horizon, overlying a slowly permeable clay loam subsoil B horizon which is slightly or moderately stoney. Hydrologically, the Cegin soil series tend to be seasonally waterlogged, classed as ‘commonly’ or ‘usually wet’, with the topsoil wet for much of winter and early spring with most of the water moving laterally through the upper parts of the soil due to the impermeable nature of the subsoil (Thompson, 1982; Rudeforth, 1984).

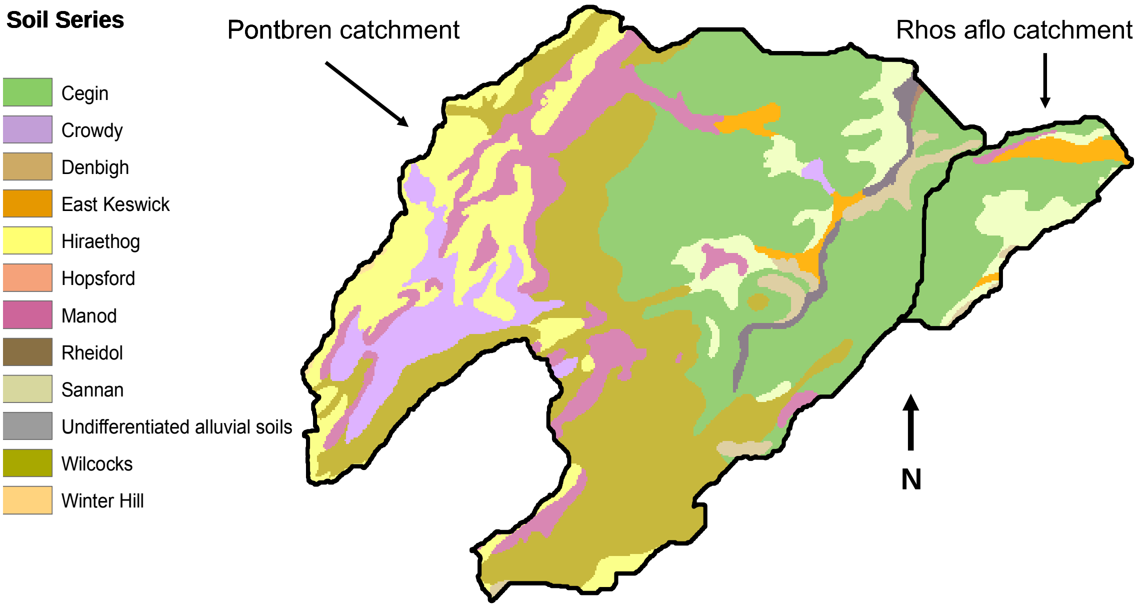


Figure 3-4. Catchment soils.

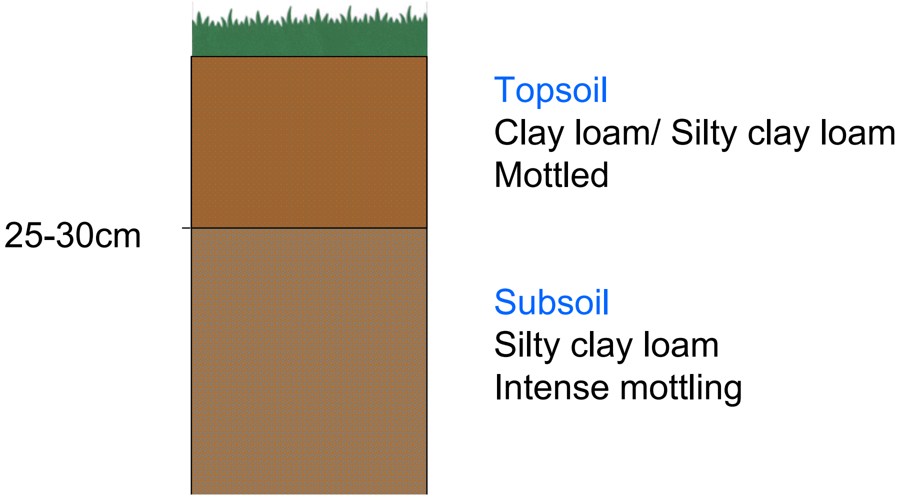


Figure 3-5. Profile of Cegin soil series.

At the same time as the soil mapping exercise, an assessment was made of the state of soil structural properties across the catchment. The methodology employed was that used for the assessment of soil structural conditions in a number of agricultural catchments in the UK including one in the Ardleen district in the upper Severn catchment, following the flooding in 2000/2001 (Holman *et al.* 2003). However, direct comparisons were limited, due to the restricted range of land management at Pontbren (almost exclusively improved and unimproved pasture) compared with that found in the Ardleen district. Pontbren also has extensive areas of soils with organic topsoils along with more localized deposits of peat soils.

Table 3-1. Soils of Pontbren Catchment (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 3-2. Soil degradation classes and defining features according to the NSRI

Degradation class	Description of hydrological implications	Soil degradation features
Severe	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	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	Soil degradation generates localised areas of enhanced runoff where slopes allow	Slight poaching (locally severe); weak subsurface structure/compaction
Low	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

The assessment indicated widespread soil structural degradation across the catchment and identified approximately 15 %, 58 %, and 25 % of the area being slightly (low degradation class), moderately, or highly degraded, respectively. A summary of the degradation classes according to NSRI is provided in. It was found that all highly degraded soils were confined to areas under improved grassland production. Furthermore, anecdotal evidence suggests that the Wilcocks series with its peaty surface layer may have in recent years retreated somewhat up the hillside being replaced by the Cegin series.

This may have occurred as a result of land management intensification such as increasing stock densities and the installation of field drains.

3.4 LAND USE AT PONTBREN

Historically, a shift occurred from relatively small farms at the beginning of the 20th century, practicing mixed farming systems, to a more intensive, solely pastoral, system, driven by government incentives to improve productivity. Records dating as far back as 1845 indicate that the land was occupied by tenant farmers who practiced both arable and pastoral farming with relatively low stocking densities. Field sizes in these times tended to be small, accompanied by large areas of common grazing land. The depression that followed World War I resulted in a number of farms going out of business and average farm sizes increased as farmers were able to buy land at relatively low prices. The shift to a more pastoral system came about as a result of World War II and government incentives to improve productivity. This included the provision of grants to install field drains and carry out ploughing. Government incentives continued during the 1970's, which saw a rapid increase in intensification of land management with the increased use of fertilizers and field drainage system installation. During this time ploughing was encouraged and field sizes increased with the removal of hedgerows and riparian buffer strips. Stock numbers also increased dramatically. Between 1969-1978 sheep numbers increased by a factor of 6 and the number of cows by a factor of 3 at Tyn y Bryn Farm, within the Pontbren catchment. Although cutbacks in government and European Union subsidies and incentives in the early 1980's resulted in some reduction of productivity, it remains relatively high compared to the beginning of the 20th century. In the last decade European Union legislation such as the Water Framework Directive (CEC, 2000) and the Habitats Directive (CEC, 1992), and associated UK legislation and best practice guidelines, have encouraged farmers to establish tree plantations, provide buffer strips along stream banks and drainage ditches and to re-establish hedgerows.

Today, the land at Pontbren is almost exclusively under grassland land management, which occupies approximately 88 % of the land, mainly used for sheep production, with some beef and dairy herds. Of this grassland, almost 66 % is deemed to be improved pasture, the rest being unimproved. Figure 3-6 shows an aerial photograph of the Pontbren and Rhos aflo catchment along with the surrounding area. The photograph illustrates how pasture dominates the landscape. The lighter colour to the west is unimproved pasture, confined to the higher ground within the Pontbren study site. Woodland areas occupy 7 % of the land, and the remaining 5 % is crops, roofs, paved areas, private gardens and open water.

Approximately 70 % of the agricultural land area in England and Wales has been drained and most improved grassland within Pontbren has been artificially under-drained at some point between the 1940's and 1980's (although some original drainage installation dates as far back as Napoleonic times). Typically under-drains consist of a network of tile or, more recently, perforated plastic pipes installed at a depth of approximately 0.7 m. 'Moling' (dragging a bullet shaped piece of metal through the soil) has also been used in the past to improve soil drainage however, this practice in the area is relatively uncommon.

Around 43 % of the Pontbren and Rhos aflo catchments are farmed by the 'Ponbren group'. This is a consortium of 10 contiguous farms, whose aim, amongst others, is to provide a more sustainable, less intensive farming system. Part of the group's management strategy adopted by some of the farmers has been to fence off areas of land and plant trees to provide shelter for livestock. This allows the animals to remain out on the land for longer over winter and hence reduces the cost of housing over winter. The presence of these tree-planted shelter belts provides an ideal opportunity to investigate their hydrological impact and potential to mitigate flow peaks at the hillslope scale.

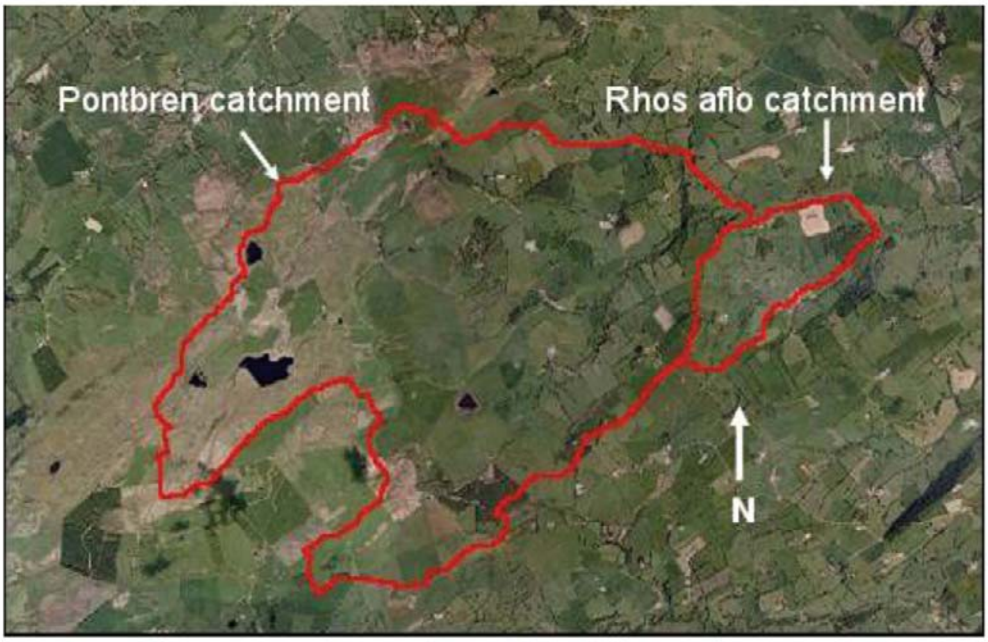
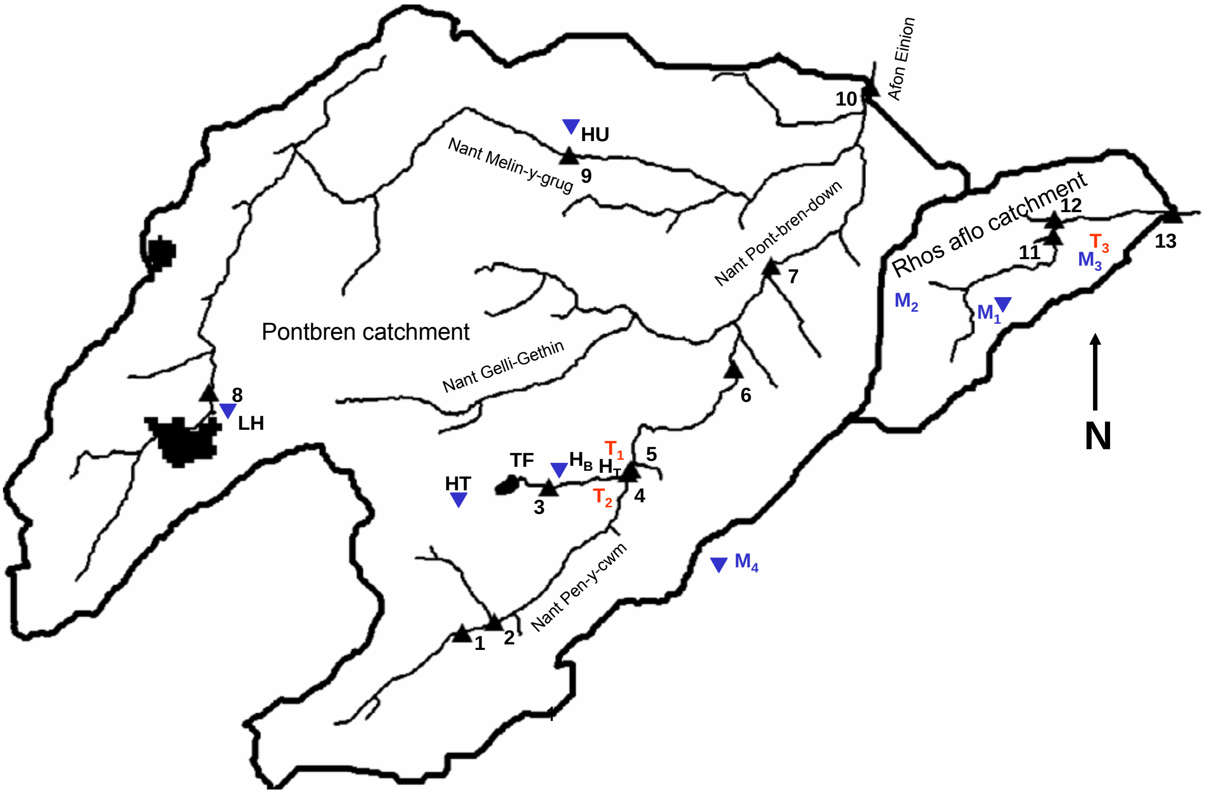


Figure 3-6. Aerial photograph of Pontbren and surrounding locale.

4. The Pontbren field experiment

The Pontbren field study is a multi-scale experimental programme designed to monitor the hydrological response at a range of scales. At the plot scale (~100m^2 or 0.0001 km^2), the effects of land use change on hydrological response are being investigated directly at four sets of manipulation plots, as well as within four tree shelter belts. Data from the hillslope scale (~ 0.1 km^2) is being used to support model development and underpin the conceptual understanding of the hydrological response of these clay-rich, relatively impermeable, catchments which have been subject to extensive land management intensification and field drainage installation. Catchment-scale (1 to 10 km^2) monitoring is taking place at a number of locations, including different land management regimes, in order to better understand the integrated effects of land use on flow peaks at different scales of observation. Across the study site, components of the hydrological cycle are measured either directly or indirectly to understand the hydrological response. Components measured are: precipitation, potential evapotranspiration, interception, throughfall, stem flow, infiltration, soil water state (moisture content and pressure potential), groundwater elevation, drain flow, overland flow, drainage ditch flow, and stream flow. Figure 4-1 shows the location of the main instrumentation sets, details of which are provided in Table 4-1. Although the catchment is relatively intensely instrumented, there are inevitable limitations to how well the area can be sampled. Sampling sites were selected to be as representative as possible given available resources, access constraints and other practical considerations. Subsidiary experiments, including dye tracer tests, vegetation interception monitoring, as well as in-situ and ex-situ determination of soil physical properties have also been undertaken.

This chapter describes the experimental setup and methodology of the field experimental work undertaken at the Pontbren study site. The soil characterisation experimental methodology is described before discussion of the manipulation plot, tree shelter belt, hillslope scale, and catchment-scale monitoring programmes.



Legend: LH Llyn Hir; ; **HT** Tyn y Bryn Hilltop; **TF** Tyn y Bryn Top field; **H_B** Instrumented Hillslope – The Bowl; **H_T** Instrumented Hillslope – Tree planted hillslope; **T_n** Tree planted study site; **M_n** Manipulation plots; **HU** Hirrhos Uchaf; **▲n** Stream and drain flow monitoring site; ▼ Rain gauge.

Figure 4-1. Pontbren study site instrumentation location.

4.1 SOIL CHARACTERISATION

Soil hydraulic properties are fundamental to the understanding of soil hydrological response and the application of physically-based modelling tools. Hence a number of experiments have been carried out on the dominant soil types at Pontbren to characterise the soil physical properties and investigate the influence of land management regime on water movement through these soils.

Soil moisture characteristic curve, dry bulk density, and saturated hydraulic conductivity determination of Pontbren soils

The soil moisture characteristic curve, SMCC, dry bulk density, ρ_b, and the saturated hydraulic conductivity, K_{sat}, are fundamental physical characteristics of the soil. The ability to describe the SMCC, i.e. the relationship between soil moisture content and pore water pressure, is required for most physically-based soil water flow and transport models. The SMCC allows pressure measurements to be related to moisture content changes, and the SMCC also indicates the available soil moisture storage within the soil.

For any given porous medium such as soil, there is a relationship between the pressure head, ψ, and soil water content, θ (expressed either volumetrically or gravimetrically). This relationship is not unique, since it depends to some extent on whether the medium is taking up water (adsorption) or water is being withdrawn (desorption) (Hillel, 1980).

Atmospheric pressure is commonly taken as a zero pressure reference (ψ = 0 cm H_2O). When suction is applied to that soil, once a critical value is exceeded, the largest pores within the soil will empty. This is known as the air entry suction (Hillel, 1980) and is dependent on the size of the largest pores. As greater suction is applied, progressively smaller pores will empty. The pore size distribution within the soil will therefore be the fundamental influence on the soil moisture status of the soil. This is governed by the particle size distribution, along with the soil structure. Coarse textured soils, with a relatively high sand content, will tend to have a greater number of large pores compared to fine textured, clay rich, soils. This will mean that they will tend to lose water more quickly at lower suctions, compared to fine textured soils. Figure 4-2a shows hypothetical soil moisture release curves for clayey and sandy soil. Soil structure will also have an important influence on the soil moisture characteristic curve. Compacted soils will have a reduced total porosity, especially the number of larger interaggregate pores, and this will also have an affect on the soil moisture characteristic curve (Hillel, 1980) (see Figure 4-2b).

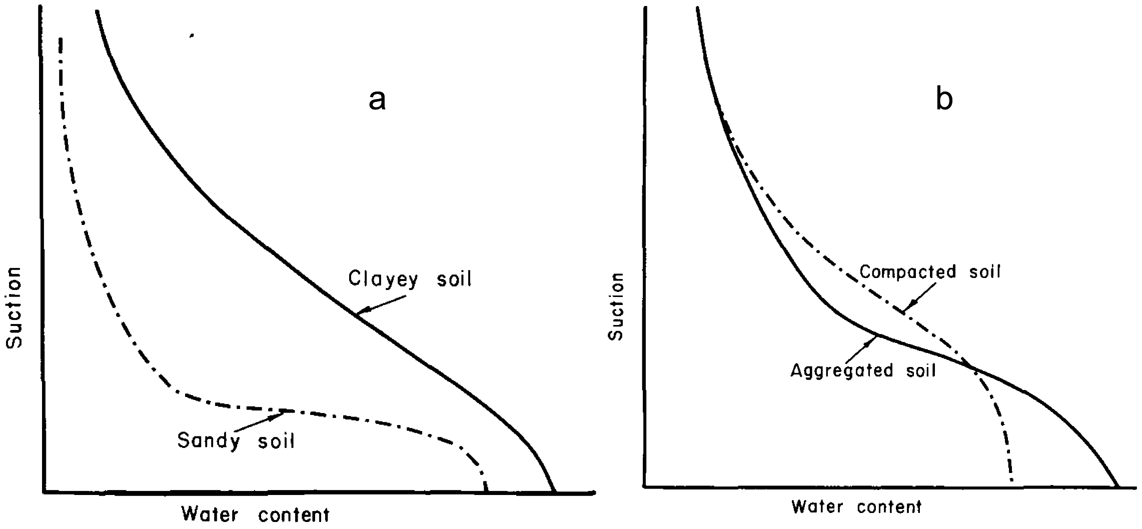


Figure 4-2a and b. The effect of texture and structure on soil-water retention respectively (after Hillel, 1980).

The SMCC has been measured across the study site; measurements will continue in the manipulation plots as the treatments mature. Intact and disturbed samples were collected from the A and B horizons of the soil from the instrumented hillslope (see Section 4.4) (including from within the tree planted shelter belt), all 3 plots within each of the 4 manipulation plot sites, and from the tree areas ($T_{1\text{-}3}$) (see Section 4.2). Undisturbed samples were saturated and then placed on a tension table apparatus to determine the soil moisture characteristic curve at the wet end of the scale, up to ~ 0.1 bar (100 cm H_2O) applied suction. Disturbed samples were placed on a pressure plate apparatus, saturated, and then used to determine the SMCC at the dry end of the scale, between 0.33 and 15 bar suction. At the same time the soil dry bulk density, ρ_b (gcm^{-3}), was also measured.

At each of the sampling sites, replicate samples were collected from both the A and B soil horizons. Soil samples for soil moisture release curve determination were collected from each of the manipulation plot sites described in Section 4.2. At each of the four sites, three sub-samples were collected from within each of the treatment plots. Once manipulation treatments have become established, resampling will be undertaken to determine whether treatments have had an impact on the soil moisture characteristic curve. Samples were also collected from the three tree area sites described in Section 4.3 ($T_{1\text{-}3}$) to investigate the impact of tree age. Samples were also collected from both 'the bowl' and the tree planted hillslope of the instrumented hillslope described in Section 4.4.

Measurement of the saturated hydraulic conductivity of the Pontbren soils

The saturated hydraulic conductivity, K_{sat} (md^{-1}) is a measure of the rate at which water can be transported through a porous medium, when saturated. The hydraulic conductivity will decrease as a soil dries and the pores progressively empty. From knowledge of K_{sat} and the SMCC, the full unsaturated hydraulic conductivity relationship can be estimated.

K_{sat} is dependent on the distribution of pore sizes throughout that medium, with larger pores allowing water to move through them faster than smaller pores. The pore size distribution is dependent on the texture of the soil, with sandy soils, with their larger grain sizes, tending to have a higher K_{sat} than fine textured clay soils. Changes in soil structure and density will also have a significant effect on the K_{sat} due to changes in the pores size distribution. Compaction will result in reduction in the total porosity, mainly reducing the number of large pores which are able to transport water relatively quickly.

K_{sat} will also vary in time and space. For example, inter-annual cycles caused by climatic variations will have an impact on K_{sat}. The drying of clay soils, and the action of freezing and thawing can have an impact on the soil structure. K_{sat} will tend to decrease with depth as a result of the soil weight, anthropogenic influences and geochemical processes, and is often assumed to decay exponentially with depth (Beven, 1986). Because of the heterogeneous nature of soil, K_{sat} will vary across the landscape and also at the scale of observation. The presence of preferential flow pathways, due to changes in density or the presence of macropore structures (such as cracks between soil peds and biotic structures such as earthworm channels or decaying root channels, for example) can have a dramatic effect on K_{sat}.

The situation is further complicated as soils become unsaturated. As soils dry, the hydraulic conductivity, $K(\theta)$, will decrease as the larger pores progressively empty and the water will tend to move through films of water that surround the soil pores. $K(\theta)$ is therefore dependent on the soil moisture status and also how well these films of water are connected. This is also strongly affected by the texture of the soil. This is not a linear relationship but can be estimated from the K_{sat} value of a soil and knowledge of the soil moisture characteristic curve. For sandy soils, with their relatively high K_{sat} values, hydraulic conductivity will tend to decrease rapidly as the soils dry out. A slight drop in moisture content from saturation will lead to a relatively sharp drop in K in sandy soils compared to clay rich soils which, despite the relatively low K_{sat} will tend to maintain $K(\theta)$ values as suction increases. Hence at lower moisture contents, clay rich soils will tend to have higher $K(\theta)$ values than coarse textured sandy soils. $K(\theta)$ is difficult to measure and requires simultaneous measurements of K and θ. It is often approximated by empirical formulae such as those derived by van Genuchten (1980) and van Genuchten-Maulem (Maulem, 1986) making use of the soil moisture characteristic and K_{sat} which are more easily measured.

Two methods have been used at Pontbren to determine K_{sat}. Intact soil cores were collected from the A and B horizons of the improved pasture within the instrumented hillslope (see Section 4.4) and from within Pant Powsi, one of the tree shelterbelt areas (see Section 4.3). A falling head permeameter device was used to measure K_{sat} using the cores collected. *In situ* measurement of K_{sat} of the A and B horizons was also undertaken, using a Guelph permeameter device, at the instrumented hillslope as well as at each of the manipulation plot sites (see Section 4.2) prior to any manipulation occurring.

A total of 22 soil cores were sampled and tested for the A horizon within the improved pasture of the instrumented hillslope. Sampling from the B horizon was less successful, and data for this depth was sampled using a Guelph permeameter. 6 soil cores from the A horizon of the Pant powsi tree area were also sampled and tested. All cores were collected from the Cegin soil series. Studies have shown that surface compaction by grazing is limited to the top 5 cm of a soil profile (Greenwood et al., 1997). Therefore to test for evidence of surface compaction, 9 soil cores sampled from the A horizon under improved grassland management had the turf layer removed prior to testing.

Dye tracer tests

To improve understanding of water movement through the soil, a dye tracer test was undertaken at two 1.2 m x 1.2 m plots, in a field adjacent to the site of the instrumented hillslope described in Section 4.4. The aim of this study was to investigate the impact of the soil structure, and particularly the role of macropores, on the movement of water through these clay rich soils under improved grassland management. Both sites were located on the Cegin soil series.

At each plot the turf layer was removed before a Brilliant Blue FCF dye solution was ponded on the soil surface and infiltrated. Once infiltrated, plots were carefully excavated to allow examination of the dye staining patterns to give an indication of water flow paths through the soil profile. The tests were undertaken in July 2005 when the soils where relatively dry. Because of this, plots were pre-watered before applying the dye solution in order to saturate the soil and encourage preferential flow. As well as excavation of the actual plots, trenches were also dug downslope to investigate subsurface lateral flow.

A dye tracer test was also carried out at a plot under an established tree shelterbelt to improve our understanding of how trees and tree roots influence the movement of water through these clay rich soils. A Brilliant Blue FCF dye solution was applied to the surface of a 1.13 m x 1.13 m plot, Cegin soil series, using a sprinkler system to simulate rainfall. An irrigation rate of ~ 13 mmh^{-1} was applied and the brilliant blue FCF dye solution was allowed to infiltrated. An overland flow trap down slope of the plot was installed to capture any potential runoff which might occur as overland flow. After 80 mm of applied dye solution rainfall the plot was carefully excavated and the dye staining patterns examined to indicate of water flow paths through the soil profile.

4.2 MANIPULATION PLOT EXPERIMENTS

To investigate directly the impacts of land management on hydrological response, four manipulation plot sites were established in Pontbren in June 2005 (Figure 4-1 shows the locations). The sites were selected to provide a range of representative slopes and aspects. Each site has three 12 m x 12 m replicate plots across the hillslope separated by a 10 m strip. Baseline data were collected within each plot until January 2007, when three different land management practices were applied:

- Planting trees (with the exclusion of sheep)
- No grazing (i.e. sheep excluded)
- Grazing (i.e. the control).

The treatments were randomly assigned to the plots within a site.

Figure 4-3 shows a diagrammatical representation of the manipulation plot site layout and experimental design. Table 4-1 provides detail of the temporal resolution of data collection. Overland flow and soil pore water pressure, ψ, is measured on a 10 minute timestep interval within each of the plots. Overland flow is collected from 2.5 m x 10 m isolated sub-plots using a gutter and measured by means of a tipping bucket system connected to a data logger (see Figure 4-4). Soil pore water pressure is measured at 10 cm, 30 cm, and 50 cm depth using an array of tensiometers. Neutron probe access tubes installed within each plot allow measurement of profile moisture content, $\theta\,(\text{cm}^3\text{cm}^{-3})$, to depth of 120 cm. Prior to treatment implementation, samples from each plot were collected from the soil's A and B horizons to determine the organic matter content (%), dry bulk density (g cm^{-3}), particle size distribution and soil moisture release characteristic. Soil sampling will be repeated once the treatments have been established, to investigate any treatment effects.

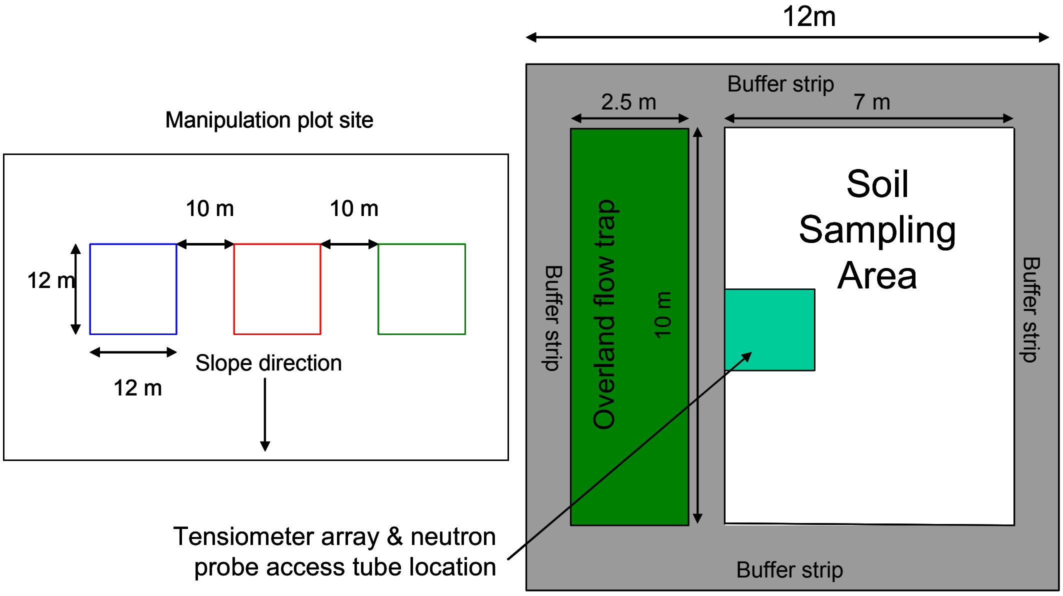


Figure 4-3. Manipulation plot site layout and experimental design

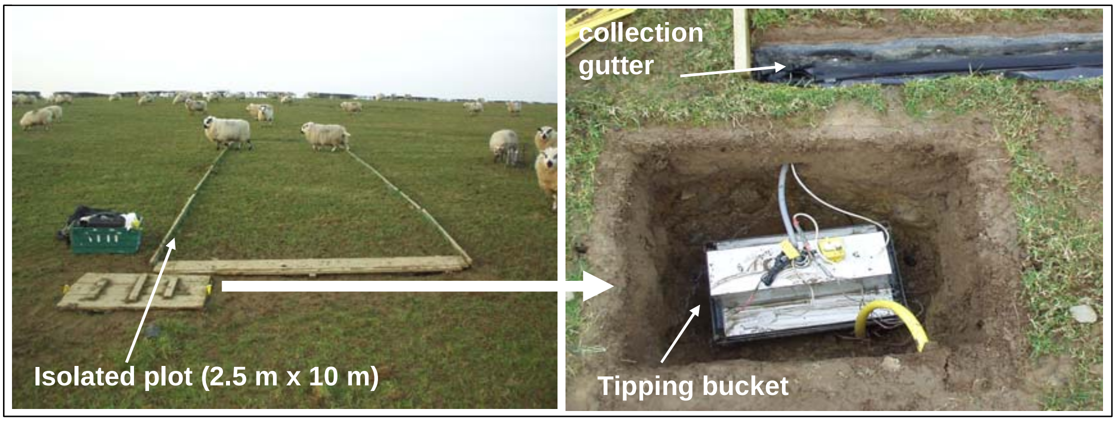


Figure 4-4. Manipulation plot overland flow trap and tipping bucket system.

4.3 TREE SHELTERBELT MONITORING

To understand the hydrological impacts of linear woodland features (tree shelterbelts) planted in agricultural landscapes, plot scale experiments have been established at three locations (T_{1-3}) across the Pontbren study area (See Figure 4-1). In all three tree-planted areas, similar measurements were taken in order to determine rainfall interception and the throughfall 'shadow' effect on the soil moisture status within the tree planted areas, as well as in the adjacent improved pasture. At Pant Powsi, T_1, the trees are predominantly *Betula* spp., (established during winter 2000/01) and Cae Drains, T_2, predominantly *Betula* spp., (established during winters of 1994/95 – 1995/96). The 'throughfall shadow effect' (see Figure 4-5) is being investigated by measuring rainfall along transects of rain gauges (see Figure 4-6) perpendicular to the shelterbelt, both on the windward and leeward side in the adjacent pasture fields. Note that rain gauges were located above ground to avoid disturbance by sheep. To account for possible differences in rainfall collection caused by the raised collection vessel, a similar type of rain gauge was installed adjacent to the standard rain gauge at the bowl study site so that the method of collection could be standardised. The tree area at Tyn y Fron, T_3, is located at the western edge of a mature forest stand (established 1952/53), the edge of which contains an area of *Betula* spp. Here transects measure rainfall in the adjacent pasture on the main windward side. A further tree planted shelterbelt, Half moon, is nested within the hillslope scale study and is described in section 4.4.

At all sites, throughfall and stemflow are measured (see Figure 4-7 and Figure 4-8) from a representative sample of trees. Transects of neutron probe access tubes allow changes in moisture content θ (cm^{3}cm^{-3}) to be measured, to a depth of 120 cm, in both the tree areas and the adjacent pasture. Within each of the tree areas an array of tensiometers (10 cm, 30 cm, and 50 cm) provides 10 minute time step data on ψ (cm H_2O). Table 4-1 provides a summary of the instrumentation and sampling regime undertaken at each of the sites. Figure 4-9 provides a diagrammatical representation of the instrumentation within the tree shelterbelts. Figure 4-10 shows the location of sites T_1 and T_2 with respect to the experimental hillslope described in Section 4.4, together with the half moon shelterbelt.

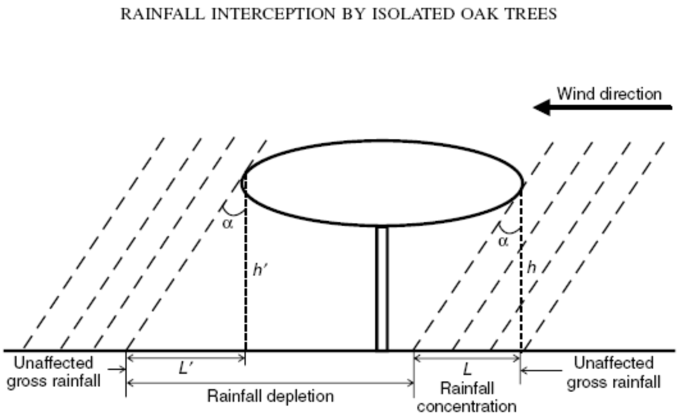


Figure 4-5. Illustration of rainfall interception and the throughfall shadow effect. *Source*: David et al. (2006).

Figure 4-6. Photograph of throughfall shadow rain gauges at Pant Powsi, T_1. Also showing neutron probe in centre of photograph.

Figure 4-7. Photograph of trough style throughfall collectors.

Figure 4-8. Stem flow collector attached to a silver birch.

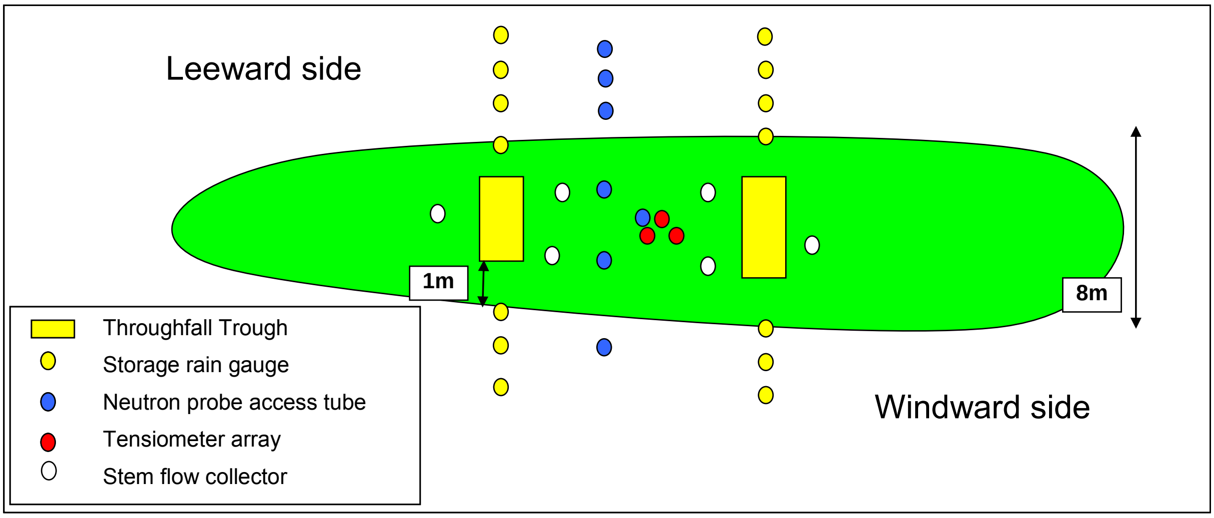


Figure 4-9. Example layout of the instrumentation in the tree shelter belts.

4.4 HILLSLOPE-SCALE MONITORING

A representative area at Tyn y Bryn Farm in the Pontbren catchment has been instrumented to measure the hydrological response and investigate the impact of field drains and the presence of tree shelterbelts on runoff response at the hillslope scale. The hillslope is under improved grassland production, that is to say, it receives regular fertilizer applications and has field drains installed. It is also used exclusively for sheep production. Figure 4-1 shows the hillslope location and Table 4-1 provides details of the instrumentation. The site ranges in elevation from approximately 279 m to 317 m AOD and has an average slope of around 12.5 %. The length of the field is approximately 300 m in the downslope direction and the width of the fields varies between approximately 70 m and 130 m. The topography of the hillslope exhibits a terraced effect, a feature commonly observed across the catchment. The soil at the experimental hillslope is predominantly classified as being of the Cegin soil series (slightly stony clay loam). However, 1/3 of the upper part of the instrumented hillslope, known as the Bowl, is classified as being of the Sannan soil series (slightly stony silty clay loam). Undifferentiated alluvial soils are found at the bottom of the hillslope, along the stream bank.

The instrumented hillslope is divided into two distinct experimental sites, namely the ‘bowl’ and the ‘tree planted hillslope’ (see Figure 4-10 and Figure 4-11). The bowl is the uppermost part of the experimental hillslope between 305 m and 317 m AOD. It is a 0.52 ha natural depression, draining to two field drain outlets to the southern edge of the field. Drain flow from the southeast drain outlet is monitored and is assumed, based on visible drain lines, to drain an area of 0.36 ha. Overland flow occurring from a 0.44 ha area of the bowl is collected by means of a gutter as indicated in Figure 4-10. During the winter of 2005/06, overland and drain flow were both monitored using separate tipping bucket systems connected to data loggers. Since Autumn 2006, both overland and drain flow have also been monitored using V-notch box weirs with pressure transducers, to improve accuracy at high flows (1 minute samples are averaged over a 5 minute period).

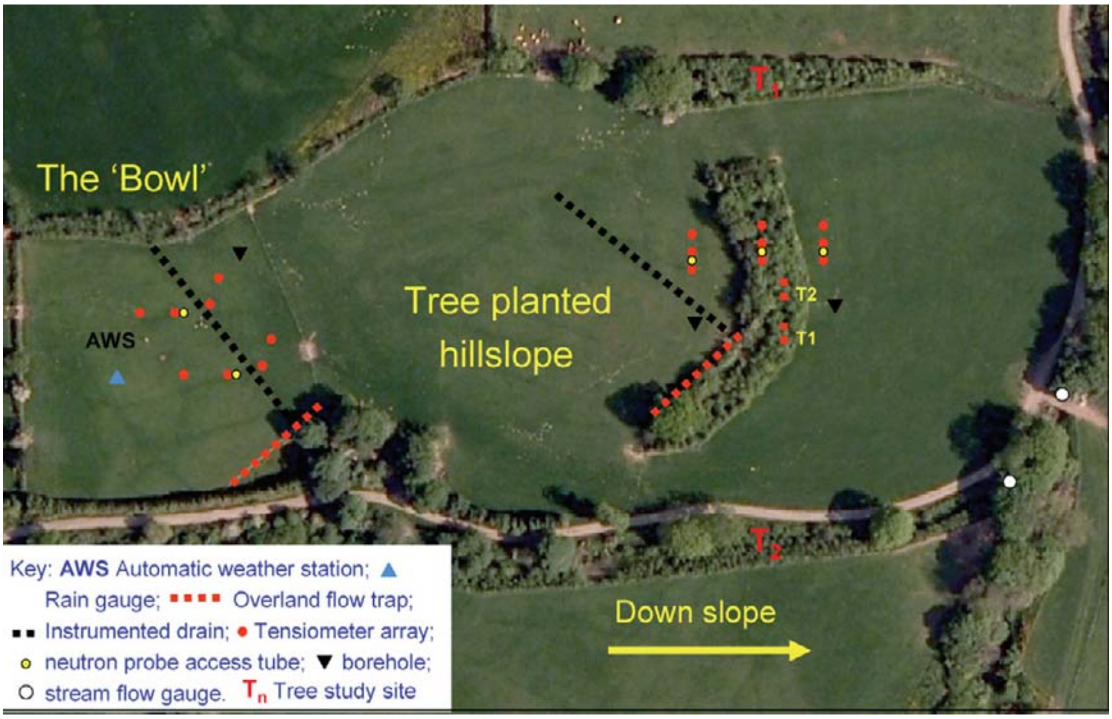


Figure 4-10. Experimental hillslope instrumentation layout.

The tree planted hillslope is approximately 230 m in length ranging in elevation between 279 m and 309 m AOD and comprises the lower two terraces below the bowl. In 1995 a tree shelterbelt, known as Half-Moon, was established between the two terraces perpendicular to the slope. Tree species present are: *Betula pendula* L. (silver birch), *Betula pubescens* L. (downy birch), *Quercus robur* L. (oak), *Corylus avellana* L. (hazel), *Fraxinus excelsior* L. (ash), *Larix* spp. (larch) and *Pinus sylvestris* L. (Scots pine). Two v-notch box weirs with pressure transducers continuously measure drain flow and overland flow from an area of pasture above the tree planted shelterbelt. Cumulative overland flow is also measured bi-weekly from two 0.0025 ha isolated plots within the tree area.

Transects of tensiometers have been installed in the bowl and the tree planted hillslope to provide continuous data (sampled every 10 minutes) on changes in ψ (cm H_2O). Transects are 20 m apart with tensiometer arrays 5 m apart within each of transect. Figure 4-10 and Figure 4-11 show the tensiometer array location. Within each array tensiometers are installed at 10 cm, 30 cm, and 50 cm depths apart from in the tree areas where tensiometers are only installed at the top two depths. Neutron probe access tubes have also been installed at the experimental hillslope to a measuring depth of 120 cm. Changes in θ (cm^3cm^{-3}) are measured bi-weekly.

