6. Conclusions and Recommendations

Conclusions and recommendations

The aims of this project have been to investigate meteorological and hydrological processes operating in the Mawddach catchment with the objectives of producing a high resolution flood forecasting model, and identifying catchment management strategies to reduce flood risk.

Field investigations have revealed more complex patterns of processes than had been expected:

Rainfall events over the Mawddach catchment can be classified as either *frontal* or *convective* in origin. Frontal storms are by far the most common. They can occur in close succession, producing heavy rainfall for several days and leading to flooding by a *saturation-excess* mechanism. Convective thunderstorms are short lived but can generate severe flash flooding by an *infiltration-excess* mechanism.

Two main patterns of frontal rainfall are observed:

Type A storms produce a band of heavy rainfall extending diagonally across the catchment from Trawsfynydd in the NW, through Rhobell Fawr, to Aran Fawddwy in the SE. These events are associated with air masses moving up the Mawddach estuary and penetrating inland along the Mawddach and Wnion valleys. Precipitation may occur as valley airflows are forced to rise at the valley heads, triggering further upwards motion of unstable air in the middle troposphere.

Type B storms produce a north-south band of heavy rainfall roughly following the axis of the Rhinog mountain chain. These events are associated with air masses moving northwards across the Mawddach estuary and impacting directly on the Rhinog massif.

Heavy rainfall zones associated with the *Type A* pattern support exceptional vegetation growth. Areas of deep mosses are found beneath mature forestry plantations in the Hermon area of Coed y Brenin, and prolific growth of grasses, ferns and bilberry occur at Pared yr Ychain. These are outstanding natural habitats which should be conserved.

Areas of forest along the axis of heavy rainfall exhibit humidities close to saturation for extended periods. This in turn promotes the growth of extensive ground vegetation, and the development of deep soil profiles through trapping of sediment washed downslope. The deep forest soils have an important effect in absorbing storm runoff and reducing flood discharge into streams. The deep soils can quickly be lost by erosion after clear felling, leading to soils with poor water retention properties which allow rapid storm runoff.

Mature forestry plantations with thick moss ground vegetation are playing an important role in flood runoff reduction and should be conserved. Where harvesting is necessary, this should be carried out by continuous cover methods rather than clear felling in order to preserve the deep forest soils.

The *Type A* high rainfall axis supports peat blanket bog at Waen y Griafolen, which was the subject of a case study during this project:

Two contrasting forms of peat accumulation occur within the bog: *older humified peat* forming the upper plateau, and *younger undecomposed peat* which infills a former river channel network incised into the plateau surface. These zones have contrasting hydrological properties.

The older peat has low hydraulic conductivity, and is close to saturation for much of the year. Any remaining water storage capacity can be filled within a few hours of heavy rainfall, leading to overland flow as the main storm runoff mechanism.

Water leaving the plateau surface of the bog will enter the channel network occupied by the younger peat. The saturated younger peat and its overlying mass of wet vegetation forms a reservoir, regulating the outflow of storm water into the gravel channels of the Mawddach headwaters. The younger peats play an important role in reducing rapid storm outflow from the blanket bog.

The whole vegetation system of Waen y Griafolen is considered vulnerable. Preservation of both the older and younger peats depends on maintaining the high water table across the bog. The risk to peat by de-watering is discussed by Bragg and Tallis (2001), and the sensitivity of *Sphagnum* moss to water stress is discussed by Clymo (1973) and Harris, Brynat and Baird (2006).

It is recommended that the blanket bog be monitored, and weirs be installed on the outlet stream to restore groundwater levels if significant downcutting by the stream is observed.

Within the *Type B* high rainfall zone, a series of peat blanket bogs are developed in glacial basins below the Rhinog mountains from Cefn Cam in the south, through Crawcwellt, to Cefn Clawdd in the north. These peat areas are also found to saturate rapidly in response to storm events. During the period of the project, however, no significant flood discharges originated from the Eden sub-catchment along the foot of the Rhinog escarpment. This can be explained by two factors: The Rhinog Grit formation is massively jointed, allowing rainfall to rapidly infiltrate to the groundwater store, where it is released gradually after the peak of the storm. A substantial proportion of the storm discharge which does flow from the Rhinog escarpment is diverted northwards into Trawsfynydd reservoir by the Ardudwy leat, rather than continuing southwards into the Mawddach system.

Glacial and periglacial deposits are widespread within the Mawddach catchment, particularly on the floors and sides of valleys. These deposits have contrasting hydrological properties, and can be locally important in controlling hillslope runoff during storm events.

Field investigations at Pared yr Ychain produced the surprising result that glacial till allowed high volumes of throughflow during and following storm events. This was probably due to the derivation of the till from acid igneous rock, producing a high quartz sand content. The general assumption of boulder clay impermeability may not always be valid.

Throughflow was monitored in a succession of periglacial sands, gravels and scree infilling the Afon Wen valley. The volume of water flowing downslope through this material occasionally increased dramatically following a series of rainfall events. The occasions of very high recorded throughflow corresponded exactly with periods of flooding some 8km downstream in the Mawddach valley. It appears that saturation of periglacial deposits infilling the valleys of Coed y Brenin is an important precursor to flooding. Monitoring of hillslope throughflow at Hermon could give advance warning of conditions likely to initiate flooding during subsequent rainfall events.

