45th Congress of the European Regional Science Association,
Amsterdam, August 2005

# The role of forestry in flood management in a Welsh upland catchment

GRAHAM HALL & ROGER CRATCHLEY

Centre for Arid Zone Studies and School of Agricultural and Forest Sciences,
University of Wales, Bangor, UK.
grahamhall@beeb.net

**Abstract**

Flooding has been a persistant problem in the town of Dolgellau in North Wales through historical times. Research is being carried out into hillslope and river processes in the main sub-catchments of the Mawddach and Wnion. Areas of forestry are found to have significant moderating effects on flooding downstream through several different mechanisms. Mature conifers produce humid microclimates on steep Atlantic-facing hillslopes, allowing prolific moss growth and the development of deep forest brown earth soils with improved water storage capacity during storm events. Clear felling, however, leads to rapid soil erosion and increased surface runoff. The effect of forestry within floodplains is significant in enhancing temporary storage for overbank discharge. Modelling indicates a water depth increase of up to 1m in comparison to grassland. Stabilisation of river banks by natural broadleaf woodland minimises erosion of periglacial gravels which otherwise accumulate downstream, reducing the effectiveness of flood defences. A forestry management scheme is proposed which incorporates the above processes to reduce flood risk for Dolgellau.

**Key words**

conifers; flooding; flood plain forestry; North Wales; river gravel.

Flooding in the Mawddach catchment

This paper is a case study of the role of forestry in developing a flood management strategy for the town of Dolgellau in north Wales.

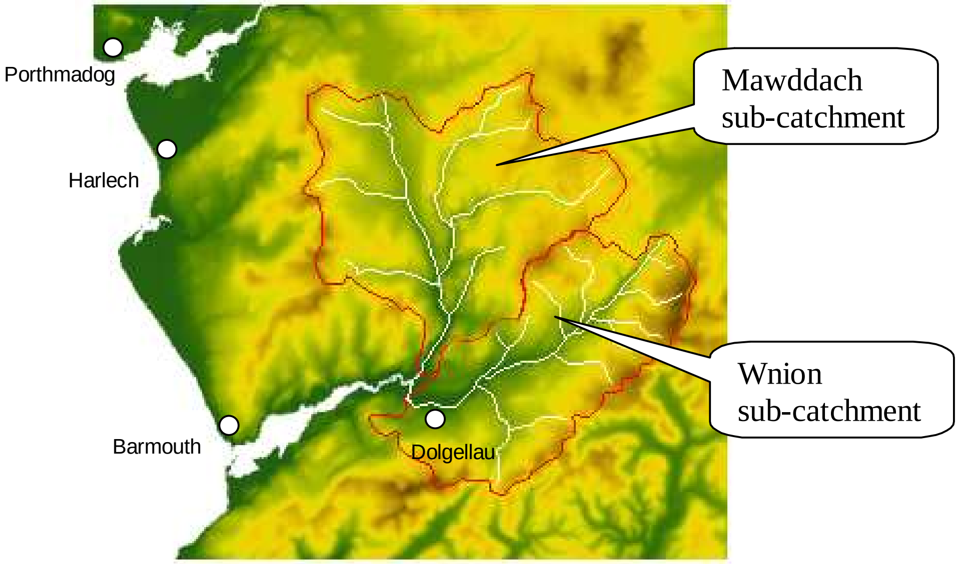



**Figure 1**: The Mawddach Estuary drainage basin

Dolgellau lies on the Afon (River) Wnion, just inland from the Mawddach estuary and the confluence with the Afon Mawddach. Throughout historical times, the town has been subject to flooding (Barton, 2002).

**Figure 2**: The Dolgellau floods of 1964.

Following serious flooding of the town centre on 12 December 1964 the Local Authority carried out a major flood defence scheme, with construction of masonry walls along a 1km stretch of the Afon Wnion north of the town.

**Figure 3:**
River stage near to the upper level of flood defences in Dolgellau,
3 February 2004

In recent storm events, river levels have come close to overtopping the flood defences. Hard engineering options to further raise walls and embankments are likely to be costly and environmentally intrusive, so catchment management strategies to reduce flood generation are worthy of serious consideration.

The Wnion sub-catchment has three principal land use zones:

- Valley floodplain, with improved grassland for sheep grazing.
- Lower hillsides, which are too steep for agricultural use and are largely given over to mixed woodland or conifer plantation.
- Mountain slopes, kept as moorland for rough grazing of sheep.

Research is currently being carried out at the University of Wales, Bangor, to investigate mechanisms of flooding in the region. Five river gauging stations have been operating in the Mawddach/Wnion catchment over the period 2002-2005. Example data from stations near the source of the Wnion at Pared yr Ychain, and near the tidal limit on the Wnion 1km downstream from Dolgellau, are shown in figure 4.