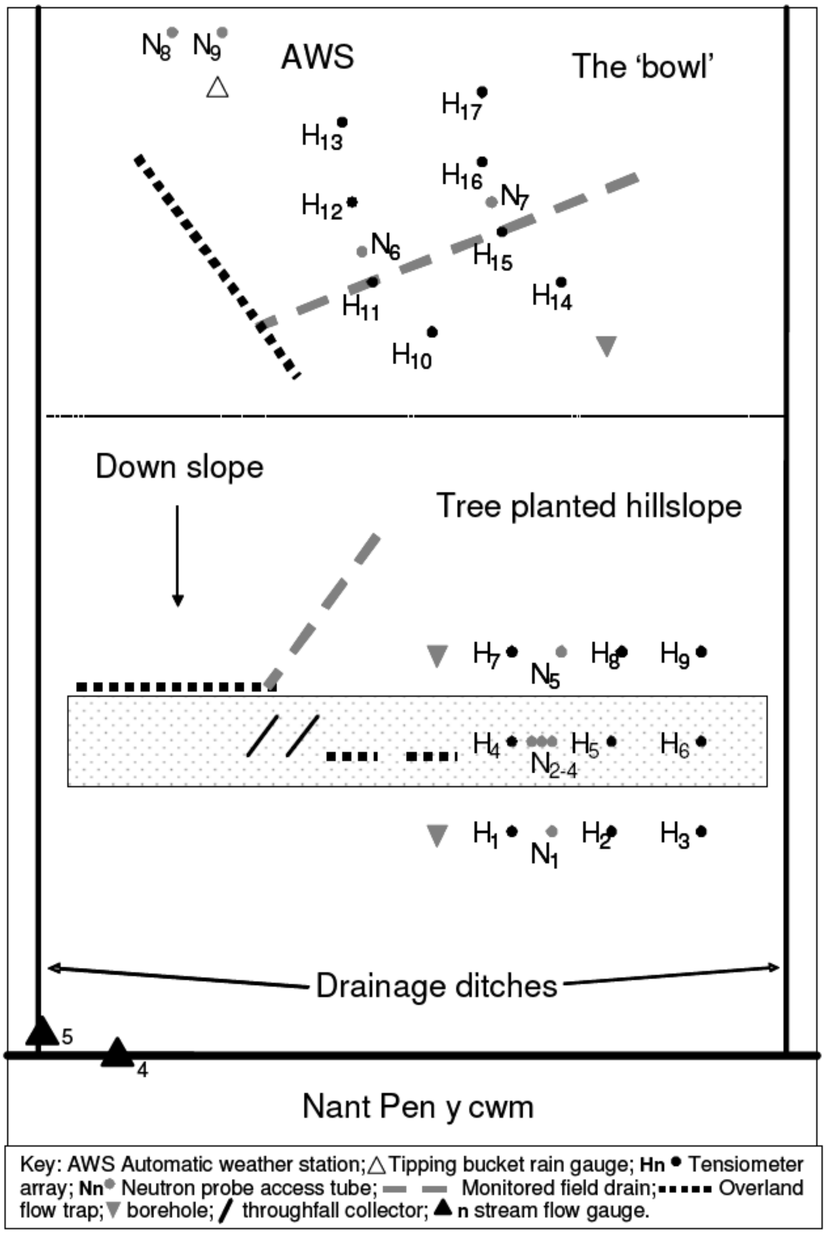


Figure 4-11. Diagrammatical representation of instrumented hillslope layout.

Table 4-1 List of instrumentation

Location and Code*	Instrumentation	No.	Purpose	Sampling Frequency
Tyn y Bryn – Hilltop **HT**	Storage rain gauge	1	rainfall (mm)	monthly
	Tipping bucket rain gauge (0.2 mm)	1	rainfall intensity (mmh^{-1})	10 minute
Tyn y Bryn – Top field **TF**	Borehole with pressure transducer	2	Groundwater elevation (m AOD)	30 minute
Tyn y Bryn – Instrumented hillslope- Bowl **H$_B$**	Automatic weather station	1	Wind speed (ms^{-1}), Wind direction (degrees), Solar radiation (Wm^{-2}), Net radiation (Wm^{-2}), Air temp. (^oC), Soil temp. (^oC), Relative humidity (%)	10 minute & daily ave.
	Tipping bucket rain gauge (0.2 mm)	1	rainfall intensity (mmh^{-1})	10 minute
	Tensiometer array (10, 30, and 50 cm depth)	8	Soil pore water pressure (cm H_2O)	10 minute
	Neutron probe access tubes (z = 120 cm)	4	Soil moisture content, θ (cm^3cm^{-3})	Bi-weekly
	Overland flow trap (0.44 ha)	1	Overland flow (m^3s^{-1})	5 minute
	Drain flow (0.36 ha)	1	Drain flow (m^3s^{-1})	5 minute
	Borehole with pressure transducer	1	Groundwater elevation (m AOD)	30 minute
Tyn y Bryn – Instrumented hillslope- tree planted hillslope **H$_T$**	Throughfall collector	1	Throughfall (mm)	Bi-weekly
	Tensiometer array (10, 30, and 50 cm depth)	9**	Soil pore water pressure (cm H_2O)	10 minute
	Neutron probe access tubes (z = 120 cm)	4	θ (cm^3cm^{-3})	Bi-weekly
	Overland flow – pasture	1	Overland flow (m^3s^{-1})	5 minute
	Overland flow – tree area (0.0025 ha)	2	Overland flow (m^3)	Bi-weekly
	Drain flow – pasture	1	Drain flow (m^3s^{-1})	5 minute

Table 4-1 List of instrumentation

cont.

Tyn y Bryn – Cae Draens – tree planted study site **T_1**	Storage rain gauge	14	rainfall (mm)	Bi-weekly
	Throughfall collector	2	Throughfall (mm)	10 minute
	Tensiometer array (10, 30, and 50 cm depth)	1	Soil pore water pressure (cm H_2O)	10 minute
	Neutron probe access tubes (z = 120 cm)	4	θ (cm^3cm^{-3})	Bi-weekly
	Stem flow collector	7	Stem flow (mm)	Bi-weekly
Tyn y Bryn – Pant powsi – tree planted study site **T_2**	Storage rain gauge	14	rainfall (mm)	Bi-weekly
	Throughfall collector	2	Throughfall (mm)	10 minute
	Tensiometer array (10, 30, and 50 cm depth)	1	Soil pore water pressure (cm H_2O)	10 minute
	Neutron probe access tubes (z = 120 cm)	5	θ (cm^3cm^{-3})	Bi-weekly
	Stem flow collector	6	Stem flow (mm)	Bi-weekly
Llyn Hir **LH**	Storage rain gauge	1	rainfall (mm)	monthly
	Tipping bucket rain gauge (0.2 mm)	1	rainfall intensity (mmh^{-1})	10 minute
Hir Rhos Uchaf **HU**	Storage rain gauge	1	rainfall (mm)	monthly
	Tipping bucket rain gauge (0.2 mm)	1	rainfall intensity (mmh^{-1})	10 minute
Rhos aflo – manipulation plots 1 **M_1**	Storage rain gauge	1	rainfall (mm)	monthly
	Tipping bucket rain gauge (0.2 mm)	1	rainfall intensity (mmh^{-1})	10 minute
	Tensiometer array (10, 30, and 50 cm depth)	3	Soil pore water pressure (cm H_2O)	10 minute
	Neutron probe access tubes (z = 120 cm)	3	θ (cm^3cm^{-3})	Bi-weekly
	Overland flow – tree area (0.0025 ha)	3	Overland flow (m^3s^{-1})	10 minute
Rhos aflo – manipulation plots 2 **M_2**	Tensiometer array (10, 30, and 50 cm depth)	3	Soil pore water pressure (cm H_2O)	10 minute
	Neutron probe access tubes (z = 120 cm)	3	θ (cm^3cm^{-3})	Bi-weekly
	Overland flow – tree area (0.0025 ha)	3	Overland flow (m^3s^{-1})	10 minute

Table 4-1 List of instrumentation

cont.

Penllwyn – manipulation plots	Storage rain gauge	1	rainfall (mm)	monthly
M_3	Tipping bucket rain gauge (0.2 mm)	1	rainfall intensity (mmh^{-1})	10 minute
	Tensiometer array (10, 30, and 50 cm depth)	3	Soil pore water pressure (cm H_2O)	10 minute
	Neutron probe access tubes (z = 120 cm)	3	θ (cm^3cm^{-3})	Bi-weekly
	Overland flow – tree area (0.0025 ha)	3	Overland flow (m^3s^{-1})	10 minute
Tyn y fron – manipulation plots	Tensiometer array (10, 30, and 50 cm depth)	3	Soil pore water pressure (cm H_2O)	10 minute
M_4	Neutron probe access tubes (z = 120 cm)	3	θ (cm^3cm^{-3})	Bi-weekly
	Overland flow – tree area (0.0025 ha)	3	Overland flow (m^3s^{-1})	10 minute
Tyn y fron – tree planted study	Storage rain gauge	9	rainfall (mm)	Bi-weekly
site **T_3**	Throughfall collector	2	Throughfall (mm)	10 minute
	Tensiometer array (10, 30, and 50 cm depth)	1	Soil pore water pressure (cm H_2O)	10 minute
	Neutron probe access tubes (z = 120 cm)	5	θ (cm^3cm^{-3})	Bi-weekly
	Stem flow collector	6	Stem flow (mm)	Bi-weekly
Streams & drainage ditches	Acoustic Doppler Velocity meter	10	Flow (m^3s^{-1})	15 minute
▲	V-notch weir with pressure transducer	2	Flow (m^3s^{-1})	10 minute
	Stage recorder (pressure transducer)	1	Flow (m^3s^{-1})	10 minute

* See Figure 4.1 for location details
** No 50 cm depth within hillslope tree plated area

4.5 CATCHMENT-SCALE MONITORING

Rainfall is measured using 0.2 mm tipping bucket gauges at 6 locations across the catchment chosen to represent topographic and spatial variability (see Figure 4-1). At five of these sites storage gauges are also used to provide monthly totals. This does not include the transects of rain gauges installed as part of the tree planted study described in Section 4.2.

Stream and ditch flow is monitored continuously at 13 locations across the study site using a combination of Acoustic Velocity Doppler (ADV) meters (sampled every minute and averaged over a 15 minute period), V-notch weirs (with pressure transducers sampled every minute and averaged over a 10 minute period), and a natural rated section (with pressure transducer sampled every minute and averaged over a 10 minute period) (see Figure 4-1 and Table 4-1). During the period of monitoring spot measurements have been carried out using a current meter to check the accuracy of the monitoring equipment and where necessary calibrate (McIntyre and Marshall, in press). Sites were chosen to represent different land uses and different scales of observation to monitor how the flow peak propagates as one moves downstream.

5. Results and Discussion of Experimental and Monitoring Programme

5.1 SOIL CHARACTERISATION

5.1.1 Soil moisture characteristic curve, dry bulk density, and saturated hydraulic conductivity determination of Pontbren soils

Soil dry bulk density determination of Pontbren soils

Table 5-1 and Figure 5-1 show the mean soil dry bulk density, ρ_b (gcm^{-3}), for the Cegin and the Sannan soil series, obtained during the soil moisture characteristic curve determination. For both the Cegin and the Sannan there is, as expected, an increase in mean ρ_b as one moves from the A to the B horizon associated with a decrease in total porosity. Looking at the impact of trees, and or absence of livestock, the mean ρ_b of the Cegin A horizon under the tree areas is less than that measured under the improved pasture. This suggests that the porosity of the surface soil increases when land use is changed from that of improved pasture to tree planted areas with livestock excluded. However, variability is much higher beneath the trees. This is probably due, in part, to the difference in age of the stands (as discussed later in relation to Figure 5-2), and partly because of the more heterogeneous nature of woodland soils. Comparing soil series, it appears that there is a decrease in mean A horizon ρ_b, moving from the Cegin to the Sannan. This is as expected, with the Sannan series described as slightly more freely draining than the Cegin soil series. Comparing ρ_b data for the B horizons, the greatest mean value belongs to the Cegin series soil under improved pasture. In comparison, the soil beneath the trees has a value similar to that of the more freely draining Sannan series soil.

Table 5-1. Mean soil dry bulk density, ρ_b, for soils at Pontbren

Soil Series	Horizon	Land Use	ρ_b (gcm^{-3})	s.d.	n*
Cegin	A	Improved pasture	0.95	0.08	32
		Tree area	0.80	0.20	15
	B	Improved pasture	1.13	0.11	33
		Tree area	1.06	0.12	12
Sannan	A	Improved pasture	0.85	0.04	10
	B		1.03	0.11	12

* no. of samples

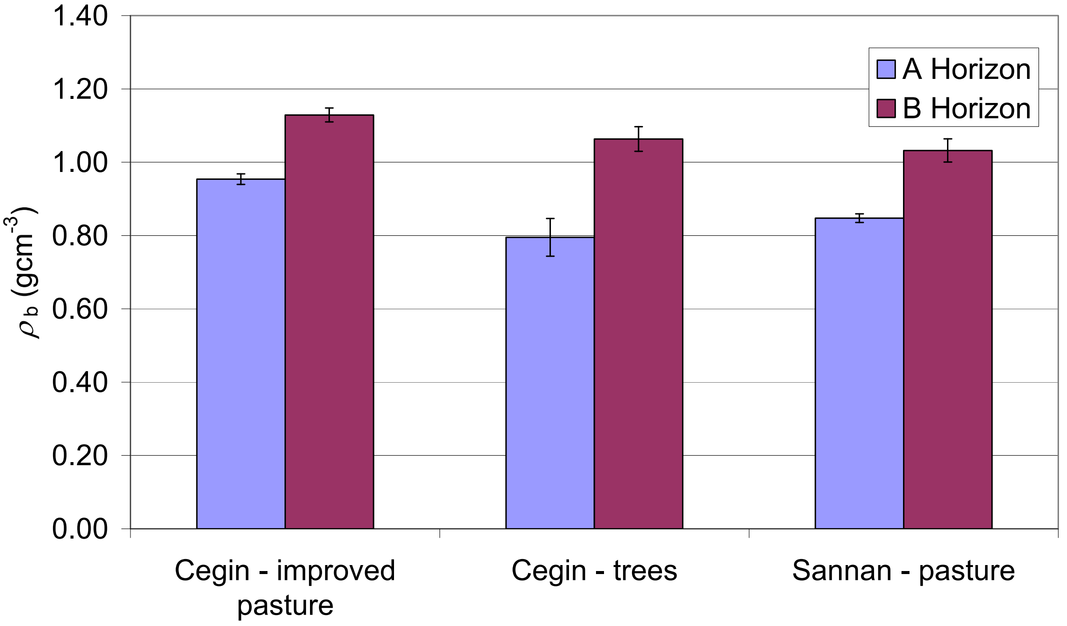


Figure 5-1. Mean soil dry bulk density, ρ_b, for soils at Pontbren. Error bars give the standard errors (refer to Table 5-1 for sample sizes).

Table 5.2 and Figure 5-2 show ρ_b for the individual tree sites. Examining the results from the A horizon there appears to be a general trend of decreasing ρ_b with increasing age of trees. A decrease in ρ_b over time may occur due to a number of reasons: removal of livestock reducing compaction, an increase in organic matter in the soil, decay of old tree roots resulting in an increase in porosity. However, caution must be given to this interpretation due to the dramatic drop in measured ρ_b between the sites Cae Drains and Half-Moon. Half-Moon and Cae Drains were established in the years 1994 and 1994/95 respectively and it is therefore unlikely that the difference between these sites is solely as a result of differences in the age of the trees. Other possible explanations include: differences in tree species with different root morphologies, differences in topography, local differences in parent soil, or the sample size was not large enough to capture all of the variation. Measured ρ_b values for the B horizon appear to be greatest at Pant powsi, the youngest tree area. No samples were collected from the B horizon of Half-Moon.

Table 5-2. Tree shelterbelt areas mean soil dry bulk density, ρ_b, for soils at Pontbren

Soil Series	Site	Established	Horizon	ρ_b	s.d.	n*
				gcm^{-3}		
Cegin	Pant powsi	2000/01	A	0.98	0.09	3
			B	1.23	0.08	3
	Cae Drains	1994/95 – 1995/96	A	1.04	0.04	3
			B	0.99	0.10	3
	Half-Moon	1995	A	0.76	0.06	3
			B	-	-	-
	Tyn y Fron trees	1952/53	A	0.60	0.04	6
			B	1.02	0.02	6

* Number of samples

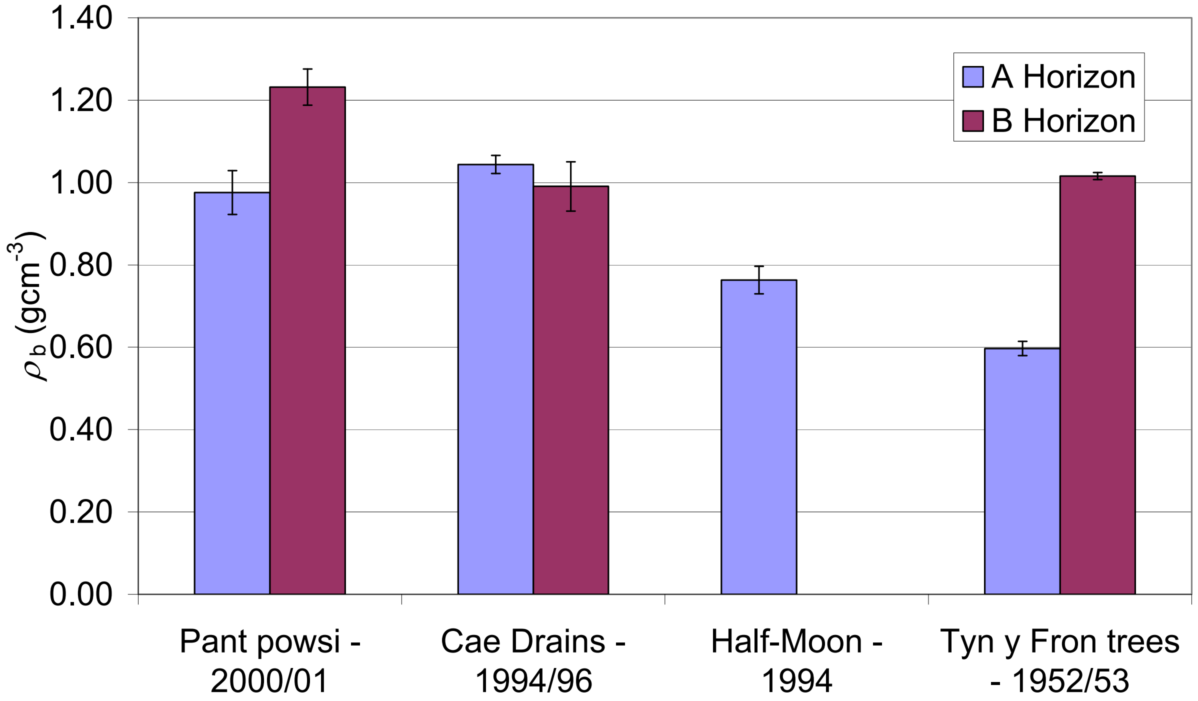


Figure 5-2. Tree shelterbelt areas' mean soil dry bulk density, ρ_b, for soils at Pontbren. Error bars give the standard errors (refer to Table 5-2 for sample sizes, n). Dates are when the shelterbelts were established.

Soil moisture characteristic curve determination of Pontbren soils

Figure 5-3 shows the mean soil moisture characteristic curves, SMCC, for the Cegin soil series A and B horizons under improved pasture and trees. Table 5-3 indicates the soil water suction, i.e. pressure head, $-\psi$, at which different pore sizes will drain. Comparing the results of the SMCC and the numbers in Table 5-3, one can estimate the pore size distribution of a given soil. SMCC data are presented for the wet end of the curve, from saturation to field capacity, arbitrarily set between $\psi = -50$ and $\psi = -100$ cm H_2O (Rowell, 1994). The dry end of the SMCC, i.e. suctions > 100 cm H_2O ($\psi < -100$ cm H_2O), was not determined for all sites and mean values for suctions greater than 100 cm H_2O are not yet available for the tree areas. However, as the concern here is with flood flow generation rather than water availability, e.g. for plant production, it is the wet end of the range that is of greatest interest.

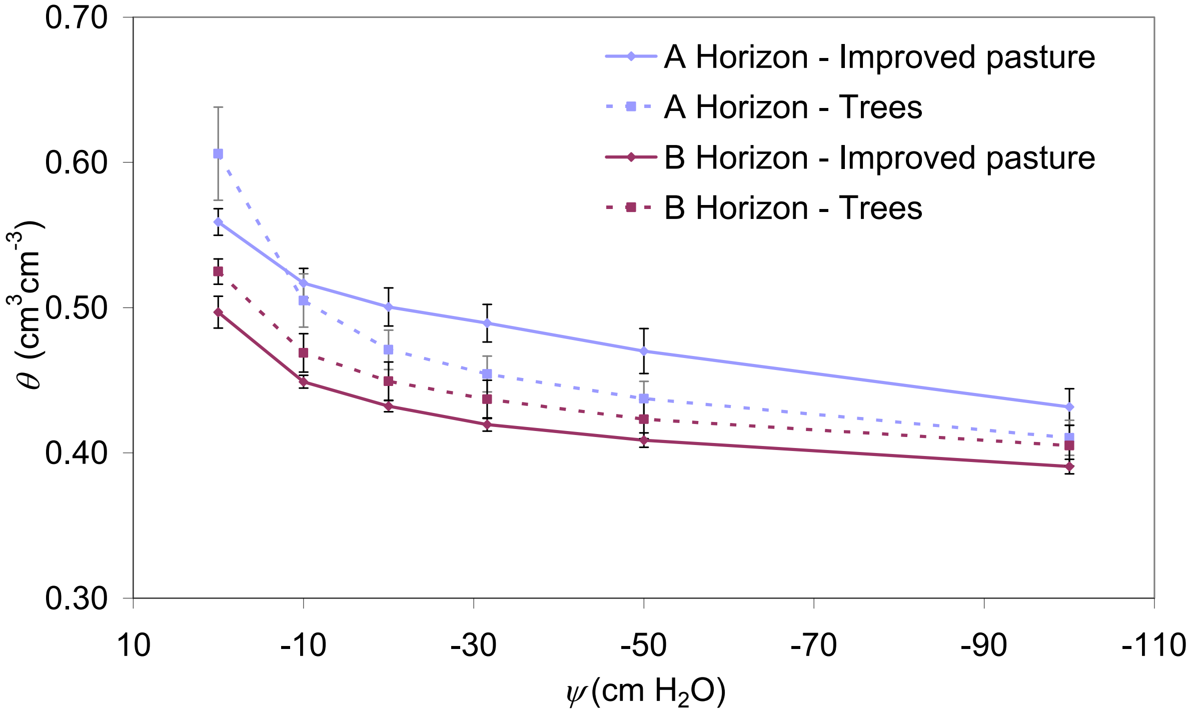


Figure 5-3. Soil Moisture Characteristic Curves for Cegin soil series at Pontbren. Each point is the mean of n replicates, n = 32; 15; 33; 12 in the order of the legend. Error bars give the standard errors.

Table 5-3. Comparison of soil water suction and drainable pore size (Rowell, 1994)

Soil water suction (cm H_2O)	Pore size diameter (mm)
0.1	30
1	3
10	0.3
100	0.03
1000	0.003

Comparing the soil moisture release curves in Figure 5-3, there are differences between land management practices. In the A horizon, the soil under the tree areas has a higher mean saturated water content, θ_{sat}, compared to the soil under improved pasture. The soil under the tree area desaturates more rapidly and when ψ = -100 cm, θ is less than that of the soil under improved grassland. This suggests that a difference in pore size distribution exists between the soils under the two different land uses, with the tree area A horizon soil having a greater amount of larger pores. This is illustrated by the relatively rapid decline in θ as well as an increased mean θ_{sat} value. The SMCC of the improved grassland A horizon shows a relatively slow decline at the lower suctions and is typical of a heavy textured, clay rich soil, with a relatively small amount of highly transmissive pores.

Comparing the B horizon SMCCs with those of the A horizon in Figure 5-3 there is a reduction in θ_{sat}. This is probably due to a reduction in the organic matter content and compaction caused by the overlying soil reducing the porosity, especially a reduction in the larger pores. There appears to be a slight increase of θ values for corresponding suctions, comparing the soil of the B horizon under trees with that under improved pasture, at least at these relatively low suctions.

Comparing the SMCCs for the soil under the tree areas of different ages (Figure 5-4 and

Figure 5-5) there would appear to be an effect of age, with the soil under the oldest trees, at Tyn y Fron, having the greatest moisture content under saturated conditions in the A horizon.

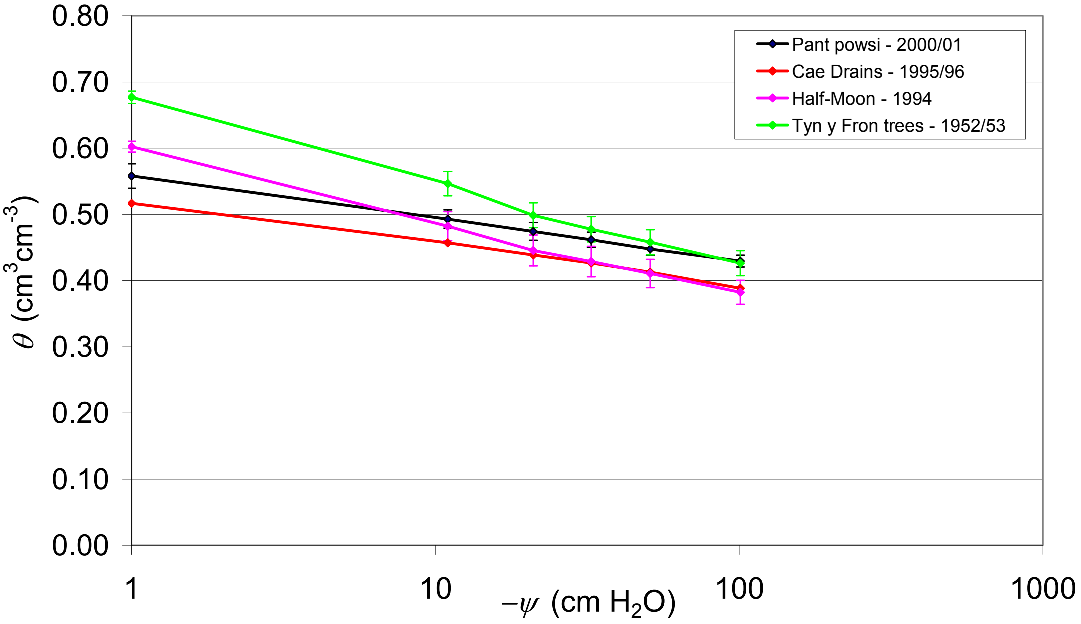


Figure 5-4. Soil Moisture Characteristic Curves for A horizon tree areas at Pontbren. Each point is the mean of n replicates, n = 3; 3; 3; 6 in the order of the legend. Error bars give the standard errors.

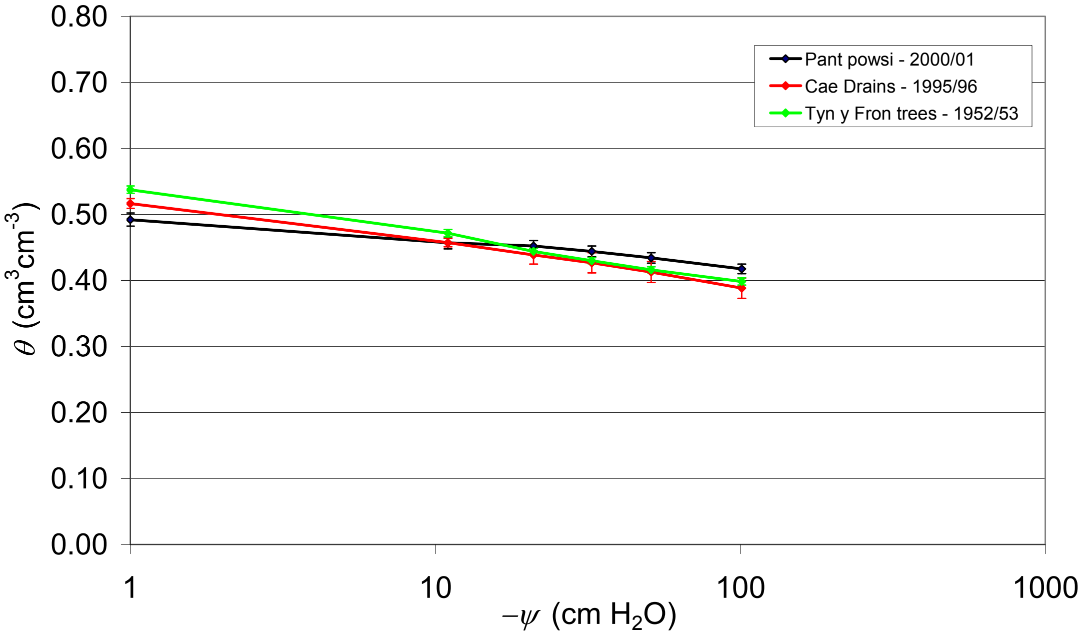


Figure 5-5. Soil Moisture Characteristic Curves for B horizon tree areas at Pontbren. Each point is the mean of n replicates, n = 3; 3; 6 in the order of the legend. Error bars give the standard errors.

The *field capacity* of a soil is an approximate concept, taken as the water content of a wetted soil when it has drained for about two days (Marshall and Holmes, 1988). The pore space available at field capacity, air capacity (cm^3cm^{-3}), when $-50\ cm \geq \psi \geq -100\ cm$, is an indicator of how much soil pore space is likely to be available for infiltrating rain water under typical winter conditions. Using the method of Hall et al. (1977), we selected a value of 0.05 bar ($\psi = -50\ cm\ H_2O$) to represent field capacity. Here the air capacity of soil is calculated using θ_{sat} as an indication of total porosity, i.e. air capacity = $\theta_{sat} - \theta(\psi = -50\ cm\ H_2O)$.

Table 5-4 and Figure 5-6 show the mean air capacity of the A and B horizons under different land uses. The mean air capacity in the A horizon under the trees is greater than under improved pasture. Figure 5-7 also indicates a general trend of increasing air capacity with increasing age of trees.

Table 5-4. Cegin soil series air capacity at Pontbren.

Horizon	Land Use		Air Capacity cm^3cm^{-3}	s.d.	n*
A	Improved pasture		0.09	0.04	32
	All Trees		0.17	0.06	15
	Trees	Pant powsi	0.11	0.02	3
		Cae Drains	0.10	0.02	3
		Half-Moon	0.19	0.05	3
		Tyn y Fron	0.22	0.05	6
B	Improved pasture		0.09	0.03	33
	All Trees		0.10	0.03	12
	Trees	Pant powsi	0.06	0.01	3
		Cae Drains	0.11	0.04	3
		Tyn y Fron	0.12	0.01	6

* number of samples

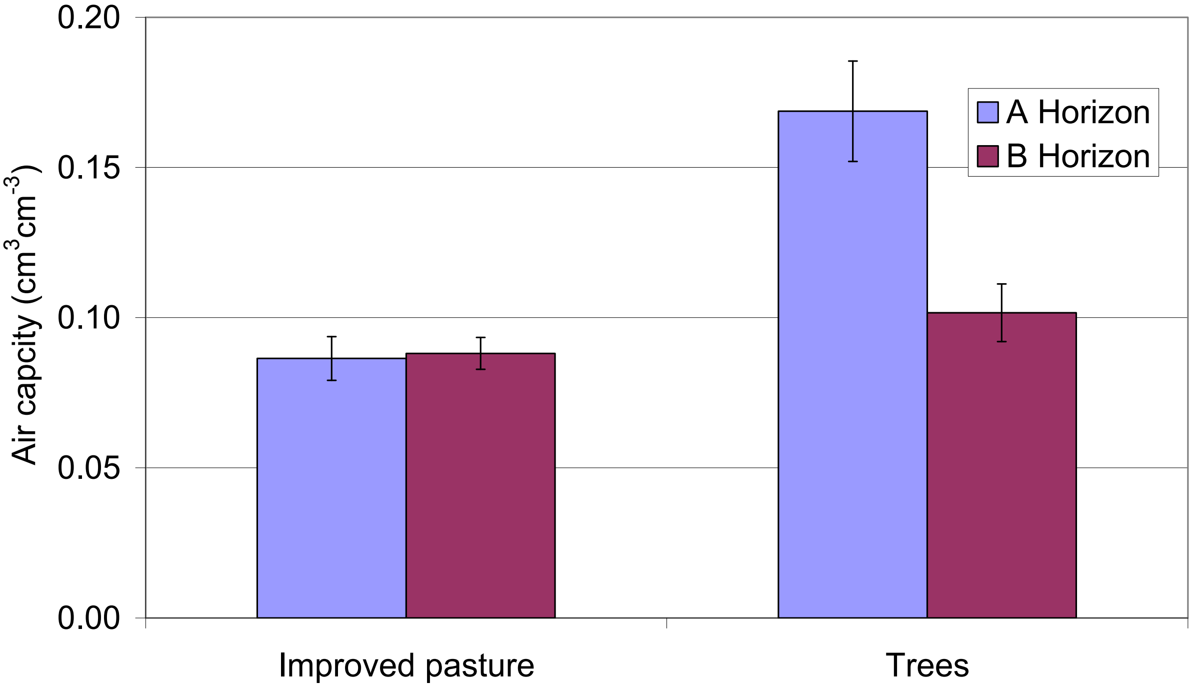


Figure 5-6. Cegin soil series air capacity at Pontbren. Error bars give the standard errors (refer to Table 5-4 for sample sizes, n).

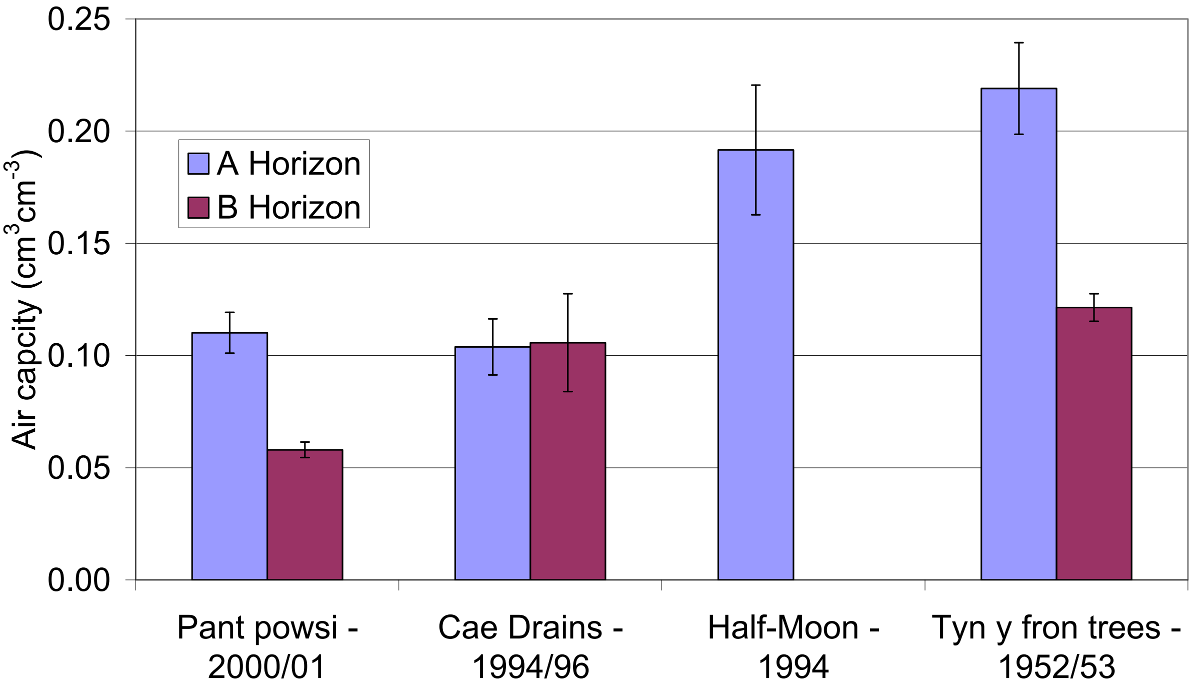


Figure 5-7. Cegin soil series tree area air capacity at Pontbren. Error bars give the standard errors (refer to Table 5-4 for sample sizes, n).

In conclusion, there is an increase in bulk density, ρ_b, with increasing depth moving from the A to the B horizon as one would expect as a result of compaction of the overlying material. Between land uses there is a decrease in mean ρ_b in the A horizon as one moves from improved pasture to the tree areas. Comparing results from the B horizon under different land uses there is again a decline in ρ_b moving from the improved pasture to the tree areas but the difference is smaller. Bulk density is also affected by tree age in the A horizon. The results of this part of the study indicate that the planting of tree shelterbelts results in a reduction in ρ_b of the soil underneath, and that this reduction in ρ_b increases with increasing age of trees. A decrease in ρ_b suggests that there may be an increase in total porosity of the soil, indicating that the presense of trees and/or absence of sheep may increase the ability of that soil to store incoming rain water or overland flow.

Differences in the SMCCs between the A horizon soils under the the two different land uses are observed. These indicate that there is an increase in the amount of larger pores when moving from improved pasture land use to the tree areas. Also, in the A horizon between $\psi = 0$ and -100 cm H_2O, the gradient of the soil moisture release curve is steeper under the trees than under improved grassland. This suggests a larger amount of available pore space between saturation and *field capacity* in the A horizon under the trees. Differences in air capacity between the A horizons of both land uses confirm this. There is also variation between the SMCCs of the B horizons at least at the wet end of the curve, with a general increase in θ values under trees compared to under improved grassland at corresponding suctions. As with the ρ_b of the A horizon, there is a difference in the SMCC when looking at the different ages of tree stands, especially between the 50 year old stand and the younger trees. The available pore space between saturation and *field capacity* is greater under the 50 year old stand than under the younger trees. Looking at the B horizon, there appears to be little difference between soil under the different aged trees.

5.1.2 Measurement of saturated hydraulic conductivity of Pontbren soils

A total of 22 soil cores were sampled and tested using the falling head permeameter, for the A horizon within the improved pasture of the instrumented hillslope. Nine of these samples were tested with the turf layer removed to test for surface compaction by sheep. Six soil cores from the A horizon of the Pant powsi tree area were also sampled and tested. Sampling from the B horizon was less successful using the falling head permeameter, since the soil layer was dense and stony. Data for the B horizon was collected using a Guelph permeameter. The results are summarised below. More detailed analysis and discussion can be found in Chell (2007).

Previous studies have found that soil permeability data follow a log normal distribution (Biggar and Nielsen, 1976; Chappell and Lancaster, 2007). Despite the relatively low number of samples there was evidence here to suggest that the data followed a log-normal distribution, therefore median K_{sat} values are presented in Table 5-5. Data from the falling head permeameter work indicate that variability within groups is high: Coefficient of variation values of 78 % for the grazed pasture; 128 % for the grazed pasture with turf layer removed; and 137 % for the tree area A horizon sample set; consistent with decreases in samples size (n = 13, 9, and 6 respectively). This is not unusual as the presence or absence of macropore structures, such as earthworm channels, within the relatively small sampling volume can have a significant impact on the hydraulic conductivity, especially in these clay rich soils.

Table 5-5. Saturated hydraulic conductivity, K_{sat}, for Cegin soil series at Pontbren.

Horizon*	Land Use	Q_1	Median K_{sat}	Q_2	IQR	95 % CI of Median	n
		md^{-1}					
A	Improved pasture^1	1.70	3.43	6.55	4.85	1.54 to 7.031	13
	Improved pasture^2	0.26	1.67	4.93	4.67	0.152 to 5.29	9
	Tree area	5.15	8.34	12.21	7.05	1.43 to 66.8	5
B	Improved pasture	0.002	0.018	0.039	.037	0.002 to 0.042	18

*A horizon determined using falling head permeameter. B horizon determined using falling head and Guelph permeameter.
Improved pasture^1 = grazed pasture – turf layer intact
Improved pasture^2 = grazed pasture – turf layer removed
Q_1 =lower quartile value
Q_1 =upper quartile value
IQR = interquartile range (Q_1-Q_2)

Comparing improved pasture with and without turf, a parametric t-test on the normalised distributions comparing sample means and a non-parametric Mann-Whitney test on the medians indicated that, at the 95 % confidence level, there was no difference in A-horizon K_{sat} distributions. Median K_{sat} values for the sample sets were 3.43 md^{-1} and 1.67 md^{-1} for the turf layer intact samples and turf layer removed sample sets respectively. These results would suggest that there is no effect of compaction on K_{sat}, which is in contrast with the implications of the soil bulk density data. However, the sample sizes compared are relatively low and the volumes sampled are small. The method of removal of the turf layer results in a deeper section of the soil profile being sampled. An increase in depth down a soil profile tends to result in an decrease in K_{sat} caused by compaction. Therefore direct comparison between samples is questionable.

A one tailed t-test suggests that there is a significant difference between the K_{sat} values in the A horizon of the improved grazed pasture with turf and those in the tree area, with higher K_{sat} values in the tree areas. Again, the variability of results is high and the sample size is relatively small. Whilst the results demonstrate a difference between the tree area and grazed pasture, they give no indication as to how trees influence soil hydraulic properties in the upper soil profile. Possibilities include a change in soil structure due to the presence of tree roots and a reduction in compaction due to the removal of livestock.

Analysis of the results of the work carried out using the Guelph permeameter illustrated that measuring K_{sat} using this device was unsuitable for the A horizon of the Cegin soil series at Pontbren. The theory underlying this method assumes a bulb of saturation around the borehole where the measurement is made. The minimum depth of measurement using the Guelph permeameter is 15 cm. This was regularly just above the interface between the A and B horizon, often found at around 20 cm depth. Therefore there is no opportunity for the saturated bulb to establish in a homogeneous soil. Furthermore, the B horizon has a much lower hydraulic conductivity, and therefore lateral movement is likely to occur at this interface. In this instance the Guelph permeameter theory breaks down. The B horizon is deemed more suitable for this method and 18 tests were conducted the results of which are presented in Table 5-5. Results indicate that median K_{sat} of the B horizon is 2 orders of magnitude smaller than that measured for the A horizon above, suggesting a dramatic decrease in conductivity as one moves from the A to the B horizon.

The results of this study indicate that the presence of trees and/or the absence of sheep may have a significant effect on the soil hydraulic conductivity, especially in the upper part of the soil profile, compared to that under improved pasture. When saturated, the A horizon soil underneath the trees is able to conduct water more quickly than the soil under improved pasture. However, significant variability is observed within each treatment.

5.1.3 Dye tracer tests

Improved grassland dye tracer test

Qualitative assessment was made of how water moves through the Cegin soil series at Pontbren through the examination of dye staining patterns from the two tracer tests carried out in a field adjacent to the instrumented hillslope at Tyn y Bryn farm (see Francis, 2005). On excavation of the plots, dye staining patterns, which initially started off as relatively uniform across the revealed soil layer (see Figure 5-8), became increasingly discrete with depth in the soil profile. Dye staining patterns found on the surfaces of stones (See Figure 5-9), and earthworm burrows (see Figure 5-10) indicated that these features were allowing preferential movement of water down through the soil profile, bypassing much of the soil matrix. The excavation of a trench downslope from both plots revealed significant staining, indicating lateral movement of water downslope through the topsoil layer, at the interface between the A and B horizons (see Figure 5-12), and in macropores within the B horizon (Figure 5-11). The effect of these preferential flow paths was further illustrated when dye solution was found in the drain outflow within 2 hours of the start of the experiment. With drains installed at ~ 0.75 m depth, this would indicate an effective hydraulic conductivity of 9 md^{-1} which is almost 3 times that of the mean K_{sat} in the A horizon and 500 times that of the B horizon measured using and Guelph permeameter work (See Section 5.1.2).