A notable feature of the Mawddach catchment is polycyclic relief, developed by successive periods of uplift and erosion during Tertiary times. A consequence is that the middle courses of streams are steep and deeply incised, with rocky gorge sections developed along the Afon Gain, Afon Mawddach and Afon Wen within Coed y Brenin.

Monitoring of river bed temperatures in the gorge of the Afon Wen provided evidence that groundwater resurgence takes place during storm events. Modelling suggests that resurgence can increase river flows by up to 10%, but this effect occurs over a period of six to twelve hours after the peak flood discharge has passed. It is therefore unlikely that groundwater resurgence causes any increase in the severity of flooding. It appears that groundwater effects can safely by omitted from a flood forecasting model for the catchment.

It has been of interest to investigate whether the cultivation of flood plain woodland in the lower Wnion valley could reduce flood peak levels downstream in Dolgellau by providing enhanced conditions for temporary overbank storage.

A design is presented for a flood reduction scheme on the Afon Wnion in the area of Bont Newydd. This combines the construction of a weir and creation of an area of wet woodland. The scheme could provide an economic and environmentally acceptable alternative to the further enlargement of flood defence walls in the town.

Concern has been expressed about the accumulation of river gravel along the Afon Wnion through Dolgellau, particularly in the area of Bont Fawr. High volumes of gravel are also transported by the Afon Mawddach and deposited in the lower Mawddach valley around Llanelltyd. The sources of the gravel are the easily eroded glacial and periglacial materials infilling the river valleys of the catchment, with additional coarse sediment being supplied by erosion of the riverside spoil tips of disused metals mines in the Coed y Brenin area.

Field observations and modelling suggest that gravel accumulation is progressively raising the bed levels of the lower Mawddach and Wnion, and will lead to an increased flood risk for the town of Dolgellau. Periodic removal of gravel from the Bont Fawr area will be insufficient to alleviate the risks.

It is recommended that the supply of gravel to the lower Wnion and Mawddach valleys be controlled by the planting of native broadleaf woodland to stabilise sections of riverbank where severe erosion of (peri)glacial deposits is occurring. It would also be advisable to construct weirs upstream of Dolgellau to create interception basins where gravel sediment could be trapped and removed.

It had been anticipated that an additive effect would be found between tidal flows and river flood hydrograph peaks, leading to the possibility of particularly severe flooding. River monitoring at the tidal limits of the Mawddach and Wnion surprisingly indicated that no river-tidal interaction occurs, and each flow process can by treated in isolation in a flood model as if the other were not present.

Effects of land reclamation in the upper basin of the Mawddach estuary were examined, where flood embankments have been progressively added to enclose agricultural land. Modelling indicates that land reclamation is having no adverse effect on tidal flooding in the upper estuary basin. However, reclamation can reduce the capacity for absorption of river flood waters and worsen the effects of river flooding upstream towards Dolgellau. It is recommended that the remaining tidal marshes of the upper estuary basin are conserved, and no further land reclamation undertaken.

An objective of the project was to develop a methodology for high resolution flood forecasting in the Mawddach catchment.

It is not practicable to examine soils at sufficient localities within the catchment to allow a detailed hydrological map to be constructed from field evidence. An automated system for determination of hydrological parameters is therefore proposed. A scheme has been developed for soil categorisation based on slope characteristics, parent material and vegetation. The scheme uses an available 50m gridded digital elevation model, geological and vegetation maps.

A starting point for flood modelling was the use of the HEC-1 distributed model. This model did not allow for the antecedent moisture conditions which appear critical to the modelling of sequences of rainfall events. The design of a new hillslope model is presented, forming the interface between meteorological, groundwater and river routing components. The hillslope model is based around the computation of soil hydraulic conductivity in response to varying soil saturation, using the van Genuchten equation.

Rainfall patterns over the region are complex, depending on the tracks of frontal systems or the development of convective activity. It was shown that rainfall generated by these processes could be predicted with acceptable accuracy by the MM5 meteorological model. It is likely that the accuracy of forecasting will increase with the introduction of the more advanced WRF modelling system which is to replace MM5.

Improvements in forecasting by the WRF model will be dependant on a better understanding of the microclimate effects of mountains, and in developing more reliable convective modelling schemes. These developments are helped by the facility of WRF to run idealised cases, in which particular aspects of weather systems and atmosphere - land surface interactions can be examined.

Rainfall radar is a promising technique for monitoring the progression of storms and the estimation of rainfall rates. At the present time, however, numerical weather modelling appears to provide more accurate predictions of rainfall patterns than forecasting by rainfall radar.

A flood forecasting system is proposed in which the Mawddach hillslope runoff model is combined with the programs GSTARS for river routing and River2D for floodplain overbank modelling. Rainfall input may be provided by MM5, or its successor WRF.

The methodology for catchment characterisation and flood modelling developed in the Mawddach catchment could be usefully applied in other upland catchments of North Wales, in particular the Glaslyn and Conwy.

Integrated meteorological/hydrological modelling techniques incorporating MM5-WRF have a wider application in the prediction of flood events associated with weather systems approaching western Britain from the Atlantic, and could be usefully extended to regions of Scotland, Ireland and the Lake District.