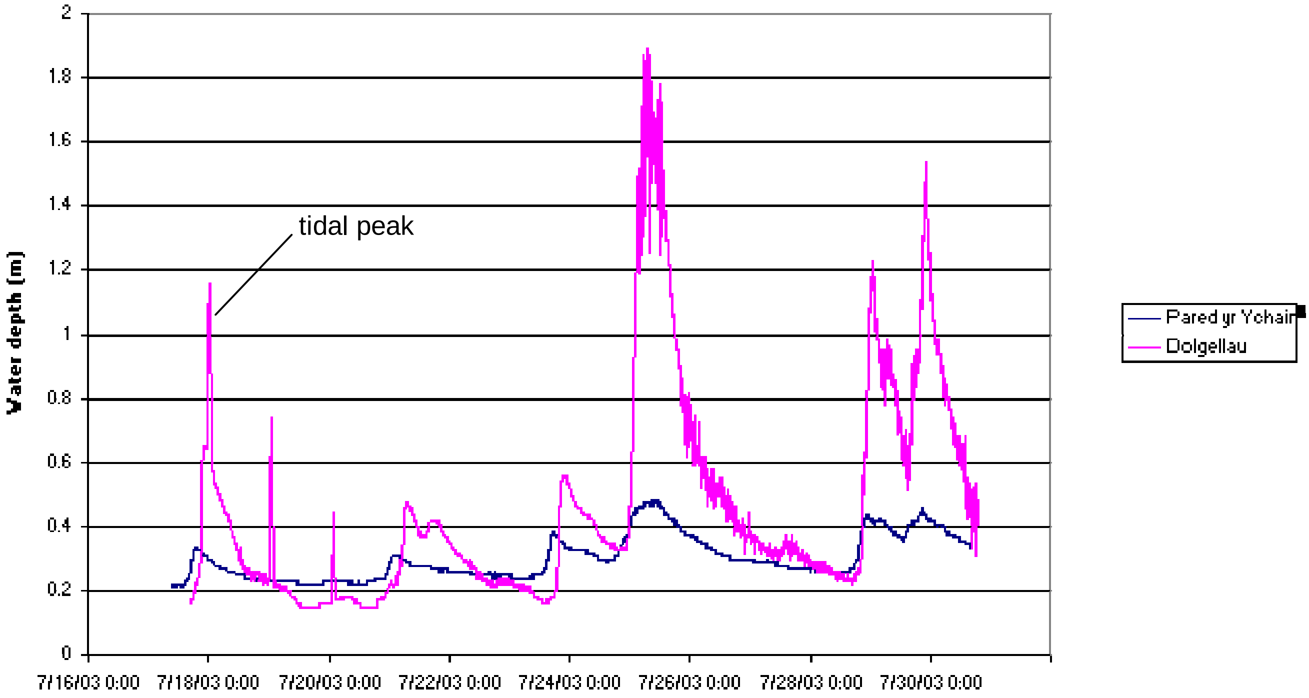



**Figure 4(a)** : Original hydrographs recorded

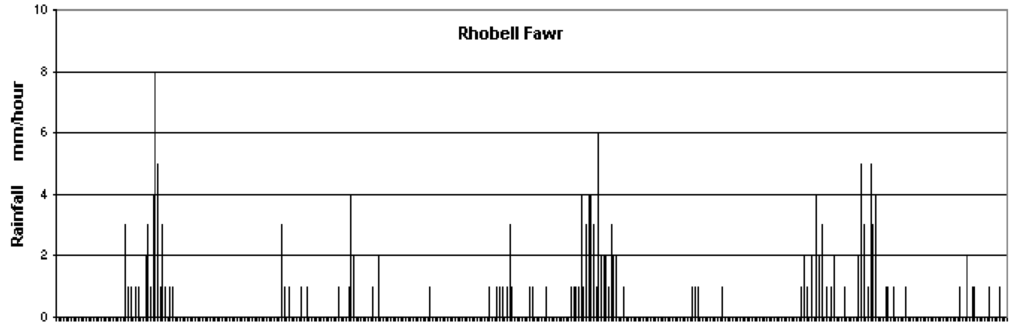



**Figure 4(b)**: Rainfall for the period 16 July – 31 July 2003

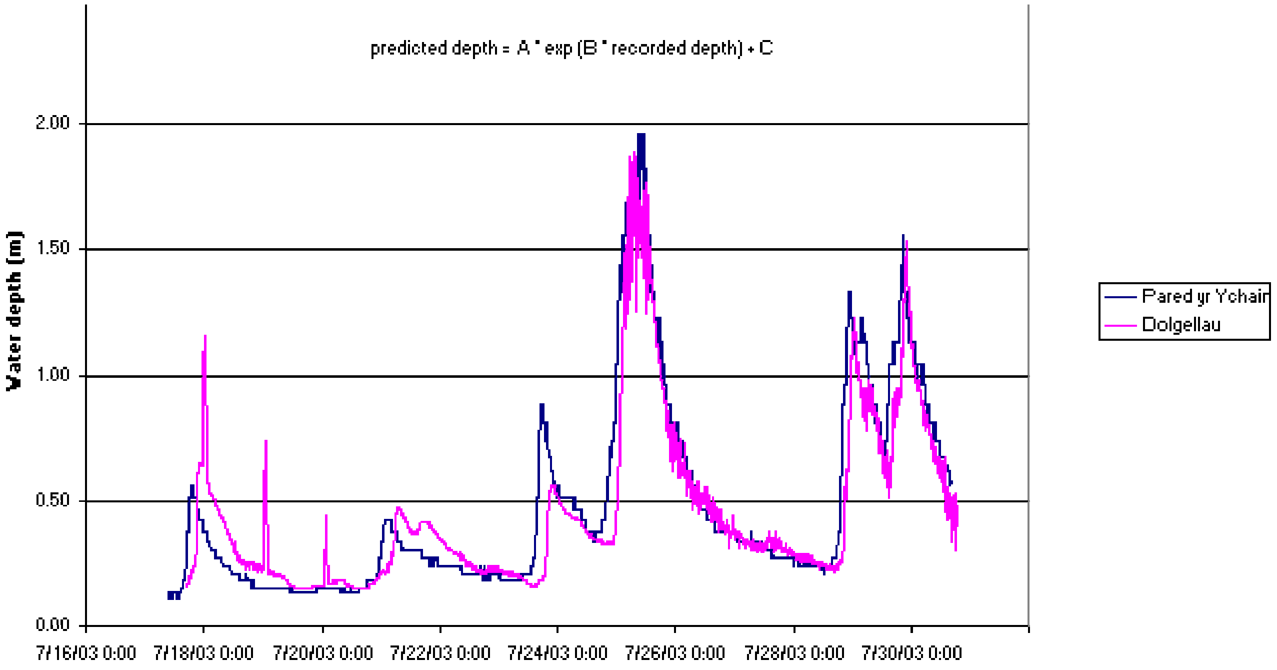



**Figure 4(c)** : Hydrographs after transformation of the Pared yr Ychain data

Rise in stream level is observed in the source area of the Wnion within 15 minutes of the onset of storm rainfall, although the volume of flow is strongly controlled by antecedent conditions. The example hydrographs were recorded after a period of 24 days with no precipitation, so initial rainfall had limited effect until soil moisture deficit was overcome. It is found that a simple mathematical transformation

$$P = 0.05 \exp(8.2 R) - 0.15$$

can convert the recorded stream stage R at Pared yr Ychain (metres) to a graph line P which closely follows the stream stage at Dolgellau, but with a time advance of 3 hours 30 minutes. This relationship could provide useful early warning of flooding in the town.

At the hydrograph site downstream from Dolgellau, the Wnion is limited to a maximum stage height of 1.8m due to overbank discharge as shown in figure 5.

**Figure 5**: Overbank discharge onto floodplain at the head of the Mawddach estuary.

The Wnion hydrographs suggest that flood peaks in the town of Dolgellau are caused primarily by fast runoff entering streams within a few hours of a storm event.

## Hillslope hydrology

Hillslope water flow measurements have been carried out in the Pared yr Ychain source area to investigate mechanisms of runoff (Smith, 2003). Several sites have been instrumented to record surface runoff to a depth of 10cm and shallow stormflow (throughflow) at a depth of 1.5m, as shown in figure 6. The area investigated is one of high rainfall accompanied by prolific growth of ground vegetation – principally mosses, ferns and grasses amongst a young conifer plantation.

Typical results from flow measurements are shown in figure 7. An intermediate acidity (oligomull) peat soil is developed to a depth of 20 – 25cm on sandy clay glacial till derived from acid volcanic rocks.

**Figure 6(a)**
Site prepared for instrumentation, showing peat soil on glacial till

**Figure 6(b)**
Site after installation of water flow recorders and data loggers

As in the case of stream discharge, the volumes of hillslope water flow are strongly controlled by antecedent conditions. Nearly all downslope movement of water occurs as stormflow within the glacial till, with insignificant amounts of surface runoff recorded. This seems to be due to the absorbent effect of ground vegetation and routing of water downwards through the thin peat layer. It is significant that large volumes of sub-surface stormflow occur some four to six hours after the onset of heavy rainfall, which may be too late to directly influence flood peaks downstream. Stormflow can, however, continue for up to two days after rainfall and may control antecedent base flow levels for subsequent storm events.

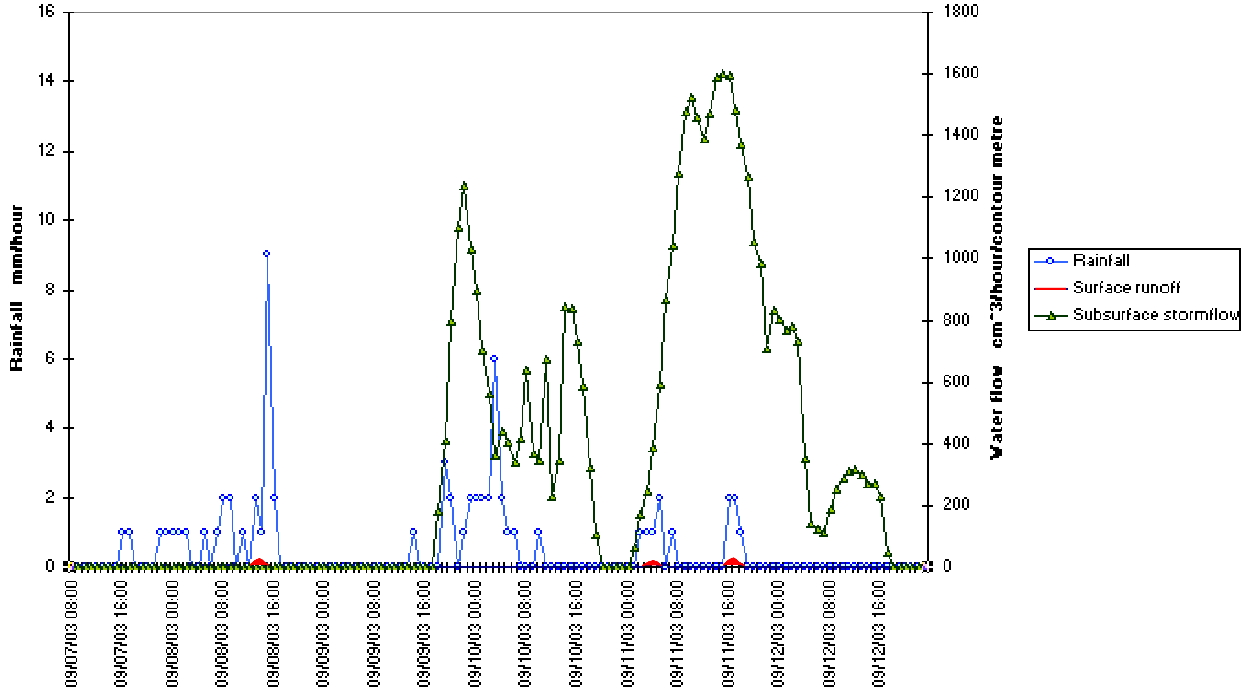



**Figure 7**: Hillslope water flows at Pared yr Ychain, 7 - 12 September 2003

Fast surface runoff appears to be the controlling mechanism for flooding and has been observed regularly during storm events in the region (figure 8).