This illustrates the importance of macropores, and preferential flow paths in the movement of water through clay rich soils under improved grassland production. The presence of the dye solution in the drain outflow within 2 hours of application is a clear indication of the importance of preferential flow pathways in rapidly transporting rainwater through the soil profile and into the drains, drainage ditch and stream network.

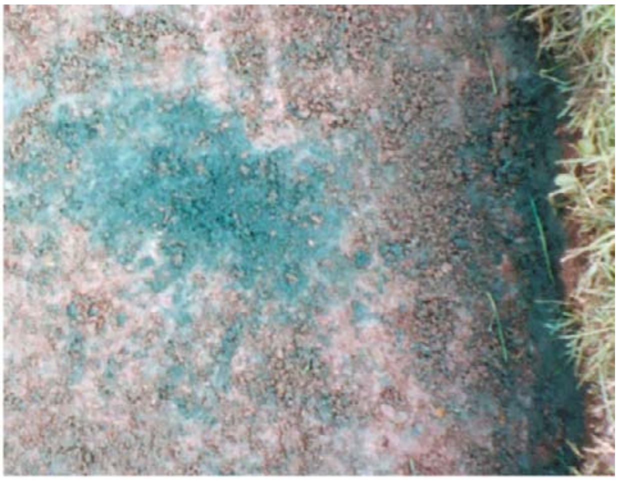


Figure 5-8. Dye staining pattern at 15 cm depth.

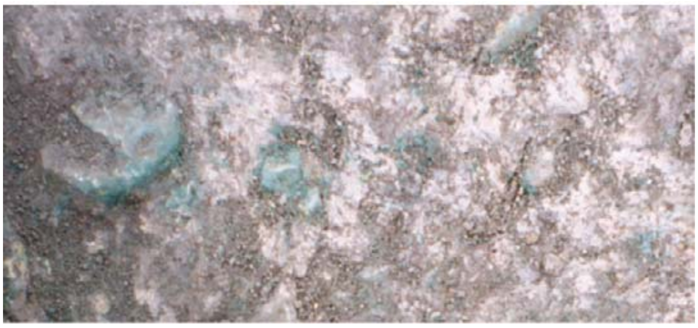


Figure 5-9. Stones in upper clay layer stained with dye, ~ 20cm depth.

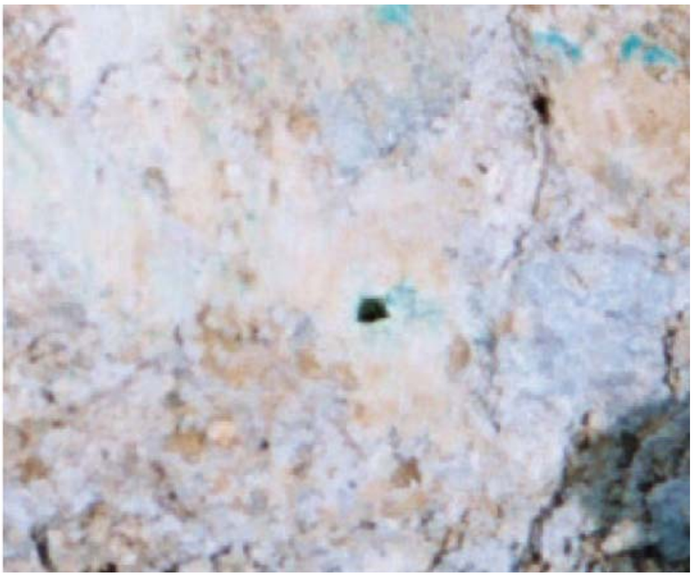


Figure 5-10. Earthworm burrow in lower clay layer stained with dye, ~ 45cm depth.

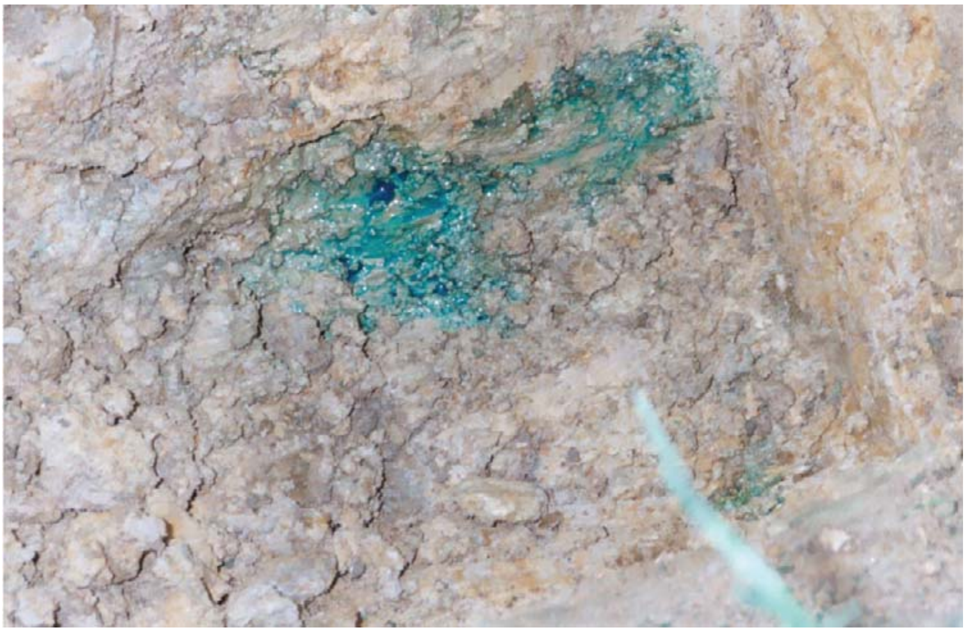


Figure 5-11. Seepage from cracks in lower clay layer, ~ 50cm depth.

Figure 5-12. Staining pattern at A and B horizon interface in trench down slope from dye tracer plot.

Tree area dye tracer test

The dye tracer test undertaken in a tree area took place during August 2007 and despite the relatively wet summer that had preceded this period, the soil was relatively dry prior to rainfall application. No overland flow was recorded after 80 mm of simulated rainfall, applied at a rate of ~ 13 mmh^{-1}. Excavation of a series of vertical profiles allowed a 3-dimensional picture of dye staining to be established and a qualitative assessment of how water moved through soil planted with trees at Pontbren. Preferential flow paths were indicated by the heterogenous staining of the soil profile. An example of these patterns is shown in the colour corrected photograph in Figure 5-13.

Detailed investigation of these preferential flow paths revealed that much of the staining was associated with living tree roots, despite the presence of other macropore structures such as cracks and earthworm burrows. Tree species appeared to have a strong influence on the flow patterns through the structure of their root systems. The presence of the birch (*Betula* spp.) roots caused intense staining in top of the profile and half-spherical distribution to a depth of 45 cm. The ash (*Fraxinus excelsior* spp.), with its strong horizontal roots below the turf layer, from which vertical roots extend with almost root free zones in between, caused finger-shaped dye patterns. Under the influence of the ash root system, dye staining patterns show up clearly at 65 cm depth around a single tree root. Interestingly, neighbouring earthworm channels were only rarely stained.

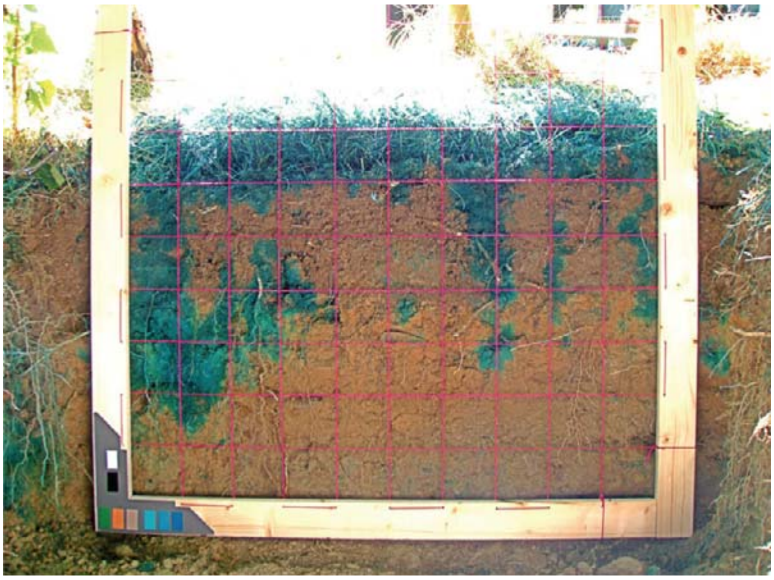


Figure 5-13. Colour corrected photograph highlighting dye staining of preferential flow paths occurring during the tree area tracer test.

The results from the dye sprinkler test carried within a tree area clearly indicated the importance of preferential flow paths through the Cegin soil series found at Pontbren. The dye staining patterns concentrated round living roots illustrating the importance of these as preferential flow pathways and it is interesting to note the apparent difference in staining patterns depending on the tree species present as a result of differences in root morphology.

5.2 METEOROLOGICAL SUMMARY

This section summaries the meteorological data experienced at Pontbren during the period of study, 2005 – 2007. Frontal rainfall dominated precipitation events. Figure 5-14 shows the monthly total precipitation recorded at site **HT** (see Figure 4-1). The maximum monthly total occurred in December 2006. Snow was infrequent during the period of observation and snow melt was not considered as significant in contributing to observed high flow events. (This has not always been the case; anecdotal evidence from one farmer of the Pontbren group relates a large flow event to snow melt in the 1960's on the Nant Gethli-Gethin which is said to have resulted in significant erosion and movement of sediment within the stream channel.) Rainfall intensity was measured over 10 minute periods and the greatest rainfall intensity recorded was 54 mmh^{-1} at manipulation plot site $\mathbf{M_1}$ during one convectional summer storm event during June 2007. This event was highly localized and similar intensities were not recorded at other rain gauge sites across the catchment.

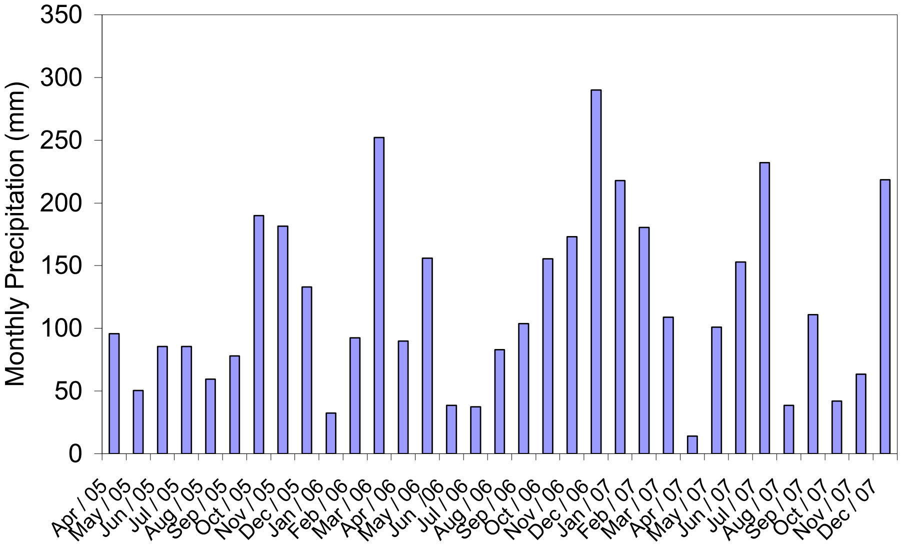


Figure 5-14. Monthly precipitation recorded at Tyn y Bryn Hilltop HT.

The summer of 2006 was an exceptionally hot and dry at Pontbren (Figure 5-26shows the UK Meteorological Office (MORECS data) estimation of the soil moisture deficit for the grid square within which Pontbren in located for the years 2005 – 2006). According to the UK Meteorological office this was one of the warmest summers on record.

Rainfall tends to be concentrated during the autumn/winter half of the year (October – March), however significant inter-annual variation was recorded. According to the UK Meteorological Office, the summer of 2007 was the wettest since 1912 for England and Wales. In 2007, high rainfall during June and July resulted in flooding of the nearby town of Welshpool (see Figure 3-1 for location).

Detailed observation during the winter of 2006/07 through to summer 2007 showed that rainfall patterns differed between the seasons and this is summarized in Table 5-6. A much wider range of rainfall intensities was observed during the summer months, but the majority of the rainfall (68 %) fell at rates of ≤ 6 mmh^{-1}. Just over 8 % of the rain in the summer fell at rates > 22 mmh^{-1}. Rates as high as this did occur in the winter, but this only constituted 1 % of the total rainfall. In comparison to the wide range of summer rainfall intensities, 96 % of winter rainfall was at intensities of $\leq$ 6mmh^{-1} (Figure 5-15a).

The difference in windspeed during rainfall events between the seasons was even greater. Rainfall events with low windspeeds of up to 2 ms^{-1} accounted for half of the rainfall amount recorded in the summer, but for only 10 % of winter rainfall. Typical windspeeds during rainfall events in winter ranged from 4 to 8 ms^{-1} and almost 20 % of rainfall in winter was accompanied by windspeeds exceeding 8 ms^{-1}. The highest windspeeds recorded during summer rainfall events were between 4 and 5 ms^{-1} (Figure 5-15b). Together the seasonal differences in rainfall intensity and windspeed caused large differences in the rainfall inclination angle between summer and winter. Using a calculation procedure specified by David et al. (2006), it was estimated that almost all of the summer rain fell at angles to the vertical of < 30˚, whereas almost all of the winter rain fell at angles > 30˚ (Figure 5-15c).

Table 5-6 Summary of meteorology for the period winter 2006 to end of June 2007.

	SUMMER	WINTER
Rainfall intensity	Wide range 68 % < 6 mmh^{-1}	Narrower range 96 % < 6 mmh^{-1}
Wind speed	Low 50 % < 2 ms^{-1}	Higher Most 4-8 ms^{-1} 20 % > 8 ms^{-1}
Rainfall inclination angle and wind direction	50 % < 30 ^{o} ENE	Almost all > 30 ^{o} WSW

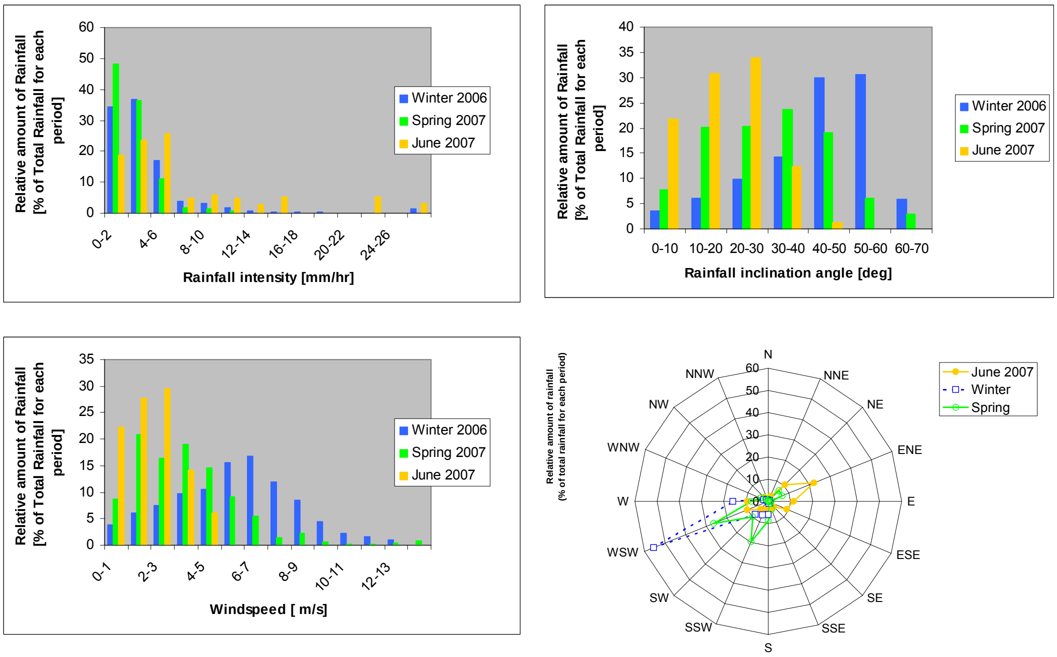


Figure 5-15a-d. Meteorological conditions during rainfall at the research site 2006/07. 'Winter' refers to the months December to February, 'spring' March to May and 'summer' June only.

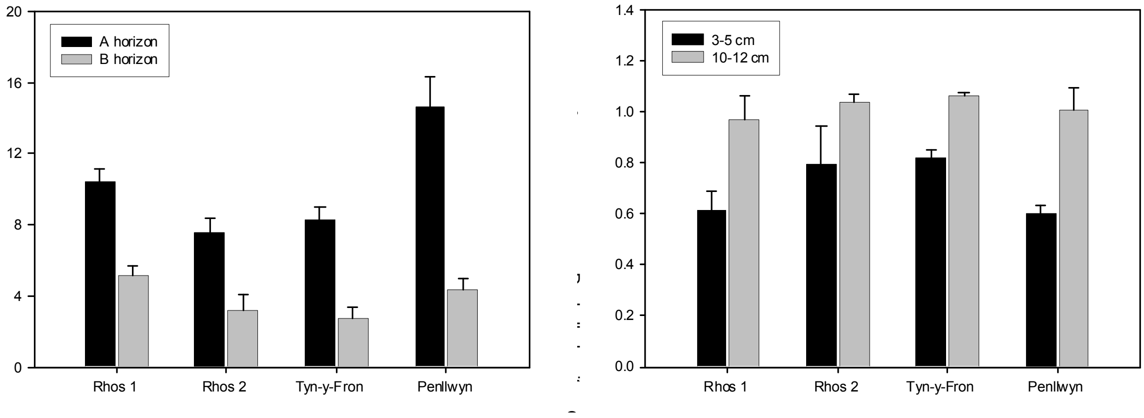
5.3 MANIPULATION PLOT EXPERIMENTS

The different land use manipulations commenced in February 2006, and are now just over a year old. This is not long enough to assess the impact of land use on the soil, therefore, only some of the preliminary data are presented here. Table 5-7 gives some characteristics for each site, along with some initial data. The sites range in elevation from 210 m to 310 m (AOD), with an aspect of SE for two of the sites and N and NW for the remaining sites. The soil type for three of the sites is the Cegin, with only Site 1 (Rhos 1) located on the Sannan soil series. The Sannan is a slightly more permeable soil then the Cegin and consequently is not as extensively waterlogged during the winter and early spring.

Table 5-7. Baseline soil data for the manipulation plots.

	Rhos 1 Site 1	Rhos 2 Site 2	Tyn-y-Fron Site 3	Penllwyn Site 4
Elevation (m o.s.l)	220	240	210	310
Aspect	N	SE	NW	SE
Soil Series	Sannan	Cegin	Cegin	Cegin
Organic matter (%) A horizon	10.43	7.56	8.32	14.63
Organic matter (%) B horizon	5.17	3.21	2.73	4.33
Bulk Density (g cm^{-3}) 3-5cm	0.61	0.79	0.82	0.60
Bulk Density (g cm^{-3}) 10-12cm	0.97	1.03	1.06	1.01
Texture A horizon	Silty Clay loam	Silty Clay loam	Silty Clay	Silty Clay loam
Texture B horizon	Silty Clay/Clay	Clay	Clay	Clay

The average organic matter content for each site ranges from just under 8 % (Site 2), to just under 14 % (Site 4) for the A horizon, with lower values for the B horizon (Figure 5-16). Any change in organic matter content will be investigated for each plot once the treatments are 3 years old. The soil bulk density was determined for 3-5 cm and 10-12 cm depth (Table 5-7, Figure 5-16). The values for 3-5 cm range from 0.60 to 0.82, which are relatively low for heavy textured grassland soils (Rowell 1994). In the top 5 cm of soil there is a very dense network of grass roots. Although samples were taken below the main root mass (3 cm depth), the root density was still high. Although these roots do not account for much mass within the sample, they do take up volume. This would result in a lower bulk density then expected. The data for 10-12 cm depth, shows larger bulk density values, and are more typical for this type of land. As for organic matter, any change in bulk density will be examined after the treatments are 3 years old.


(a) Soil organic matter

(b) Soil bulk density

Figure 5-16. Baseline data for the manipulation plots for (a) Soil organic matter content and (b) Soil bulk density.

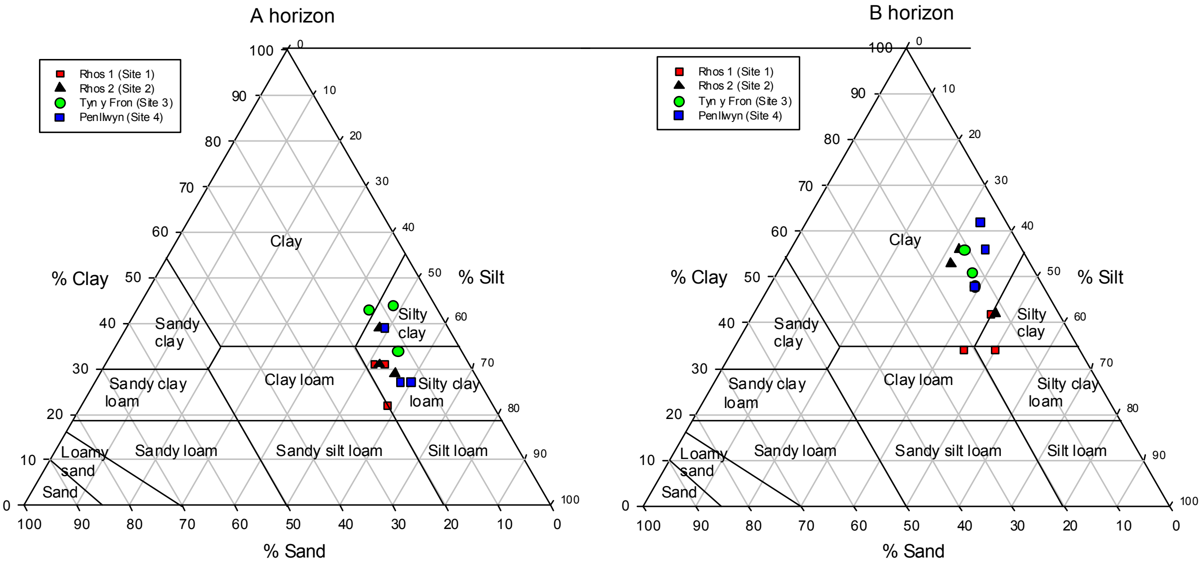


Figure 5-17. Soil texture in the manipulation plots for the A horizon and B horizon.

The soil texture for each site, for the A and B horizon, is shown in Figure 5-17. The largest clay contents for the A horizon were found at Site 3, although all sites showed a range in values, with at least two different textural classes at each site. The textural class for the A horizon included clay, silty clay and silty clay loam. The B horizon had a larger clay content then the A horizon, with most plots giving a textural class of clay. The main exception to this is Site 1, which has a lower clay content than the remaining sites, reflecting the different soil series found at this location.

Soil pore water pressure (tensiometer data) and the profile of moisture content with depth (neutron probe data), are not given here as these measurements are discussed elsewhere in the report and provide no additional information at present. As monitoring continues, any changes in these observations, associated with the land use manipulations, will be identified.

Some initial overland flow data for the Rhos 2 manipulation site are summarized in Table 5-8, with some of the data presented in Figure 5-18. The rainfall events in the first half of this table represent baseline data and the second half, data once the treatments have begun. The final two columns in the table show the ratio of overland flow in each plot compared to plot 1 (the control plot once treatments commenced). If the amount of overland flow were the same across the field then the ratios would be close to one.

The baseline data for overland flow showed considerable variability within a site, reflecting the variation in micro-topography and the spatial variation in soil properties. This highlights the importance of collecting data before changing the land use; to help distinguish the effects of land use change from the inherent variability of an area. For example, Figure 5-18 and Table 5-8 show that on the 10/01/2006, Plot 3 produced the most overland flow and Plot 1 the least. These differences, however, were not constant and for the 05/03/2006 Plot 1 and 3 were similar, but very different from Plot 2. Overland flow generation will depend on factors such as the antecedent soil moisture conditions. The tensiometer data for three plots indicate that the soil was saturated when these overland flow events occurred, producing ‘saturation excess’ overland flow. This, therefore, does not account for the variability between plots and it is likely that this can be related to the total rainfall, the maximum intensity of this rainfall and the duration of the event.

In June 2007 one of the highest intensity rainfall events occurred, reaching maximum intensities equivalent to 54 mm h^{-1} (for a 20 minute period). The overland flow for this event, however, was small, which can be attributed to the fact that the soil surface was not completely saturated over this time. This is discussed in greater detail in Section 5.5.

The data for December 2007 and January 2008 show large volumes of overland flow for the control plot 1 (up to 74% of the total rainfall). This was one of the wettest periods of data collection in Pontbren where the soil was saturated for the majority of the time, which explains why, with only 17mm of rainfall, such large overland flows were recorded (Table 5-8). For Plot 2 (ungrazed) and Plot 3 (ungrazed with trees planted) the ratios to the control plot appear to have decreased from the baseline data. However, more data is required before a more definitive conclusion can be made with regard to this.

Table 5-8. Summary of overland flow data for storm events at the Rhos 2 manipulation site.

Date	**Total rainfall**	**Max Intensity**	**Overland flow**			**OLF % rainfall**			**Ratio to control plot**	
			Plot 1	Plot 2	Plot 3	Plot 1	Plot 2	Plot 3	Plot 2	Plot 3
	mm	mm/hr	mm	Mm	mm	%	%	%		
04/12/2006	34.2	10.8	1.7	2.7	1.8	4.8	7.9	5.3	1.6	1.1
12/12/2006	18.8	14.4	1.1	0.4	1.0	5.9	2.0	5.4	0.3	0.9
29/12/2006	18.6	14.4	0.27	1.42	1.94	1.44	7.61	10.44	5.3	7.2
10/01/2007	22.2	6	2.0	2.6	3.3	8.9	11.9	14.9	1.3	1.7
05/03/2007	20	10.8	3.7	1.8	3.3	18.7	9.2	16.6	0.5	0.9
10/06/2007	40	54	3.33	1.89	2.22	8.33	4.74	5.56	0.6	0.7
06/12/2007	41.8	10.8	20.8	12.9	5.7	49.7	30.8	13.6	0.6	0.3
08/12/2007	16.4	4.8	7.0	2.4	1.1	42.9	14.9	6.5	0.3	0.2
15/01/2008	17	4.8	12.6	5.5	3.3	74.0	32.6	19.5	0.4	0.3

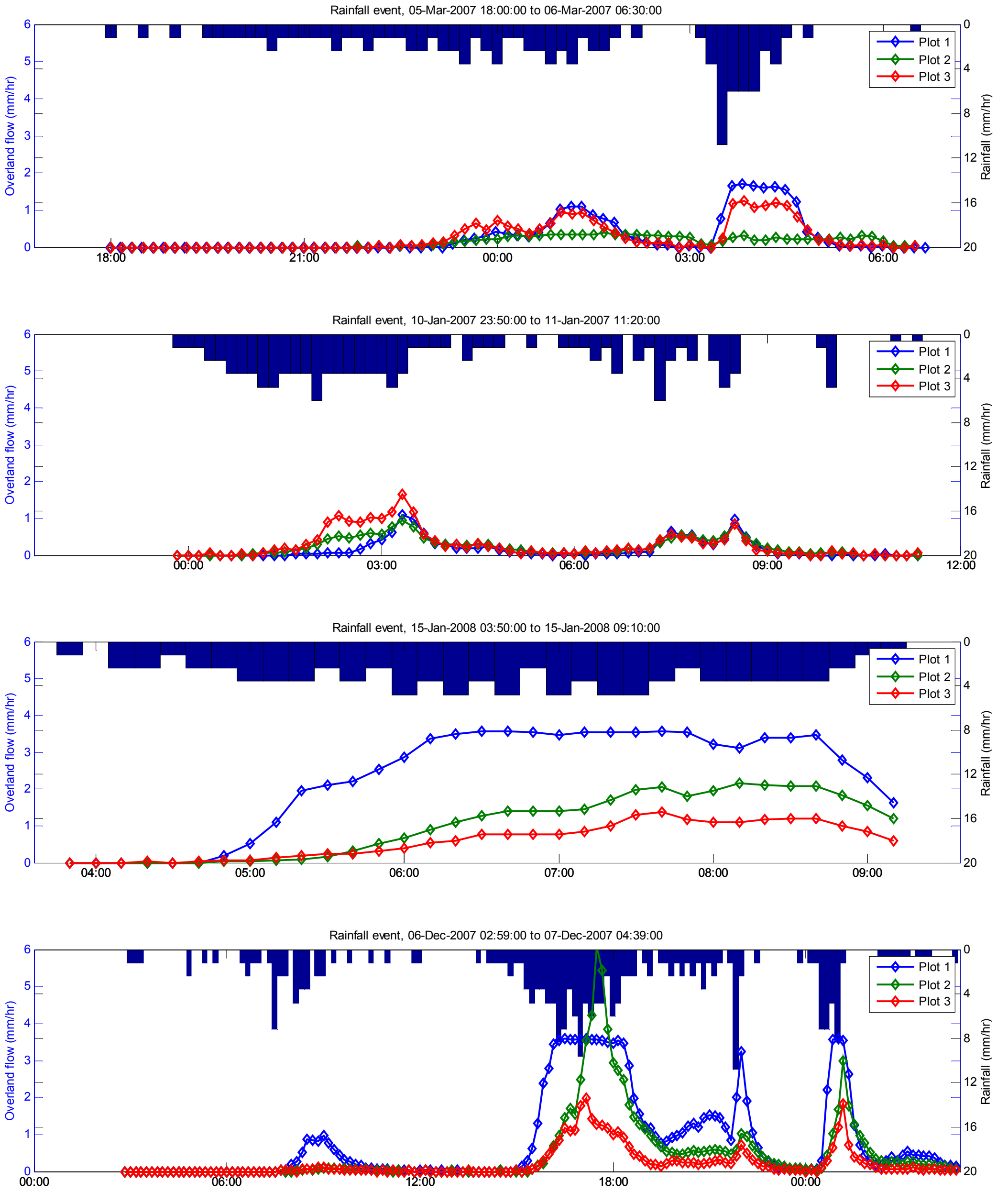


Figure 5-18. Overland flow data for rainfall events at the Rhos 2 manipulation site. Plot 1 is the control plot, Plot 2 is ungrazed and Plot 3 ungrazed and planted with trees.

5.4 TREE SHELTER BELT MONITORING

The effects of tree shelter belts on soil hydrology and runoff processes will depend on changes to soil properties, as discussed above, but also on other factors, for example changes to incident rainfall due to interception loss. There are also wind shadow effects to be considered. Hence, detailed studies of these effects are underway as part of an ongoing PhD project (Solloway, in preparation), and preliminary results are presented here.

Spatial variability of net rainfall outside the tree shelter belts

Results are presented as a percentage of gross rainfall measured at the Bowl study after compensating for any differences in measurement values due to the different rain gauge heights as discussed in Section 4.3.

The rain gauge transects outside the tree shelter belts revealed a high degree of spatial variability in the amounts of rainfall reaching the ground. Figure 5-19 shows that, during winter, the area where rainfall was influenced by the presence of the tree shelterbelt was not restricted to the area of the canopy, but extended over a width of at least 6m from the edge on the leeward side. In contrast, there is little or no spatial variability during the summer (Figure 5-19) when lower windspeeds and higher rainfall intensities combined to give smaller rainfall inclination angles and a greatly reduced area of rainfall depletion.

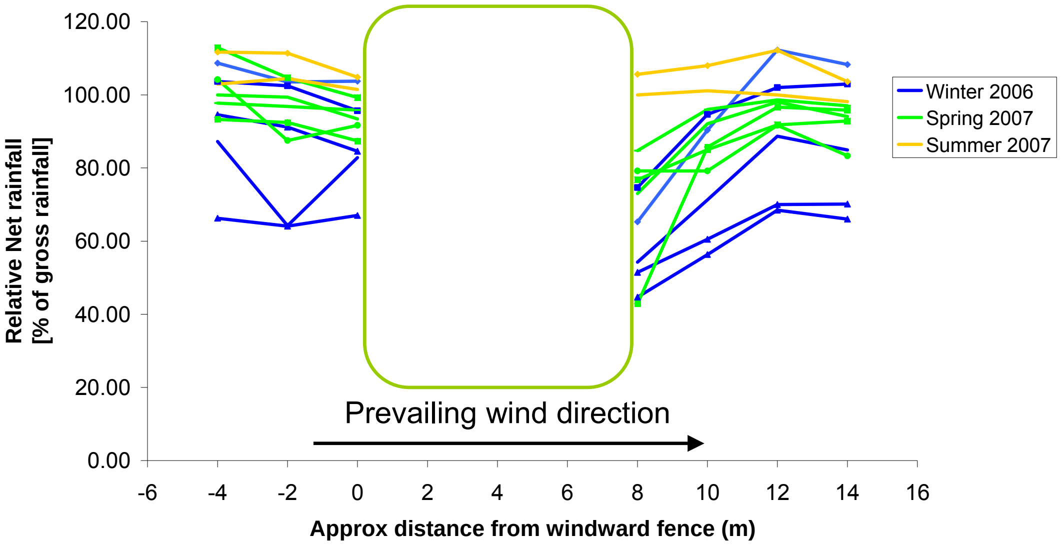


Figure 5-19. Spatial distribution of throughfall at Cae Drains, T$_2$, along 2 transects either side of the tree shelter belt. Colours represent seasons: blue markers indicate measurements made during winter 2006; green, spring 2007 and gold, summer 2007. Green rectangle indicates position of tree shelter belt. Tree height here is between 4 and 8 metres.

Spatial variability of soil moisture outside the tree shelter belts

As with net rainfall, the soil moisture measurements show spatial variability across the ground areas influenced by the tree shelterbelts. At depths below 30 cm, on the leeward edge of the shelterbelt, the lowest moisture contents in the adjacent pasture are recorded nearest to the tree shelterbelts, an example of which is illustrated in Figure 5-20b. Soil moisture then tends to increase as one moves away from the tree planted area. This is probably attributable to the spatial variability in net rainfall distribution down wind of the tree shelterbelt. At depths of 30 cm and above, the pattern is reversed (see Figure 5-20a), which is counter-intuitive, and the subject of further analysis. Care must be taken when interpreting these neutron probe data as site specific calibrations have not yet been performed. Therefore, analysis should focus on *changes* in soil moisture content with time, rather than absolute values. It should also be noted that near-surface neutron probe measurements are inaccurate, due to the large sphere of influence of the device leading to the escape of neutrons to the atmosphere.

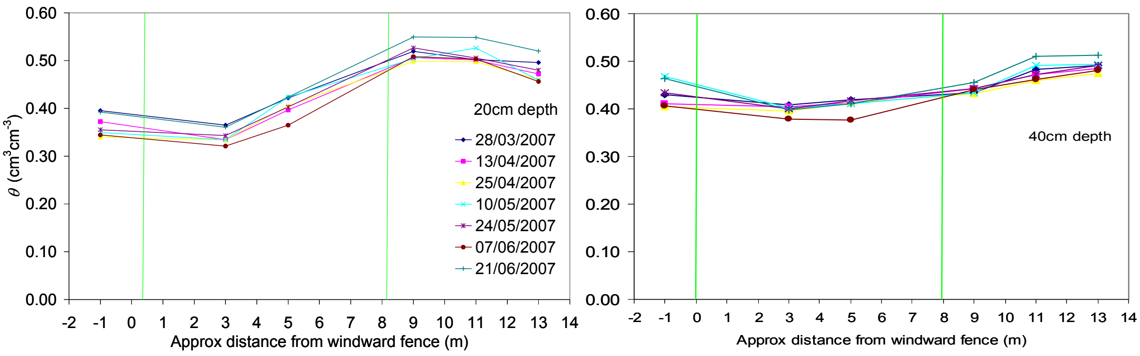


Figure 5-20a and b. **Cae Drains, T_2, Transect moisture content θ(cm^{3}cm^{-3}) at 20 cm and 40 cm depth respectively.**

Throughfall within the tree shelter belts

Figure 5-21 shows cumulative total rainfall versus throughfall for the period of measurement for two tree planted sites. At each site cumulative rain throughfall (mm) is compared with cumulative total rainfall (mm) recorded by a nearby standard tipping bucket rain gauge. At the Tyn y Fron site, T_3, an established woodland edge, 56 % of the total rainfall measured was collected in the throughfall collectors located underneath the trees. Slightly less rain was observed to reach the ground beneath the younger Cae Drains trees (46 %).

In order to calculate the total interception loss, stem flow measurements are required. These data are being collected, but are not yet available in quality assured form.

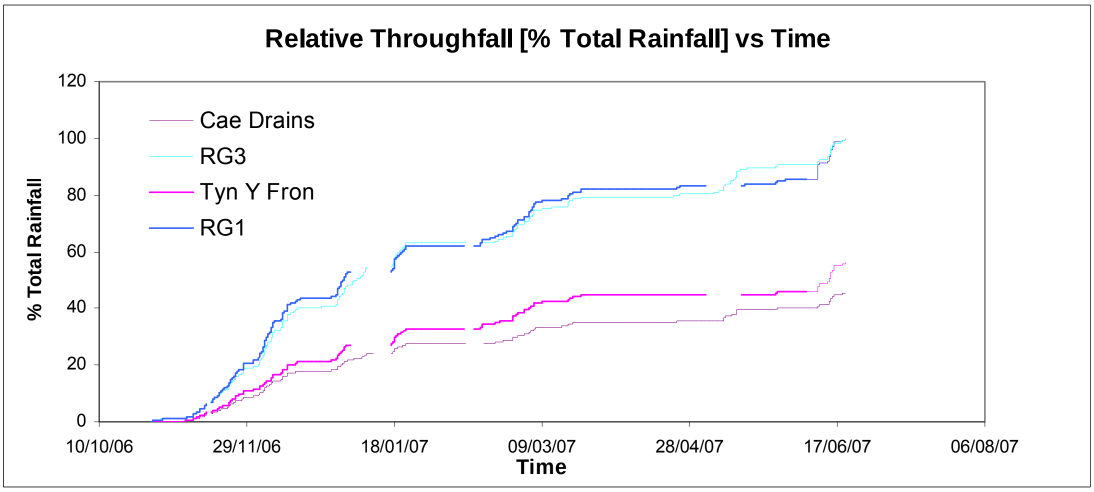


Figure 5-21. Cumulative total rainfall versus throughfall at Cae Drains, T_2, and Tyn y Fron, T_3.

The data show that linear woodland features planted as shelter belts on an upland hill farm can significantly influence the amounts and patterns of rainfall reaching the ground both within, and on the leeward side of the tree shelter belt. Within the tree shelterbelts, the amount of incident rainfall reaching the ground as throughfall is decreased. At present, it is too early to fully quantify the interception losses for these tree areas as reliable stem flow measurements are needed.

The influence of tree shelterbelts on rainfall patterns in the wider landscape is determined by the wind direction and inclination angle of the rain during rainfall events. Inclination angle is a function of rainfall intensity and wind speed and these factors vary seasonally. Winter rain events are typically of low intensity (≤ 6 mmh^{-1}) and associated with higher windspeeds (4 to 8 ms^{-1}), reflecting the dominant influence of oceanic frontal systems on the weather as reported in section 5.2. As a result, the inclination angle is greater and the zone of rainfall depletion extends further to the leeward side of the tree shelterbelt (at least 6 m for a 4 - 8 m high TSB). In contrast, a much wider range of intensities was observed during the summer, due to the occurrence of both frontal and high intensity convectional rain storms. Wind speeds during summer rainfall events were generally lower (< 2 ms^{-1} for 50 % of events) resulting in a smaller inclination angle and reduced area of rainfall depletion to the lee of the tree shelterbelts.

Conclusions
Conclusions from the tree shelterbelt monitoring programme are:

- soil moisture patterns are complex but the tree shelter belt appears to affect the soil moisture status both within and on the leeward side of the tree planted area
- there is a reduction in the amount of throughfall occuring underneath the trees but stemflow data is required in order to determine interception losses.

5.5 HILLSLOPE-SCALE MONITORING

<u>What are the relative roles of surface and subsurface flows in runoff generation?</u>
Pore water pressure data, ψ, from tensiometer array H_{11} along with rainfall data are presented in Figure 5-22 for the period December 2005 – May 2006. Positive ψ values indicate that the soil is saturated and one can see that at the 30 cm and 50 cm depths, the soil remains saturated for much of this monitoring period. Even at the 10 cm depth there is a considerable amount of time during this period when positive ψ values are observed. The same patterns are observed at all monitoring locations. Figure 5-23a-d shows ψ data from plot 1 of each of the manipulation plots, M_{1-4} respectively. The data shown in Figure 5-23 are for the same monitoring period as shown in Figure 5-22 and positive ψ values at each site indicate similar saturated soil conditions. Comparing ψ values observed for the 10 cm depth with corresponding θ values of the SMCC for Cegin soil series A horizon under improved pasture land use (see Figure 5-3), it appears that there is little change in estimated moisture content between $\psi = 0$ and -50 cm H_2O. This indicates that the soil profile is remaining close to saturation for most of this period. Figure 5-22 indicates that saturated conditions were maintained at least until May of 2006. Note that at no point during the period of observation do any of the tensiometers reach '*field capacity*', i.e. when ψ is between -50 and -100 cm H_2O (Rowell, 1994).

Rapid response of tensiometers following the onset of rain (see Figure 5-22) indicates preferential movement of water. Tensiometers installed at 50 cm depth responded in less than 2 hours, suggesting either that water is moving faster than suggested by the median measured K_{sat} values (see Section 5.1.2), or that infiltration at the surface into a near-saturated profile is displacing water lower in the profile. Preferential flow pathways exist, such as those highlighted by the dye staining patterns observed during the dye tracer test (see Section 5.1.3), allowing rapid movement of water down through the soil profile bypassing much of the soil matrix. Preferential flow paths are expected to be activated when soil is saturated and/or when rainfall intensity exceeds the hydraulic conductivity of the soil matrix.

To illustrate the role of groundwater, the groundwater trace from the borehole located at the bowl study site is presented in Figure 5-24 for the monitoring period August 2005 – November 2007. Up until October 2006, the groundwater appears relatively unresponsive to the rainfall. During the period December 2005 – May 2006 groundwater elevation never reached closer than 101 cm to the soil surface. Tensiometer data for this period, shown inFigure 5-22, indicate that the soil was saturated for most of this period at least to 50 cm depth, suggesting that there is an impeding layer below this depth, and that there is little local interaction between ground and soil water. The same saturated soil conditions are observed across monitoring sites, including manipulation plots. This is consistent with the impermeable nature of the Cegin series subsoil as described by Thompson (1982), which prevents much of the rainwater reaching the groundwater, resulting in saturated topsoil conditions.