**Figure 8:** Surface runoff in Cwm Prysor during the July 2001 Mawddach flood.

Photograph: Robert Chilton

Hillslope processes operating in the Wnion catchment are summarised in figure 9 below. It is estimated that approximately 25% of land cover within the Wnion catchment is forestry.

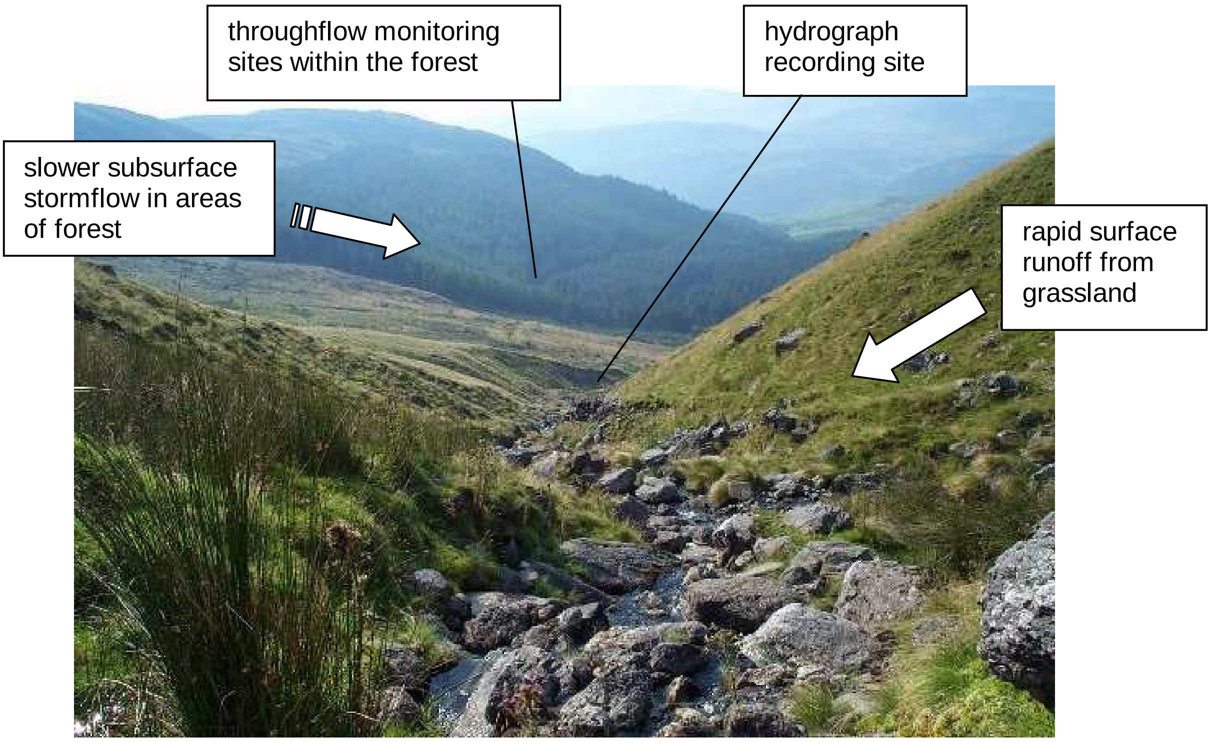



**Figure 9**: Near the source of the Wnion at Pared yr Ychain, Aran Fawddwy

To investigate the effects of vegetation on surface runoff production for the Wnion, a further series of experimental sites were set up on hillslopes overlooking the village of Hermon in the neighbouring Mawddach sub-catchment. Three sites were chosen which were closely similar in slope angle and all underlain by a thick sequence of clay, sand and gravel periglacial valley infill deposits:

**site 1**: mature conifer plantation

**site 2**: clear felled

**site 3**: permanent grassland

The area is one of heavy rainfall, regularly experiencing over 50mm of rain in individual storm events. A consequence is that prolific growth of ground vegetation occurs within the conifer plantation at **site 1**, as shown in figure 10.

**Site 2**, although originally having similar forest cover to site 1, has now been clear felled to leave bare hillside.

**Experimental site 3** was situated at the base of the permanent grassland slope seen in the middle distance of figure 11.

**Figure 10:**

Ground vegetation beneath Douglas Fir. Mosses *Polytrichum* and *Plagiothecium* predominate.

**Figure 11**:

Clear felled hillslope at Hermon site 2

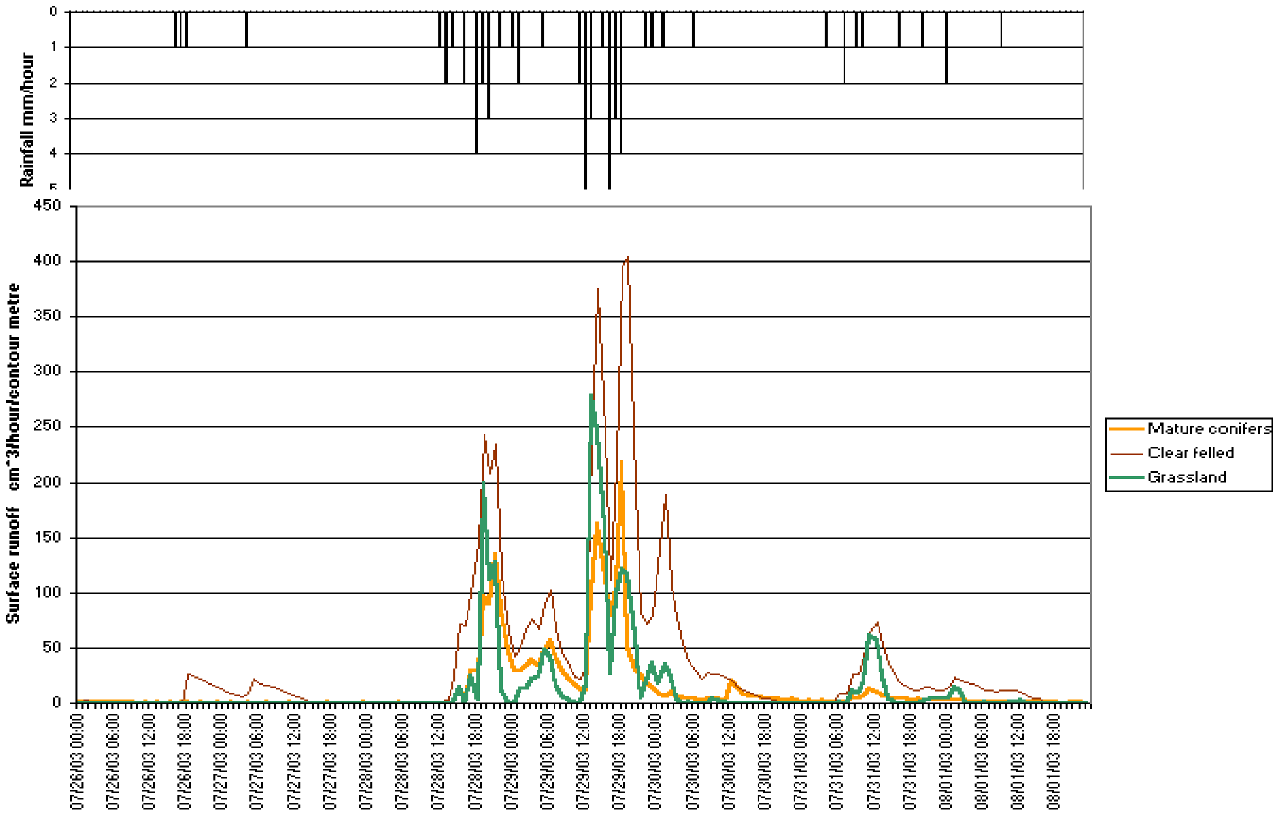



**Figure 12**: Surface runoff at experimental sites, 26 July – 1 August 2003

Surface runoff to a depth of 5cm was collected over a series of storm events. Typical results are illustrated in figure 12 above. Runoff production is significantly higher from the clear felled hillslope in comparison to the mature conifer plantation, with permanent grassland giving an intermediate response. It is possible to link this result directly to the soil profiles developed beneath the sites.

Conifers at site 1 were planted during the 1950's and have developed beyond commercial maturity. This has allowed a progressive rising and opening of the forest canopy, promoting the growth of ground vegetation. The combined effects of trapping slope wash sediment and addition of organic material over a 50 year period has led to the development of around 140cm of forest brown earth.

At site 2, clear felling was accompanied by the die-back of mosses and ferns through reduced humidity. Graphs of temperature at sites 1 and 2 are similar, but contrasting values of relative humidity have been recorded as shown in figure 14. Within one year of clear felling, severe soil erosion led to the removal of over a metre of forest brown earth to leave only 30cm of matted humus as a relatively impermeable hillslope cover above periglacial deposits.

**Figure 13(a)**:
soil profile beneath forestry at site 1

**Figure 13(b)**:
soil profile beneath clear felled hillslope at site 2

Soil development beneath the grassland has reached a stable profile depth of around 90cm. The limited depth in comparison to the conifer plantation may be due to less efficient trapping of downslope sediment wash by grasses.

Although the surface runoff at the Hermon forest is seen to be low, even lower values were recorded in forestry at Pared yr Ychain (figure 7), where the ground vegetation productivity is greater.

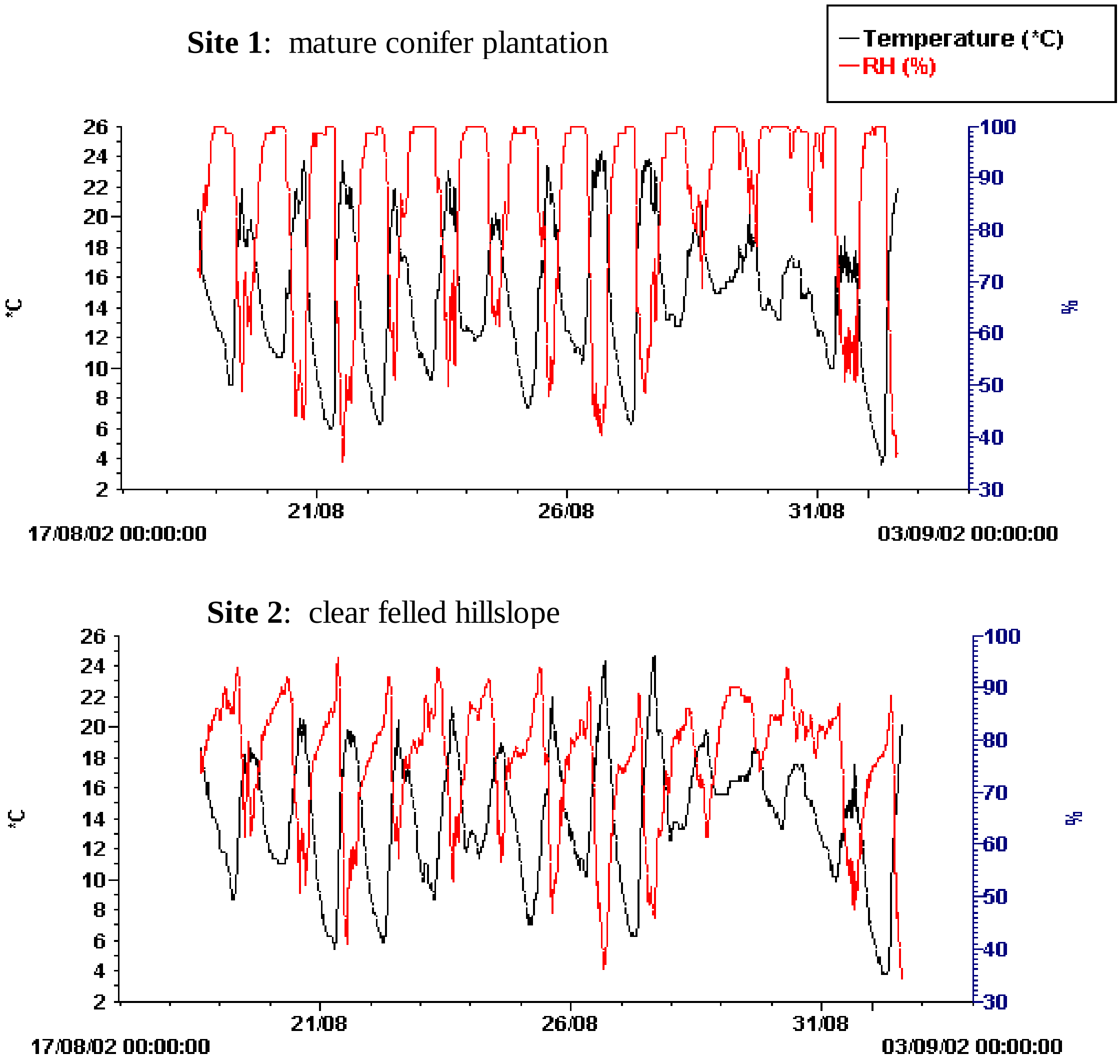



**Figure 14**: Humidity levels on hillslopes, measured at 50cm above ground level

At an early stage in the project it became apparent that a complex pattern of rainfall occurs across the region. A grid of 22 continuous-recording raingauges was established in the Mawddach/Wnion catchment, extending from near sea level to the higher slopes of the mountain hinterland. A series of storm events occurring during the period October 2002 to November 2004 has been recorded in detail.

Rainfall distributions during individual storm events often follow a similar pattern, with highest rainfall concentrations occurring in a zone inland of the Rhinog mountain range: from Trawsfynydd in the north, through the Coed y Brenin forest to the Aran mountains in the south east. This pattern has also been generated theoretically by computer modelling using the MM5 system developed by US National Centre for Atmospheric Research (figure 15).