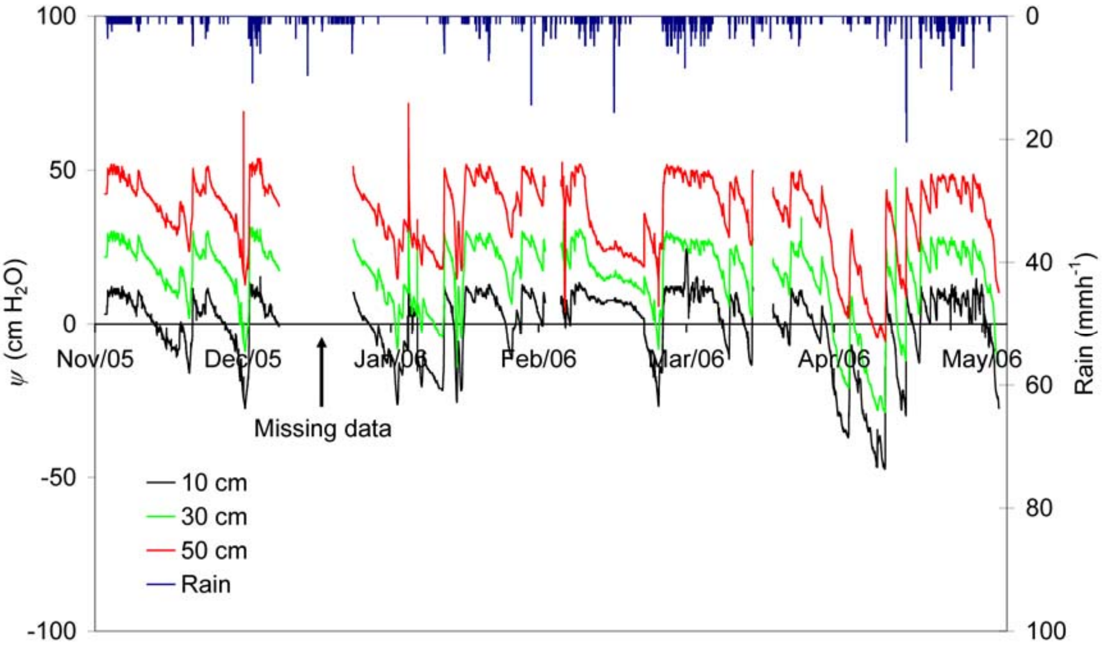


Figure 5-22. **Pore water pressure, ψ, from tensiometer array H_{11} from the Bowl study site for the period December 2005 – June 2007.**

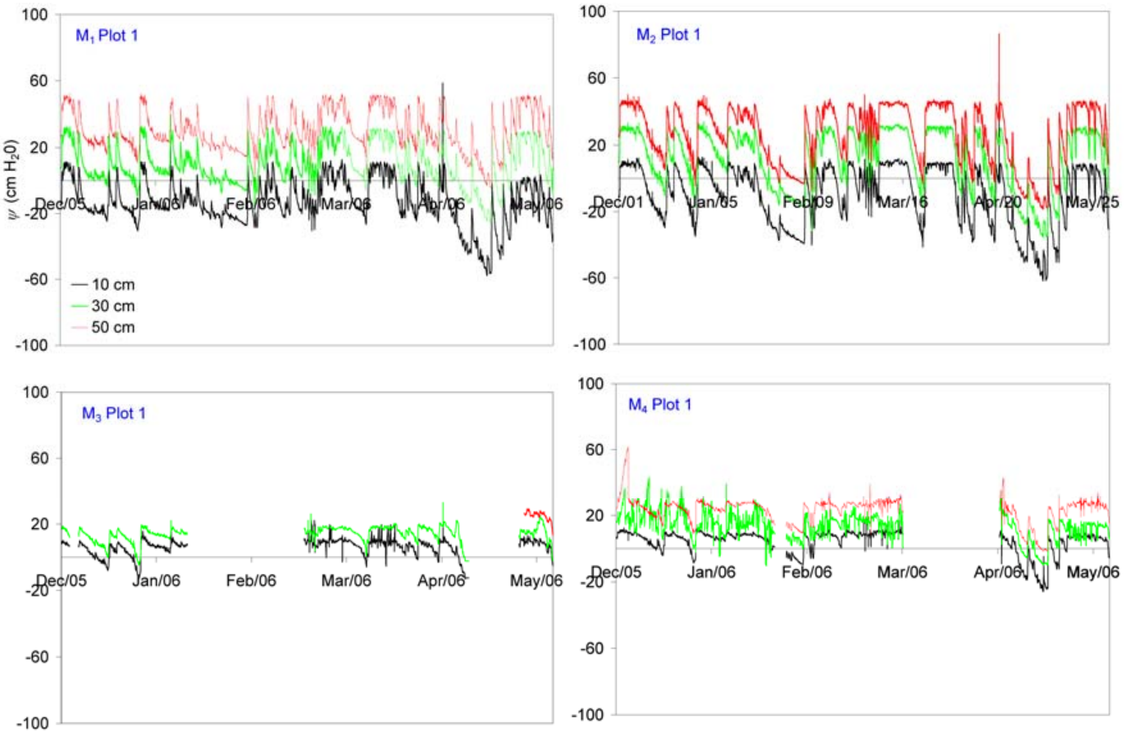


Figure 5-23a-d. Pore water pressure, ψ, from plot 1 tensiometer array from each of the Manipulation plots $M_{1\text{-}4}$ respectively, for the period December 2005 – June 2007.

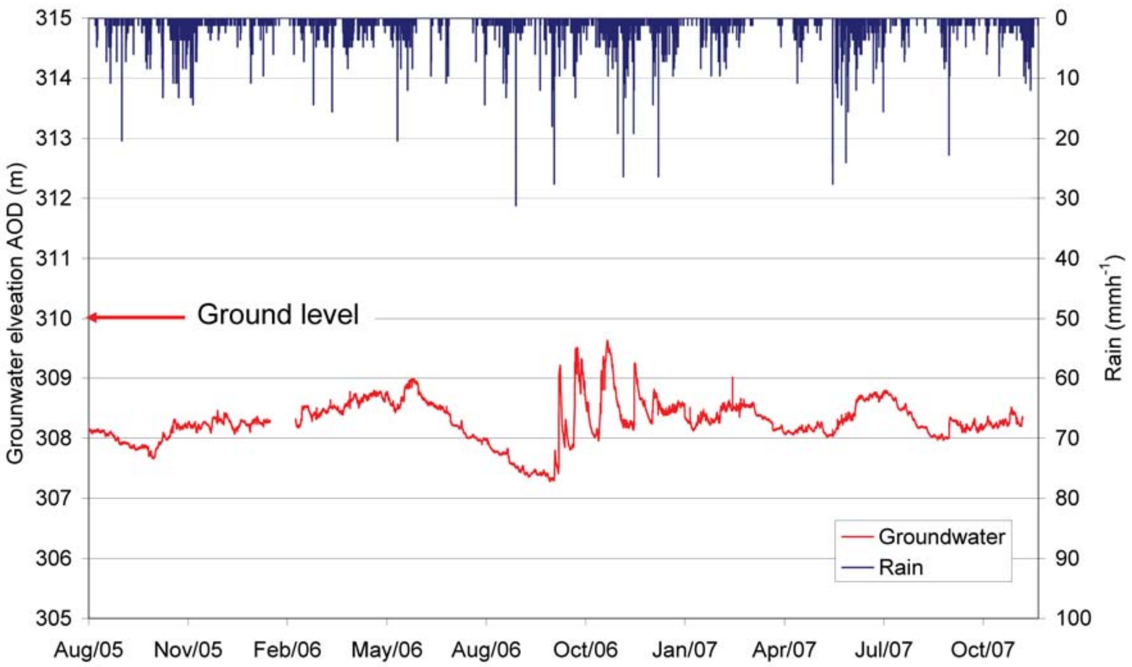


Figure 5-24. **Groundwater elevation (m) in the bowl study site borehole.**

Between October 2006 and January 2007 the groundwater becomes relatively responsive, with distinct fluctuations in elevation in response to rainfall (See Figure 5-24). During this time groundwater elevation rises to 37 cm from the soil surface. Figure 5-25 shows tensiometer data for the period end of November 2006 – beginning of January 2007. It is apparent that the soil surface (10 cm depth) is remaining drier than in the winter of 2005 – 2006, despite increases in groundwater elevation and relatively high rainfall intensities and volume. It is believe that this change in hydrological response occurred as a result of the very hot dry weather that occurred during the summer of 2006. MORECS estimation of the soil moisture deficit, SMD, for the grid square within which Pontbren is located indicates a much greater deficit in 2006 compared to that of 2005 (see Figure 5-26). This resulted in the drying out of soil at Pontbren and the opening up of preferential flow paths in the form of large cracks, visible at the soil surface. These preferential flow paths not only allowed rapid movement of water down through the soil profile, bypassing much of the soil matrix, but also allowed rainwater to reach the groundwater through the previously, relatively impermeable, subsurface layer. It is interesting to note that the groundwater elevation appears to return to the more ‘normal’ unresponsive nature, presumably as a result of these large cracks having closed up.

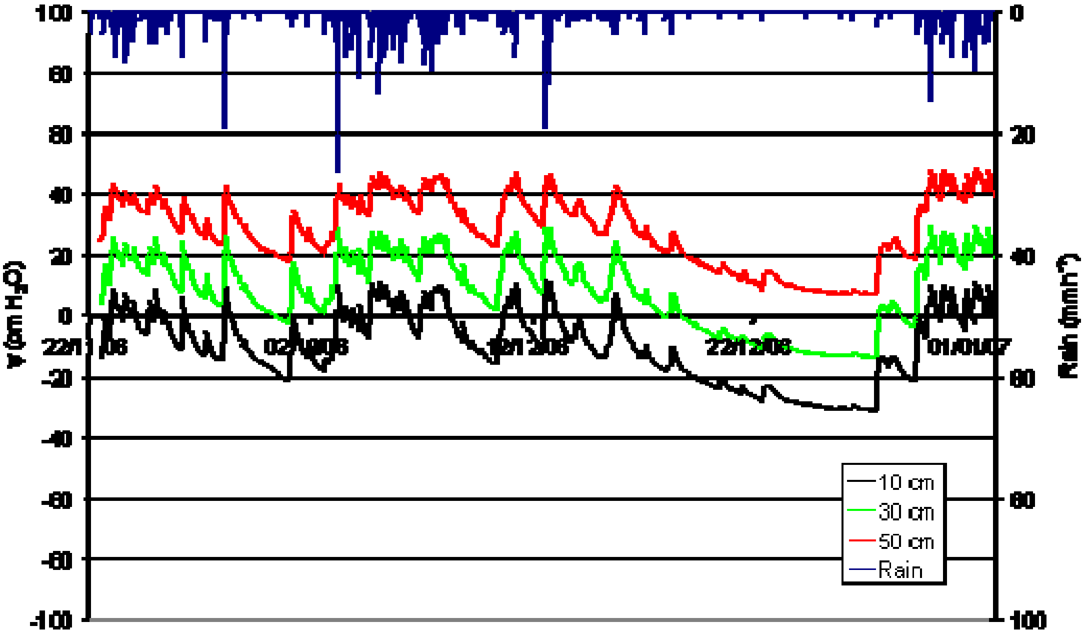


Figure 5-25. Pore water pressure, ψ, from tensiometer array H_{11} from the Bowl study site for the period November 2006 – January 2007.

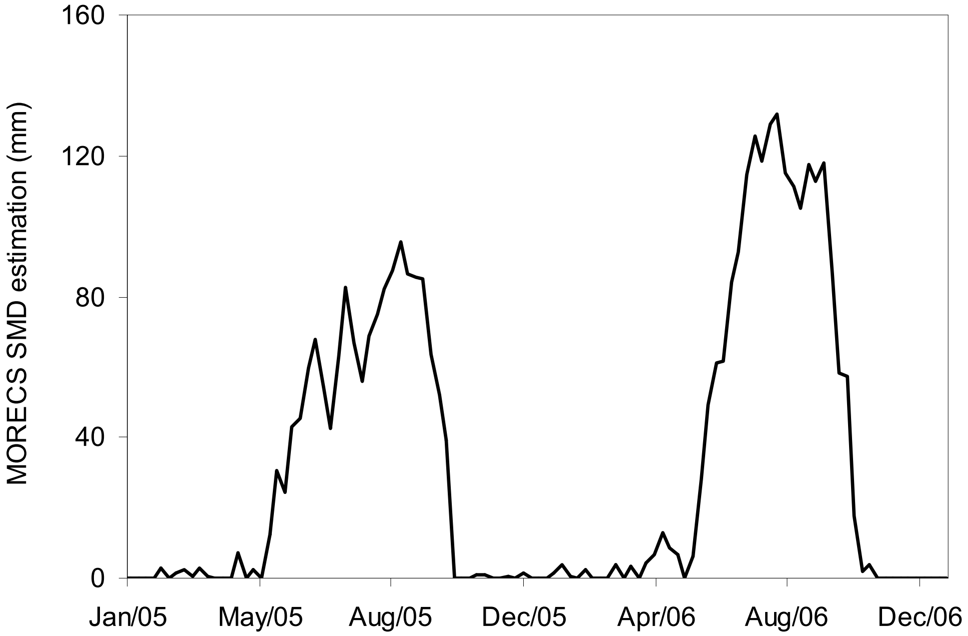


Figure 5-26. MORECS estimation of soil moisture deficit. © Crown copyright. All rights reserved, Met Office.

Differences in runoff response are observed from the bowl study site before and after the hot dry summer of 2006. The term runoff is used here to refer to any water moving off the hillslope either as overland or drain flow. Figure 5-27a-d show overland flow, OLF, and drain flow measured during December 2005 and 2006 along with ψ from the 10 cm depth tensiometer at H_{11}. The positive pore water pressures at 10 cm depth shown in Figure 5-27c indicate that the soil surface is remaining saturated for longer during the December 2005 event compared to the event in 2006 despite lower rainfall intensities and volume. As a result of drier soil conditions, there are significant differences in runoff response (Figure 5-27a and b). Caution must be given to the interpretation to the overland and drain flow data from the event in 2005 as this was prior to the installation of weir boxes to measure runoff from the bowl study site (concern over the accuracy of the initially installed tipping buckets, especially at high flows, led to the installation of weir boxes with pressure transducers). However, this period of data was chosen as it is believed to be accurate in terms of the relative contributions of the different processes and presents runoff data from the bowl study site prior to the hot dry summer of 2006. There is a significant decrease in the relative amount of rainfall coming off the land in the form of OLF. During the 2005 event, OLF intensity often exceeds that of the drain flow, whereas during the 2006 event OLF intensity never exceeds that of the drain flow despite greater rainfall intensities and volume. The change in hydrological response is attributed to the effect of the hot dry summer of 2006 on increasing the bulk permeability of the soil, allowing water to drain more freely into the deeper soil profile with the result that the soil surface remained drier for longer and the amount of overland flow was reduced. Both events demonstrate the importance of drain and OLF in the movement of water at the hillslope scale, and importantly indicate that OLF occurs here as a result of saturation excess as opposed to infiltration excess. Under ‘normal’ conditions, saturated upper soil layers occur in these soils due to the perched water table caused by the impermeable subsurface layer. Once this saturated layer reaches the soils surface, OLF is initiated. Widespread infiltration excess OLF is unlikely to occur on these soils when one considers the measured K_{sat} values discussed in Section 5.1.2. This is only likely where the soil has been severely compacted possibly at field gates, for example, where livestock movement is concentrated.

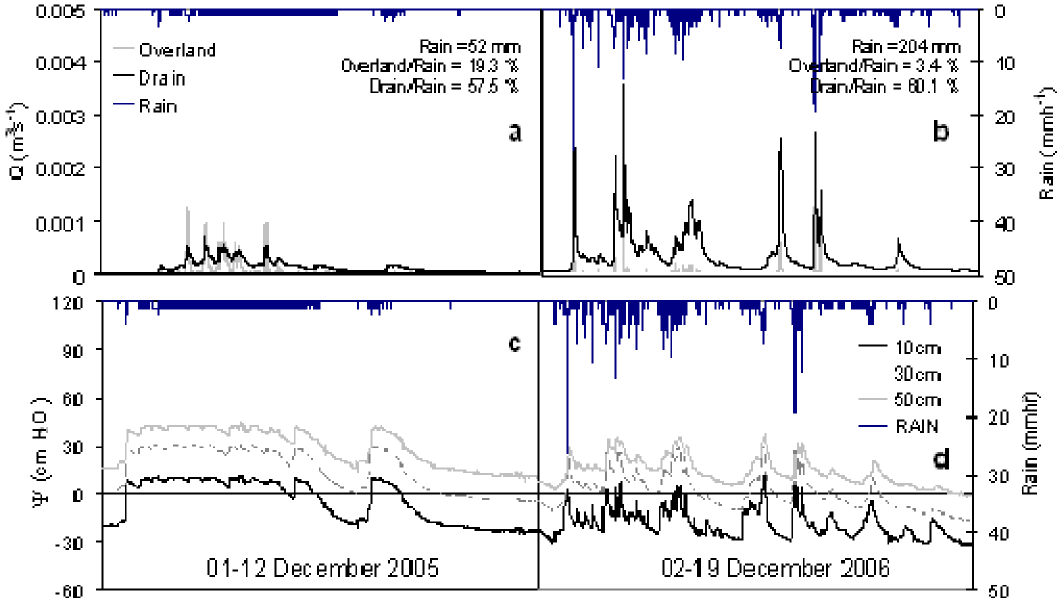


Figure 5-27a-d. Overland and Drain flow along with soil pore water pressure measured at to tensiometer array H_{11} for two rain events in December 2005 and 2006.

Figure 5.28 shows OLF and drain flow from the bowl study site for the monitoring period October 2006 – December 2007. OLF and drain flow are normalized into units of mmh^{-1} by dividing the rate of flow by the catchment area. OLF and drain flow rates from the bowl study site were sampled every minute and averaged over a 5 min period. Figure 5-29 shows normalised total runoff from the bowl study site for the same monitoring period, where total runoff here is equal to the OLF and drain flow combined. Figure 5-28 indicates that peak flows tended to be dominated by drain flow. However, OLF contributes significantly to a number of events, depending on antecedent moisture conditions, and exceeds that of the drain flow during particular events.

The largest event recorded during this period occurs on 18/01/07 when 5.28 mmh^{-1} total runoff was recorded. During this event OLF and drain flow contribute 52 % and 48 % to peak runoff intensity respectively (see Figure 5-30a). The relatively high contribution to peak flow occurs as a result of saturated soil surface conditions during this event as shown by the positive pore water pressure measured at 10 cm depth (see Figure 5-30b).

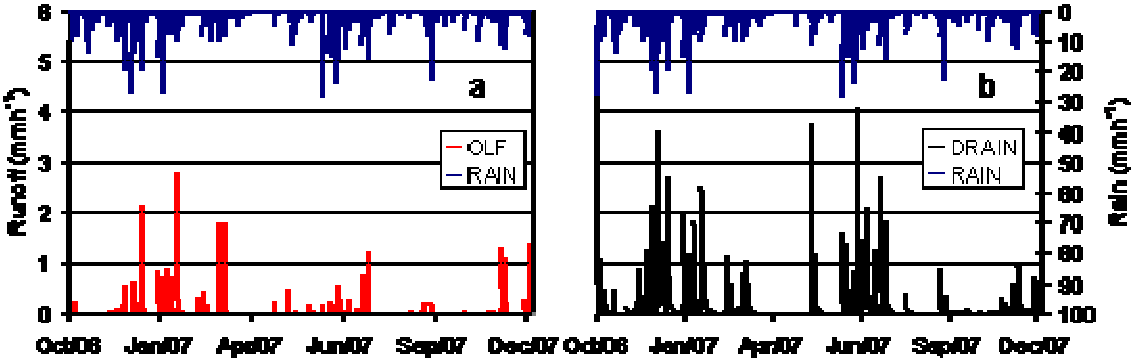


Figure 5-28a and b. Overland and drain from the bowl study site for the period October 2006 – December 2007. Note missing data 19/10/06-3110/06, and 13/03/07-29/03/07. System frozen 08/02/07-10/02/07, and 21/12/07-22/12/07.

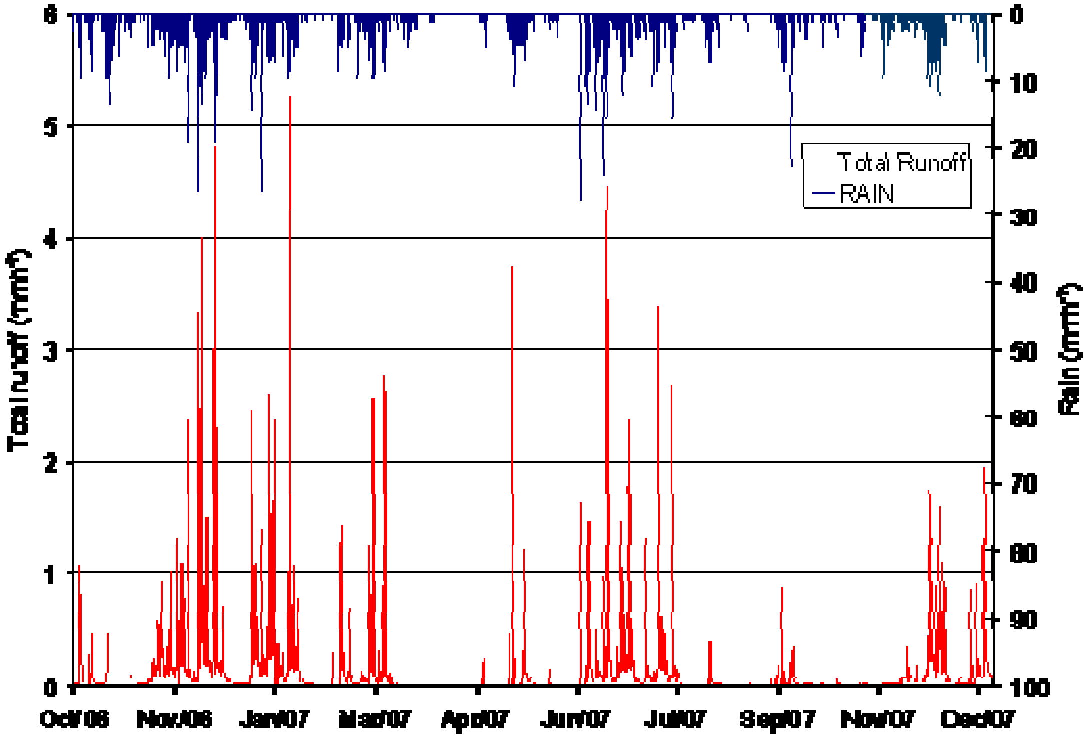


Figure 5-29. Total runoff from the bowl study site for the period October 2006 – December 2007. Note missing data 19/10/06-3110/06, and 13/03/07-29/03/07. System frozen 08/02/07-10/02/07, and 21/12/07-22/12/07.

Significant runoff events were measured during the summer of 2007 when Pontbren, like many parts of England and Wales, experienced unusually high volumes of rainfall for this time of year. A total runoff peak of 4.47 mmh^{-1} was measured on 25/06/07. During this event, antecedent soil surface moisture conditions resulted in a different hydrological response (see Figure 5-31a and b) with OLF and drain flow contributing 9.5 % and 90.5 % to the peak flow respectively. Comparing Figure 5-30b with Figure 5-31b it is evident that there is relatively little difference in surface pore water pressure, but the fact that the surface layer is not completely saturated, i.e. $\psi < 0$, results in a marked reduction in the amount of OLF occurring. Temporal variability in the time to peak is observed between OLF and drain flow from the bowl study site. During the event, which occurred on 18/01/07 (see Figure 5-30a), both OLF and drain flow occurred at exactly the same time, whereas during the event in 25/06/07, a 30 minute difference in peak OLF and drain flow resulted in a reduction in peak total runoff intensity. Runoff data from the bowl study site from the beginning of December 2007 is presented in Figure 5-32. During this event a difference of 230 minutes is observed between the peak OLF and drain flow. Variations in rain events such as rainfall intensity, duration and volume, will have an important impact on which of the two processes will dominate and also the time to peak flow following the onset of rain. Antecedent moisture conditions will also have an important impact as well as the hydraulic conductivity. Temporal variations in hydrological response have been observed as a result of climatic impacts on soil hydraulic properties. The relatively wet summer of 2007, which followed the hot dry summer of 2006, has further demonstrated the point that temporal changes in hydraulic conductivity may result from climatic variability, the uncertainty of which is set to increase with climate change.

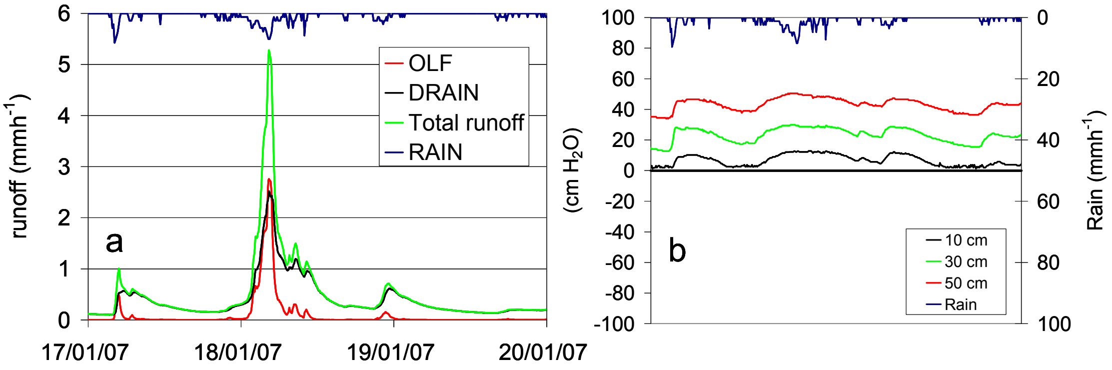


Figure 5-30a and b. Runoff and pore water pressure data (H_{11} tensiometer array) from the bowl study site for the period 17/01/07 – 20/01/07.

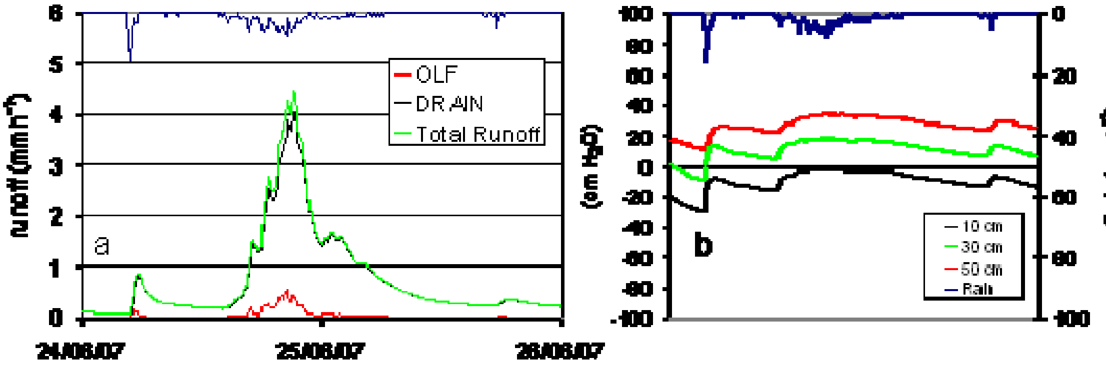


Figure 5-31a and b. Runoff and pore water pressure data (H_{11} tensiometer array) from the bowl study site for the period 24/06/07 – 26/06/07.

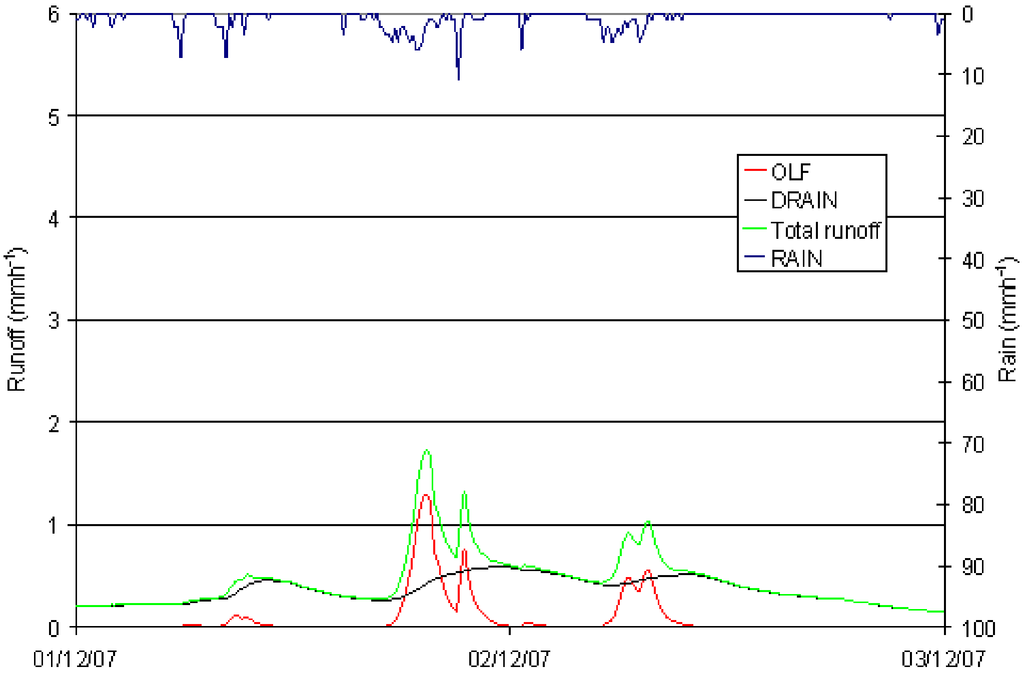


Figure 5-32. Runoff response from the bowl study site for the period 01/12/07 – 03/12/07.

In conclusion, evidence suggests that both overland flow and drain flow are important runoff processes, contributing to peak flow rates from hillslopes under improved grassland. The outflow from field drains, commonly installed in such soils to improve agricultural production, tended to dominate peak flows during this period of monitoring. However, depending on antecedent soil moisture conditions, overland flow is often an important contributor to peak flow rates, and can exceed those rates observed from drains. Temporal variability in climatic conditions directly impacting on soil hydraulic properties complicates the matter, in terms of the relative importance of these two runoff processes in hydrological response. Overland flow in these conditions (grazed improved grassland) occurs as a result of saturation excess due to an impermeable subsurface layer, and the relatively small amount of available pore space to take up incoming rainfall. It is also supposed that the soil water holding capacity of these soils is less than that of the open moorland soils from which it was once converted from, due to the decrease in soil organic matter caused by the affects of drainage, changes in vegetation, and effects of intensive livestock grazing.

In general, the goundwater observations show highly damped, seasonal response, very different from the highly dynamic response of the surface soils, and the associated overland- and drain flow. Localised occurrence of groundwater in the catchments is evident, however. Several of the farms take their water supply from wells, and interaction between surface and groundwater systems is visible at various springs within the wider catchment – indeed some field drains have been installed to remove groundwater seeps. However, as many of the Pontbren streams have run dry during summer months this suggests that there is no major baseflow component provided by groundwater. And where adjacent boreholes were drilled in the upper part of the hillslope, very different groundwater levels were obtained. We conclude that in general, the role of groundwater is limited, heterogeneous, and in the main disconnected from storm runoff response.

Can trees reduce local surface runoff?

Cumulative overland flow was collected from two isolated 5 m x 5 m plots, T_1 and T_2, within the Half-Moon tree planted area (see Figure 4-10 and Figure 4-11). Data are presented for the period

30/11/2005 – 13/12/2005 and 28/11/2006 – 03/01/2007. These times were chosen to facilitate comparison with the bowl runoff data and to represent a time when interception losses by the trees were at a minimum due to the absence of leaves at this time of year. During the second period, only T_1 was in operation. For both periods, the amount of overland flow collected is calculated as a percentage of the incident rainfall and compared with that measured in the bowl over the same time periods. For the period 30/11/2005 – 13/12/2005 the amount of overland flow collected was 3.8 % and 3.7 % from T_1 and T_2 respectively, compared with 19.3 % from the bowl. For the monitoring period 28/11/2006 – 03/01/2007 the amount of overland flow collected from T_1 was 0.8 % compared with 2.9 % from the bowl. Thus for both periods the amount of overland flow within the tree planted plots is small compared to that within the bowl. Differences between sites may result from interception losses by the tree canopy, an increase in the infiltration capacity (Carroll et al., 2004b) due to the trees, and/or the exclusion of sheep. Although consistent with prior expectations, these results must be viewed with some caution. The area of each plot within the trees is 25 m^2 while the bowl area is 4400 m^2, and so scale effects may partly cause the differences. In addition, there are differences in topography between the bowl and the tree planted area, which, although minor, may be another important factor (Anderson and Burt, 1978).

Figure 5-33a and b show soil moisture content profiles for two dates, 17/08/2006 and 20/12/2006, for the neutron probe access tubes, N_1, N_2 and N_5, located below, within, and above the tree planted shelterbelt respectively (see Figure 4-10). The two dates are when neutron probe sampling indicated that the soil was at its driest and wettest during the period of observation. The data indicate that, in the top 80 cm of the profile, the soil within the tree planted area was drier than the soil within the adjacent grazed areas at each sample time. Also, the soil profile above the shelterbelt consistently remains significantly wetter than that below. Again, care must be taken when interpreting these neutron probe data as site specific calibrations have not yet been performed. Analysis should focus on *changes* in soil moisture content with time, rather than absolute values. It should also be noted that near-surface neutron probe measurements are inaccurate, due to the large sphere of influence of the device leading to the escape of neutrons to the atmosphere.

When differences between the wet and dry profiles are calculated, it appears that the greatest change in moisture content, $\Delta\theta$, occurs below the shelterbelt and not within the tree area as might be expected. However, this does not necessarily suggest that there is a greater available soil water storage capacity within the soil under improved pasture, because, due to the relatively infrequent neutron probe sampling (every 2 weeks), transient effects may be missed. Results from the SMCC determination (see Section 5.1.1) indicate a difference in the A horizon characteristic for the wet end of the scale, suggesting that a greater proportion of the pore space of the soil under the tree areas is occupied by large pores compared to the soil under the improved pasture. Soils with a greater number of large pores will tend to drain more quickly at the wet end, as indicated by the steeper gradient of the SMCC of A horizon soil under the trees (see Figure 5-3). Thus relatively large pores, as well as macropores, will tend to drain very quickly and could easily be missed by the fortnightly neutron probe sampling programme. Much greater K_{sat} values measured in the A horizon under the tree areas compared to those under improved pasture (see Section 5.1.2) further suggest that under trees water could more easily infiltrate down through the soil profile, resulting in reduced overland flow. The dye tracer study conducted underneath the tree area illustrated how preferential flow paths down the surfaces of living tree roots allowing rapid movement of water to potentially deeper storage areas than could be accessed by shorter rooted grass species.

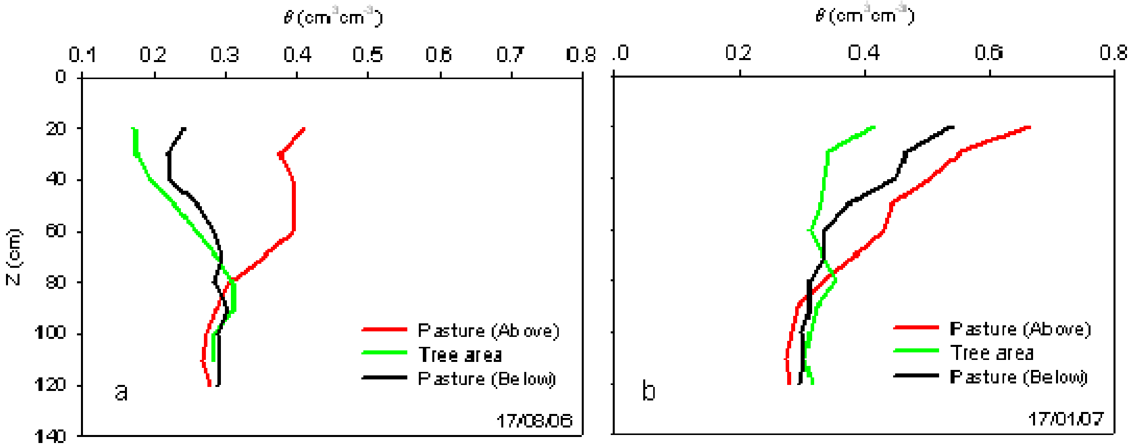


Figure 5-33a and b. Driest and wettest profile moisture content measured above within and below the tree planted shelterbelt at the instrumented hillslope.

The evidence from our experiments therefore supports the hypothesis that tree shelterbelts protected from grazing may reduce local surface runoff. The experiments discussed here, and the work by Carroll et al (2004a), indicate that increased permeability of the soils is a significant explanatory factor, and the increased hydraulic conductivity measured during this study supports that. However, there are a number of uncertainties regarding this theory. Is the increased storage capacity suggested by the measured SMCCs significantly large enough to reduce runoff when trees are strategically positioned across a hillslope? Considering mean air capacity values for the 2 different land uses as shown inTable 5-4, there is an average absolute increase of 8 % in the A horizon moving from improved pasture soil (12 %) to tree shelterbelt soil (20 %), i.e. a relative increase of 75%. With an average A horizon depth of 22 cm, this would give an increase of about 18 mm extra available storage when at *field capcity*. Profile moisture contents illustrated in Figure 5-33a and b suggest that the soil remains drier under the trees and there is therefore further available storage space for incoming rainwater/overland flow compared to the improved pasture. This is especially so when considered in conjuction with the suggested increase in mean θ_{sat} under trees, as indicated in Figure 5-3 when $\log\psi = 0$. Part of the reason for the apparent consistently drier soil profile underneath the tree planted area is the significant increase in K_{sat} underneath the tree areas, allowing water to infiltrate more easily into the soil profile. Rain water can then be released more gradually as it moves through the soil profile rather than discharging rapidly off the hillslope in the form of overland flow.

5.6 CATCHMENT SCALE EXPERIMENTS

Has past land management increased catchment-scale runoff intensity?

Normalised hydrographs of total runoff from the bowl were compared with hydrographs of the stream flow monitoring sites 5, 6, and 7, located on the Pen-y-cwm and Pont-bren-down streams (see Figure 4-1 for locations), and are presented in Figure 5.34a-d respectively. Data shown for each of the stream flow sites were calibrated as described in McIntyre and Marshall (in press). There is an apparent decrease in peak flows with increase in drainage area (see Table 5-9). All sites have similar land use with the % of land estimated to be under improved grassland production shown in Table 5-9. Figure 5-35 shows the flow duration curves for the Bowl, along with those of Sites 5, 6, and 7 for the same monitoring period presented in Figure 5-34a-d. Figure 5-35 indicates a reduction in peak flows with increasing drainage area. Peak flows recorded during this monitoring period were 5.27, 2.82, 2.05, and 1.79 mmh^{-1} for the Bowl, and Sites, 5, 6, and 7 respectively.

Table 5-9. Monitoring locations drainage areas and % area under improved grassland production.

Monitoring location	Drainage area	Area under improved grassland
	ha	%
Bowl	~ 0.5	100
Site 5	242	70
Site 6	318.5	77
Site 7	572	80
Site 8	110	0
Site 9	402.25	14

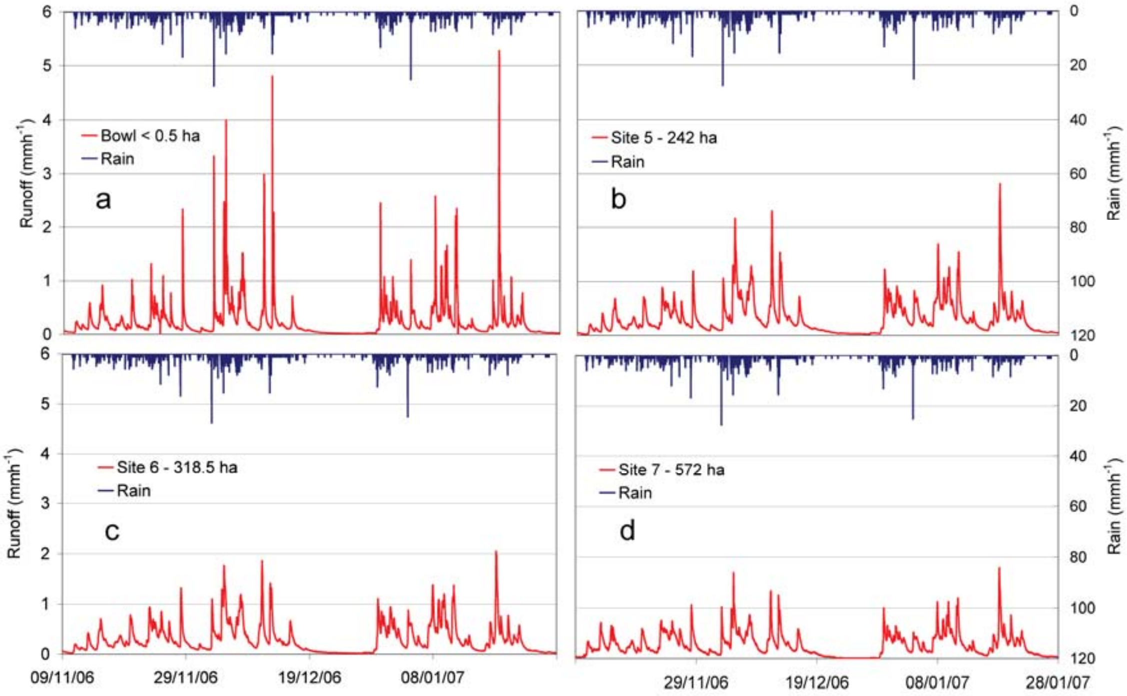


Figure 5-34a-d. Hydrographs of total runoff from the Bowl and stream flow gauging Sites 5, 6 and 7 respectively for the period 09/11/06 – 28/01/07.

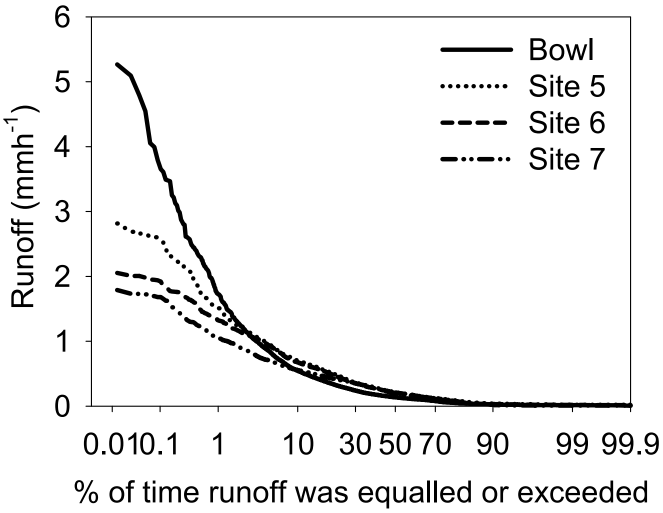


Figure 5-35. Flow duration curves for the Bowl study site, along with Sites 5, 6, and 7 for the period 09/11/06 – 28/01/07.

Total runoff from the bowl was then compared with sub catchments with contrasting land use patterns. Figure 5-36a and b show the normalised hydrographs of total runoff from the bowl along with those from Site 6 on the Pontbren stream (~ 318 ha), and Site 9 on the Melin y grug (~ 402 ha) for the period 09/11/2006 – 28/01/2007. Site 6 is a stream outlet from a subcatchment where there is a high proportion of improved grassland (77 %), compared to only 14 % for Site 9. Figure 5-36a and b show that the upper Pontbren stream, the Nant Pen y cwm, has a flashy response (similar to that of the bowl) whereas the Melin y grug response is visibly more damped with a more gradual receding limb and reduced peak flows. Figure 5-38 shows the flow duration curves for Sites 6 and 9 for the same monitoring period along with that of Site 9-8 (discussed later). In Figure 5-38, differences in peak flows are observed, with maximum values of 2.05 mmh^{-1} and 1.46 mmh^{-1} recorded for Sites 6 and 9 respectively. It is speculated that the contrast in stream flow responses between these sites is due mainly to two factors: a lake at the source of the Melin y grug and the differences in land management practices. More specifically, the land management factors that may have contributed to the flashier runoff response at Site 6 compared to Site 9 include the removal of native flora, installation of drainage systems, intensification of livestock production and associated compaction of the soil surface, reduction in soil organic matter, and modification of natural wetlands and lakes.