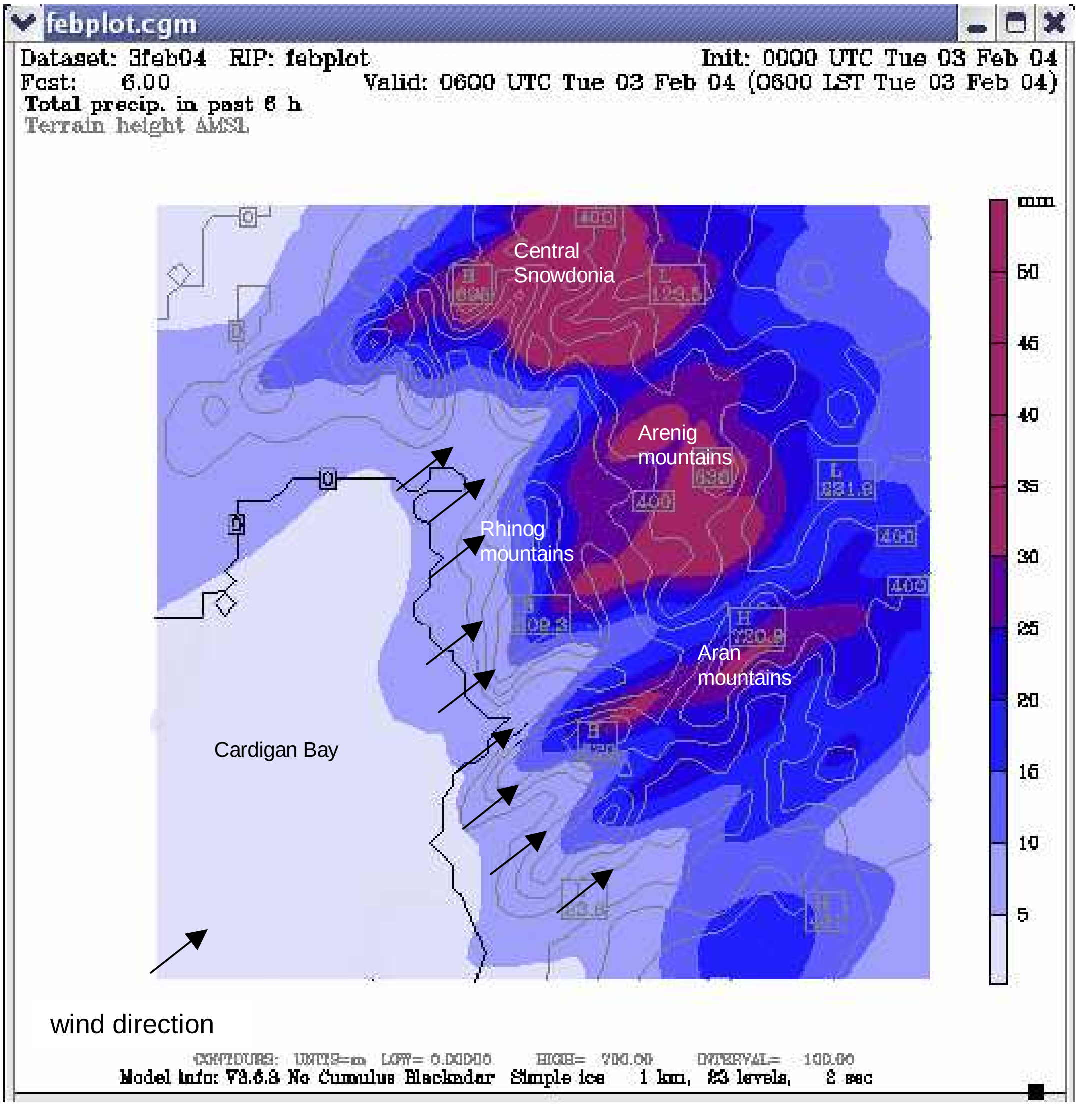
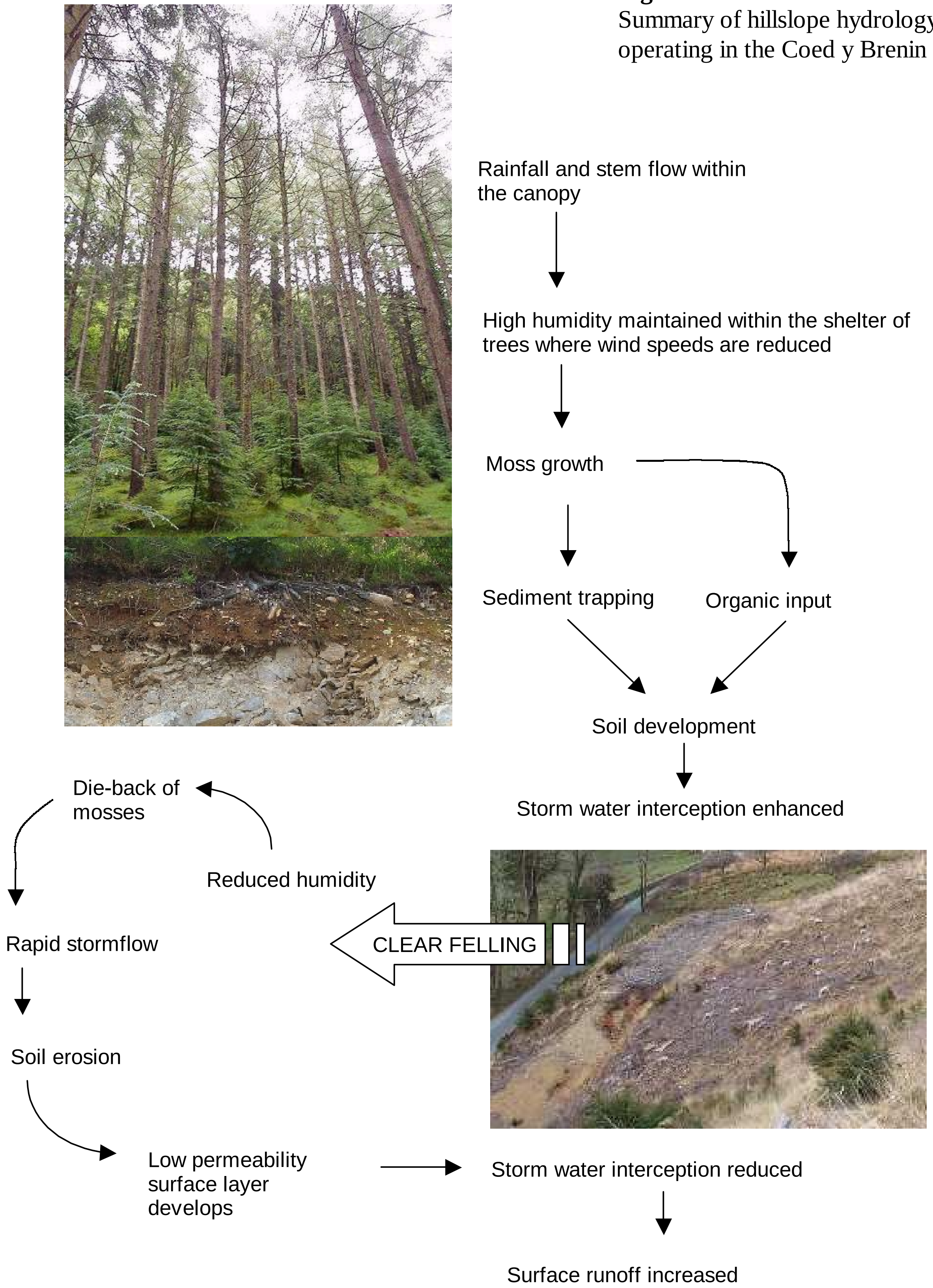



**Figure 15**: Rainfall distribution for 3 February 2004, illustrating the zone of high precipitation inland of the Rhinog mountains.

Hillslope processes are summarised in figure 16. Mature conifer and broadleaf woodlands lying within the high rainfall zone are both able to develop the prolific moss and fern ground vegetation seen at Hermon. Moss growth maintains humid conditions within the forest. Thus, the ecological system becomes self-sustaining and soil accumulation is promoted. Clear felling destabilises this moss-fern association, leading to soil erosion. The greatly altered nature of the hillslope surface produces a substantial increase in surface runoff during storm events.

**Figure 16**:
Summary of hillslope hydrology processes operating in the Coed y Brenin forest



## River sediment

The Wnion and Mawddach are gravel streams, obtaining their sediment load primarily from erosion of glacial and periglacial deposits infilling the upland valleys.

Gravel deposition along the course of the Wnion in Dolgellau is of serious concern, causing a rise in bed level which reduces the effectiveness of flood embankments. Gravel removal is carried out periodically by the Environment Agency in the area of the town bridge, Bont Fawr, but within little more than a year the arches can be refilled with sediment.

**Figure 17(a):** Bont Fawr, Dolgellau, after gravel clearance in March 2003

**Figure 17(b):** Bont Fawr, Dolgellau, with arches refilled by sediment.
Photo: February 2005

Very high bank erosion rates are observed on the upper courses of the Mawddach and Wnion. Gravel trains, released during flood events, move intermittently downstream to accumulate at the head of the estuary. Figure 18(a) illustrates the extent of bank erosion during the July 2001 Mawddach flood which exhumed a large area of bedrock, whilst figure 18(b) shows an accumulation of cobbles and boulders washed down from the Rhobell Fawr during the same event.

**Figure 18(a):**
Zone of sediment loss during the July 2001 flood event.
Afon Mawddach at Bedd y Coedwr.

**Figure 18(b):**
Cobble and boulder accumulation on a tributary of the Wnion at Rhydymain following the July 2001 flood.

The scale of the sediment problem has been investigated using the software packages SED2D and GSTARS to model gravel erosion, transport and deposition (figure 19). For readily erodable banks, it is estimated that the Mawddach can provide a gravel bedload of 1600 cubic metres per year at the estuary confluence. The Wnion can provide a gravel bedload of 1000 cubic metres per year, representing an annual bed rise of 10 cm along the river reach through the town of Dolgellau in the absence of manual sediment removal.

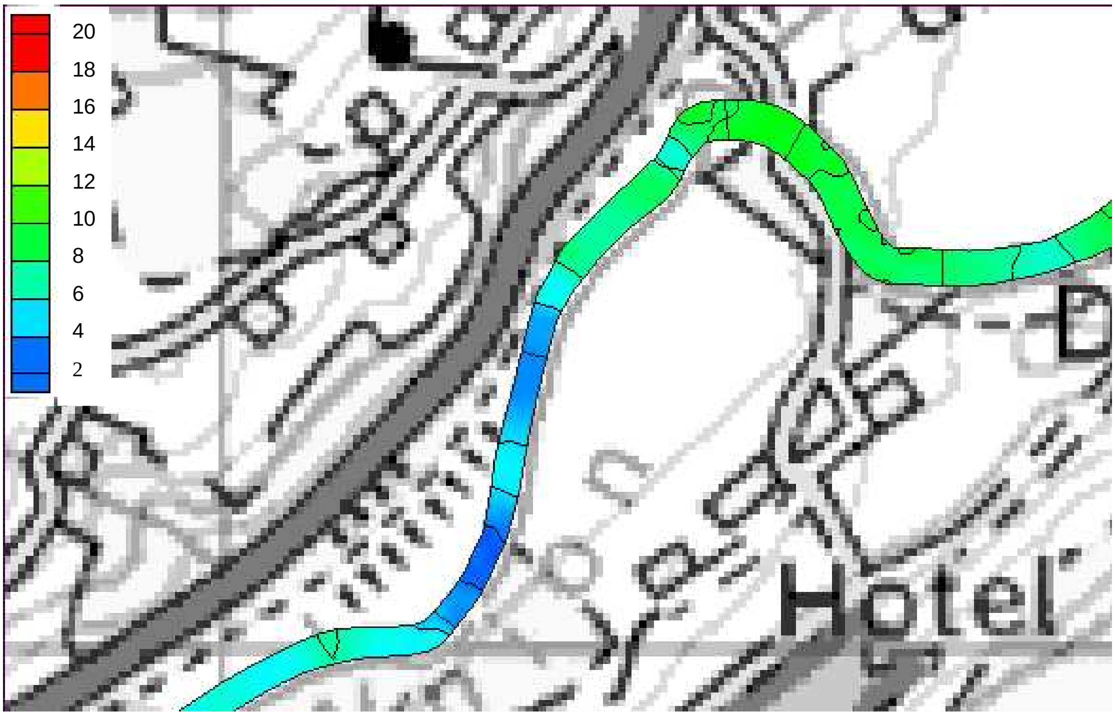



**Figure 19:** Modelling of gravel bedload deposition (cm) during the July 2001 flood event, Afon Wnion at Dolserau

Measures to reduce sediment supply will clearly be beneficial in the reduction of flood risk. Within the mountain valleys, conifers with their shallow root systems show no evidence of protecting river banks from erosion (figure 20a). By contrast, broadleaf woodland can develop deep intertwining root systems which effectively bind and stabilise soft bank sediments, providing considerable resistance to flood erosion (figure 20b). The soil regime of the upland valleys, being poor in nutrients and moist to well-drained on steep slopes, favours an Oak-birch association (table 1).

| | | soil nutrient regime | | | |
|---|---|---|---|---|---|
| humus form | | very poor | poor | medium | |
| soil moisture regime | slightly dry | | | | |
| | fresh | | W17 woodland community<br>Oak – birch with bilberry | | |
| | moist | | | | |
| | very moist | | | | |

**Table 1**: Environmental range for the Oak-birch association (after Pyatt G. et al., 2001)

**Figure 20(a):**
Douglas Firs, displaced by bank erosion of periglacial deposits. Afon Wen valley.

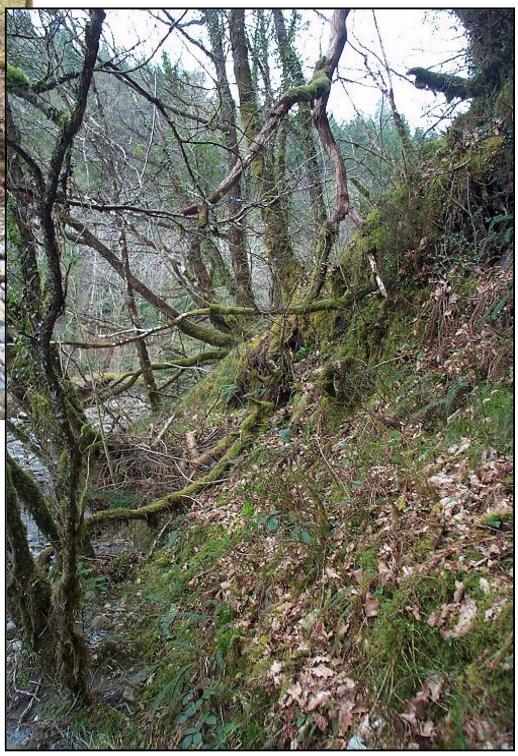


**Figure 20(b):**
A similar river bank of periglacial deposits in the Afon Wen valley stabilised by oaks.

## Floodplain forestry

Hydrological modelling by the Forestry Commission has indicated the potential of flood plain forestry in reducing hydrograph peak levels (Thomas and Nesbit, 2004). To investigate the effects of floodplain forestry in the Mawddach catchment, detailed surveying and modelling using the River2D software package has been carried out (O'Connell, 2004). Three sites were chosen, as shown in table 2.

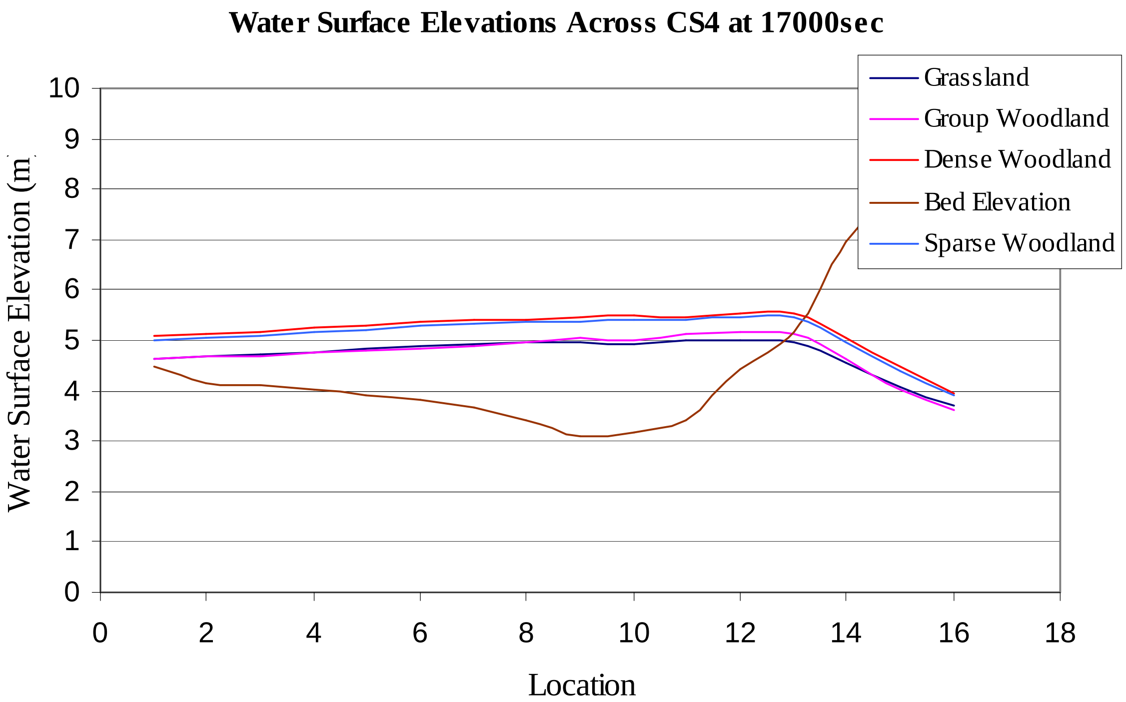
A simulation of the July 2001 flood event on the Mawddach was run for each site, assuming different types of ground cover. Model parameters were adjusted for best estimates of surface roughness and the degree of turbulence generated by different vegetation patterns.

:

| | | |
|---|---|---|
| **Site A**<br><br>Tyddyn Gwladys | Low density of mature conifers over 50 years. Flood debris accumulates around tree bases, providing an obstruction to overland flow. |  |
| **Site B**<br><br>Cefn Deuddwr | High density of juvenile conifers 5 to 20 years, with natural broadleaf woodland along the river banks. Mat of ground vegetation can obstruct overland flow. |  |
| **Site C**<br><br>Gelligemlyn | Valley floor grassland liable to flooding, with remnants of former river channels forming wet hollows |  |

**Table 2:** floodplain forestry modelling sites on the Afon Mawddach

At **Site 1,** the predicted difference in maximum floodplain waterlevel is 35cm when comparing dense forestry cover to grassland, and at **Site 2** the predicted waterlevel difference is 20cm. The relatively small sizes of these flood plain fragments make their useful capacity for flood control very limited.