Figure 5-37 shows the normalised stream flow hydrograph of Sites 6 and 9, this time with the influence of the lake at the top of the catchment removed by subtracting the flow data of Site 8 from Site 9. Subtraction without considering time-lags between the two sites is justified as the travel time between gauging Sites 8 and 9 is relatively small. The catchment area between Site 8 and Site 9 is ~ 292 ha which is similar to that at Site 6 (~ 318 ha). There is still a significant difference in land use with 19 % of the drainage area of Site 9 – 8 estimated to be under improved pasture compared to 77 % for Site 6. There is a greater similarity between hydrographs plotted in Figure 5-37, both showing a relatively flashy response and Figure 5-38 clearly indicates a difference in peak flows. Site 9-8 peak flow rate during this period is 1.74 mmh^{-1} compared to 2.05 mmh^{-1} for Site 6. This suggests that there is still a general trend of increased peak flow rates associated with the heavily improved pasture subcatchment although this is not wholly consistent; there is at least one event in Figure 5-37 when peak flows are greater at Site 9 than those recorded at Site 6. This illustrates the importance of the lake and surrounding unimproved grassland and open moorland at the source of the Melin y grug in dampening the runoff response.

shows the flow duration curves again for Sites 6 and 9 but for the period December 2004 – January 2008. Here there is a clear distinction between peak flows for this longer record of events. Peak flows recorded are 3.31 mmh^{-1} and 1.59 mmh^{-1} for Sites 6 and 9 respectively. Long term data are not available for Site 8, therefore the same comparison cannot be made.

The relative importance of the lake and the surrounding moorland is still unknown and requires further investigation. Current challenges include identifying the relative importance of these land management features, including analysis of responses under more extreme events through continued and additional monitoring of intensively managed improved subcatchments. In addition to factors such as land use and the presence of lakes, differences in soil type and channel routing are also expected to affect catchment-scale flow response. Figure 3-4 indicates that the unimproved pasture of the upper reaches of the Melin y grug is dominated by peaty soils (Hiraethog, Crowdy, and Wilcocks) which remain seasonally or permanently waterlogged. The drainage of such soils will result in a reduction in the amount of organic matter as decomposition rates increase under aerobic conditions. Anecdotal evidence from Pontbren suggests that the Wilcocks Series may have in recent years retreated up the hillslope, being replaced by the Cegin Series, in response to land use change. It is therefore important when considering the impact of soils on the hydrological response to also consider the impact that land use change may have on the soil.

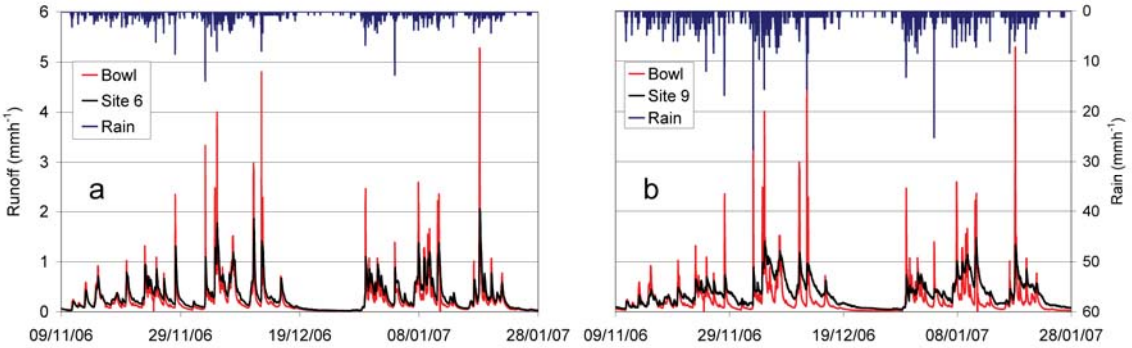


Figure 5-36a and b. Hydrographs of runoff from the Bowl and stream flow gauging Sites 6, and 9 respectively for the period 09/11/06 – 28/01/07.

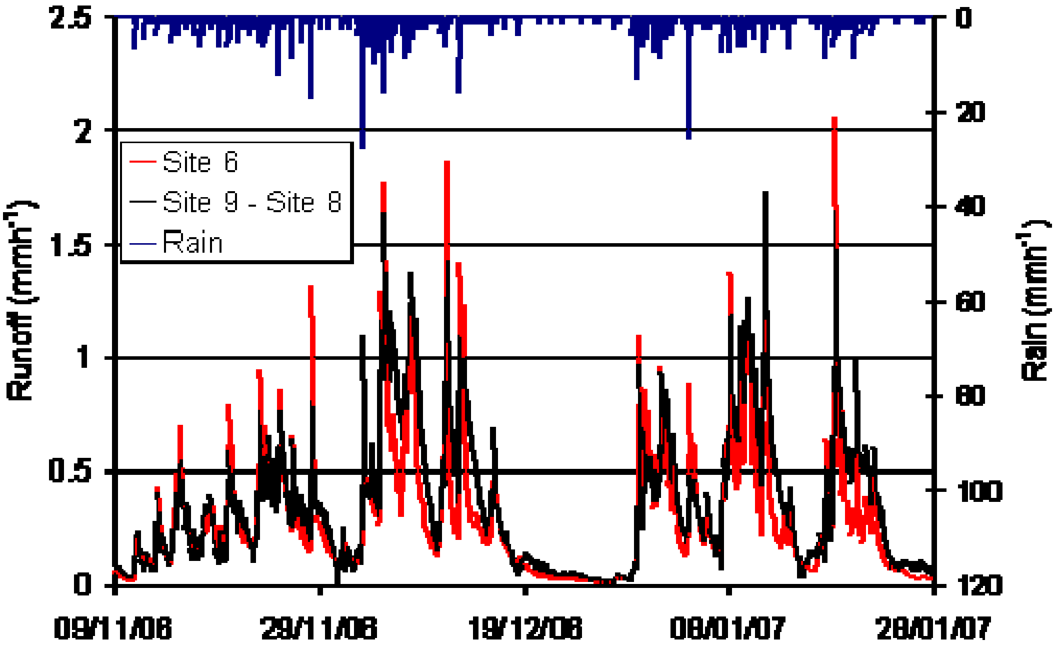


Figure 5-37. Hydrographs of runoff from stream flow gauging Sites 6, and 9 (minus Site 8 flow data) respectively for the period 09/11/06 – 28/01/07.

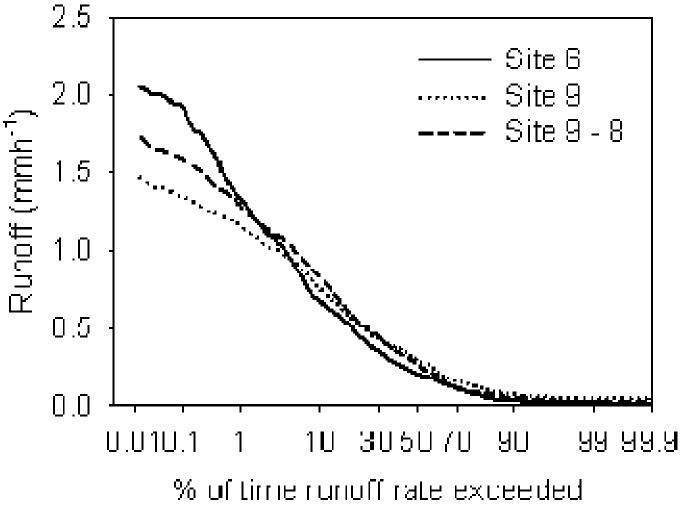


Figure 5-38. Flow duration curves for Sites 6, 9 and 9-8 for the period 09/11/06 – 28/01/07.

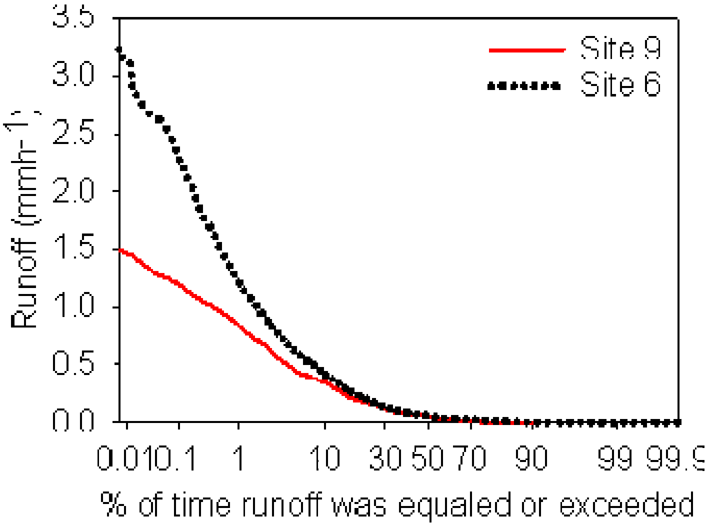


Figure 5-39. Flow duration curves for Sites 6 and 9 for the period December 2004 – January 2008.

In conclusion, the Pontbren data show that a relatively natural subcatchment stores more water and produces smaller flow peaks than an adjacent subcatchment which has been subject to more agricultural improvements. Stream flow data indicate that as the size of the catchment area increases there is a dampening of the flow peak. Significant differences in stream flow peak response are observed between the relatively improved catchment and that which has remained relatively natural or unimproved. A clear influence of the lake and natural moorland in dampening flow peaks is illustrated in the hydrographs presented. However, the relative importance of the lake and the surrounding moorland is still not clear. Evidence also suggests that flow peaks may be increased as a result of agricultural intensification in the form of improved grassland. Evidence from the bowl study site indicates that at the hillslope scale under improved grassland production relatively high peak flows are observed in the form of drain and overland flow. Although not of the same magnitude, a similar flashy response is observed at stream gauging sites were large proportions of the drainage area are under similar land management. Where there is a reduction in the amount of improved pasture there appears also to be a reduction in peak flows.

5.7 CONCLUSIONS FROM THE EXPERIMENTAL AND MONITORING PROGRAMME

The aim of the experimental and monitoring programme at Pontbren was to measure the hydrological response at different scales of observation and develop a conceptual framework to support the project's modelling programme. Conclusions here are therefore drawn together with that aim in mind.

Heavy textured, clay-rich soils dominate the Pontbren landscape. Increases in bulk density with depth suggest a corresponding reduction in the overall porosity of the soil. Two hydrologically distinct near surface ("A" and "B") horizons exist; a marked reduction in hydraulic conductivity occurs as one moves from the A (median $K_{sat} = 3.43$ md^{-1}) to B horizon (median $K_{sat} = 0.018$ md^{-1}). When soils under the improved grassland, which dominates the landscape, are compared with soils found under tree planted shelterbelts, significant differences are observed. These differences are thought to occur as a result of the planting of trees and/or removal of sheep and result in a significant increase in the hydraulic conductivity (median A Horizon under trees $K_{sat} = 8.34$ md^{-1}), bulk density, and saturated moisture content of the soil, especially in the A horizon. This indicates an increased ability of the soil under these tree planted areas to store and conduct incoming rain water or potentially, overland flow from the hillslope above.

Dye tracer studies conducted on soils under improved grassland and under trees highlighted the importance of preferential flow pathways in conducting water through these heavy textured, clay rich soils. Under improved grassland management, macropore structures such as earthworm channels and inter-pedal cracks act as preferential flow paths, and paths around the surfaces of stones also allow rapid movement of water down through the soil profile. Rates of movement through the soil profile, as indicated by the presence of dye in a drain outflow 2 hours following tracer application, suggest bulk soil hydraulic conductivity values 500 times greater than the saturated hydraulic conductivity measured in the B horizon using a Guelph permeameter. Preferential movement through the soil profile underneath trees occurred along living roots, and dye staining patterns suggested that different root morphologies of different tree species could have a potentially important impact on how water moves.

Initial overland flow data from the manipulation plot study following treatment, suggests that the removal of sheep and planting of trees may be causing a reduction in overland flow rates. However, treatments are not long established and time is required to see whether these reductions are significant along with further soil sampling to characterise any possible changes in the soil hydraulic properties.

Moving to the hillslope scale, both overland flow and drain flow are important runoff processes contributing to peak hillslope runoff rates under improved grassland management. Drain flow tended to dominate peak flows during the period of monitoring, indicating that water was still able to move through the apparently, relatively impermeable subsurface B horizon. However, significant overland flow is recorded, and peak intensity often exceeds that of the drain flow. The relative amount of overland flow depends on antecedent soil moisture conditions. Near-surface perched water tables are observed for prolonged periods of time during the winter months, resulting in saturation excess overland flow. Measured K_{sat} values in the A horizon indicate that the rainfall rates recorded would not be large enough to cause infiltration excess overland flow.

Temporal variability in climatic conditions directly impacting on soil hydraulic properties complicates the matter in terms of the relative importance of these two runoff processes (drain flow and saturation excess overland flow) in hydrological response. It is also supposed that the soil water holding capacity of these soils is less than that of the open moorland soils from which it was once converted, due to the decrease in soil organic matter caused by the effects of drainage, changes in vegetation, and the impact of intensive livestock grazing.

The evidence from the measurement of overland flow within the tree planted area of the experimental hillslope suggests that tree shelterbelts protected from grazing may reduce surface runoff. Overland flow rates are reduced under the tree areas compared to open grassland, and neutron probe data indicates that the soil under trees is remaining drier. This data, along with the soil characterisation work intitially discussed, suggest that tree shelterbelts strategically postioned across a hillslope may act as runoff peak mitigation features at the hillslope scale, reducing surface runoff which has been shown to be an important component of the total runoff from these intensely managed improved pasture systems.

Groundwater monitoring shows a highly dampened, seasonal response, which is very different to the highly dynamic, near surface soil moisture status and associated drain and overland flow. This is as a result of the relatively impermable subsurface layer preventing much downward movement of rainwater. Despite this, surface and groundwater interactions are evident in the form of visible springs located across the wider cathcment. As well as this, some of the farmers take their water supplies from wells. However, as many of the Pontbren streams have run dry during the summer months, there does not appear to be any major baseflow component provided by groundwater. Where adjacent boreholes were drilled in the upper part of the hillslope, very different groundwater levels were obtained. We conclude that in general, the role of groundwater is limited, heterogeneous, and in the main disconnected from storm runoff response.

Stream flow data show similarities in response to rainfall when comparing runoff from the experimental hillslope with subcatchments under similar land use, i.e. improved grassland production. Subcatchments predominantly under improved grassland production show a similar flashy response to that shown by runoff from the experimental hillslope. Stream flow data indicate that, as the size of the catchment area increases, there is a dampening of the flow peak. Differences in stream flow response are observed between subcatchments with more or less intense management practices, e.g with a high % of the land under improved grassland production, and where the % of improved grassland is relatively low. The latter show a more dampened response and reduced peak flows. A clear influence of a lake and surrounding unimproved moorland in dampening the response of a subcatchment is demonstrated, however the relative importance of each of these features is still unclear. It would appear that under improved grassland production, these relatively impermeable, clay rich, catchments show a flashy response to rainfall due to rapid runoff in the form of drain and overland flow. There is therefore some indication that the increased flow peaks may be related to the relative intensity of land use.

6. Modelling strategy and tools

6.1 INTRODUCTION

To examine how changes in land management affect local scale runoff generation and how such effects propagate and combine downstream, data from the multi-scale experimental programme described previously are used to inform development and calibration of models examining the effects of land use change over differing spatial scales and levels of process representation.

The modelling programme at Pontbren has sought to address the challenges of quantifying impacts of land use management at small scale, and to develop new modelling strategies to generalise results from small scale observations to generate meaningful predictions at catchment scale. The strategy therefore has had two parallel components. One is the establishment of a physics-based, detailed model capable of representing significant hydrological processes operating in the Pontbren catchment, and similar catchments, at the plot and hillslope scales. This multi-dimensional Richards' equation model has been extended from an existing code, and, at this date, includes representation of heterogeneity and changing soil structure, e.g. changes in infiltration capacity due to vegetation or stocking changes, plant interception of rainfall, run-off, drainage, topographical effects, and macroporosity. A variety of hypotheses regarding the functioning and interactions of drains, macropores, and vegetation are included, which have been tested on available data to increase understanding. Information on the relative roles, importance and interactions of these and other quantities from the model has informed development of the second strand - a catchment scale model suitable for end users. For the catchment modelling work, a semi-distributed rainfall-runoff modelling toolkit has been developed, which is an extension of the lumped Rainfall-Runoff Modelling Toolkit (RRMT) developed by Wagener et al. (2001).

Upscaling work links physically significant parameters from the detailed representation to parameters at the catchment scale. A new meta-modelling methodology has been developed, which represents the physically-based model response in a simplified form at the scale of an individual field or hillslope. This provides the elements of the semi-distributed catchment model, which, with the addition of stream network routing, simulates catchment-scale response.

6.2 SPECIFIC MODELLING CHALLENGES

The Pontbren study is concerned with assessing the impacts of land management practices on flood generation processes. Understanding and predicting the impacts of such changes is a fundamental research challenge. Experimental and modelling studies of the link between land use management change and flooding reported in the international literature are mostly for small-scale, local flooding; the few concerned with large scale, downstream flooding have very limited data support (O'Connell et al., 2007). There are also major problems of interpretation due to landscape heterogeneity and difficulties controlling and recording the different land use or management strategies in place. The introductory sections to this report have already noted the key FD2114 review of factors contributing to runoff and flooding in the rural environment (O'Connell et al., 2004). FD2114 identified evidence of significant effects on runoff at local scales, but concluded that existing data sets provided no conclusive evidence of effects at catchment scales in the face of natural climate variability. It was also noted that model predictions of land management changes are currently unreliable even at local scales, and the effect of spatial and temporal integration of hillslope scale responses on flood peaks at large scales is unknown. Indeed, this issue of transferring information from one spatial or temporal scale to another is one of the most daunting current challenges in hydrology due to heterogeneity, scale dependence of parameters and dominant processes, and incomplete knowledge of systems (Wigmosta and Prasad, 2005).

Two key unanswered questions raised within the FD2114 report are:

(i) At the local scale, how does a given change in land use or management affect local scale runoff generation?

(ii). How does a local scale effect propagate downstream and how do many different local scale effects combine to affect the flood hydrograph at the larger catchment scale?

The role of modelling in impact assessment has great potential, but the study found no generally-acceptable theoretical basis for the design of a model suitable to predict impacts.

A major challenge then becomes developing models at local, small and large catchment scales that do have potential to predict impacts (taking into consideration the limitations of both knowledge and available data to support such predictions). Hydrological models at any scale can be broadly classified into metric, conceptual and physics-based models (Wheater *et al.*, 1993). Metric models are essentially statistical relationships between existing input and output data-sets with rudimentary, if any, physical basis. They have utility for a variety of aspects of hydrological management including short term flood prediction; however extrapolation of predictions to conditions for which data has not been collected is generally meaningless and they are not considered further here.

Physics-based fully distributed models seek to capture a system's response by incorporating significant processes through fundamental physical equations. Although it has been contested that the fully distributed physics-based models are most suitable for predictions of the effects of land use changes (Abbot *et al*., 1986), appropriate measurable parameters are rarely obtainable, and extensive calibration is generally required (Beven, 2001). Such calibration can lead to a similar problem to that seen with the metric models: extrapolation to situations not covered by the calibration data set can be misleading. Although they have great potential for scientific exploration and understanding, being built upon an understanding of how a system operates, the calibration issue and the cost of implementation often limit their potential as management tools. Computational demands also generally limit the scale to which models can be applied.

As a result, the computationally and parametrically cheaper semi-distributed dynamic conceptual models are increasingly used for predictive modelling (Wade *et al.*, 2004, Lacroix *et al.* 2006). Conceptual models involve specifying a model structure *a priori*, according to the hydrologist's conceptualisation of the perceived important component processes. This is normally done on the basis of a system of conceptual stores (which may be spatially lumped or semi-distributed). The simplified representation of physical processes, and the aggregation of spatial variability over catchments allow this type of model to be much less complex than the fully distributed model alternatives; however they retain the flexibility to represent process response explicitly and to deal with sub-annual time scales (Jackson *et al.*, 2007). Their major limitation is that insufficient data are available to adequately account for spatial variation, and there is always some degree of" lumping"; furthermore most parameters of conceptual models have no direct physical meaning, and must be estimated through calibration against observed data (Wheater et al., 1993).

The modelling strategy used in this work seeks to combine both detailed physics-based modelling and semi-distributed conceptual modelling to allow small-scale process knowledge to be utilised at the catchment scale. This allows many of the strengths of both approaches to be combined; and importantly it overcomes to a large degree the lack of physical meaning of conceptual model parameters.

6.3 STRATEGY: LINKING BETWEEN HILLSLOPE AND CATCHMENT SCALES

The main aims of the modelling work were to develop: a) an understanding of the dominant processes working at different scales within the Pontbren catchment, b) procedures to map the predictive capability of detailed physics-based models to catchment scale models, c) hence produce simulations of effects of land use and management changes up to the Pontbren catchment scale. The strategy by which these aims are approached has the six stages illustrated in Figure 6.1.

At the heart of this strategy is addressing the problem of scale. Our understanding of the important hydrological processes operating within soils is currently best encapsulated at scales of the order of 0.1 to 1m (although their dynamics are very complicated even at this scale, due to coupling between different processes and their extreme non-linearity); indeed this is the scale at which the physics-based model has been developed. However, many of the questions concerning the flow of water in the catchment, particularly in the context of flood risk, are looking at the effect of changes happening at a scale of tens to hundreds of metres (the field and changes within it) over a scale of tens to hundreds of kilometres (the Pontbren catchment, and the higher order catchments it feeds). There is a need to find a way for reliably upscaling. Given the wealth of data being collected by the FRMRC at Pontbren to improve our physical understanding of the processes operating at the small scale, the programme has created a rare opportunity to do so. As shown in Figure 6.1, the modelling strategy operates at two different scales, with a “meta-modelling” procedure linking them:

(i) At the hillslope scale, a physics-based, distributed model, capable of representing soil heterogeneity, is used to characterise hydrological processes. Data from the field site are used to inform development and calibration of the model and investigate the relative roles and significance of land drains, macropores and vegetation. This detailed, process-based model aims to capture the significant hydrological responses in operation and allow land management scenarios to be simulated in a physically meaningful manner at field scale.

(ii) At the catchment scale, upscaling work aims to apply the detailed knowledge gained from the hillslope scale to generate a model suitable for end users for flood risk management purposes. The catchment-scale model is simpler in structure but covers a much greater spatial domain. It is trained using the detailed physics-based simulations, so that it encapsulates the dominant responses of the more detailed model (“meta-modelling”). Crucially, by relating structures, parameters and derived quantities (such as storage) betweeen the models, there is some degree of internal consistency between the different scales. These catchment-scale models are further conditioned on the observed catchment-scale data.

However, not all of the land use types in the Pontbren catchment are represented by small-scale data, and so the meta-modelling procedure must be supplemented by direct representation of processes at the larger scale (the left-side arrow in Figure 6-1).

The next three sections of this report detail the work introduced above, and present illustrative results at both hillslope and catchment scales. Modelling tools and techniques used at both scales are introduced, with formal treatment of uncertainty included. At the catchment scale, the meta-modelling methodology is demonstrated and results used to create scenario predictions of the impacts of both past and future changes within the Pontbren catchment.

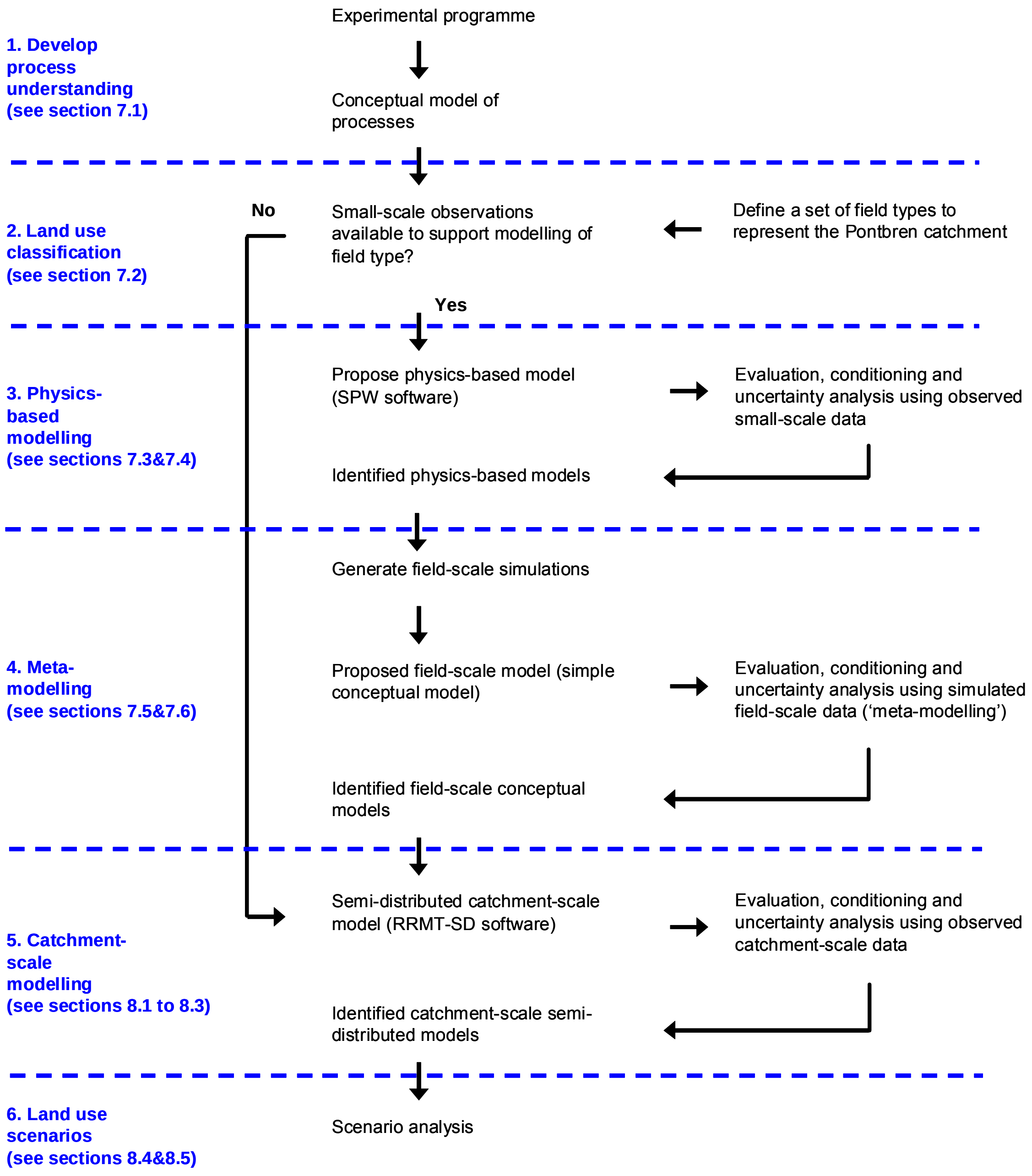


Figure 6-1. Strategy for modelling programme

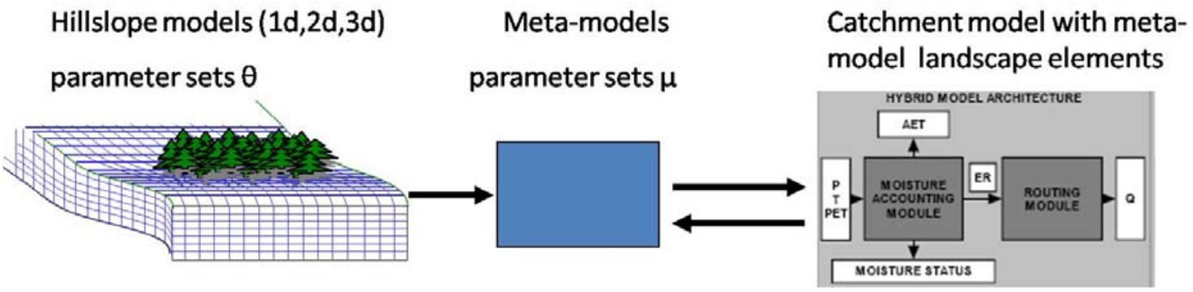


Figure 6-2. Meta-modelling: changing complex small-scale models into field-scale simple models

7. Hillslope scale modelling

7.1 PERCEPTUAL MODEL OF PROCESSES

In order to represent the hydrological processes at Pontbren, a model (or series of models) needs to be created. The model comprises two parts: a perceptual model of processes which is an attempt to describe the key processes that are perceived to be occurring; and a numerical model which is a mathematical implementation of the perceptual model. The development of a perceptual model is influenced by the available information, which can include topography, soil classification, “soft” observations made in the field (e.g. presence or absence of cracks in the soil), processes implied from the evaluation of data, and direct experimental observations such as state observations, flux data and chemical or dye tracer tests. Perceptual models are also inavoidably influenced not only by more general physical and hydrological theory, but also the pre-conceptions, whether valid or invalid, of the constructors of the model. It is important to keep both the presence of such pre-conceptions and the limitations of the data in mind when interpreting results from the later numerical models, and re-evaluate the underlying perceptual model where necessary.

Across the Pontbren catchment, the soil is predominantly heavy clay with peaty deposits at higher elevations. There are two soil types found in the vicinity of the Bowl; the Cegin and Sannan soil series, both of which are characterised as being poorly drained and being seasonally waterlogged. This information taken on its own would suggest that the site would have a relatively low infiltration capacity with little or no available soil water storage during the winter months. In a situation such as this, saturation excess overland flow would be expected to occur during the winter. The soil itself is comprised of two layers, the A-horizon (topsoil) and B-horizon (subsoil) (as described in detail in Section 3.3).

With the Bowl forming part of a hillslope the topography is such that there should be lateral movement of water primarily determined by the local gradient, although the Bowl is significantly less steep than most of the rest of the hillslope so that lateral flow is likely to be less important. The slope would also be expected to influence the soil moisture content and matric potentials with the upslope portions being drier.

During the dry summer of 2006, a considerable number of cracks were observed by the fieldwork team in the soils across the Pontbren catchment. The cracks were substantial in both size and depth with some large enough to put hands down. This was most likely an extreme event, as cracking to this extent has not been observed before or since, but nevertheless these cracks alter the hydrological processes of the soil considerably. The other important observation was captured on video and that was of streams of water moving across the grass surface during a relatively light rain event. This confirms the occurrence of saturation excess overland flow. Analyis of the data provides the most detailed information about the processes occurring within the Bowl. Throughout the data record, the overland flow coincides with the 10cm tensiometer showing the soil to be at or very close to saturation, which reinforces the notion that most overland flow generation is saturation excess.

The tensiometer records themselves show that at 50cm depth the soil remains very close to saturation for the majority of the year, only drying out during the summer months. This is consistent with the drain flow observations, which show some base flow throughout the majority of the year, again only stopping during the summer months. This would agree with the assessment of the soil classification (again, see Section 3.3) that they are slow to drain. However the drain flow observations show a quick response to individual rainfall events. This suggests some form of preferential (non-uniform) flow, whereby water moves unevenly and often rapidly along certain pathways within the soil resulting in spatially irregular wetting of the soil profile. Preferential flow mechanisms vary in their nature and occur at various scales (as described by Hendrickx and Flury, 2001). Macropore flow is a term used to describe preferential flow in continuous root channels, earthworm holes, cracks and fissures. Under these conditions, the application of the Darcy equation for laminar flow though a homogeneous porous medium would have little physical basis. Natural soil pipes also act as preferential pathways at this scale, but are considered most common in non-cohesive soils, formed by the erosive action of subsurface flows (Beven and Germann, 1982). Initiation of flow in a macropore system requires a supply of water exceeding all losses to the soil matrix and the effect of macropores will be most significant when soils are saturated; although it is known that macropores may conduct considerable quantities of water without being saturated (Beven and Germann, 1982). However, long periods of saturation (such as in waterlogged soils) are not conducive to macropore development.

The influence of macropores on runoff response is highly dependent on their interconnectivity and continuity, rather than their abundance, as they typically occupy less than 2% of the bulk soil volume (Ward and Robinson, 2000). For example, connectivity of macropores to subsurface drains may result in a flashy streamflow response to a heavy rainfall event. Indeed, Robinson and Beven (1983) found that artificial drains were much more responsive to storms in summer when the clay soils were dry and cracked, than in winter when the soil was saturated. Alternatively, macropores may allow deep percolation of rainfall to a groundwater store. Clearly, macropores will exhibit temporal variability and Beven and Germann (1983) discuss the issue of how long it takes for a macropore system to develop and how long will it remain.

Although macropores have been observed at the site in the form of earthworm burrows, vegetation routes and shrinkage cracks, the saturation within the B horizon suggests that macropores are not providing connectivity to the drains. Conversations with land owners and drain installers about the installation of the drains provided an alternative explanation: the disturbed earth above the drain lines in addition to the vestigial effects of secondary treatments such as moling may provide preferential flow pathways to the drain.

Francis (2005) studied the influence of preferential flow by conducting a dye tracing experiment in a field adjoining the Bowl study site. This provided evidence for rapid movement of water to the drains. When the dye was applied to a plot above a drain line, the dye was found in the drain effluent less than 2 hours from application whereas it was not found in the effluent when applied to a plot away from the drain line. It was also noted that the soil in the plot above the drain was looser and easier to excavate, which is corroboration of the farmers' descriptions of a more permeable backfill to the drains.

Soil samples taken as part of work carried out to determine the hydraulic conductivity of the soil at Pontbren (Chell, 2007) also showed that there were few macropores but that despite this the A-horizon was relatively permeable, at least an order of magnitude more so than the B-horizon. This suggests that saturation at the base of the A-horizon could result frequently and give rise to lateral flow where there is a gradient. As macropore and preferential flow paths can change in both location and significance under different field conditions, it is important to note that both the dye tracing test and the hydraulic conductivity work were carried out in summer periods (2005 and 2007 respectively); however the hydraulic conductivity measurements were within the wettest summer on record within the UK.

For either explanation, preferential pathways appear to be operational only near the drain in winter conditions. The severe drought of 2006, where soil cracking appears to have led to greatly increased soil infiltration capacity, suggests macropores may play a very dominant role in certain conditions.

The drains are considered to be a free drainage condition; i.e. atmospheric pressure at the drain, and it is assumed that there is negligible movement of water below the level of the drains, which given the disassociation of groundwater observed at the site seems a sensible first approximation. The perceptual model for the grassland is shown schematically in Figure 7-1 (cross section through the drain) and Figure 7-2 (cross section along the drain).

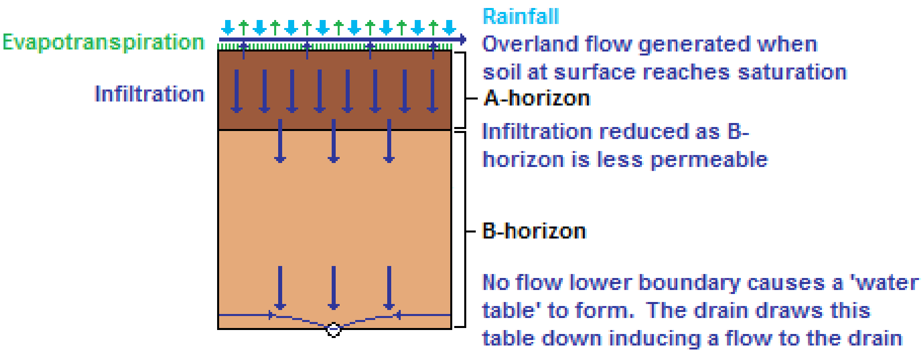


Figure 7-1. Perceptual model of the Bowl: cross section against the drain

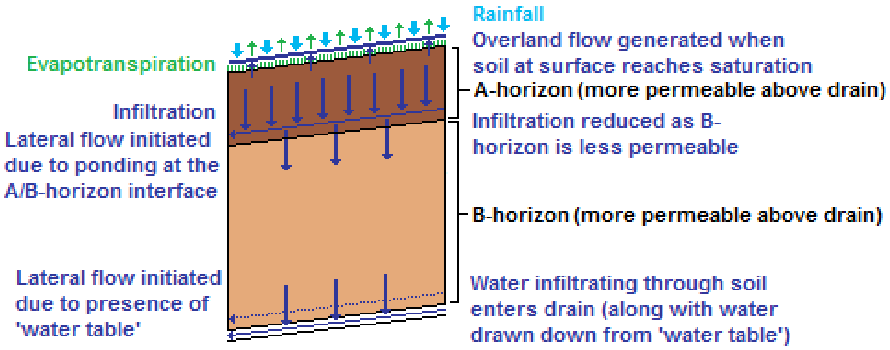


Figure 7-2. Perceptual model of the Bowl: cross section along the drain

In summary, data from the Bowl study site, if representative of improved grassland over the catchment generally, suggest that improved grassland has the following hydrological characteristics:

- Over much of the winter, there is a perched water table caused by the soil B-horizon in wet conditions.
- Groundwater is generally dis-associated (with a notable exception at the end of summer 2006).
- Soil moisture shows negligible change below 70cm (drain level).
- There is evidence of macropore flow at small scales; however the presence of a perched water table over much of winter suggests that there is either limited connectivity of these, or they exist in limited regions. They appear to be less important in the B horizon than in the A horizon.
- Flow generation in winter conditions is often dominated by overland flow.
- Drain flow remains important in winter conditions, and may be the dominant flow mechanism in summer events.

There is certainly significant small-scale heterogeneity and strong evidence for significant non-stationarity of small-scale responses. There is very little understanding of compaction effects in these soils, to allow us to distinguish the response of grazed and ungrazed grassland.

Data from tree-planted areas in Pontbren suggest:

- Increased infiltration within trees.
- Increased capacity to store water underneath trees.
- Large interception losses.
- Significant tree belt edge effects.

Despite the extensive field programme, some uncertainties in the perceptual model remain. A major knowledge gap regarding the tree planted areas is where subsurface water empties to. For extreme events, the interception and localised near-surface storage which is known to be associated with the trees is not necessarily adequate to significantly reduce runoff generation; and the activation of slow subsurface pathways and deeper stores becomes important. More knowledge about the subsurface routes below the trees is therefore key.

As noted in section 5, we have incomplete understanding of the relative functioning of unimproved grassland and wetland areas within Pontbren. Hence these areas are currently modelled and conditioned at the catchment scale only: data show that these are less flashy than improved grassland; however the extent to which the unimproved grassland dampens response is an open and important question currently being addressed.

7.2 LAND USE CLASSIFICATION

The meta-modelling strategy requires that each field in the Pontbren catchment is classified into a land use/management type, so that the corresponding set of field-scale models can be applied. The field types currently included are:

1. Grazed improved grassland
2. Tree belt/hedgerow: near bottom of slope
3. Tree belt/hedgerow: near top of slope
4. Tree belt/hedgerow: 90° to contour
5. Woodland
6. Ungrazed improved grassland
7. Grassland with drains removed
8. Unimproved grassland/rough grazing
9. Marsh/wetland

These units were chosen based on dominant land use types currently within the catchment and those management changes that were perceived as likely to have an impact on flow peaks.

The spatial dimensions of options 1 to 7 are currently modelled as a 100m by 100m strip of land to 70cm depth; a slope in one direction of 1:20 is used (as representative of the average slope over much of this catchment). The tree belts contained within field types 4, 5 and 6 have dimensions 80 × 15m; 12% of the total field area. The effect of relative placement of such an intervention is examined through simulations of three possible positionings; the first has the tree strip located towards the lower end of the slope, and surrounded by 10 (horizontal) metres of grazed profile on three sides to avoid boundary effects; this has the potential to capture approximately two thirds of any overland flow generated within the grazed grassland. In the second scenario, the same tree strip dimensions are used, but the tree strip begins 10 metres below the top of the slope. In the third, the main length of the tree strip lies parallel with the direction of flow. The relative locations of the interventions are shown in Figure 7-3.

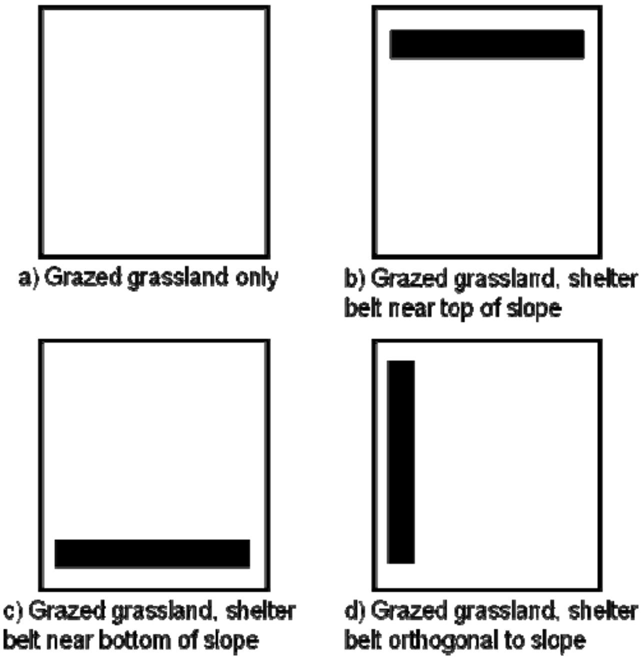


Figure 7-3. Relative locations of tree belts considered

7.3 DETAILED HILLSLOPE MODEL DESCRIPTION

The numerical model being used to perform plot and field scale simulations of the Pontbren site is an extended version of the existing Soil-Plant-Water model (SPW) which was developed at Imperial College by Karavokyris et al. (1990) and further developed by Jackson (2006). The model is a finite difference implementation of Richards' equation, and can explicitly represent up to three spatial dimensions. It was chosen as the three dimensional capability was necessary to properly represent small scale interventions, and the code was available to augment with modifications as needed. The specific needs of Pontbren have prompted substantial additions and changes to the original code, e.g. to allow macroporous flow to be represented, overland flow to be appropriately collected and routed, vegetation profiles to change laterally, and also to cope with the specific numerical problems encountered when integrating a heavy clay profile.

In SPW, the transport of water through the soil matrix in response to the forces of gravity and water pressure is represented by Richards' equation (Richards, 1931). Within Richards' equation, water flow is represented by Darcy's law, with flux related to local potential gradients through a direct proportionality relationship. The proportionality term is a nonlinear function of soil water pressure potential ψ(m), known as the hydraulic conductivity K (m s^{-1}). Water storage θ(m^3 m^{-3}) is also a function of pressure potential. Richards' equation for soil water flow in multiple space dimensions with losses due to root uptake u_w (s^{-1}) can be written as:

$$C(\psi)\frac{\partial \psi}{\partial t} = -\nabla \bullet (-K\nabla(\psi + z)) - u_w, \qquad \text{(Equation 1)}$$

where $C = d\theta / d\psi$, t is time (s), z is elevation with respect to an arbitrary datum (m), and the root water uptake term u_w depends on the plant transpiration rate; this can be calculated by coupling the soil representation to a dynamically responding plant model (Karavokyris et al., 1990; Jackson, 2006) or externally through calculations of potential evapotranspiration using Penman-Monteith (Monteith, 1965). In either case, uptake is then partitioned through the soil according to an imposed relative root distribution density.