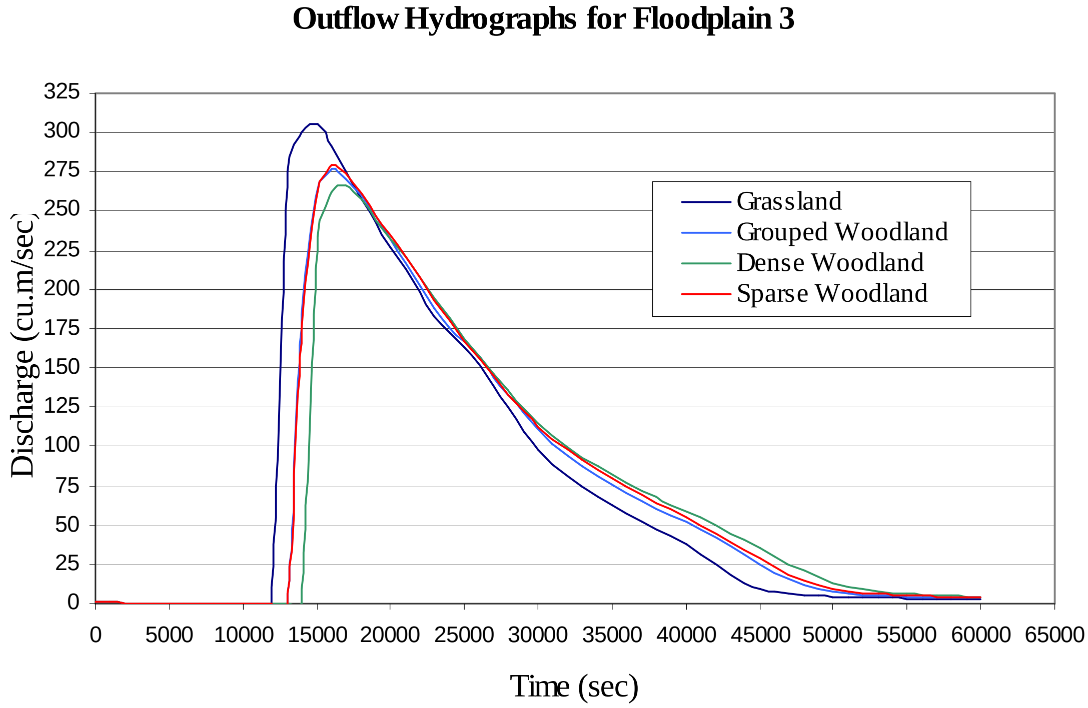




**Figure 21**: Water elevations and river hydrographs modelled for the July 2001 Mawddach flood at Site 3, Gelligemlyn, assuming different land use scenarios. (After O'Connell, 2004)

At **Site 3**, however, the modelling results are more dramatic, as shown in the example graphs of figure 21 above. The largest difference in waterlevel between dense woodland and grassland recorded during the modelling was 1.2m, representing a reduction in peak discharge of 45m$^3$/sec. This can be equated to a 30 minute delay in the peak of the flood. Forestry within the larger lowland floodplains of the Mawddach and Wnion appears to be a feasible option for flood control.

## A proposed flood reduction strategy for Dolgellau

### Control of hillslope runoff

Expansion of forestry in the high rainfall zone of Rhobell Fawr and the Aran mountains should lead to further growth of hillslope moss-fern associations, with consequent soil deepening and improved runoff interception properties. The most immediate benefits would be derived from the planting of fast growing conifers and birches, with a gradual progression to semi-natural oak woodland as a desirable long term objective.

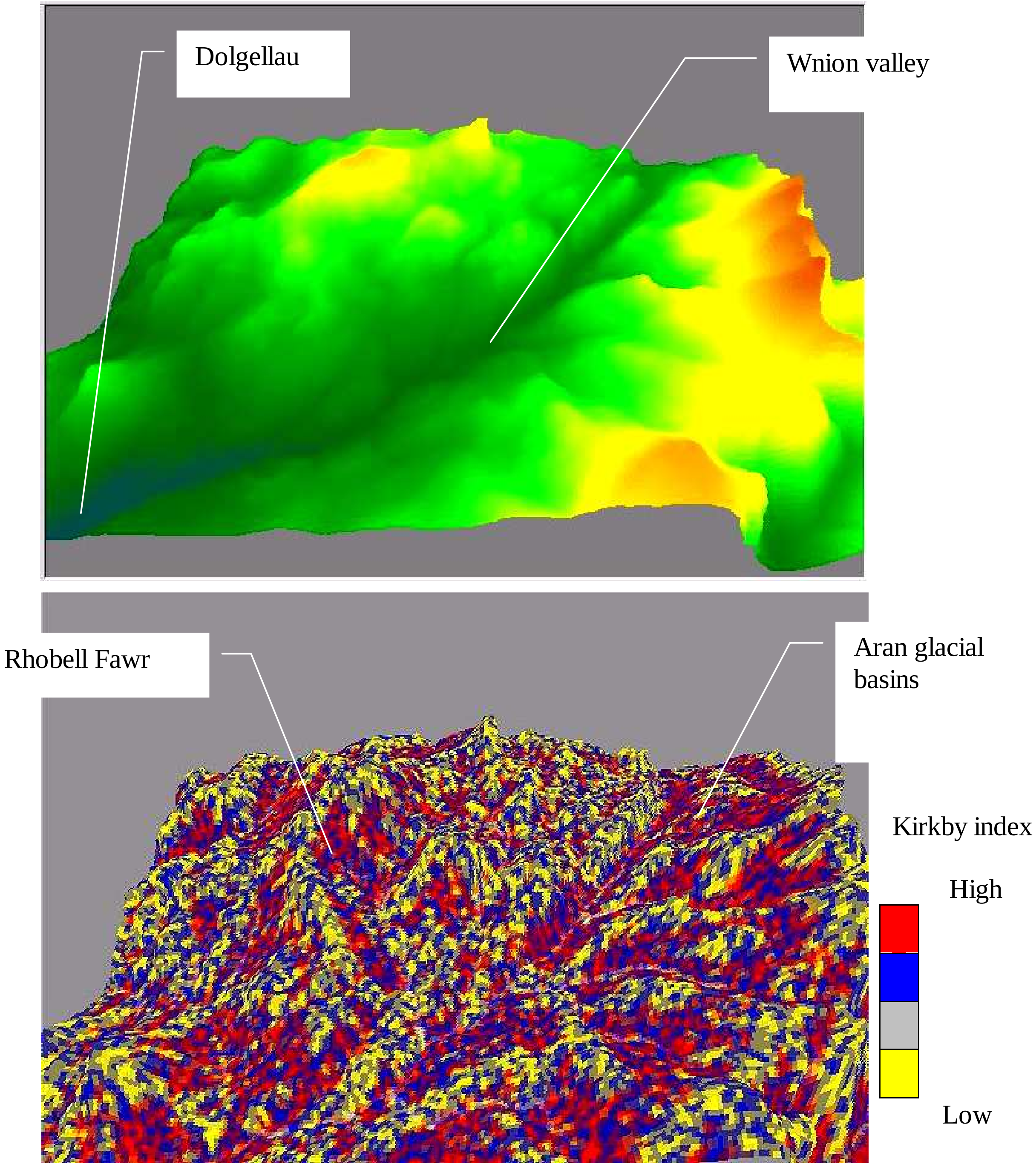



**Figure 23**: GIS plotting of Kirkby wetness index for the Wnion catchment

Continuous cover forestry practices should be employed, to avoid soil erosion from clear felled hillslopes. Trees need to grow beyond normal commercial maturity to ensure the open canopy conditions favourable for high productivity of ground vegetation.

The Kirkby wetness index has been employed to identify sites of runoff concentration during storm events where establishment of mature forest would be particularly effective in intercepting and delaying stormflow. The Kirkby index at a point on a hillslope is given by:

$$\ln (a / \tan \beta)$$

where a is the area of hillslope draining through the point, and β is the slope angle. Thus, high index values are associated with large upslope catchment areas and/or gentle slope angles, and are shown in red in figure 23. The slopes of Rhobell Fawr, and glacial basins in the dip slop of the Aran mountain escarpment appear the most beneficial sites for forest development.

**Figure 24(a):** Upper floodplain basin, Dolserau

**Figure 24(b):** Lower floodplain basin, Dolgellau

**Control of sediment supply**

Riparian zones in the steep upland valleys should be planted with oak/birch to help in the stabilisation of the thick deposits of glacial and periglacial sands, gravels and clays forming the river banks.

The lower Wnion valley above the town of Dolgellau is separated into upper and lower flood plain basins (figure 24). It is proposed that three weirs be constructed in the river reach between the lower and upper basins. Each weir would be a gentle ramp with a height gain of 2m, providing a total rise of 6m in water level at the upper basin. An exemplar for the weir design is provided by the existing weir at Dolserau bridge (figure 25) which allows free upstream passage for fish. Modelling indicates that the raising of water level in the upper basin can accommodate the accumulation of gravel likely over a 30 year period, thereby reducing sedimentation within the town flood control zone.