Formal descriptions of the dependence of soil moisture content and hydraulic conductivity on matric potential are required, entering through the functions C and K in Equation 1 above. The soil moisture content relationship provides a transformation between matric potential and moisture content in a given soil. For this study, the well-known van Genuchten relationship (van Genuchten, 1980) is used. This can be written as

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + \alpha \mid \psi \mid^n} \right]^m , \qquad \text{(Equation 2)}$$

where S_e is the relative saturation, θ_s and θ_r are the saturated and residual moisture contents of the soil respectively, α is a scaling parameter, n is a curvature parameter, and m is (usually) set to $m = 1\text{-}1/n$. The hydraulic conductivity relationship chosen was Mualem's pore-size distribution model (Mualem, 1976). Combined with the van Genuchten equation, it becomes the van-Genuchten Mualem relationship (van Genuchten, 1980), given by

$$K = K_s S_e^L \left[1 - (1 - S_e^{\frac{n}{n-1}})^m \right]^2 , \qquad \text{(Equation 3)}$$

with n and m as described above. S_e is the relative saturation (defined through the van Genuchten function), while L denotes an empirical pore tortuosity/connectivity parameter. Characterisation of the soil hydrological parameters at any node therefore involves six parameters, θ_s , θ_r , α, n, K_s and L.

Boundary conditions are also required for the model to operate. When no water is present above the surface of the soil, the upper boundary condition is imposed as a flux, equal to the water received at the soil surface minus evaporation from this surface. When infiltration limitations or soil surface saturation cause water to pond above the surface, the condition changes to a specified head, equal to the height of water above the surface. Visual inspection suggests that water moves rapidly through a dense mat of plant material above the soil surface: this movement (overland flow) is currently represented through a thin layer above the soil with a Darcy flux.

The lower boundary condition is dependent on assumptions about connectivity and locations of the drainage network, and also groundwater interactions; the extent to which it can be represented also varies according to the spatial dimensions modelled. A variety of assumptions, relating to various conceptualisations, have been tested. The following simulations assume that no interaction with the groundwater takes place (consistent with the disassociated groundwater response observed at the site over the period being simulated) and that all water reaching the drains empties to them. Hence a free drainage boundary condition is applied (assuming atmospheric pressure for any saturated soil nodes at the lower boundary; and no flow otherwise). In the absence of better information, the horizontal boundaries are treated as no-flow. Given the slow nature of flow in the clay this seem a sensible first approximation; to improve this requires information on flow regimes outside the modelled domain.

When rainfall occurs, uptake ceases as rainfall intercepted by the plant canopy saturates the surface of the leaves. Some of this intercepted water drips through to the soil (throughfall), while some is evaporated back to the atmosphere. The Rutter et al. (1972) model for canopy interception is used here. Aside from meteorological driving data, this requires a vegetation-specific canopy storage capacity parameter (defined in mm). Of late, there has been increasing recognition of the importance of adequately characterising seasonal changes in land surface characteristics, such as the leaf area index of deciduous vegetation (Hogg et al., 2000). To allow for such changes, the model takes as input a leaf area index (*LAI*, in m^2m^{-2}) and an "equivalent film thickness" parameter *s* (m), following the approach of Meriam et al. (1975). This latter is defined by the ratio of the storage capacity to twice the leaf area index; *LAI* can change seasonally if required.

A variety of hypotheses regarding the functioning and interactions of drains and macropores are included within the model; details of the representations are included in Appendix A.

The model can be set up to represent one to three spatial dimensions as well as temporal dynamics. The three dimensional capability is key in allowing the effect of small scale interventions to be explicitly represented, and three dimensional simulations are used to inform the meta-modelling and test hypotheses of hillslope response. However the less computationally demanding one dimensional representations are also extensively used; to inform calibration and test hypotheses under assumptions of homogeneity.

7.4 CALIBRATION OF A PHYSICALLY BASED MODEL USING PLOT AND HILLSLOPE DATA

The calibration stage aimed to reduce the uncertainty in the physics-based model parameters, by only accepting parameter sets which produced results which were consistent with the observed data. This was done in two stages: calibration to the soil moisture curve data from the laboratory (where available); then further calibration to the flow and soil water pressure data observed in the field (where available). After each stage, a number of satisfactory models are retained to represent uncertainty. The physics-based numerical model described in the preceeding section is used. The calibration is performed using the one-dimensional model because calibration of the three-dimensional model is numerically intractable due to long run-times. The parameters of the one-dimensional model are then incorporated into the three-dimensional model (as explained later).

A slope of 1:20 is used (as representative of the intrumented hill-slope and the average slope over much of this catchment). The modelled hillslope area is 100m by 100m, and the lower boundary of the model is 70cm beneath ground level. The grid size used was 1cm (vertical) by 1m by 1m: a total of 700,000 nodes. The sizing of the grid has been chosen to be sufficiently fine to produce accurate simulations yet coarse enough not to result in excessive run times. Macropores were not explicitly represented within the simulations; rather the parameters are considered to represent the combined effect of matrix and disconnected macropores. This is because the measured values of saturated conductivity in the top horizon were influenced greatly by the presence of macropores (earthworm burrows); hence it appears that values are more indicative of bulk soil properties than soil matrix properties. Furthermore, the perched water table present in the near-surface over most of the winter period suggests there was negligible connectivity of macropores from surface to drain (see Section 5).

Monte Carlo methods are used for automatic calibration of the model. Many sets of random numbers (e.g. 10,000) are generated, sampled from distributions of the input parameters. As no better information on the distribution of input parameters was available, parameters are sampled from a uniform distribution within a pre-determined range. Each parameter set produces a model result and the realism of this result is measured against observed data.

For improved grassland and tree-planted areas, using the Bowl and the half-moon shelter-belt, a check is made that the parameters produce a moisture release curve within pre-defined limits based on laboratory-defined moisture release curves derived from the soil samples (see Section 5, Figures 5.3 to 5.5). In the case of the grazed grassland simulations, substantial flow and tensiometer data are available at the Bowl to further constrain model outputs. The uncertainty in the grazed grassland data is hence much more tightly constrained than the tree data. In both cases, Monte Carlo samples were run until 100 acceptable simulations were obtained. The same 100 sets of grazed grassland parameters and 100 sets of tree parameters were used to generate the tree shelter belt simulations for the meta-modelling procedure (see next section).

A variety of different objective functions were assessed for their ability to produce visually satisfactory fits to the observed data. These included least squares and mean average error estimates, deviations between observed and modelled peak flow, envelope approaches where simulations were accepted when they fell between certain tolerances of the observed data, and comparisons of a number of weightings between and within profiles. The objectives chosen, in the end, fell into four categories and were based on envelope measures:

- Constraints on the drain flow.
- Constraints on the overland flow.
- Constraints on the moisture retention curve (constraints placed included absolute value constraints and also constaints in terms of relative change from the saturated moisture content).
- Constraints on the matric potential time series data.

If these were satisfied the simulation was considered feasible and assigned a probability of 1, otherwise it was assigned a probability of 0. The result of this can be considered analagous to the GLUE approach of Beven and Binley (1992), although we did not attempt to attach likelihoods to parameters sets except 0 and 1. The prior parameter ranges (i.e. prior to any calibration) were derived from literature. Some parameters were fixed to limit the number of parameters to calibrate. The ranges and values are in Table 7.1.

Site data were available to characterise soils and vegetation for both the grazed and tree-planted areas. Bird et al. (2003) presented data on rooting depth and density distributions from Pontbren; average relative root densities measured at depths between 0-10cm/10-20cm/20-30cm were 78%/19%/3% and 51%/36%/13% by volume for grass and trees respectively. These densities were used in the model runs to apportion root uptake of water over both soil profiles. Differences in interception between grazed and tree-planted areas are considered through changing the "equivalent film thickness" parameter and the leaf area index LAI. Note that average deciduous tree interception capacities are not necessarily much greater than those of grasses, in contrast to the marked increases noted in coniferous trees (Thurow et al., 1987); they may, however, be more affected by seasonal changes in leaf cover. Meriam (1975) presents values for grass between 0.08 to 0.2mm; the lowest of these was selected in an attempt to account for the shortness of the grazed grass. The leaf area index was set to 5, assuming established growth. Rutter (1975) tabulates data on interception storage capacities for different vegetations, which for deciduous forests range from 0.4-1 mm. These then need to be related to a film thickness through consideration of leaf area index. A value of 3.8 was selected as representative of leaf area index in deciduous stands during winter months (see data in Scurlock et al., 2001); taking the highest storage value, for illustrative purposes yields an equivalent film thickness of 0.15 mm.

The soil structure underlying grazed areas was divided into the two distinct A and B horizons observed in the field. It was assumed that the trees influenced soil to 50cm below the surface, based on the root density data described previously: below this the B horizon soil parameters were used.

A three month winter period, from 1st January 2007 to 31st March 2007 was selected to provide driving data; chosen as data quality in all monitored variables over this period is perceived to be relatively high, with few instrument malfunctions, animal disruption, etc. An input time-step of 15 minutes was used while hourly outputs were compared to observed hourly data. 15-minute rainfall (see Figure 7-4) was taken from the raingauge at the experimental hillslope site. Daily MORECS evapotranspiration, parameterised for deciduous trees and grass and calculated using data from the closest available weather station from a similar elevation to the Pontbren site, was used.

Table 7-1. Monte Carlo ranges for parameters used to represent soil and vegetation properties in grazed and tree belt regions

	θ_s	θ_r	α	*N*	K_s	*L*	*depth*
	m^3/m^3	m^3/m^3	*1/m*	-	*m/s*	-	*cm*
A horizon (grazed)	0.4-0.6	0.05-0.2	1.5-5	1.3-1.7	1.7×10^{-5}	-1-1	15-25
A horizon (woodland)	0.68	0.45	1.5	1.5-2.5	2.1×10^{-4}	-1-1	45-60
B horizon	0.4	0.6	1.5-5	1.3-1.7	4.3×10^{-7}	-1-1	

The ranges of parameter values used were constrained by the values measured in the field and are shown in Table 7-1. The model was capable of producing a good fit between observed and modelled drain flow and overland flow rates. However, without the constraints provided by the overland flow, model uncertainty was high and the flow rates generated by the model were dramatic in their range. A good fit between observed and modelled rates was achieved over a very small range of B horizon Ks values. The modelled drainflow was found to be most sensitive to the B-horizon conductivity; overland flow was additionally sensitive to the relative change in storage within the A horizon over field matric potential conditions. The storage capacity of the A-horizon layer is of great importance when determining rainfall-runoff responses, since the underlying B-horizon is of much lower hydraulic conductivity. In addition to the soil hydraulic properties, the model will be sensitive to other input variables. For example, a sensitivity study showed both overland flow and drainflow to be sensitive to the method used to calculate potential evapotranspiration; presumably because of the high dependence of the processes on saturation excess flow and A horizon storage.

Table 7-2. "Optimum" grazed parameter set in grazed and tree belt regions

	θ_s	θ_r	α	*N*	K_s	*L*	S	*LAI*
	m^3/m^3	m^3/m^3	*1/m*	-	*m/s*	-	*mm*	m^2/m^2
Grazed (0-22cm)	0.59	0.11	3.5	1.56	1.7×10^{-5}m/s	0.65	0.08	5
Grazed (22-70cm)	0.48	0.07	2.9	1.33	4.3×10^{-7}m/s	0.32	-	-
Tree strip (0-70cm)	0.61	0.18	1.5	2.05	2.1×10^{-4}m/s	0.17	0.15	3.8

Following calibration, observed versus simulated drainflow, overland flow and matric potential response for soil under grazed conditions (the Bowl) are presented in Figure 7-4; a representative "accepted" simulation is used. The parameters characterising this are given in Table 7.2. The model tends to slightly over-predict drying of the top soil horizon, which may be an artefact of errors in the evapotranspiration estimates, plant root density data, or bias in the moisture retention constraints caused by repacking of the measured soils. However, a very satisfactory consistency exists between observed and modelled drainflow and overland flow over both the entire three month period (Figure 7-4) and most individual events (Figure 7-5). This is heartening, as they are the quantities of direct interest for flood runoff prediction.

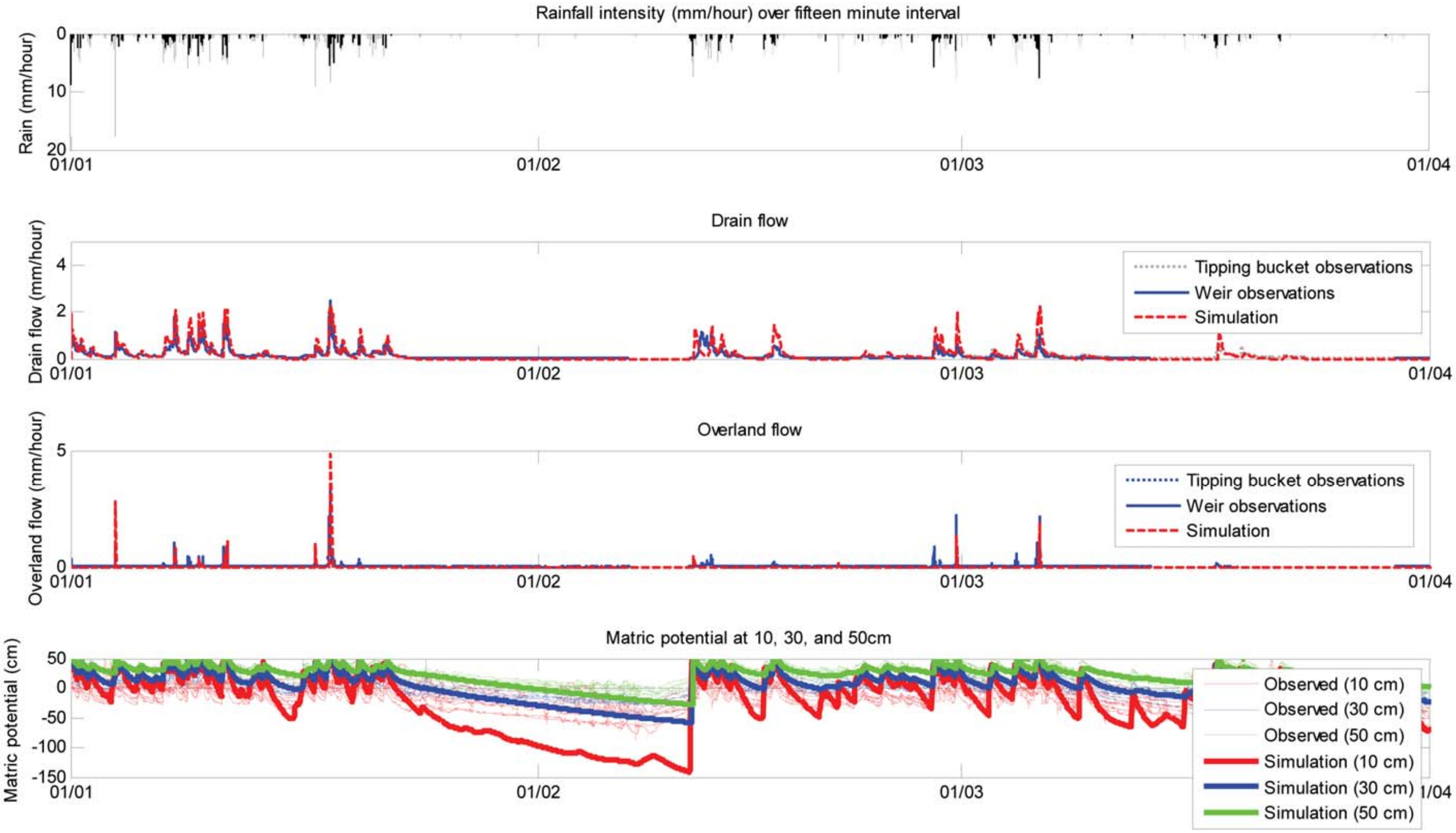


Figure 7-4. Observed versus modelled Bowl response over three month calibration period

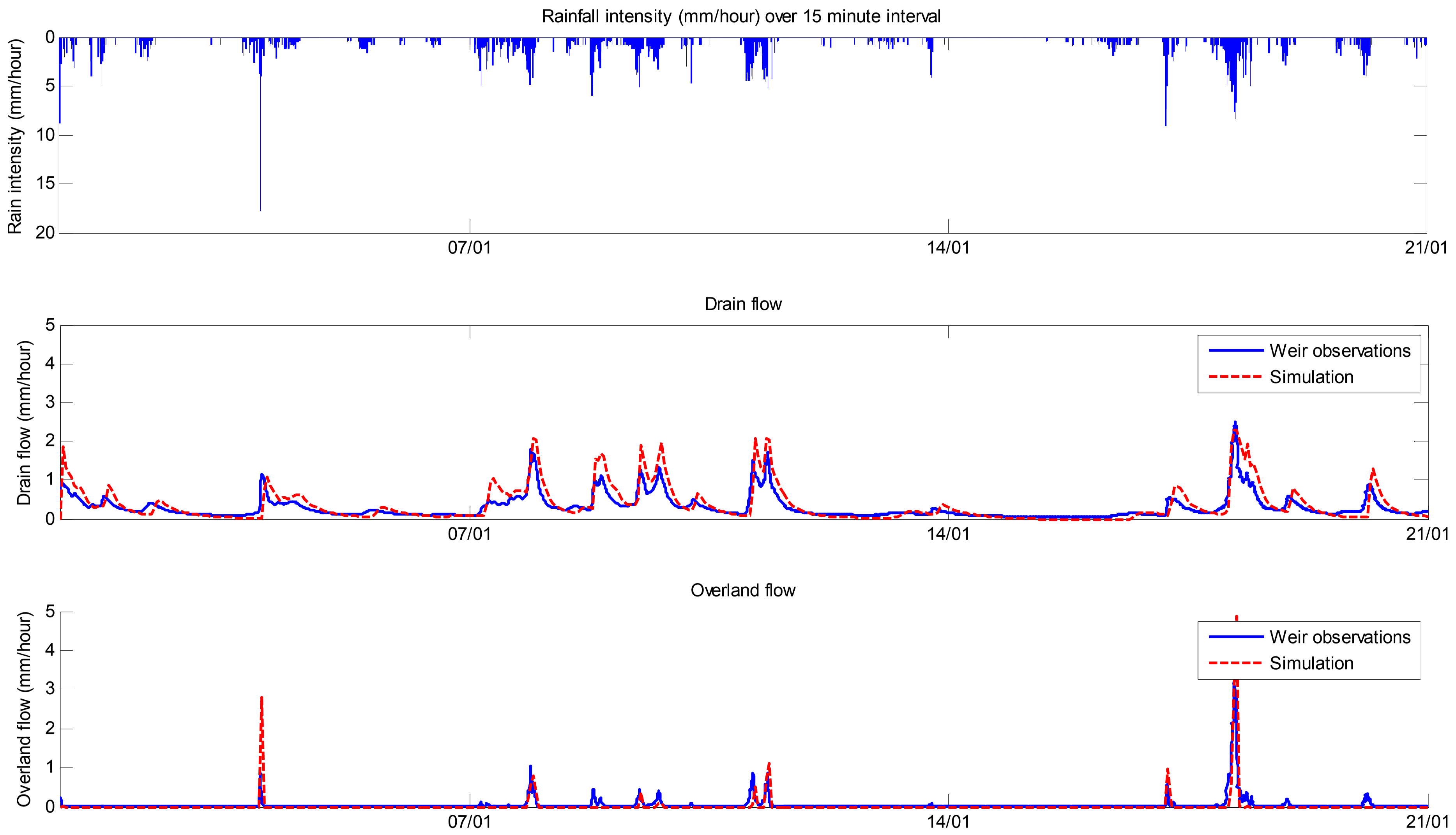


Figure 7-5. Observed versus modeled Bowl response over three week calibration period

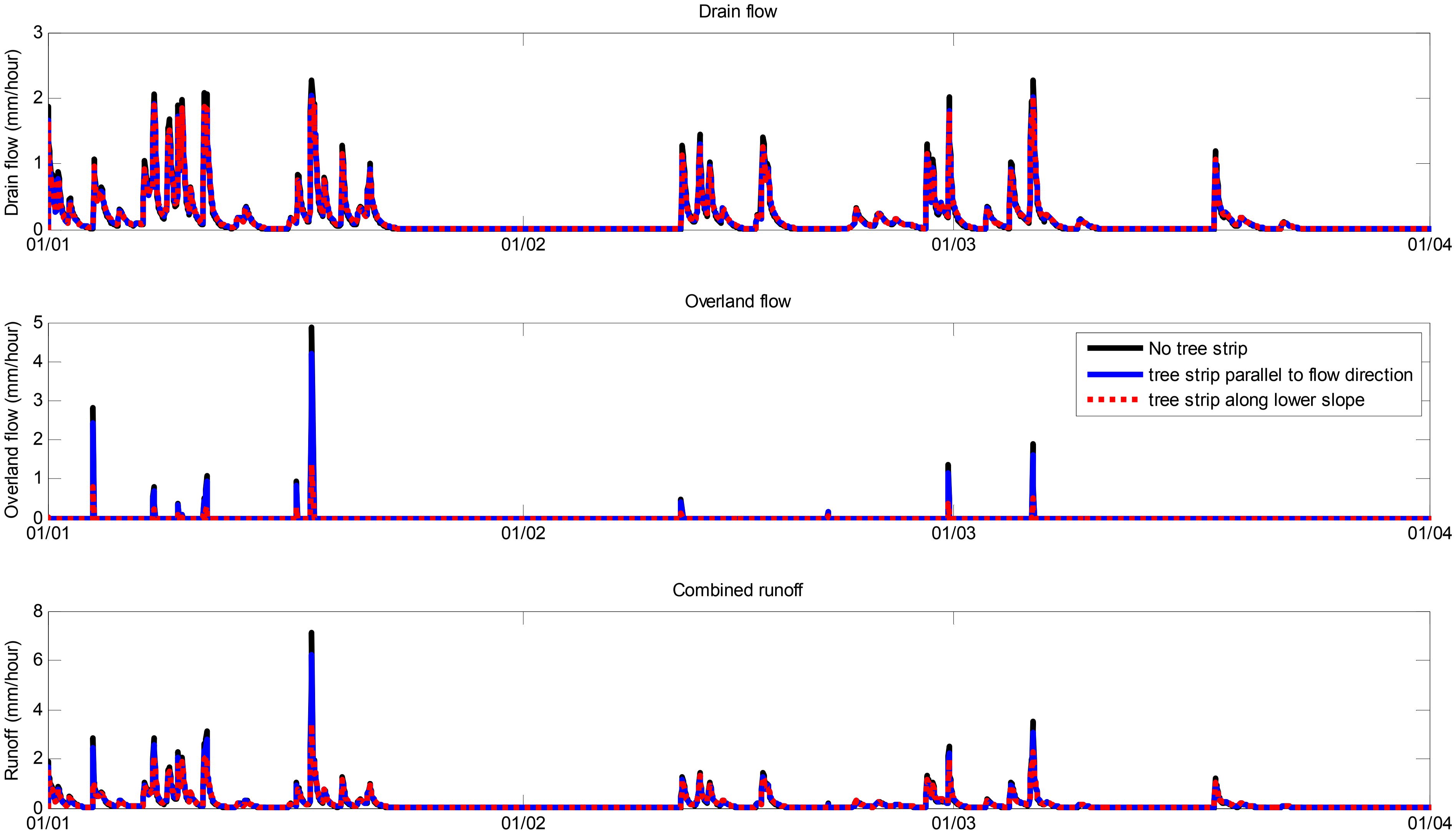


Figure 7-6. “Single optimum” runoff fluxes; with and without tree strips

7.5 GENERATION OF FIELD SCALE REALISATIONS

The next step in the modelling strategy (Figure 6-1) is to use the identified physics-based model to generate field-scale flow responses under the selected land use types. This not only generates data for the meta-modelling, but provides our best estimates of field-scale impacts of land use change.

This step involves using the parameter sets identified for the grazed grass and the trees to represent coverages of trees (0, 12% or 100%) and different orientations of trees (see Figure 7-3). It also involves representing an ungrazed field – to do so, the assumption was made that compaction effects associated with absence of grazing cause the hydraulic conductivity in the top 2cm to increase to between double and ten times the ungrazed value (when available, data to support parameterisation values will be collected from the manipulation plots).

Figure 7-6 shows the simulated runoff both with and without a tree strip present. Drainflow, overland flow, and combined runoff are shown. There is very little change in simulated drainflows when moving from the original grazed conditions to either of the tree strip geometries, but very substantial reductions in the overland flow peaks are observed. The overland flow is a very small proportion of the total runoff over the three month period but is a major contributor to peaks; the addition of the tree strip which is orthogonal to the down-slope direction led to peak reductions of the order of 40% in the highest intensity flows. The reduction in overland flow was of the order of 60%: this is likely to be extremely beneficial from a sediment and pollution perspective, as overland flow tends to carry significant nutrients and sediments with it. Indeed, at this site, stream sediment measurements from an associated study show peaks in sediment bedload to be strongly associated with overland flow occurrence (Henshaw, in press). The tree strip placed in line with the down-slope direction provided less benefit; however even this reduced peaks somewhat and can be considered to have some value within the landscape from a flooding and sediment capture perspective.

Figure 7-7 shows the realisations of field-scale runoff (drainflow + overland flow) for six of the seven meta-model land use types supported by small scale data (and hence represented by detailed model simulations). This includes the uncertainty bounds which arise from the 100 accepted parameter sets.

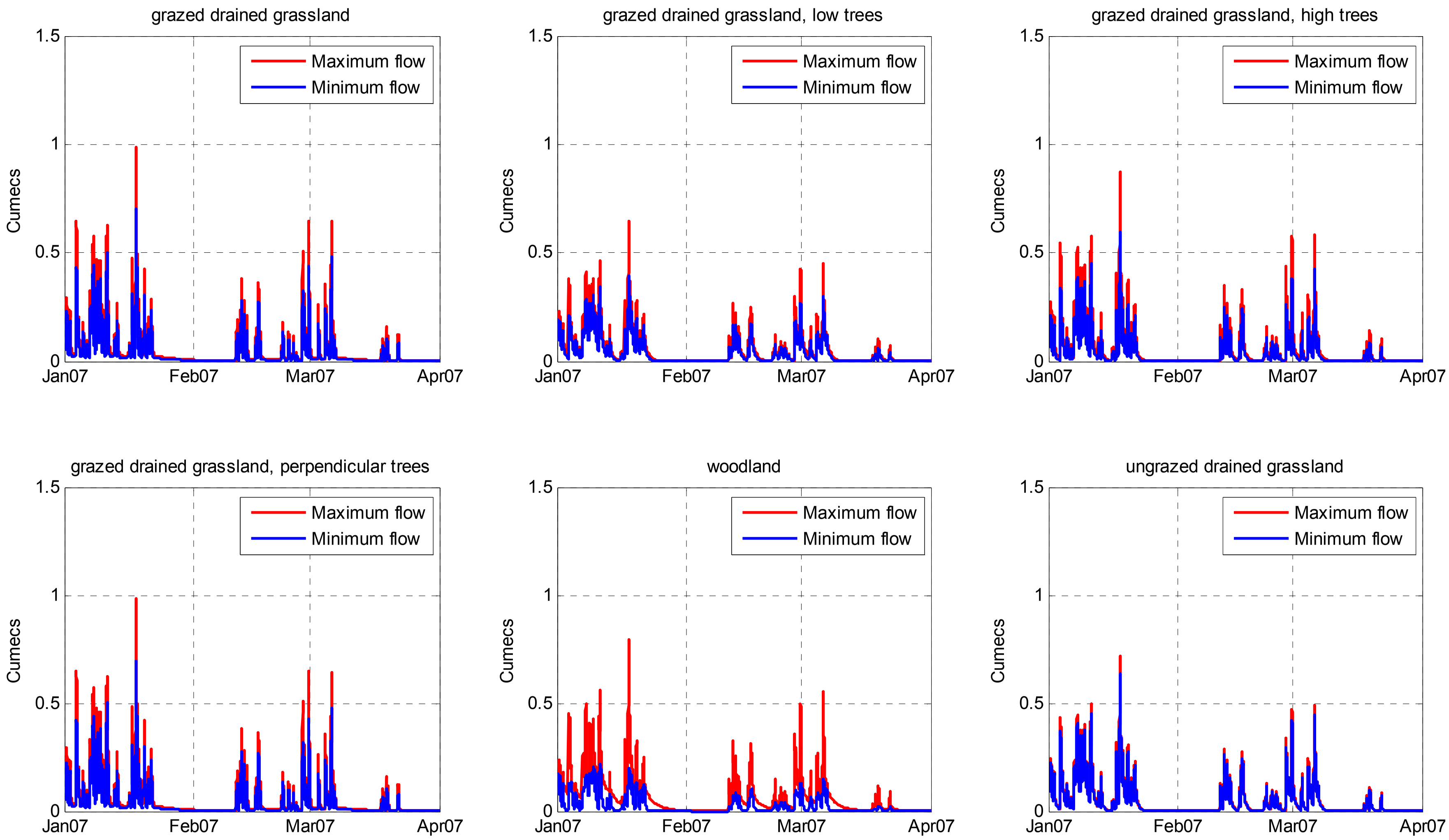


Figure 7-7. Realisations of field-scale runoff (drain flow + overland flow) for different land use types, with uncertainty bounds.

7.6 META-MODEL STRUCTURE AND CALIBRATION TO HILLSLOPE ELEMENTS

If the meta-model structure is not able to capture the characteristic behaviour of the detailed model under unmeasured land use change as well as existing conditions, it is likely to have no predictive power (and indeed extrapolation to the unmeasured conditions will almost certainly generate misleading results). The simplified structure must therefore be able to adequately translate responses caused by:

1. Changes to soil porosity;
2. Changes to rooting depth;
3. Changes to soil infiltration properties;
4. Addition or removal of artificial drainage.

It is also required to be capable of closely reproducing the changing effects caused by the relative placement of management interventions (e.g. shelter belts, lakes); the importance of placement was demonstrated in the previous section. Changes to potential evapotranspiration (PE) and interception may also be important; driving PE data is generally available for a variety of vegetation types but interception effects are rarely well handled in conceptual models.

The approach to the meta-modelling is to established a simple conceptual model with processes and parameters that can be closely linked to both the perceptual (pre-numerical) process model of Pontbren and the detailed physics-based model; so that consistency with our knowledge about processes is maintained. Various conceptual models were tried and the preferred one is described here.

The preferred conceptual model consists of a soil moisture store and three linear routing stores (Figure 7.8). It represents the key processes which are considered to be consistent with the perceptual model – the fast overland flow response when the soil is saturated and the drain flow generation when the soil is above field capacity.

The soil store simulates the soil moisture status and runoff generation processes. There are three parameters in the soil model:

cfca (mm)	the soil moisture above which soil drainage occurs
cmax (mm)	the soil moisture above which overland flow occurs
kmax ($\mathrm{mm}\Delta t^{-1}$)	the maximum rate of drainage from the soil.

Evaporation occurs at the potential rate (PE) for as long as there is water in the store. When rainfall exceeds *kmax*, the soil moisture increases, up to a maximum value of *cmax*. Any surplus rainfall beyond *cmax* becomes overland flow. The rest of the water above *cfca* becomes subsurface drainage. The three soil moisture parameters are calibrated within the meta-modelling procedure, however the values are first constrained by prior knowledge (from the field experiments) of soil moisture storge capacity and saturated hydraulic conductivity.

The routing model consists of three linear reservoirs in parallel, with parameters:

q (-)	the fraction of flow entering the quick subsurface drainage routing
rto (Δt)	the residence time of the overland flow routing
rtq (Δt)	the residence time of the quick subsurface drainage routing
rts (Δt)	the residence time of the slow subsurface drainage routing.

The first routing reservoir represents overland flow routing. In our application the residence time *rto* is fixed at zero because of the steep slopes. The lower two stores represent fast and slow response components of the subsurface drainage. The residence times of these reservoirs *rtq* and *rts* are calibrated, along with *q*.

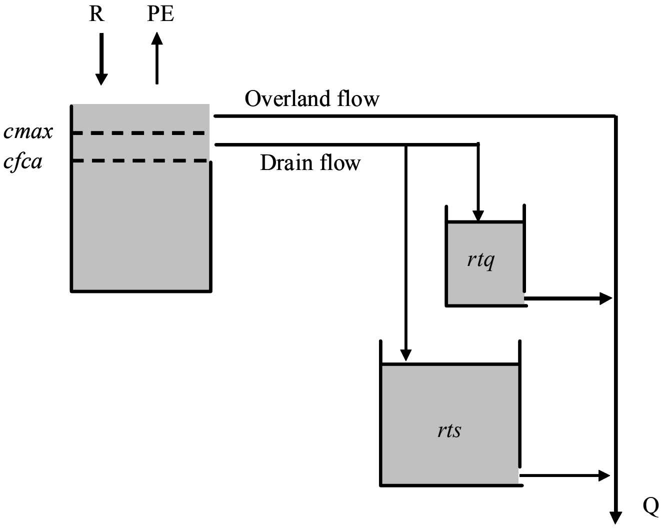


Figure 7-8. The conceptual model structure (under overland flow conditions)

This conceptual model matched recessions very well and is also able to represent the flow peaks generated by the physics-based model. Figure 7-9 shows an example match to the detailed model for one of the more difficult responses to fit - the low shelter belt.

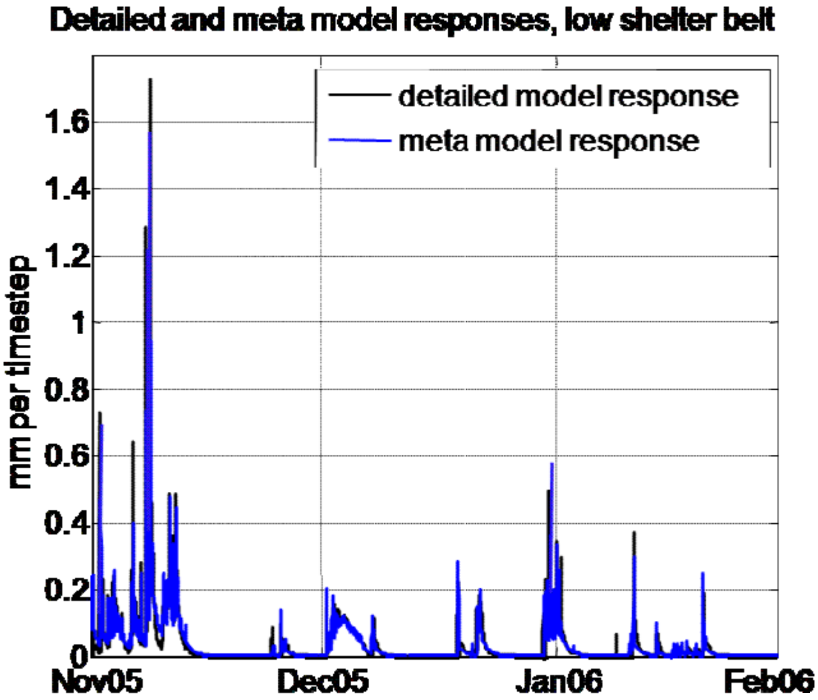


Figure 7-9. Meta model response against detailed model, low shelter belt

Those conceptual models that are conditioned on physics-based models within the meta-modelling procedure (namely: models representing grazed improved grassland, ungrazed improved grassland, improved grassland with no drains and three tree belt interventions) are by implication conditioned on small scale data. Uncertainty is handled through generating multiple samples of physics-based model responses to account for uncertainty on the data. Each individual detailed model simulation is then passed to the conceptual model and a corresponding response generated through automatic calibration to this response, using Monte Carlo simulation and a least squares fit measure. This allows a set of behavioural samples to be propogated forward within the catchment model to take account of small scale data uncertainty.

8. Catchment modelling

8.1 CATCHMENT MODEL DESCRIPTION

The semi-distributed rainfall-runoff modelling toolbox RRMTSD (Orellana et al., in preparation) is a modular framework that allows efficient building and evaluation of semi-distributed rainfall-runoff models. These models are semi-distributed in the sense that the watershed is conceptualised as a network of sub-areas for which lumped conceptual rainfall-runoff models are computed. The hydrological processes and climatological forcing data within the sub-areas are considered to be homogeneous, and the degree of spatial distribution is represented mainly through the number of sub-areas. These can represent subcatchments or hydrological response units.

Topologically, RRMTSD simulates streamflow for the uppermost stream sub-areas first and then continues with the downstream ones. The architecture comprises three component modules: moisture accounting, runoff routing and channel routing. The first module determines effective rainfall (ER), actual evapotranspiration (AET) and an estimation of moisture status; the routing module calculates the fast and slow runoff; and the channel routing module estimates discharge at the outlet of the sub-area. The formulation of the first two modules is based on the established RRMT framework (Wagener et al., 2001). A variety of pre-built modules are available which are interchangeable but others can be added providing additional flexibility.

The toolbox allows for different optimisation methods for calibration: uniform random search, the shuffled complex evolution method (Duan et al., 1999), and local nonlinear multi-constrained methods based on simplex searching. These methods can be applied with the same or different model structures representing the individual sub-areas. The input data and simulated variables in every sub-area can be analysed using a variety of visualisation tools.

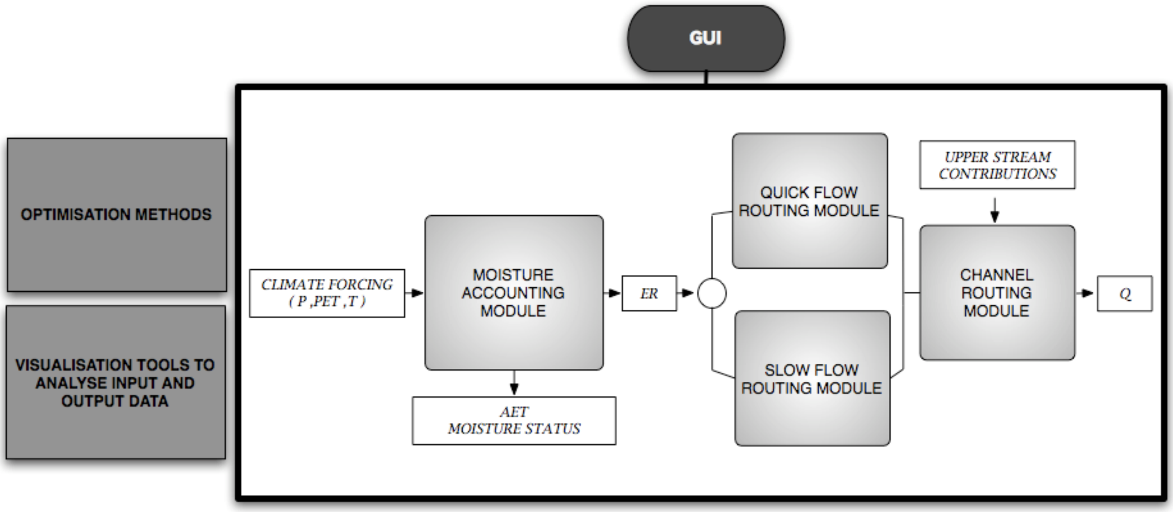


Figure 8-1. RRMTSD structure

8.2 SETUP OF CATCHMENT MODEL IN PONTBREN

This semi-distributed rainfall runoff model is used to route water from field-scale hydrological response units to and along the streams and ditches identified within the catchment. Fields were chosen as the individual response units as these seem an appropriate management unit when looking at the influence of land use changes. They also generally form sensible individual units, due to the tendency of farmers to set ditches and drainage outlets at field boundaries.

As the quality of the catchment model output is very dependant on data availability and reliability, it has been necessary to put considerable effort into collecting geographical data and processing it to allow it to be utilised in the catchment scale modelling. This allows a) identification of the field unit boundaries, b) appropriate routing between fields and river reaches to be specified and c) specification of each unit as one of the land use types previouslydefined. DEM data along with river network data has been used to identify the catchments, land use maps from three sources (LCM1990, LCM2000 and a vegetation survey circa 1990 by the Countryside Council for Wales) have been obtained, a soil map has been digitised and converted to a vector dataset within GIS, and information from Ordnance Survey maps converted into polygons with field area data, allowing the areas associated with individual fields, along with their respective proportions of soils and land uses to be identified. The response of the catchment model can then be compared to the observed response at the individual sub-basins monitored in the catchment, which are summarised in Table 8.1 and Figure 8.2.

Table 8.1. Summary of the gauged sub-basins

Flow Gauge Number	Downstream From…	Contributing Area (km^2)	Independent Contributing Area (km^2)	Percentage Improved Grassland	Name
1	None	0.72	0.72	73	SF8
2	1	1.29	0.57	68	SF9
3	None	0.21	0.21	100	Rogers's Lake
4	3	0.29	0.08	100	SF4
5	2, 4	2.39	0.81	70	SF7
6	5	3.17	0.78	77	(SF1)
7	6	5.77	2.60	80	Road Bridge
8	None	1.29	1.29	7	Lake (SF10)
9	8	4.06	2.77	14	Melin y grug
10	7, 9	12.49	2.66	58	Afon Einion
11	None	0.16	0.16	92	Weir V1
12	None	0.83	0.83	92	Weir V2
13	11, 12	1.31	0.31	85	Rhosaflo

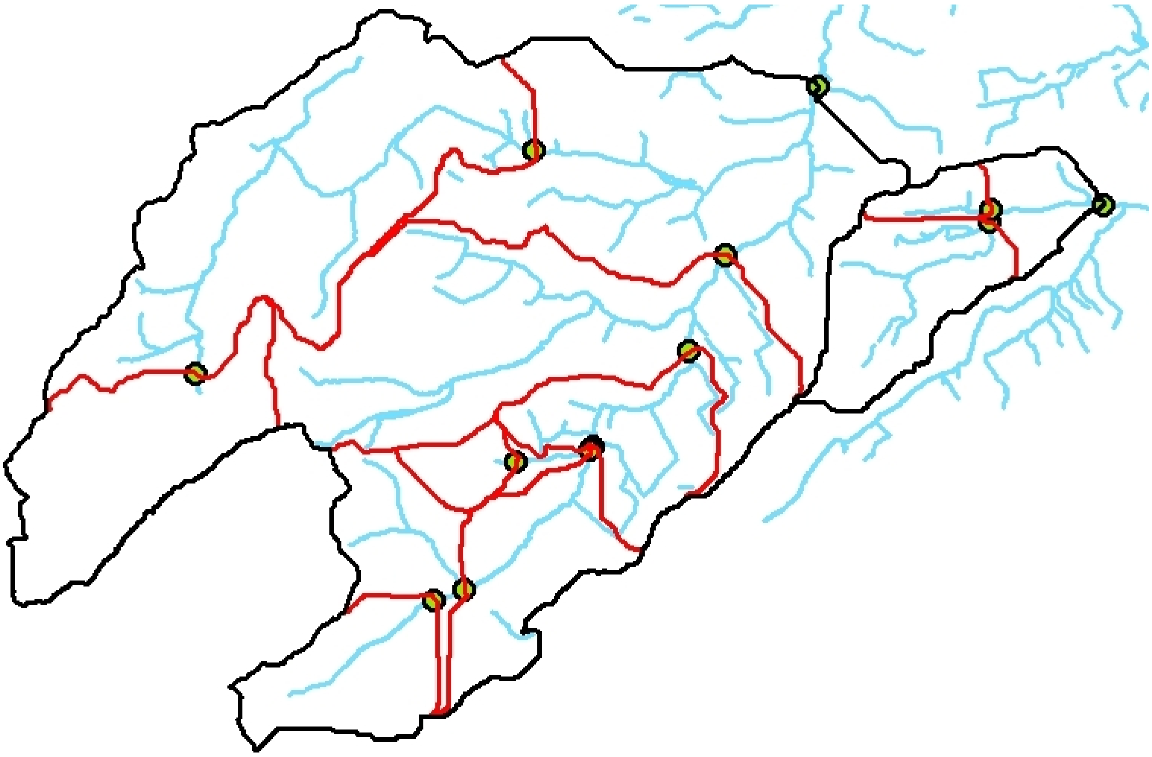


Figure 8-2. Outlines of the gauged sub-basins

The fields used to represent the small Rhos aflo catchment are shown in Figure 8-3, and those used for the wider Pontbren catchment are shown in Figure 8-4. Streams and ditches have been identified from OS map data and converted to vector data to create a stream and ditch network. That created for the small Rhos aflo catchment can be viewed in Figure 8-5. Discussions with farmers identified several problems with this network, in main missing ditch information. Much of this missing information has now been provided by the farmers, although more discussion with them, and some ground-truthing in the field, would be helpful to confirm and further refine the ditch network for future use.

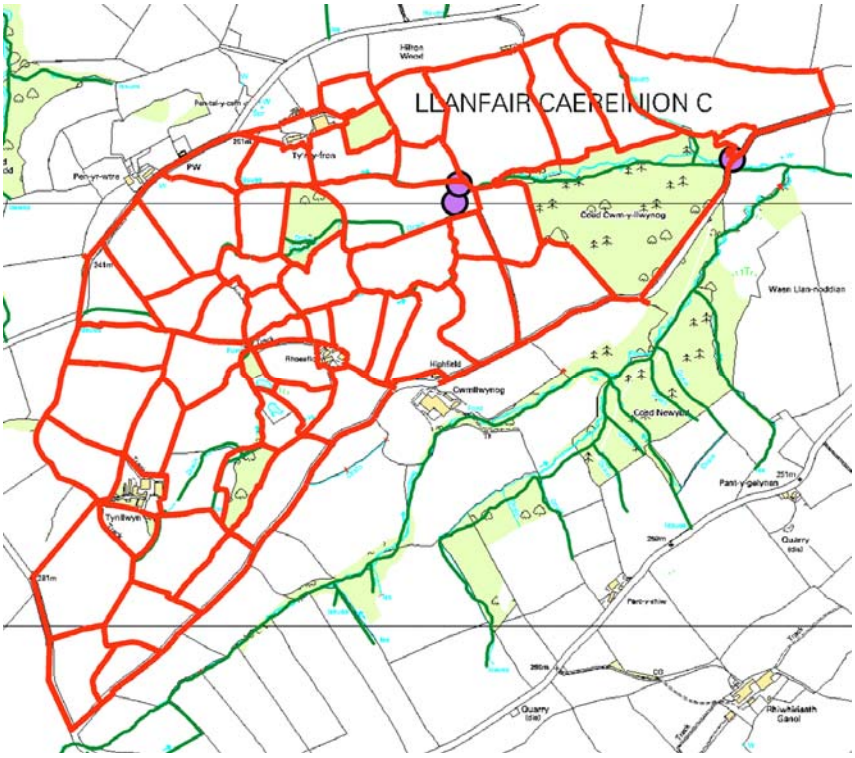


Figure 8-3. Fields in the Rhos aflo catchment setup

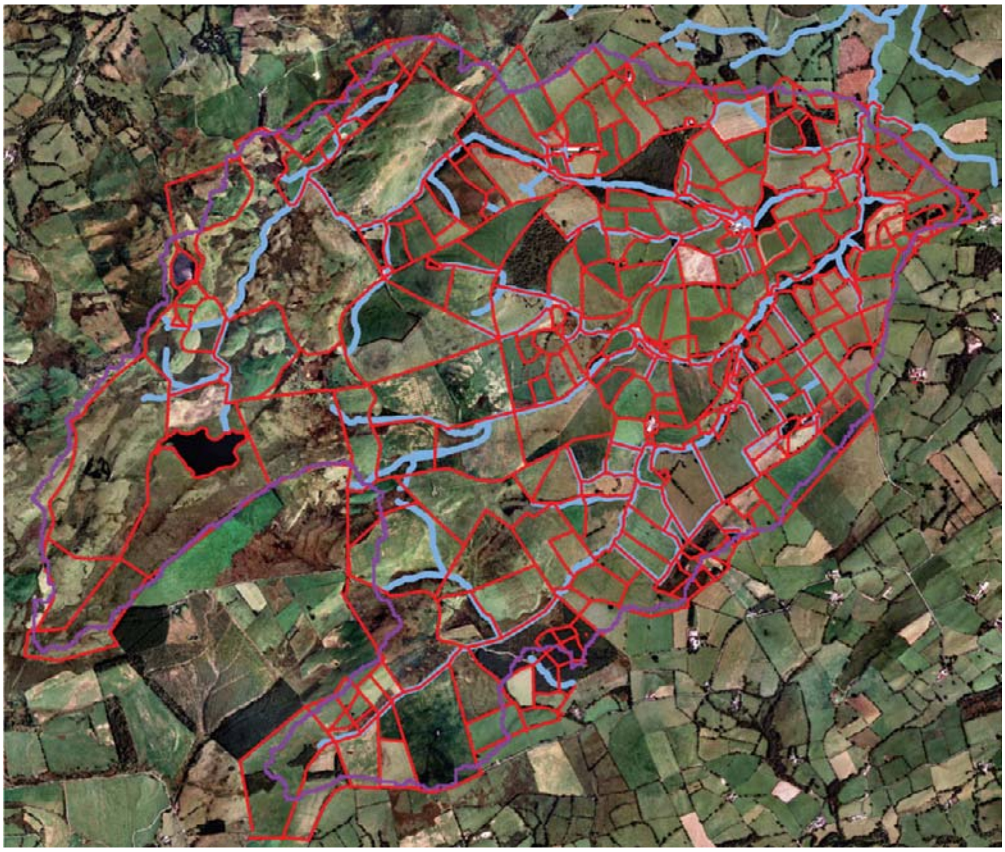


Figure 8-4. Fields in the Pontbren catchment setup

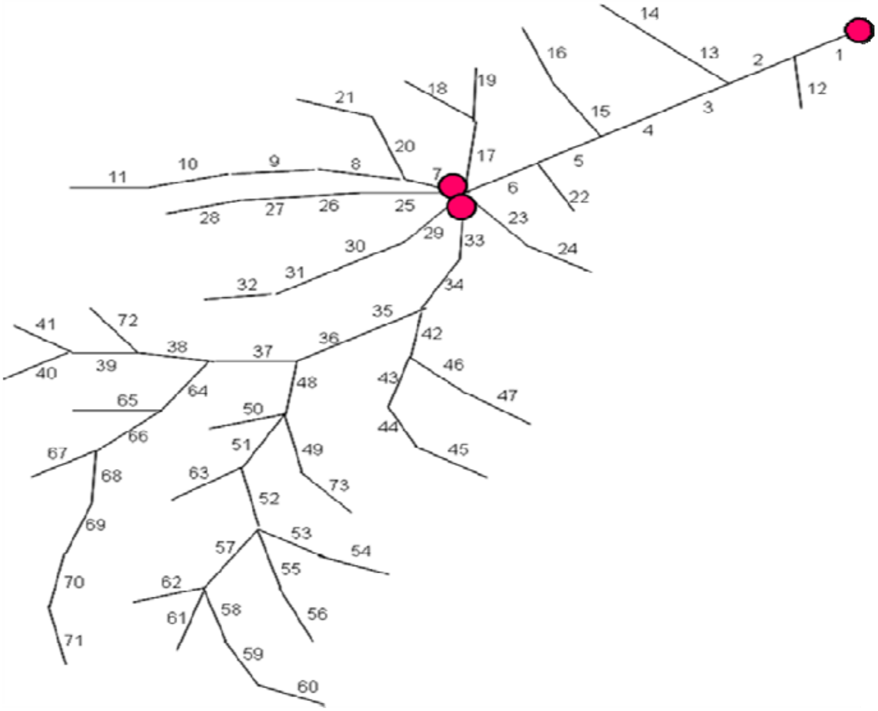


Figure 8-5. Example RRMTSD stream network for the Rhos aflo catchment. The numbers shown are the indices used within RRMTSD and the red dots indicate the locations of the flow gauges.

8.3 CALIBRATION OF META-MODEL ELEMENTS TO CATCHMENT DATA

The catchment model is conditioned on both the field scale data (where available), through the inclusion of families of meta-models conditioned on detailed models as previously described, and further conditioned on the catchment scale land use data and stream flow measurements. Each field in the catchment model is assigned to one of the meta-modelling typologies based on land use and OS data. It is assumed that the parameter values are uniform over all the fields within each land use type. Measures of fit to the observed streamflow are used to accept or reject individual realisations from Monte Carlo simulations, where the measure of fit is either 1 (within an acceptable tolerance of the observations) or 0 (not within the tolerance). A set of realisations consistent with the streamflow response is hence generated. Note that this is a subset of the models which come out of the meta-modelling step, and hence the catchment scale results remain consistent with the small-scale data sets and process information.

For the “unimproved grassland” and “wetland” land use types, which are not supported by small-scale data sets but are supported by catchment-scale data from flow gauges (especially gauges 8 and 9), prior ranges of parameter values are conditioned only on these catchment-scale data.

After the conditioning steps, the results from the optimal field-scale models (Figure 8-6) and the resulting catchment scale response at monitored points within the Pontbren catchment (Figure 8-7) are shown, and the uncertainty associated with the meta-model for each land use management class (Figure 8-8). Flows which are below the low-flow measurement threshold of the Starflow meters (see McIntyre and Marshall, in press) are neglected in the conditioning, hence the apparent poor fit for the low flow data.

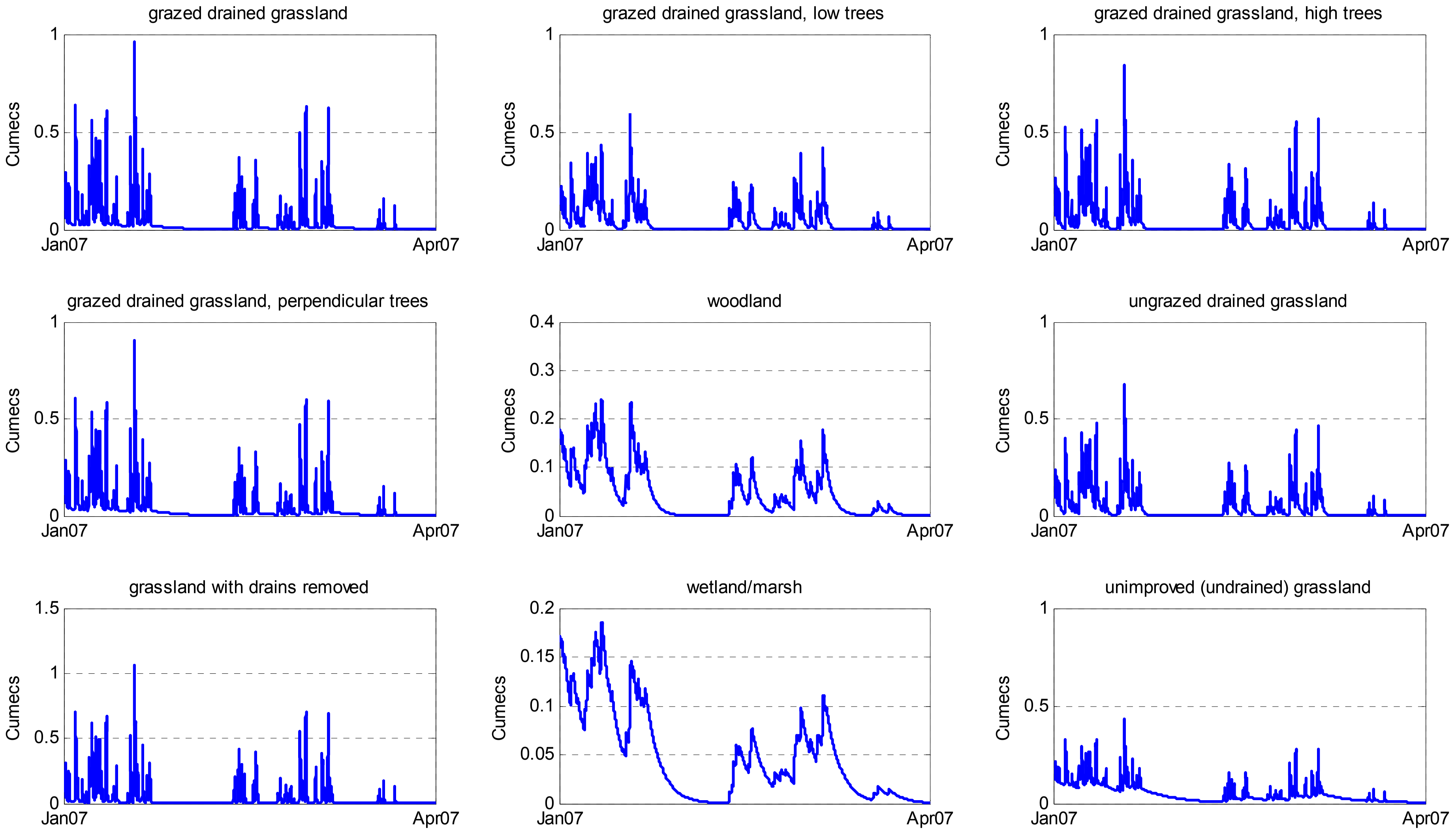


Figure 8-6. Meta-model responses (deterministic)

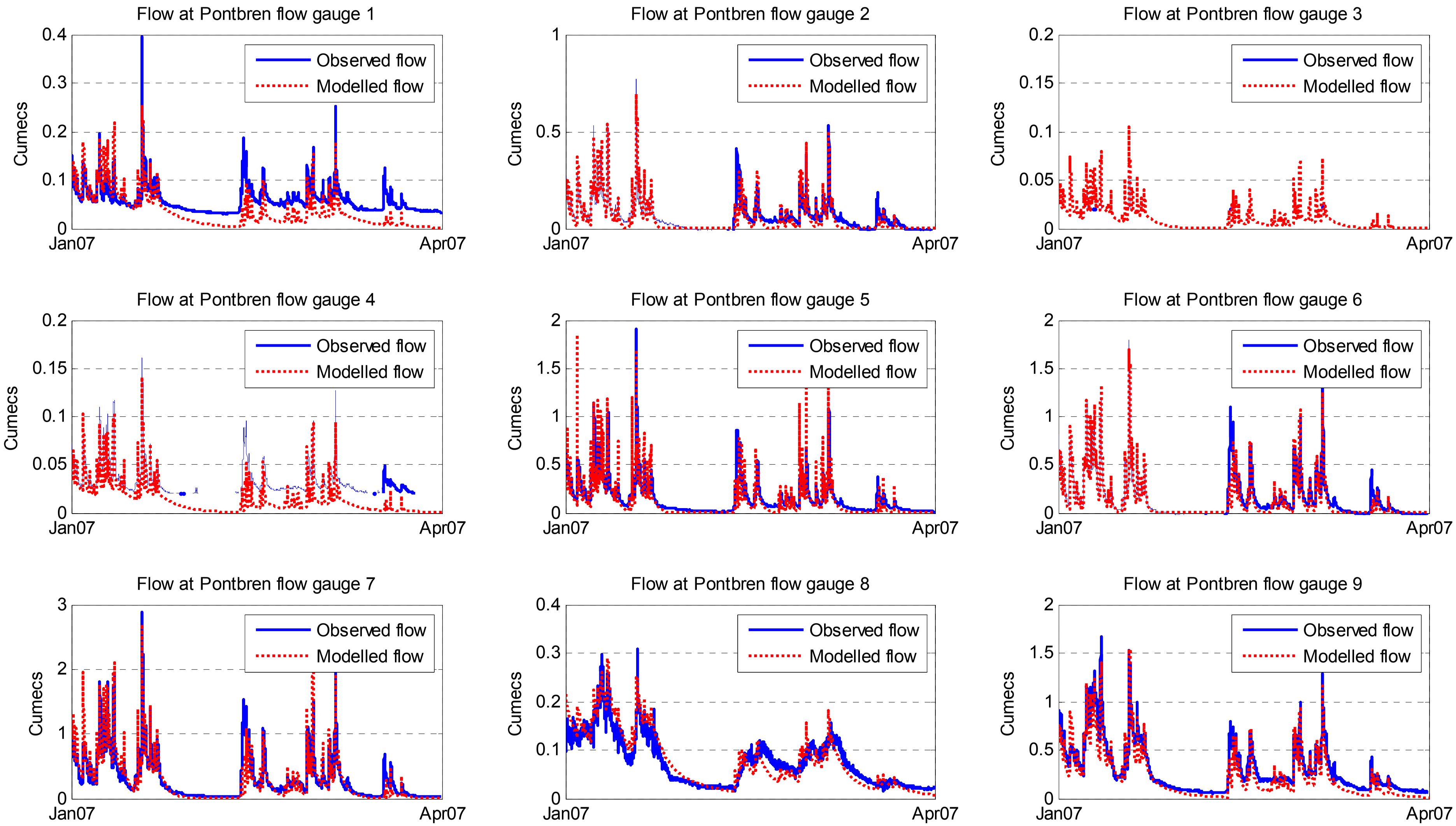


Figure 8-7. Pontbren stream flow at gauges 1 to 9, observed and modelled; simulations conditioned on both hillslope scale (through meta-models) and catchment scale data. Only one realisation of modelled flow, out of 100 accepted results, is shown.

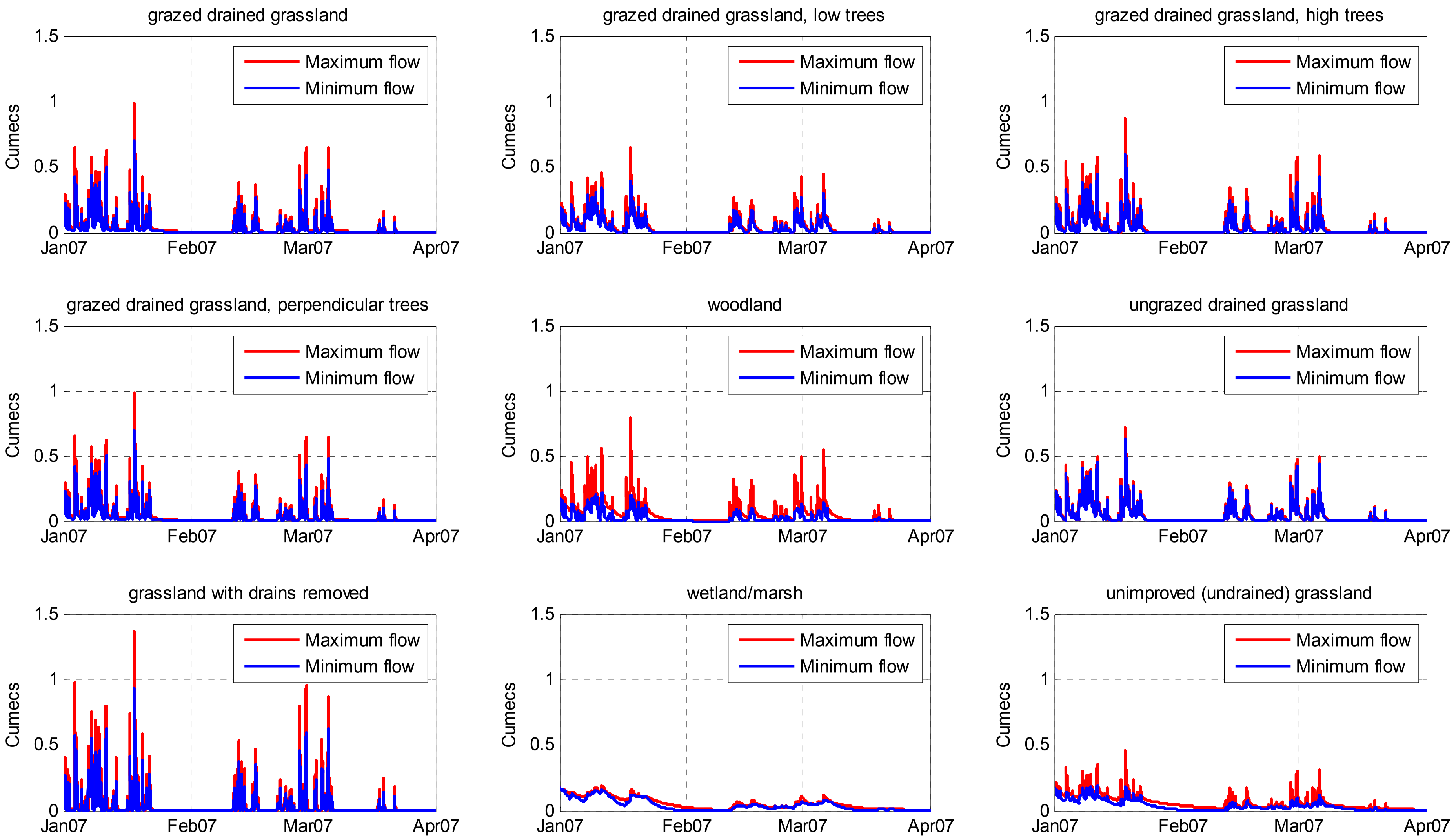


Figure 8-8. Meta-model responses (envelope of uncertain responses)

8.4 SCENARIO PREDICTIONS

Four land management scenarios are shown, for the Pontbren catchment at gauge 7. Observed 15-minute rainfall inputs from the experimental period are used here (in the next sub-section, a more extreme event is considered). The scenarios are:

- the baseline is the current day land use within the two catchments;
- the first scenario removes the effect of the Pontbren consortium tree plantings (and hence takes the catchment back to something approximating the intensive use of the early 1990s);
- the second adds shelter belts to all grazed grassland only sites;
- the third assumes the entire catchment is woodland.

Figure 8-9 shows the best-estimate results. Figure 8-10 shows the uncertainty bounds for each scenario, defined by the maximum and minimum flow generated by the 100 acceptable parameter sets at each time-step, focussing on the largest observed event, 18th January 2007. Table 8.2 shows the maximum, minimum and median changes in peak flows for this event, and also the median change in time-to peak. Uncertainty is high, and results are best summarised using the upper and lower uncertainty bounds:

- removing trees planted within the last decade causes between 6 % to 18 % increase in the main flow peak from the baseline condition;
- adding tree shelter belts across the lower parts of all grazed grassland sites causes between 13 % and 48 % decrease in the main flow peak from the baseline condition;
- afforestation of the whole catchment causes between 9% and 69 % decrease in the main flow peak from the baseline condition;
- there was no apparent uncertainty in time-to-peak results, due to the 15-minute resolution of the model. The woodland cover increased time-to-peak by 45 minutes, while the shelter belts increased it by 15 minutes.

The median reduction in peaks between the most intensely farmed scenario and with optimally placed shelter belts is approximately 40%, demonstrating the potential utility of small-scale, strategic tree planting within the catchment. The effect of the small scale planting within the Pontbren consortium over the last few years appears to have a significant effect at the catchment scale.

Table 8-2. Changes from baseline time-to-peak and peak flow under three scenarios using the January 2007 Pontbren event

	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

The woodland simulations could be considered as the maximum effect that could possibly be induced within the catchment through tree planting (i.e. if the entire area was wooded). This scenario gave a median result of 50% reduction in the main flow peak, however the uncertainty is especially large (Figure 8-10) due to the uncertainty asscociated with subsurface storage and flows underneath the woodland. In some realisations of the model, the woodland caused very little reduction in flow peak or even an increase (Figure 8-10). However in general the results clearly show the importance of retaining woodland units and any tree strips or hedgerows currently within the catchments.

The analysis was repeated using the Rhos aflo catchment. There was a greater negative impact associated with reversion to the 1980s landscape in Rhos aflo – this is because, since 1980, more trees have been planted in Rhos aflo. Apart from that, results were very similar to those shown for Pontbren.

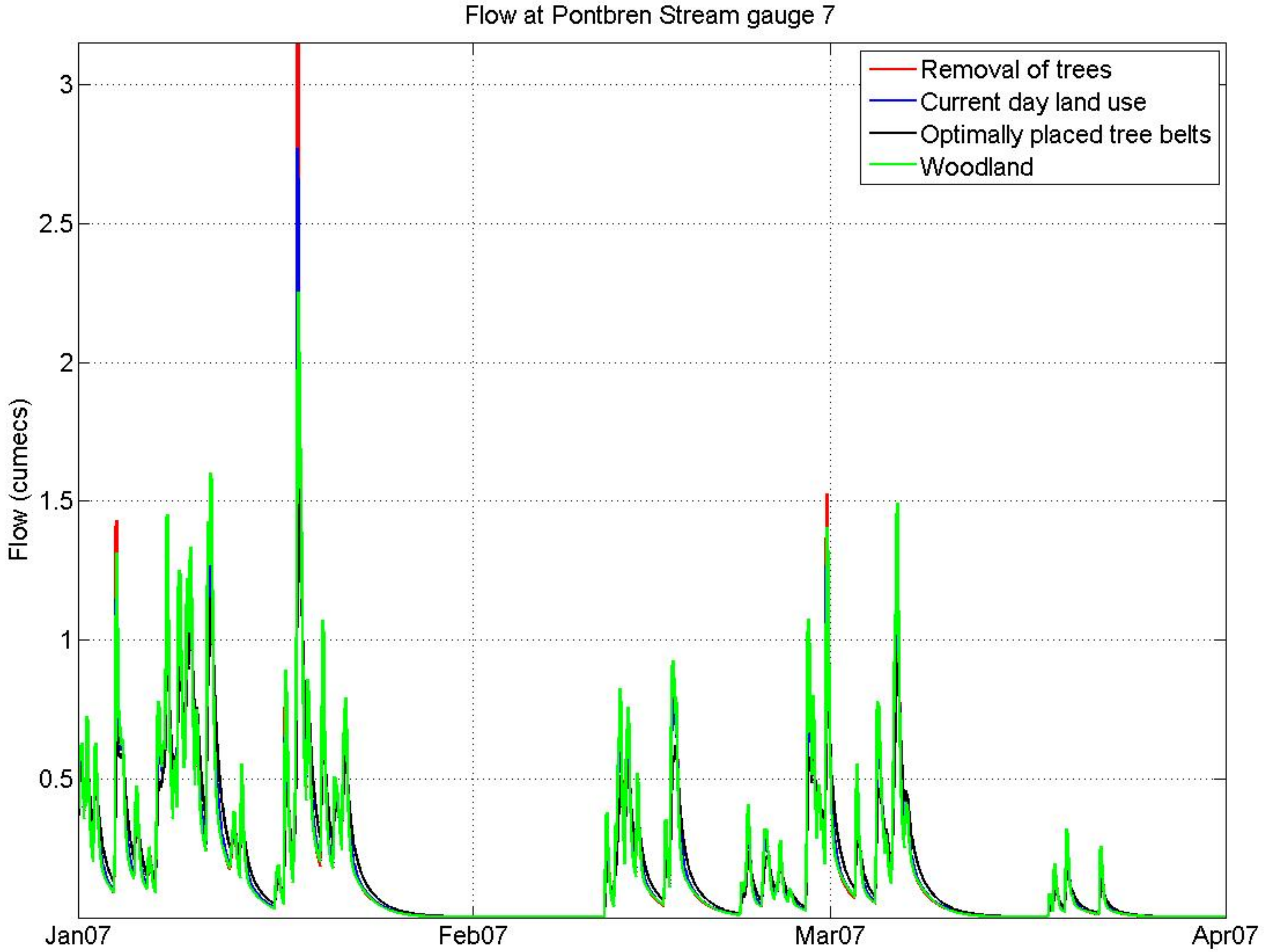


Figure 8-9. Pontbren stream flow at gauge 7: scenario predictions using winter 2007 data

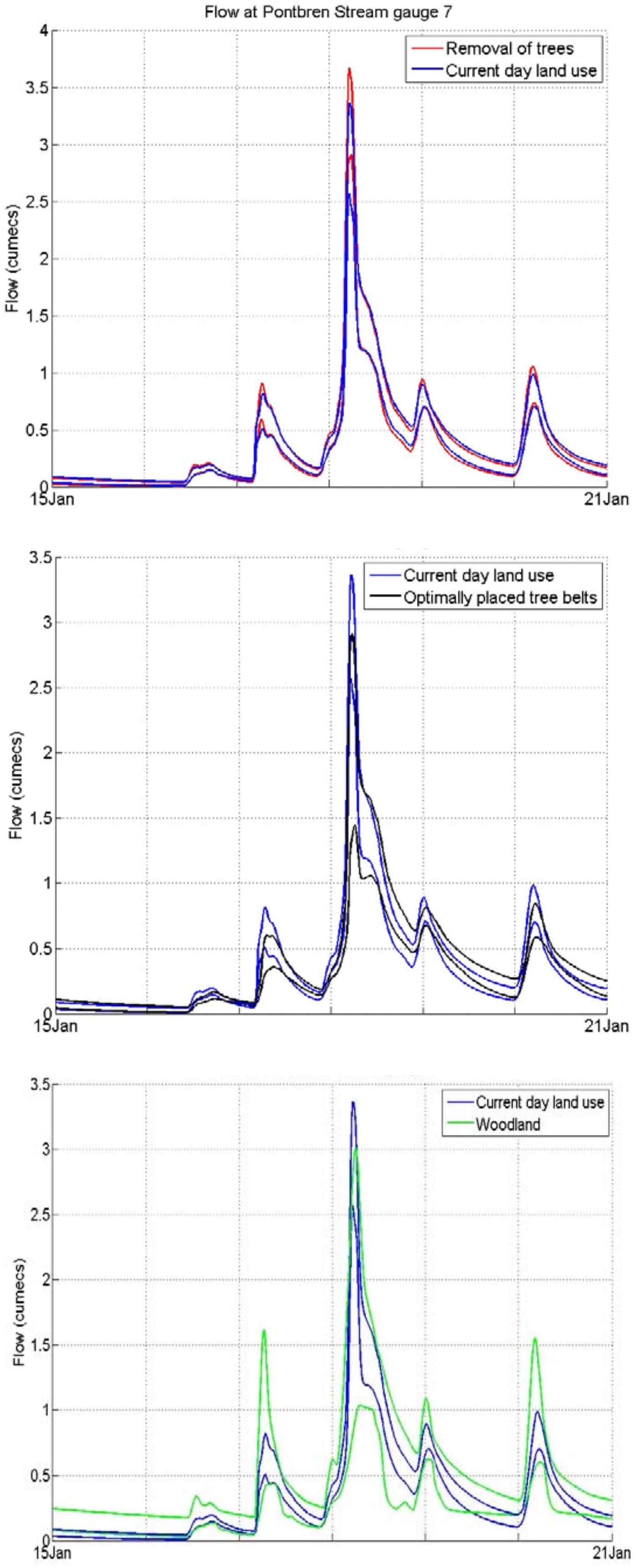


Figure 8-10. Uncertainty in scenario predictions for Pontbren event of 18 January 2007

8.5 CATCHMENT RESPONSE TO EXTREME EVENTS

A major question when considering flood risk mitigation potential of land management changes is the degree to which changes are effective during extreme rainfall events. However, an analysis of rainfall events experienced over the duration of the Pontren monitoring period (up to October 2007) did not show any evidence of "extreme" rainfall, with all volumes in day, five day, and ten day periods well under the regional volumes quoted for 10 and 25 year return periods in Fowler and Kilsby (2003). In June and July 2007, a period where the UK experienced considerable flooding, volumes and intensities were well under those observed in other parts of the UK.

An unanswered question then becomes the response of the catchment to land management scenarios under larger events. The generation of physically and regionally consistent "extreme" rainfall inputs for the site will be addressed in later work. At present the Carlisle rainfall data from January 2005 (at the Aisgill gauge) has been used to represent a hypothetical, yet plausible, very extreme rainfall. The rainfall total over 2 days was 140mm with an estimated return period of 180 years.

This rainfall data was used to drive the baseline simulation and three land management scenarios at Pontren. The initial conditions were assumed to be dry (to represent a summer event) and then wet (winter), however this did not make a significant difference to the peak flow due to that large volume of water in the days preceeding the main event. The results without uncertainty are in Figure 8-11, and Figure 8-12 shows the uncertainty limits focussing on the large event. Table 8-3 shows the maximum, minimum and median changes in peak flows, and also the median change in time-to peak.

In summary, under very extreme rainfall:

- removing trees planted within the last decade causes between 3 % to 7 % increase in flow peaks from the baseline condition;
- adding tree shelter belts across the lower parts of all grazed grassland sites causes between 2 % and 11 % decrease in flow peaks from the baseline condition;
- afforestation of the whole catchment causes between 10 % and 54 % decrease in flow peaks from the baseline condition.
- there was no apparent uncertainty in time-to-peak results, due to the 15-minute resolution of the model. The tree removal reduced time-to-peak by 15 minutes, woodland cover increased time-to-peak by 30 minutes, while the shelter belts had no effect.

Table 8-3. Changes from baseline time-to-peak and peak flow under three scenarios using the extreme (Carlisle January 2005) event

	Change from baseline			
	Time to peak (mins)	Peak flow, lower bound (%)	Peak flow, median (%)	Peak flow, upper bound (%)
Tree removal	-15	3.5	5.1	7.2
Optimally placed tree belts	0	-1.9	-5.0	-10.9
Woodland over whole catchment	30	-10.3	-36.1	-53.5

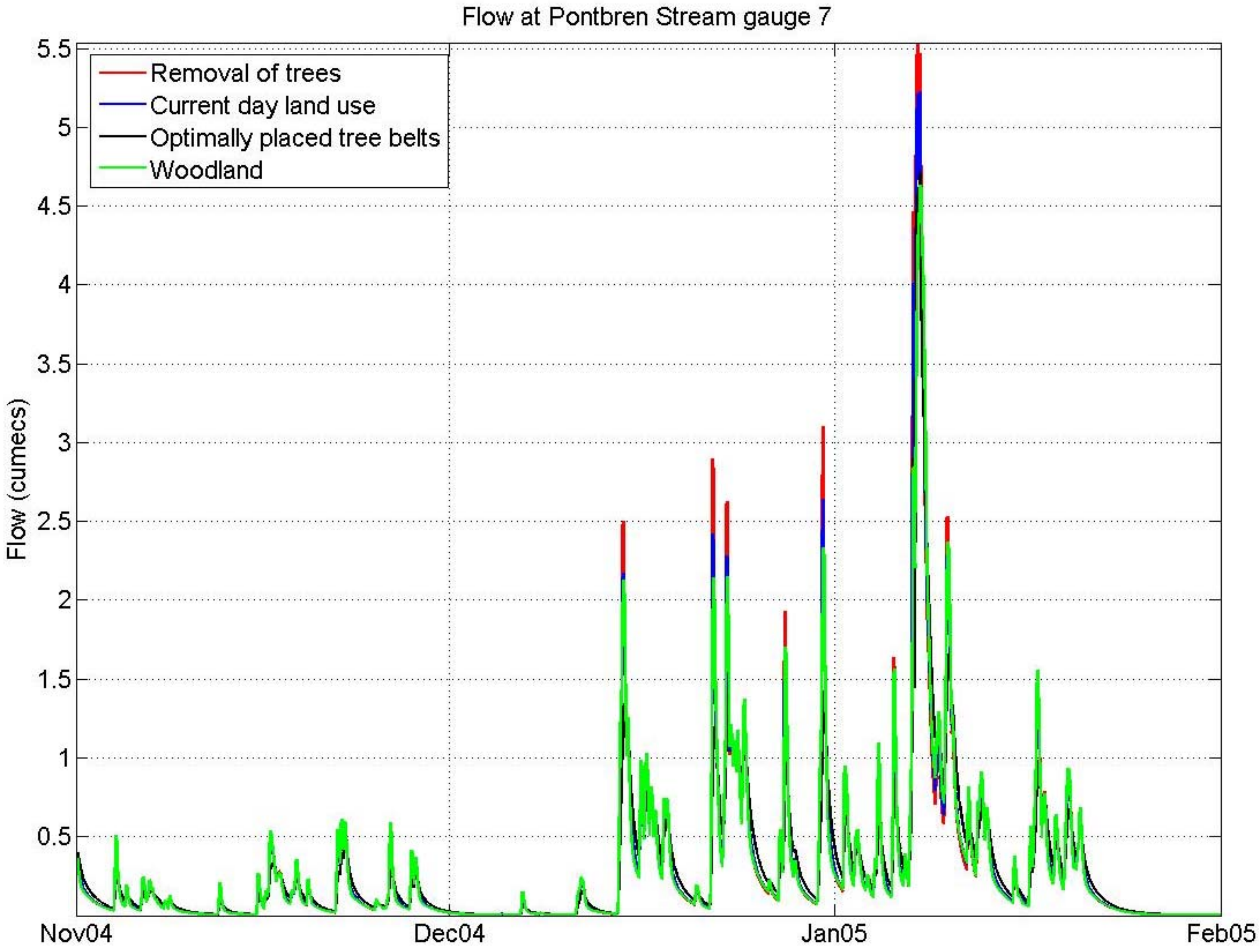


Figure 8-11 Pontbren stream flow at gauge 7: scenario predictions using extreme (Carlisle January 2005) rainfall event

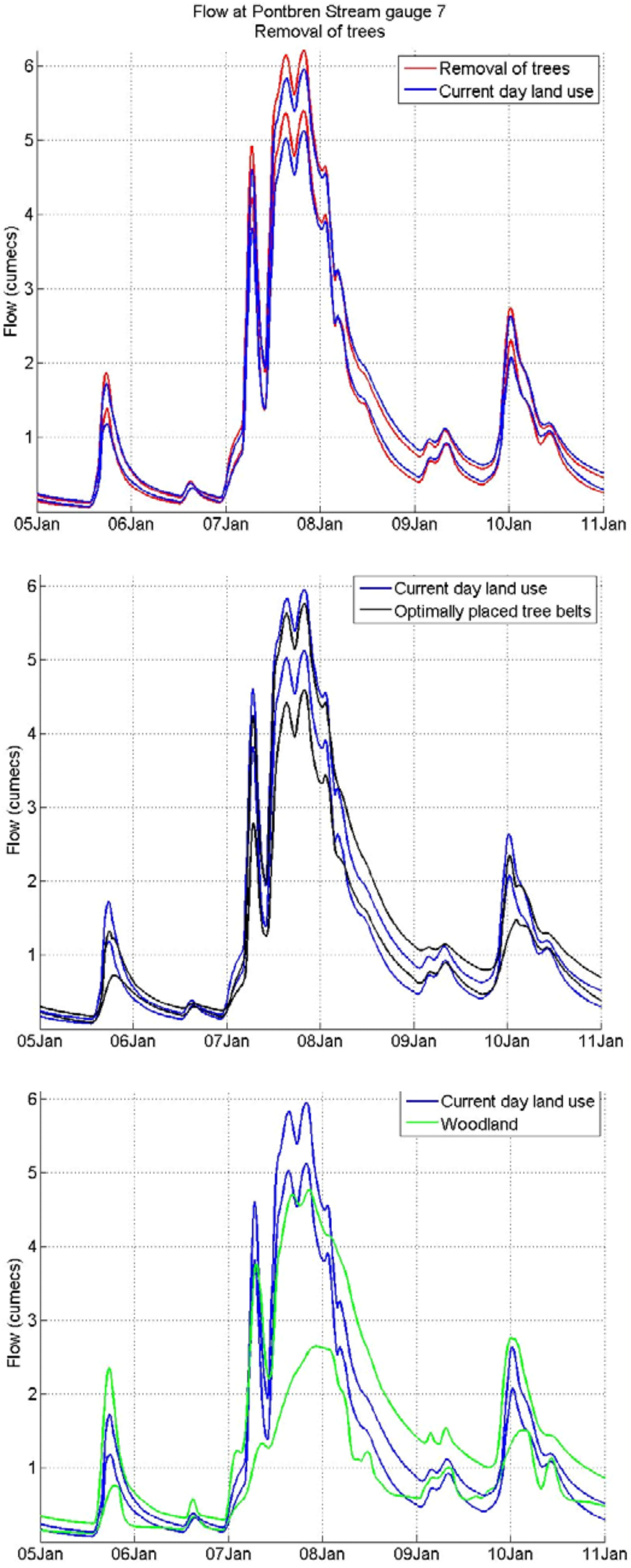


Figure 8-12. Uncertainty in scenario predictions for extreme (Carlisle January 2005) rainfall event

9. Reflections, future programme, and suggestions for extensions to future modelling work

9.1 ACHIEVEMENTS TO DATE

New generic modeling capabilities have been developed and implemented. The methodology allows investigation of the hydrological effects of land use management at the scale of individual fields, and evaluation of the associated catchment-scale effects. The methodology has been applied to Pontbren, and used to quantify effects of grazing and the planting of tree shelter belts and/or buffer strips on flood runoff at both field and catchment scale.

At the field scale, a physics-based model has been extended and calibrated on site data. This has allowed a variety of hypotheses of process response to be tested, and has substantially increased our understanding of the dominant responses within the more intensively managed areas of the Pontbren catchment. Realisations from this model conditioned on site data have been carried forward to a catchment scale model, and allow small-scale process response to be represented at this larger scale: an achievement not formerly possible due to the restrictions of generic catchment-scale model structures and further computational restrictions on the detail and scale possible in such models.

Use of these models with the data collected within the experimental programme suggest scope for significant reduction of flood risk in low permeability landscapes (such as clay catchments) at local scales. Specifically, the programme has established the importance of trees, which provide local improvements to the structure and permeability of soils, and the storage within these soils, in mitigating small to medium rainfall events. Placement of single trees or small strips of woodland will generally have a positive effect on flooding, as the action of trees on soil tends to increase interception losses, available water storage within the soil and the rate at which water can move from the ground surface into the subsurface. However, the significance of such changes will vary depending on location: trees positioned down-slope of areas where water tends to collect on the surface are likely to be of most benefit. Results to date suggest peak reduction of 40% may be achievable given optimal placement of tree shelter belts and/or hedgerows.

Although both our process knowledge, and modelling capabilities, in the Pontbren and similar upland systems has been substantially augmented by the work programme detailed above, a variety of knowledge gaps remain. The remainder of this section discusses these in detail, and gives concrete suggestions regarding how these gaps might be narrowed or removed.

9.2 TARGETING PERCEPTUAL GAPS IN UNDERSTANDING

The programme has demonstrated: a) the importance of conditions in the upper soil horizon in generating rapid runoff from saturation-excess overland flow, b) the significant role of drainflow and c) the importance of the combined effects of trees and lack of grazing in improving soil structure and reducing overland flow. However, it has as yet not established unequivocal evidence that compaction per se is important in improved grassland regions of the Pontbren catchment, although some data on soil properties and premininary results from the manipulation plotes suggest this is likely to be the case.

The experimentally-determined soil properties and the plot observations of overland flow show large variability. There is a need to establish the degree of both small-scale and large scale heterogeneity within land use types, and to investigate further the non-stationarity observed within small-scale responses, and understand how this scales.