**Figure 25** :
Weir at Dolserau bridge

**Control of river discharge through floodplain storage**

Floodplain forestry zones would be developed in both the upper Dolserau basin and the lower Dolgellau basin. It is likely that a semi-natural willow association will grow well with the encouragement of braided gravel channels through the woodland to maintain groundwater levels over a wide riparian zone. This type of woodland already exists around the head of the estuary downstream from Dolgellau (figure 26).

**Figure 26**:
Floodplain forestry on the Afon Wnion, Dolgellau

Modelling of flows on the Wnion have been carried out using hydrograph data from the July 2001 flood (figure 27). The extension of the overbank flood area resulting from the proposed weir installation is seen. Reduction in water velocity would occur within the upper floodplain area, leading to gravel deposition well above the town.

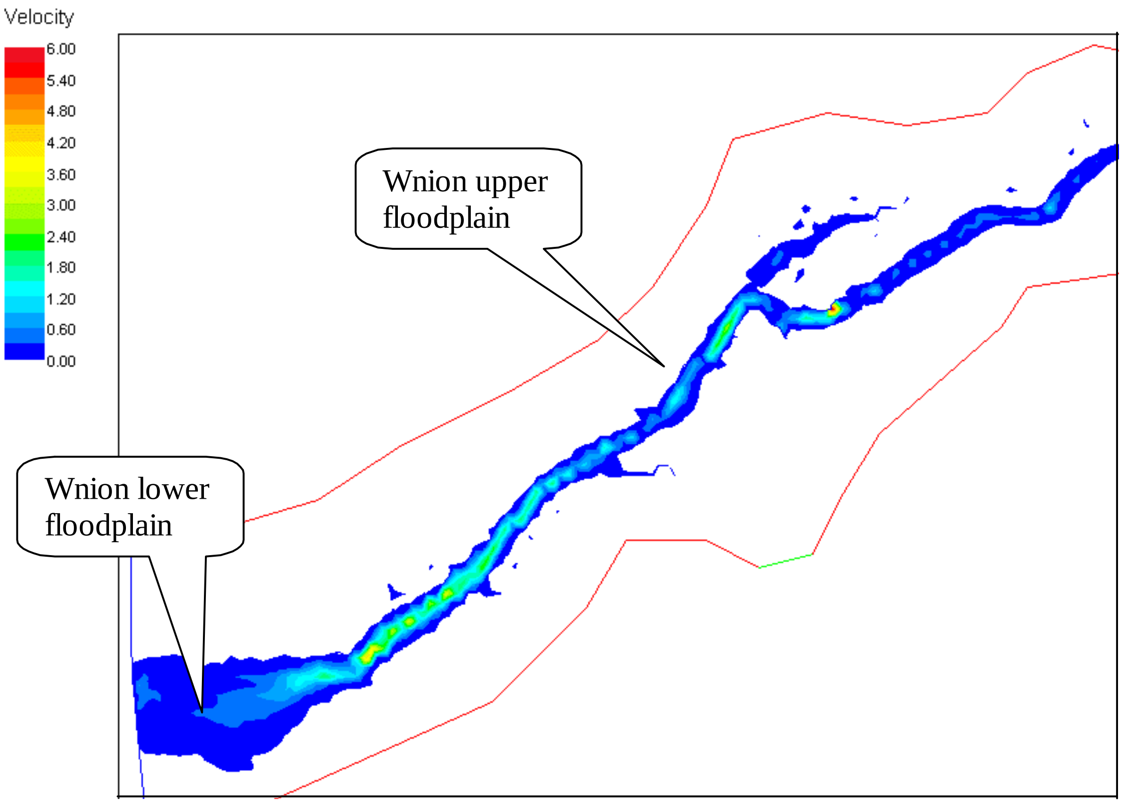



**Figure 27(a)**: Flood extent and water velocity model for the July 2001 Wnion flood event

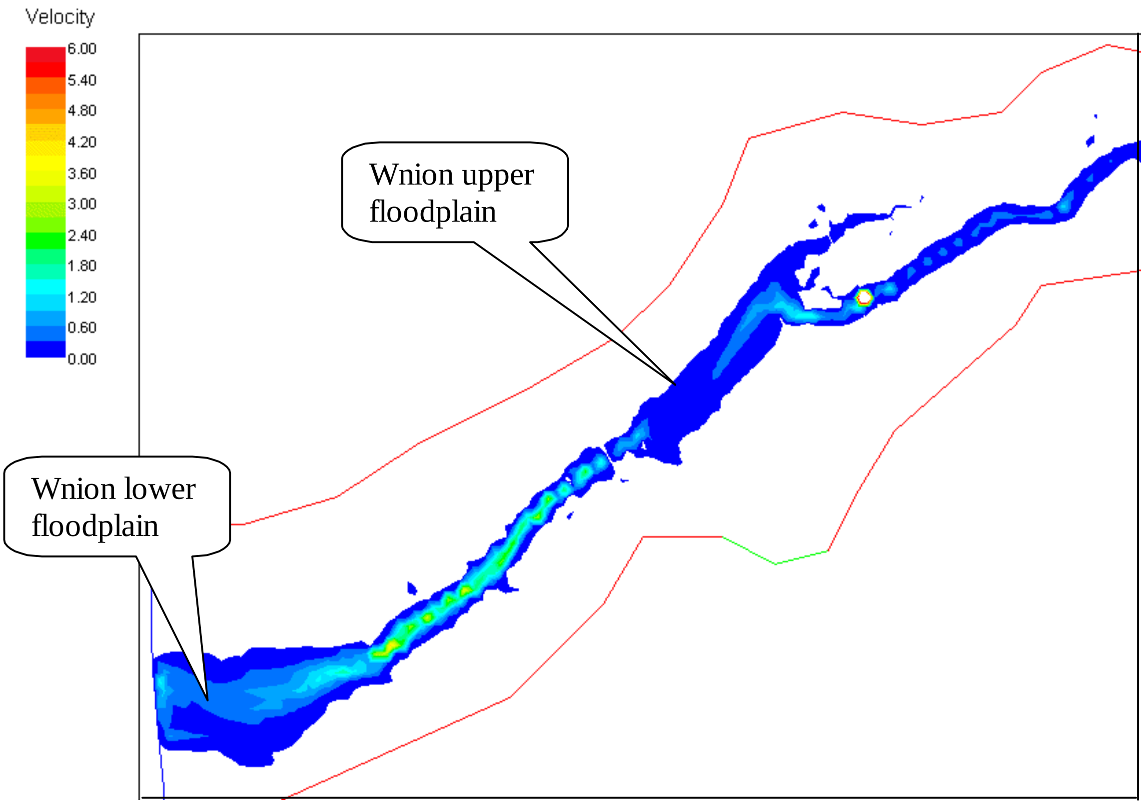



**Figure 27(a)**: Flood extent and water velocity model for the July 2001 Wnion event, simulating the effects of the weir scheme in extending the upper flood plain basin

## Conclusion

A feasible flood management scheme for the Wnion valley and town of Dolgellau can be developed which incorporates:

- reduction of fast surface runoff from hillslopes during storm events by extension of existing coniferous forestry plantations and conversion to semi-natural oakwoods.
- reduction of hydrograph peaks through temporary storage of floodwaters within extended floodplains in the lower Wnion valley. Storage effects will be enhanced by development of floodplain forest.
- control of sediment accumulation in river channels by bank stabilisation using semi-natural oak and birch riparian woodlands along upland reaches, and by sediment trapping within the proposed weir-controlled upper floodplain basin.

**References:**


Barton, J. (2002) Flooding: past, present and future. A case study of Dolgellau and the Mawddach catchment. MSc Dissertation, University of Wales, Bangor.

Blackburn J. and Steffler, P.M. (2002) River 2D two dimensional depth averaged model of river hydrodynamics and fish habitat. University of Alberta.

Dudhia J. *et al.* (2005) PSU/NCAR mesoscale modelling system. Tutorial class notes and user's guide: MM5 modelling system version 3. National Centre for Atmospheric Research, Boulder Colorado.

Forestry Commission (1994) The management of semi-natural woodlands: 8. Wet woodlands. Forestry Commission.

O'Connell J. (2004) Assessing the potential of floodplain woodland in flood amelioration. MSc Dissertation, University of Wales, Bangor.

Peterken G.F. and Hughes F.M.R. (1995) Restoration of floodplain forests in Britain. Forestry, vol 68 no 3.

Pyatt G. et al.(2001) An ecological site classification for forestry in Great Britain. Forestry Commission Bulletin 124.

Thomas H. and Nesbit T.R. (2004) An assessment of the hydraulic impact of floodplain woodland. Forestry Commission.