A major knowledge gap regarding the tree planted areas is uncertainty concerning the drainage of subsurface water. The experimental programme established the importance of more permeable soils, and the storage within these soils, in mitigating small to medium rainfall events. However, under high intensity and/or high volume rainfall events, it is expected that these soils will rapidly fully saturate. If underlain by low permeabity soils, their mitigation facility is likely to then decrease rapidly, with limited drainage and hence the generation of substantial volumes of overland flow. However, it is also possible that the soils may tap deeper subsurface storage or preferential pathways, allowing the near-surface water to move within the subsurface, and either exit through another pathway. For example, the degree of uncertainty about these pathways is evident in the uncertainty in predictions shown in Figures 8-10 and 8-12. Understanding the extent to which the deeper subsurface can store and/or delay transmission of water from these near-surface permeable stores to the stream must be explored further within the second phase of the FRMRC program. To reduce flooding downstream, the volume of water released from an upstream catchment during a storm must reduce and/or the rate of discharge of this water must be decreased. Flood mitigating land management changes must therefore increase available water storage (either within the subsurface or open water bodies) and/or slow the drainage of this water. The subsurface routes below the trees are therefore a key factor which needs to be investigated to reduce uncertainty about impacts of trees.

We have little understanding of the functioning of unimproved grassland and wetland areas within Pontbren, and this presents a knowledge gap that has not been satisfactorily resolved due to constraints in project resourcing.

9.3 EXTENDING MODELLING CAPABILITIES

Further uncertainty analysis of outputs from the current modelling sequence (physics-based, meta model, catchment model) is important.

Topography can be an important factor in determining runoff (e.g. Anderson and Burt, 1978), and local topographic effects have not been represented within the modelling work to date (which has assumed uniform slopes); an extension of the model to allow for better treatment of local topography (for example, by including a finite element representation) and testing sensitivity would be beneficial.

The current approach to calibrating the three dimensional model uses a one dimensional calibration procedure, which reduces the scope for including heterogeneity. The sensitivity of the models to heterogeneity should be tested, and results used to suggest ways to include heterogeneity within the framework (if necessary)

An interesting but problematic issue in representing drainage under saturated conditions within the detailed model occurs due to the large head gradient generated from the weight of standing water above the drains, combined with the Darcy assumption that flux out is directly proportional to this head gradient and the hydraulic condictivity. This can empty pores close to the drains far faster than those above, leading to a rapidly changing zone of unsaturated soil with a perched water table above, and associated numerical problems. As the ability of the soil to transmit water under saturated or near-saturated conditions is key, further attention to this issue in the detailed model is warrented.

9.4 EXTENDING AND COMPLEMENTING THE SCALING WORK

Progress has been made in developing meta-model suites for heavy clay landscapes; however more work would be advantageous, to take forward information from the developing conceptual model of Pontbren the question of how best to structure and to parameterise meta-models over the entirety of the UK and beyond. This can only be answered by applying the strategy to different catchments and to larger scales. It is also difficult to know the scale at which the meta-modelling procedure may break down and alternative or complementary strategies become necessary. The answer will be dependent on computer power as well as data and place understanding; representing units in detail at the field or similar scales within large catchments may become feasible in the coming decade.

The methodology developed allows a set of behavioural samples to be propogated forward in scenario predictions to take account of small scale data uncertainty; example results for this are shown in Figure 8-8. However this does not take the full effect of heterogeneity in soil response into account. Also the parameters within the detailed model may be of a smaller scale than those at the conceptual scale. This may allow some general information on soil properties with scale to be utilised, e.g. as the size of the soil being considered increases, there is a tendency for a greater bulk conductivity. Questions on how best to include spatial variability of parameters remain and are likely to be important as the methodology is applied at larger scales.

A black box approach, fitting a simplified, fast running model that emulates the response of the physically based model, and particularly its response to changes in land use, was also used. Further work on the latter approach, or some other methodology for creating a faster and/or less parameterised meta-model would be interesting in the context of uncertainty studies as it allows efficient sampling of uncertainty, e.g. using the Gaussian Emulator methodology of Kennedy and O'Hagan (2000).

An alternate approach to the scaling issue is to attempt to find an independent understanding of the processes at the larger scale; this is known as downscaling and provides a useful complement to the upscaling approach. It also has the advantage of being less dependent on forthcoming modeling and data collection work before it can be started (although forthcoming data will still be invaluable to this approach also). The data based mechanistic modelling approach presented by Young (1998), based on fitting a variety of transfer factor models to data, and from these, identifying what pathways (and associated residence times, which may vary temporally) appear to be significant, allows some information on dominant pathways, and the hydrological functioning of different parts of the catchment, to be gathered. Furthermore, although it is difficult to see how this approach could identify changes in land use and appropriate parameterisation of such changes, differences between those pathways and residence times identified for improved and unimproved regions may provide some meta-information on the dominant processes operating in either. The Bowl data, with detailed runoff and drainflow measurements, along with rainfall, also provides an opportunity to directly compare information gained using the transfer factor approach with that gained through the physically based modelling. The CAPTAIN toolbox, with routines allowing this data based mechanistic modelling approach to be applied to data, has been obtained from Lancaster University and work is underway as part of the second phase of FRMRC work to apply this to the Bowl, and to look at differences in identified pathways between a) improved and unimproved grasslands and b) over different scales of the catchment (e.g. the response within the first few reaches versus the larger, more integrated responses).

9.5 LINKAGE WITH INFORMATION TRACKING METHODOLOGY

Although results from the upscaling work show promise, there is a need to combine insights from this with other approaches to contribute to solutions to the major problem of how flood peaks combine as scale increases (and more generally, how information from data or model results can be exchanged over different time and space scales) . The University of Newcastle have recently developed a novel water-tracking hydraulic routing component (O'Donnell et al., 2008) that works in combination with distributed hillslope runoff generation models. Water-tracking, using velocity fields from the hydraulic modelling, is used to link a downstream hydrograph with the locations, timing and nature of runoff processes. This directly addresses the link between local scale runoff generation and downstream propagation. As part of FRMRC2, the information tracking procedure will be combined with the meta-modelling strategy to track the individual meta-modelling elements with the catchment scale representation.

9.6 TOTAL UNCERTAINTY ANALYSIS

Although a framework for uncertainty has been applied for most aspects of the modelling, it is challenging to know how best to condition and allow for uncertainty within the catchment scale model, paying due respect to constraints at all scales and also uncertainty within the experimental data. The following simulation (Figure 9-1) shows the uncertainty in the Rhosaflo catchment occurring due to flow data uncertainty only.

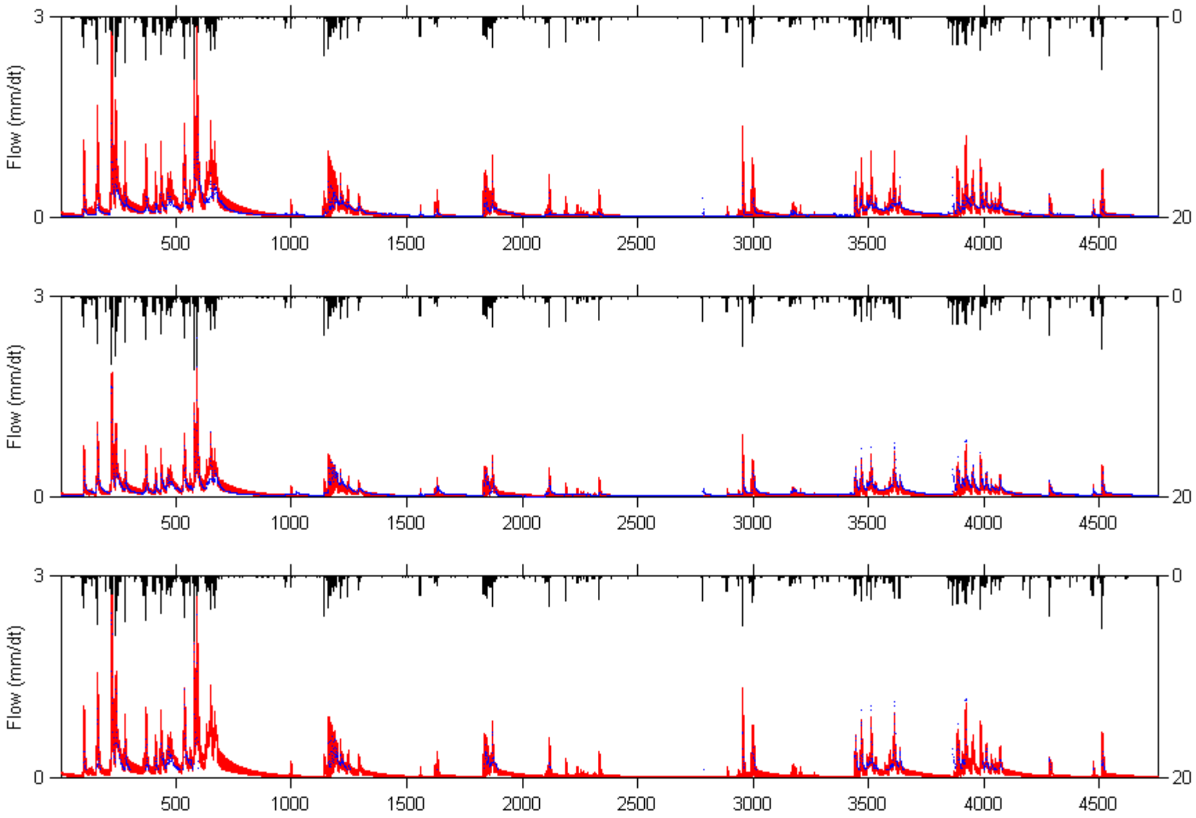


Figure 9-1. Model response with flow uncertainty considered; Rhosaflo catchment

Furthermore, although the rainfall data appears generally to be of good quality, significant differences can be observed between gauges, even over this relatively small catchment area as is shown by the cumulative rainfall amounts within Figure 9-2. It is difficult to tell from the existing gauges whether these differences are due to a spatial pattern in rainfall, an association with elevation, local differences due to aspect or other factors, or data errors: indeed it is very possible the discrepancies are due to a combination of these possible explanations. As this first phase of the FRMRC land management project comes to an end, a further gauge has been established in a high elevation, northwest corner of the catchment to interogate correlations with topography and/or spatial locations further. Potential evaporation data has also been identified as a source of uncertainty, with drainage and overland flow events highly sensitive to potential evaporation. The problem of appropriate handling of all sources of uncertainty, which is highly dependent on adequate data checking, is left for further work within the second phase of FRMRC.

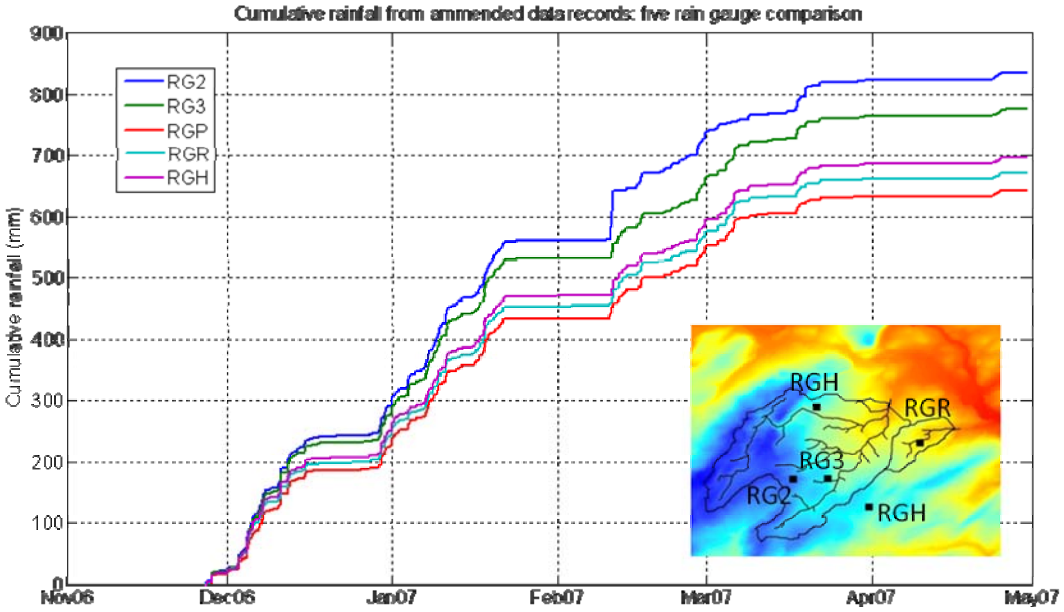


Figure 9-2. Cumulative differences observed between rain gauges over five month period

9.7 GENERALISING RESULTS BEYOND PONTBREN

FRMRC2 will test concepts and tools derived using data and/or understanding of processes operating at Pontbren on contrasting catchments at larger scales; the Eden catchment in Cumbria (322 km^2) and the 939 km^2 upper Severn catchment (of which Pontbren is a headwater). It will also take first steps towards regionalisation, with evaluation of the utility of regional soils data (physical properties and/or HOST) and associated uncertainty.

10. Conclusions

Severe flooding within the UK over the last decade has prompted increased research into understanding the cause of floods and how we might reduce their impact. One possibility for such reduction is to target agricultural and other land management practices. In a comprehensive literature study, O'Connell et al (2004) concluded that there was insufficient evidence to support the view that catchment scale flooding is significantly affected by land management. Furthermore, the review identified that local scale effects are complex and not fully understood particularly in upland agricultural catchments of the UK where little research has been undertaken in this context. The multi-scale hydrological and modelling experiment at Pontbren has been established to address these issues in relation to upland hill farming as practiced extensively throughout Wales, particularly in the headwaters of major Welsh river systems such as the Severn, Wye and Dee.

The hydrological research has benefitted from a unique partnership with a consortium of ten farmers with contiguous land holdings covering a significant proportion of the Pontbren catchment. Recent initiatives by these farmers have begun to produce a revitalised landscape, through planting of hedgerows and woodlands, de-intensification of stock, and fencing to protect riparian areas; and the farmers are actively supportive of research into the environmental effects of these changes. This presented an excellent opportunity to investigate the hydrological effects of a range of recent and historic land management features at a range of scales.

The Pontbren catchment has been instrumented at the plot (~100 m^2), hillslope (~0.1 km^2) and catchment scale (~10 km^2) to allow observation of the effects of land use, and development of conceptual models and data sets to support the modelling work.

10.1 CONCLUSIONS FROM THE EXPERIMENTAL PROGRAMME

In grazed grassland, saturation excess overland flow is often the dominant runoff pathway. The presence of a relatively impermeable subsurface soil layer results in a perched water table forming form prolonged periods of the year resulting in saturated upper soil surface conditions. As a result, surface runoff from these hillslopes occurs when the perched water table reaches the soil surface.

Surface runoff occurring as a result of rainfall intensity exceeding soil infiltration was not recorded during the monitoring study. This type of infiltration excess surface runoff is unlikely to be widespread on these soils due to the relatively high hydraulic conductivity values measured in the A horizon. However, it may occur locally around areas such as field entrances and paths where livestock movement is concentrated.

Flow from artificial under-drainage is a second key runoff component from the hillslope in these systems. Field drains installed to improve agricultural productivity were shown to respond rapidly to rainfall inputs under wet conditions. The presence of soil macropores and perched water tables under wet conditions are important to the generation of flow in the drains. During the period of monitoring, drain flow tended to dominate runoff: the relative importance of overland flow was dependant on antecedent moisture conditions of the soil surface.

Climatic variability also has a very significant effect on runoff processes due to changes to soil structure. The relatively hot dry summer of 2006 resulted in large preferential flow paths opening up in the form of large cracks which allowed rapid movement of water down through the soil profile bypassing much of the soil matrix. This resulted in a reduction of the amount of overland flow occurring due to the soil surface remaining unsaturated for longer. These cracks have since closed up with a subsequent reduction in the bulk soil hydraulic conductivity of the soil. Temporal changes in soil structure appear to be relatively dynamic. If, as predicted, climate change results in more extreme weather, this temporal variability in runoff processes, is set to increase.

Compared to grazed grassland, there is significantly less overland flow within tree planted areas where sheep are excluded. The upper 80 cm of soil within the trees is also much drier than under grass. However, this does not necessarily mean an increase in the amount of available pore space for incoming water. Comparison of soil moisture release data from soils under improved grassland and under tree areas indicates that under the trees, at least in the topsoil there was a greater number of larger pores which would drain easily and hence be available for the uptake of incoming water. This is also reflected in the increased saturated hydraulic conductivity of the soil under trees. An ongoing programme of measurements at the experimental manipulation plots and utilising established tree shelterbelts aims to identify the relative importance of stock exclusion, tree development and canopy interception to the hydrological response of the shelterbelt woodlands.

Catchment-scale streamflow data illustrate the significant attenuation of flood peaks are the flood wave moves down the Pontbren stream network. With increasing size of drainage area there is a decrease in the flood wave peak when comparing subcatchments under similar land use.

C**atchment-scale streamflow data demonstrated that subcatchments dominated by agriculturally improved land produced higher flood peaks than those with more natural landscapes.** It is clear that the presence of a lake and surrounding moorland is causing attenuation of a flood wave peak in a relatively unimproved subcatchment but at present the relative importance of either of these two factors is not clear. The factors responsible for these differences are being investigated at a small scale using manipulation plot experiments. Initial results post land use treatment suggest that runoff may be reduced at the plot scale due to the exclusion of sheep and planting of trees. However, land use treatment application is relatively recent and time is required to assess the true impact under at the plot scale.

10.2 CONCLUSIONS FROM THE MODELLING PROGRAMME

New modeling capabilities allowing interrogation of small-scale interventions and linking hillslope and small catchment scales have been developed and implemented. At the field scale, a physics-based model has been calibrated on site data and has allowed a variety of hypotheses of process response to be tested. This has substantially increased our understanding of the dominant responses within the more intensively managed areas of the Pontbren catchment. Realisations from this model conditioned on site data have been carried forward to a catchment scale model, and allow small-scale process response to be represented at this larger scale: an achievement not formerly possible due to the restrictions of generic catchment-scale model structures and further computational restrictions on the detail and scale possible in such models.

Use of these models with the data collected within the experimental programme suggest scope for significant reduction of flood risk in low permeability landscapes (such as clay catchments) at local scales. Specifically, the programme has established the importance of increased permeability, and storage within these soils in mitigating small to medium rainfall events.

Placement of single trees or small strips of woodland will generally have a positive effect on flooding. The action of trees on soil tends to increase interception losses, available water storage within the soil and the rate at which water can move from the ground surface into the subsurface.

The significance of changes varies substantially depending on location: mitigation measures positioned down-slope of areas where water tends to collect on the surface are likely to be of most benefit.

Results to date suggest that flow peak reduction of around 40% may be achievable given optimal placement of tree shelter belts and/or hedgerows; this effect is seen at both field and small catchment (circa 12km^2) scales.

The substantial variation at individual sites, and lack of information on the subsurface, must be properly accounted for at both this and other sites. Uncertainty exists in the hydraulic conductivity and moisture retention data collected within wooded soils in the Pontbren catchment, and there is incomplete knowledge of the connectivity of these soils to drains and/or other fast routing pathways. Changes in these can significantly perturb these results. The modelling presented here has been implemented within a framework of uncertainty analysis, but time and computation limitations, as well as a variety of remaining perceptual gaps have prevented all sources of uncertainty being treated within this. The resources needed to develop the tools presented here, and the ambitious scale of the experimental program, places us only now in a position where the tools and data are available to begin this fuller treatment. Success will however require further quality assurance and critical interrogation of data, further work on appropriate objective functions to use in calibration, and further information on rough grazing.

There is a lack of understanding on how flood peaks from upland catchments combine as they move down-river remains, and there is also a need to extrapolate concepts derived from Pontbren to contrasting catchments, and collect further data collection and information on extremes. Research addressing these important issues is now beginning as part of the second phase of FRMRC work.

Both experimental and modelling studies from this site illustrate the potential significance of small-scale land management changes for reducing hillslope runoff peaks: this poses a challenge to scientists, land managers and policy makers. How can we best establish and optimise strategies for mitigation of flood peaks, given other landscape objectives such as economically viable farming, ecological needs, legislative requirements and leisure utilisation?

10.3 LOOKING FORWARD: RESEARCH NEEDS WITHIN FRMRC2

These are as follows:

Provide guidance to the user community concerning the potential role of land management for flood risk mitigation across a range of meterological conditions and event frequencies. The present study has evaluated response to the range of conditions experienced during the monitoring period at Pontbren. The effects for increasing severity of events have yet to be evaluated; clearly these will also depend on antecedent catchment conditions.

Target perceptual gaps in understanding. It is necessary to: a) establish evidence for or against compaction in Pontbren, and similar, and contrasting landscapes, b) establish the degree of heterogeneity within landscapes and methodologies for representing the same, c) further investigate the non-stationarity observed within small-scale responses, d) understand better subsurface drainage below key permeability-enhancing vegetation (such as trees) and e) understand better the functioning of unimproved grassland and wetland areas.

Further uncertainty analysis of outputs from the current modelling sequence (physics-based, meta model, catchment model) are important and extension of model capabilities to represent alternate land management practices

Take forward information from the developing conceptual model of Pontbren the question of how best to structure and to parameterise meta-models over the entirety of the UK and beyond by applying the tools and insights developed at the Pontbren site to different catchments and to larger scales. FRMRC2 will test concepts and tools derived using data and/or understanding of processes operating at Pontbren on contrasting catchments at larger scales; the Eden catchment in Cumbria (322 km^2) and the 2025 km^2 upper Severn catchment (of which Pontbren is a headwater). It will also take first steps towards regionalisation, with evaluation of the utility of regional soils data (physical properties and/or HOST) and associated uncertainty.

Combine insights from the upscaling work with other approaches to contribute to solutions to the major problem of how flood peaks combine as scale increases (and more generally, how information from data or model results can be exchanged over different time and space scales). As part of FRMRC2, the information tracking procedure will be combined with the meta-modelling strategy to track the individual meta-modelling elements with the catchment scale representation.

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APPENDIX A: Macropore and drainage representations

The most common approach to dealing with macroporous soils in a modelling context has been to invoke a dual domain approach with a transfer term to describe the interaction between the two domains (Milly, 1988). Whilst this requires an over-simplification of the physical processes it is generally found to be a significant improvement over the classic single domain representation. In the review he argued that whilst it was obvious to represent the matrix domain using Richards' equation it is unclear how macroporosity should be modelled or how interactions between domains should be represented.

He postulated two obvious suggestions for representing the macropore domain:

a) A macropore continuum that overlaps the matrix continuum

b) An exactly defined void space, cut into the matrix, whose geometry is known

Whilst b) is arguably physically more realistic, it is not practical to use this interpretation for field-based studies where the available geometry is unlikely to be sufficiently detailed for anything more than an approximation.

There are two types of dual domain model, both assume that the soil profile consists of two interacting regions, one associated with the macropore system and the other dealing with the micropore system of the soil matrix. The difference between the two types of model is that in a dual porosity model, water within the soil matrix is considered immobile whereas matrix flow is possible in the dual permeability model (Šimůnek et al., 2003). The assumption that water movement through the matrix is negligible only holds in a limited range of conditions. It is a reasonable approximation when the soil profile consists of bedrock however, in studies of undisturbed soils [e.g. White, 1985], water flow has been observed to occur in the matrix as well as the macropores. For this reason a dual-permeability is physically more realistic. The main advantage in using dual-porosity models is they require fewer parameters than equivalent dual-permeability models (Köhne et al., 2006).

Two common dual-permeability models have been included within SPW. The first formulation, by Gerke and van Genuchten (1993) applies Richards' equation (A.1) to both regions yielding:

$$\begin{aligned}\frac{\partial\theta_f}{\partial t} &= \frac{\partial}{\partial z}\left[K_f(h_f)\left(\frac{\partial h_f}{\partial z}+1\right)\right]-S_f-\frac{\Gamma_w}{w}\\ \frac{\partial\theta_m}{\partial t} &= \frac{\partial}{\partial z}\left[K_m(h_m)\left(\frac{\partial h_m}{\partial z}+1\right)\right]-S_m-\frac{\Gamma_w}{1-w}\end{aligned} \qquad \text{(A.1)}$$

where w is the fraction of the total pore volume provided by the macropores. In this instance Γ_w [$L^3 L^{-3} T^{-1}$] is defined as

$$\Gamma_w = \alpha_w\left(h_f - h_m\right) \qquad \text{(A.2)}$$

where α_w [$L^{-1}T^{-1}$] s a first-order mass transfer coefficient. There are several different methods for evaluating the mass transfer coefficient. If the soil does not have a strongly defined geometry Šimůnek et al. (2003) suggested that

$$\alpha_w = K_a^*\left(\bar{h}\right) \qquad \text{(A.3)}$$

where K_a^* [L^{-1}T^{-1}] is an effective hydraulic conductivity of the fracture-matrix interface. In order to evaluate this term, the arithmetic mean involving h_f [L] and h_m [L] is used as below:

$$K_a^*(\bar{h}) = 0.5\left[K_a^*(h_f) + K_a^*(h_m)\right] \tag{A.4}$$

The use of (A.3) means that K_a^* [L^{-1}T^{-1}] is a parameter that requires calibration, it is usually assumed that

$$K_a^*(h) = \rho K_m(h) \tag{A.5}$$

where ρ is an empirical scaling factor e.g. 0.01 [Gerke and van Genuchten, 1993]. This model formulation is relatively complicated as it requires the characterisation of the moisture retention and hydraulic conductivity functions for both regions.

An alternative solution was proposed and incorporated within the MACRO model (Larsbo and Jarvis, 2003), a one-dimensional non-steady state model of water flow and solute transport in structured or macroporous field soils. It is a dual permeability model with mass exchange between the domains calculated using first-order expressions. Unsaturated water flow is implemented using a form of Richards' equation in the micropores and gravity flow in the macropores. Gravity flow is assumed because of problems in accurately determining the $\psi(\theta)$ relationship close to saturation (Larsbo and Jarvis, 2003). The equation for water flow in the macropores is:

$$\frac{\partial \theta_{ma}}{\partial t} = \frac{\partial K_{ma}}{\partial z} - \sum S_i \tag{A.6}$$

where θ_{ma} [m^{3}m^{-3}] and K_{ma} [ms^{-1}] are the macropore water content and hydraulic conductivity respectively, t [s] is time, z [m] is depth and S_i [s^{-1}] are source/sink terms for water exchange, drainage and root uptake. In MACRO a composite hydraulic function is created by combining Richards' equation (A.1) with the macropore flow equation (A.6). A user-defined 'boundary' pressure head, ψ_b [m], is used to partition the total porosity into micro- and macroporosity, while the water content, θ_b [m^{3}m^{-3}], and hydraulic conductivity, K_b [ms^{-1}], represent the saturated state of the soil matrix.

Soil water retention in the matrix is given by a modified form of the van Genuchten (1980) equation:

$$S = \frac{\theta_{mi} - \theta_r}{\theta_s^* - \theta_r} = \left(1 + (\alpha\psi)^n\right)^{-m} \tag{A.7}$$

where S is an effective water content; n, m and α [m^{-1}] are shape parameters. θ_{mi} [m^{3}m^{-3}] is the micropore water content; θ_r [m^{3}m^{-3}] is the residual water content and; θ_s^* [m^{3}m^{-3}] is a saturated water content obtained by extrapolating the fitted water retention function to zero pressure head.

MACRO uses Mualem's (1976) model to describe the unsaturated hydraulic conductivity in the micropore domain:

$$K_{mi} = K_b \left(\frac{S}{S_{mi(\theta_b)}}\right)^l \left[\frac{\left(1 - \left(1 - S^{1/m}\right)^m\right)}{\left(1 - \left(1 - S_{mi(\theta_b)}^{\;1/m}\right)^m\right)}\right] \tag{A.8}$$

where *l* is a tortuosity parameter, $S_{mi(\theta_b)}$ is the value of *S* when $\psi = \psi_b$ in equation (A.7).

The hydraulic conductivity in the macropores, K_{ma} [ms^{-1}] is given by:

$$K_{ma} = K_{s(ma)} \left(\frac{\theta_{ma}}{e_{ma}} \right)^{n^*} \tag{A.9}$$

where e_{ma} is the total active macroporosity, $K_{s(ma)}$ [ms^{-1}] is the saturated hydraulic conductivity of the macropores and n^* is a kinematic exponent. MACRO has subsequently been improved to take account of the effects of swelling and shrinkage that occurs in clay soils by allowing e_{ma} and $K_{s(ma)}$ [ms^{-1}] to vary according to simple relationships, see Larsbo and Jarvis (2003) for these and more details on the MACRO model.

By assuming gravity flow in the macropores the formulation of the model is simpler than that of Gerke and van Genuchten (1993). However since K_{ma} [ms^{-1}] is assumed to be a power law function of θ_{ma} [m^{3}m^{-3}] this approach becomes equivalent to the kinematic wave description of macropore flow described by Germann (1985).

SPW hence includes two dual permeability representations of flow: in both cases the first regime uses Richard's equation to represent soil matrix flow. The second regime can either operate as an analogue to Richards' equation, with hydraulic characterisation parameters of the second domain carefully chosen to mimic the fast-emptying behaviour of large pores, or in a similar manner to the well-established MACRO model (Jarvis et al., 1992).

Tile-drain representation

Artificial drainage is an important water management practice in agriculture. Green (1979) found that approximately 18% of soils in agricultural use in England & Wales are artificially drained, much of which is found in heavy clay soils (Heppell et al., 2000).

The traditional way of modelling drains in a field-scale model is to represent the drain as a node with system-dependant boundary conditions. The usual conditions are that for saturated conditions, the pressure head is equal to zero and for unsaturated conditions the drain flux is zero. This simplified approach doesn't account for: the contraction of streamlines near the drain, presence of a non-uniform pressure along the drain boundary or the presence of an entry head around the drain. The entrance head is the minimum head required to initiate flow in a drain (Kohler et al., 2001).

Fipps and Skaggs (1986) demonstrated that only by modelling the drain as closely to its actual geometry as possible could an accurate estimation of the drainage discharge rate be obtained. Kohler et al. (2001) noted that, owing to a lack of spatial resolution to accurately describe local non-uniformity in the flow field, most field-scale models account for the head loss caused by streamline convergence by invoking an empirical resistance. SWMS_2D (Šimůnek et al., 1994) accounts for this by reducing the hydraulic conductivity at the nodes surrounding the drain such that:

$$K_{drain} = K_s C_d \tag{A.10}$$

where K_{drain} [LT^{-1}] is the conductivity at nodes surrounding the drain, K_s [LT^{-1}] is the saturated hydraulic conductivity of the soil layer and C_d is a reduction coefficient.

Several different approaches are amongst the various codes available to model water flow and solute transport. SWAP (Kroes and van Dam, 2003) has 4 different methods to calculate fluxes to a field drainage system. These include: The use of a linear or tabular relationship between drain flux, q_{drain} [cmd^{-1}] and phreatic groundwater level midway between drains, ϕ_{gwl} [cm], such as

$$q_{drain} = \frac{\phi_{gwl} - \phi_{drain}}{\gamma_{drain}} \tag{A.11}$$

where ϕ_{drain} [cm] is the drain hydraulic head and γ_{drain} [d] is a drainage resistance. Tabular values can be used for a non-linear relationship. The second alternative applies to five common field drainage situations for each of which the drainage resistance, γ_{drain} [d] can be calculated by employing equations developed by Hooghoudt (1940) and Ernst (1956). The other two options available in SWAP are a basic drainage which includes drainage/infiltration to/from surface water systems and an extended drainage which has full interaction with a simplified surface water system.

MACRO (Larsbo and Jarvis, 2003) incorporates a quite different method to calculate field drainage by using seepage potential theory. Lateral water flow to seepage surfaces is considered a sink term in their implementation of Richards' equation. The degree of saturation in the macropores determines the position and size of the saturated zones that contribute to drain flow. The drains are assumed to be overlain by fully penetrating seepage surfaces (i.e. highly permeable backfill). Flux rates from saturated layers above the drains are calculated using seepage potential theory for layered soils of Youngs (1980). The total drainage flux, $q_{d(tot)}$ from a saturated zone is given by:

$$q_{d(tot)} = A_f E \tag{A.12}$$

where A_f [m^{-2}] is a shape factor and E [m^{3}s^{-1}] is the seepage potential given by:

$$E = \int_{h_0}^{H} K(h)(H-h)dh \tag{A.13}$$

where $K(h)$ [ms^{-1}] is the hydraulic conductivity, h_0 [m] and H [m] are the height of the base of the saturated zone the water table height respectively, both measured with respect to a datum at the base of the profile. For parallel field drains Youngs (1980) gives the shape factor, A_f [m^{-2}] as:

$$A_f = \frac{8}{L^2} \tag{A.14}$$

where L [m] is the drain spacing.

Most investigations into tile drainage, both theoretical and experimental, have considered parallel drainage systems with equally spaced tiles. In practice, many catchments including Pontbren have predominantly irregular drainage systems; often comprising single tiles draining small depressional areas e.g. the Bowl and with major drainage lines placed at irregular angles and spacings. Existing models such as those discussed above are all based on the assumptions that drainage takes place through equally-spaced, parallel drains. Few studies have considered the flow in a single tile a necessary requirement in order to model the hydrology of irregular tile systems. Single tiles are hydraulically different, drawing water from a semi-infinite distance on either side, whereas the region of influence for a tile in a parallel system is constrained by its neighbouring tiles (Cooke et al., 2001).

In order to produce a set of solutions that could be used to represent the transient behaviour of a single tile Cooke et al. (2001) adopted the method of successive steady states put forward by Lembke (1887) and demonstrated by Bear (1972). The method assumes that it is reasonable to approximate the transient behaviour as the result of a series of steady state solutions over time.

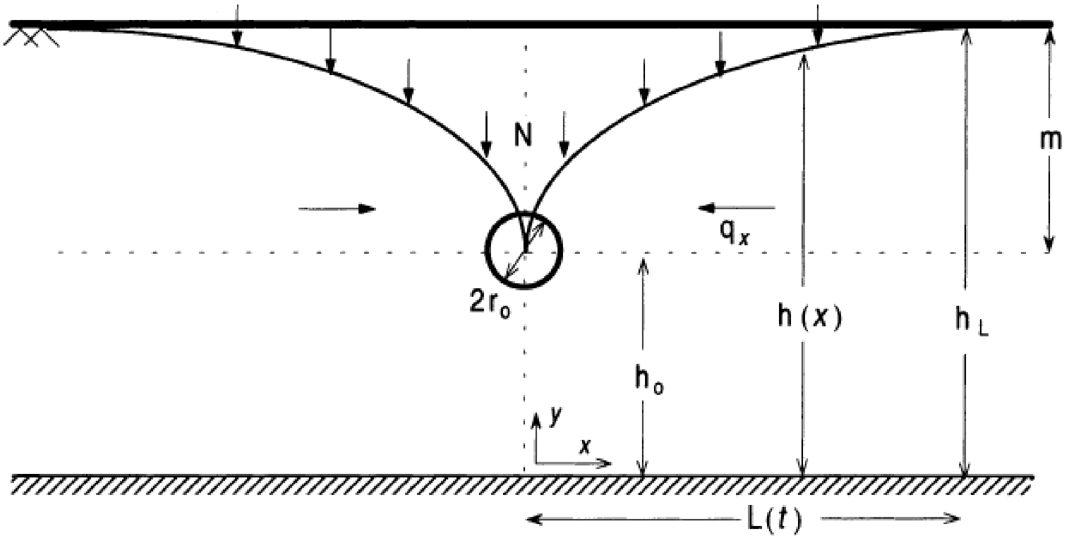

Figure A1. Flow to a single drain. (Cooke et al., 2001)

Cooke et al. (2001) provided a steady state solution for drain flow, q_{drain} [L^2T^{-1}], in a single tile centered at $x = 0$, at a height, h_0 [L] above an impermeable layer; where a constant uniform accretion rate, N [LT^{-1}] , is recharging the water table and the drain tube is simultaneously draining the profile consisting of a homogeneous soil of hydraulic conductivity, K [LT^{-1}] (Figure A1). Their solution is:

$$q_{drain} = \frac{2K}{L}\left(2d_e m + m^2\right) \tag{A.15}$$

where: L [L] is the distance at which the water table becomes essentially horizontal, $m \equiv h_L - h_0$ [L] and d_e [L] is a correction depth, developed by van der Molen and Wesseling (1991), used to account for radial flow close to the drain and defined by:

$$d_e = \frac{\pi L/8}{\ln\left(L/\pi r_0\right) + F(x)}, \text{ where } x = \frac{2\pi D}{L} \tag{A.16}$$

r_0 [L] is the radius of the drain, D [L] is the thickness of the aquifer, and

$$F(x) = \sum_{n=1}^{\infty} \frac{4\exp(-2nx)}{n\left(1-\exp(-2nx)\right)}, \text{ with } n = 1,3,5,\ldots \tag{A.17}$$

Under transient conditions, L [L] varies with time, $L = L(t)$. Cooke et al. (2001) put forward two solutions for L [L] dependant on the accretion condition. Expressions for drain flux, q_{drain} [L^2T^{-1}] can be obtained by substituting for the appropriate L [L] in Eq. (A.15). The two solutions are:

$$L(t) = \sqrt{\left[\frac{K\left(2d_e m + m^2\right)}{N}\left(1 - \exp\left(\frac{-8N}{\eta(4-\pi)m}t\right)\right) + L_0^2 \exp\left(\frac{-8N}{\eta(4-\pi)m}t\right)\right]} \tag{A.18}$$

where η is the drainable porosity of the soil and L_0 [L] is the value of L at t=0. This applies for the case of uniform accretion, when there is no accretion (N=0),

$$L(t) = \sqrt{\left[\frac{8K\left(2d_e m + m^2\right)}{\eta(4-\pi)m} t + L_0^2 \right]} \tag{A.19}$$

Cooke et al. (2001) also noted that the above equations can be modified to account for spatially variable soil properties by replacing the constant hydraulic conductivity and drainable porosity parameters with values that can be expressed as functions of the distance from the drain and/or using composite conductivity functions for flow through multiple soil layers. They also noted that the effect of slope on the above equations had not been investigated and cautioned against their use on areas with anything other than very gentle slopes. This is a potential drawback to their use at Pontbren.

As for the drainage conditions required for the model, when simulations are being carried out in one-dimension, there is no necessity to change from the current approach of not explicitly including a drain and having the lower boundary condition as free-drainage. Although if an implementation of MACRO is being used it might be of interest to incorporate the seepage theory of drainage (Youngs, 1980) that is used within that model as a comparison.

In the various other models considered, the lateral flow to the drains is calculated based on a water table height. At the Bowl, the borehole measurements suggest that the water table is below the drain and as such the concept of a water table feeding the drain is only relevant if locally a perched water table is formed. Given that for the Bowl contains an irregular drainage network it would be interesting to consider the approach adopted by Cooke et al. (2001) for determining flow to a single drain, although it is worth noting their concerns about the applicability to the method when used on a site with anything other than a very gentle gradient.

APPENDIX B: Accounting for relative placement of management interventions in simple models

One of the most challenging modelling issues facing the FRMRC project was the question of how small scale interventions, generally occurring at a far smaller scale than the hydrological response units feasible within a catchment scale model, could be represented within such catchment scale models. It is well established that differences in soils, vegetation and land use practices lead to significant differences in both surface and subsurface runoff responses, and most fully or semi-distributed hydrological models allow for spatial variations between land type units. However, due to computational constraints on the number of units that can be handled, they rarely, if ever include any facility to account for relative placement of geometries; at best percentages of land uses are routed through parallel stores and then additively combined. This is a particularly bad approximation in situations where one land use type generates significant overland flow while another's increased permeability has the capacity to allow additional infiltration under many natural conditions, as is demonstrated in the preceeding results.

However, an alternative strategy that is likely to be effective whenever the soil underlying the area of the small scale management intervention is of higher conductivity than the surrounding soil can be formulated. This could be used within a meta-modelling strategy to allow consideration of any relative geometries of land use and/or soil type present, although it is not currently included (it has however been tested as an option for the detailed model and within a GIS interface). This algorithm is as follows:

Assume two land use units within a given model unit, of types A and B. Assume area$_{A1}$ is the area of type A for which flow neither contributes to or is contributed from the area of type B, area$_{A2}$ is the area of A contributing to type B, area$_{A3}$ is the area of type A which takes contributions from B, and area$_{B}$ represents the area of type B. Assuming rainfall input is normalised to area, as is standard for most distributed one dimensional models and semi-distributed catchment models (in other cases appropriate area correction should be applied to the following algorithm), water reaching the surface becomes, rather than rainfall only, the rainfall and the overland flow generated by the upslope contributing area. This is pictorally shown in Figure B1. Hence three one-dimensional or conceptual model runs are required:

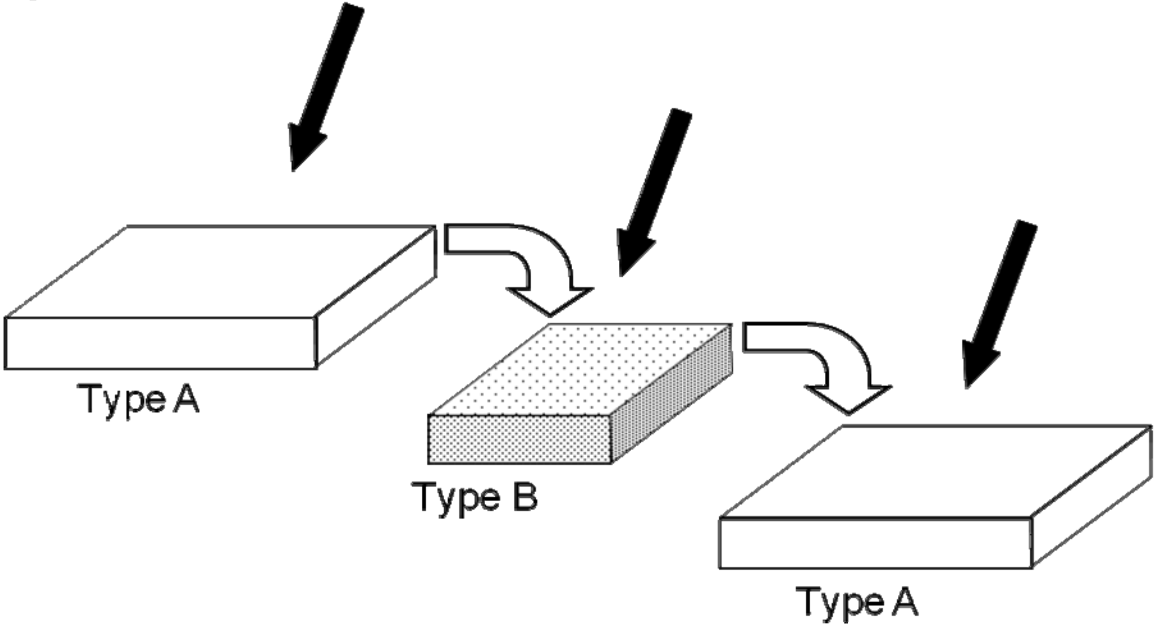

Figure B1. Cascade approach to routing overland flow

The first run uses type A soil and vegetation parameters, and water input should be rainfall as normal.

Second run: Type B, water input should be rainfall + overland flow contribution from run 1 * area_{A2}
Third run: Type A, water input should be rainfall + overland flow contribution from run 2 * area_{B}

Three model runs are needed (as opposed to two for the standard approach where land use types are routed in parallel and combined) meaning the cost of implementation remains of the same order as previously. There is no need for additional parameters, and crucially this approach means there need be no lumping of responses, allowing parameters to retain some physical basis.