1. Introduction

1.1 Objectives of the study

The Mawddach river system drains a region of upland and mountains in the south of the Snowdonia National Park within the county of Gwynedd in Wales. The overall catchment can be divided into:

- the Mawddach sub-catchment upstream of the tidal limit, with an area of approximately 160 km^2,
- the Wnion sub-catchment upstream of the tidal limit, with an area of approximately 120 km^2,
- the sub-catchment of the tidal estuary, with an area of approximately 120 km^2.

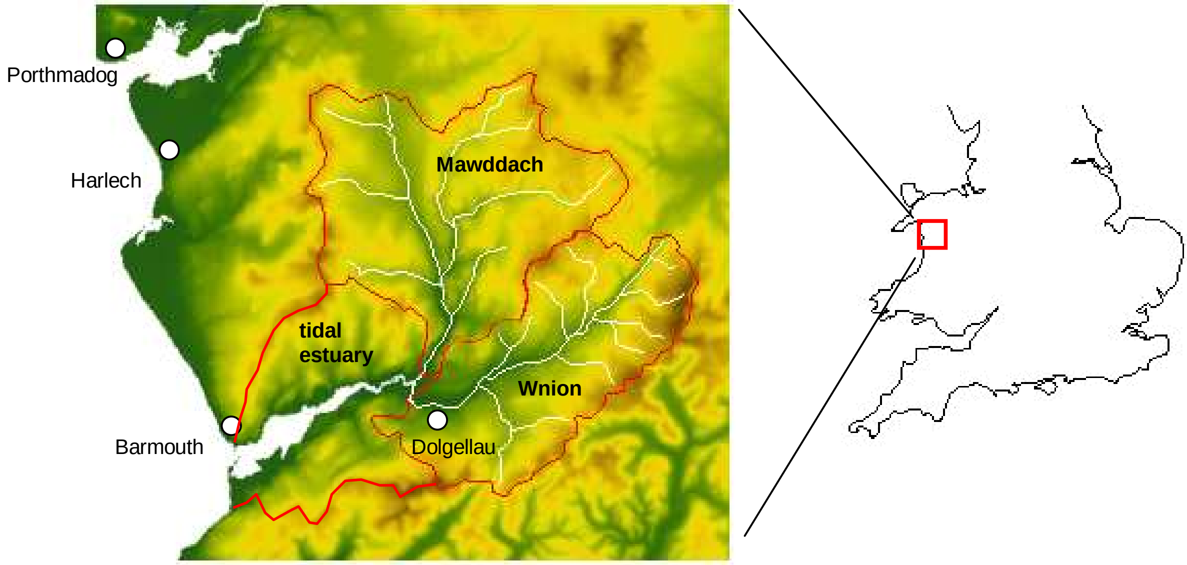


Figure 1.1 Location of the Mawddach catchment

Flooding, particularly around the town of Dolgellau, has been a problem throughout historical times (Barton, 2002). This research project has the following objectives:

- develop a realistic hydrological computer model for the Mawddach catchment based on a multi-disciplinary approach which embraces both climatic/hydrological and the various catchment characteristics,
- develop a methodology for an improved early warning system for flood prediction within the Mawddach catchment,
- identify environmental options for reduction of flood severity through land use management.

Current practice in flood forecasting

The approaches taken by the Environment Agency in flood forecasting are summarised by Moore et al. (2004).

Rainfall is determined from an array of raingauges, which around the Mawddach catchment have a spacing of approximately 10km. Alternatively, rainfall is estimated from interpretation of rainfall radar images. Computer systems are currently being developed for combining raingauge and rainfall radar data to produce improved rainfall maps during storm events. The objective of all of these approaches is to produce a catchment average rainfall value for input to a flood forecasting model.

Different hillslope-runoff and river routing models are employed to predict the effects of the observed rainfall on future river levels downstream in the catchment. Model parameters are calibrated using recorded river flows under known rainfall conditions, so that the predictive power of the model progressively improves through training. Flood warnings are issued when predictions of river depth at key locations will exceed threshold values.

The river flow forecasting period may be extended by making predictions of future rainfall over the catchment, rather than using only current observations. The movement direction and speed of the weather system is estimated, then this vector is applied to the current rainfall distribution in order to predict the location and intensity of rainfall during subsequent time intervals.

Development of an enhanced Mawddach flood forecasting system

Whilst the Environment Agency approach is a practical engineering solution for providing short term flood warnings, the system has limitations:

- Rainfall patterns over a mountainous catchment such as the Mawddach may not be adequately represented by either a widely spaced raingauge array or by low resolution rainfall radar. Localised variations in rainfall may have significant effects on hillslope runoff and river flows within particular valleys of the catchment, with consequent effects on downstream flooding.

- Weather systems may evolve rapidly during storm events, so simple spatial translation of the current rainfall pattern may not adequately predict rainfall patterns for subsequent time intervals.
- Output is restricted to the prediction of river depths at critical sites for flooding. It may be desirable to also predict the lateral extent of the floodplain to be inundated, so that more accurate warnings can be given to local residents, farmers and the emergency services.
- The approach taken in modelling only the outflow hydrographs of catchments using empirically determined model parameters gives little insight into the hydrological processes actually operating within the catchment. This limits the modelling to current experience, and gives little opportunity to predict the effects of future changes which might affect the catchment – for example: climate change, differing landuse or modifications to river channels.
- Some processes are missing from the hydrological model which may affect the location and extent of flooding in the Mawddach catchment, for example: groundwater flows, the interaction between rivers and tidal waters around the head of the estuary, and the movement of sediment in response to flood events.

This research project will investigate alternative approaches to the modelling of floods in the Mawddach catchment which could provide a longer warning period, combined with a more accurate estimation of the extent and severity of flooding. At each stage, process models will be used so that the effects of current and future catchment management practices on flooding can be evaluated.

A series of modelling components will be investigated individually, then combined into an integrated system for flood prediction (fig.1.2). An objective is to identify the key processes which are critical to flood forecasting. Equally important is the identification of processes which have only a negligible modifying effect on flooding and can safely be omitted from the final model.

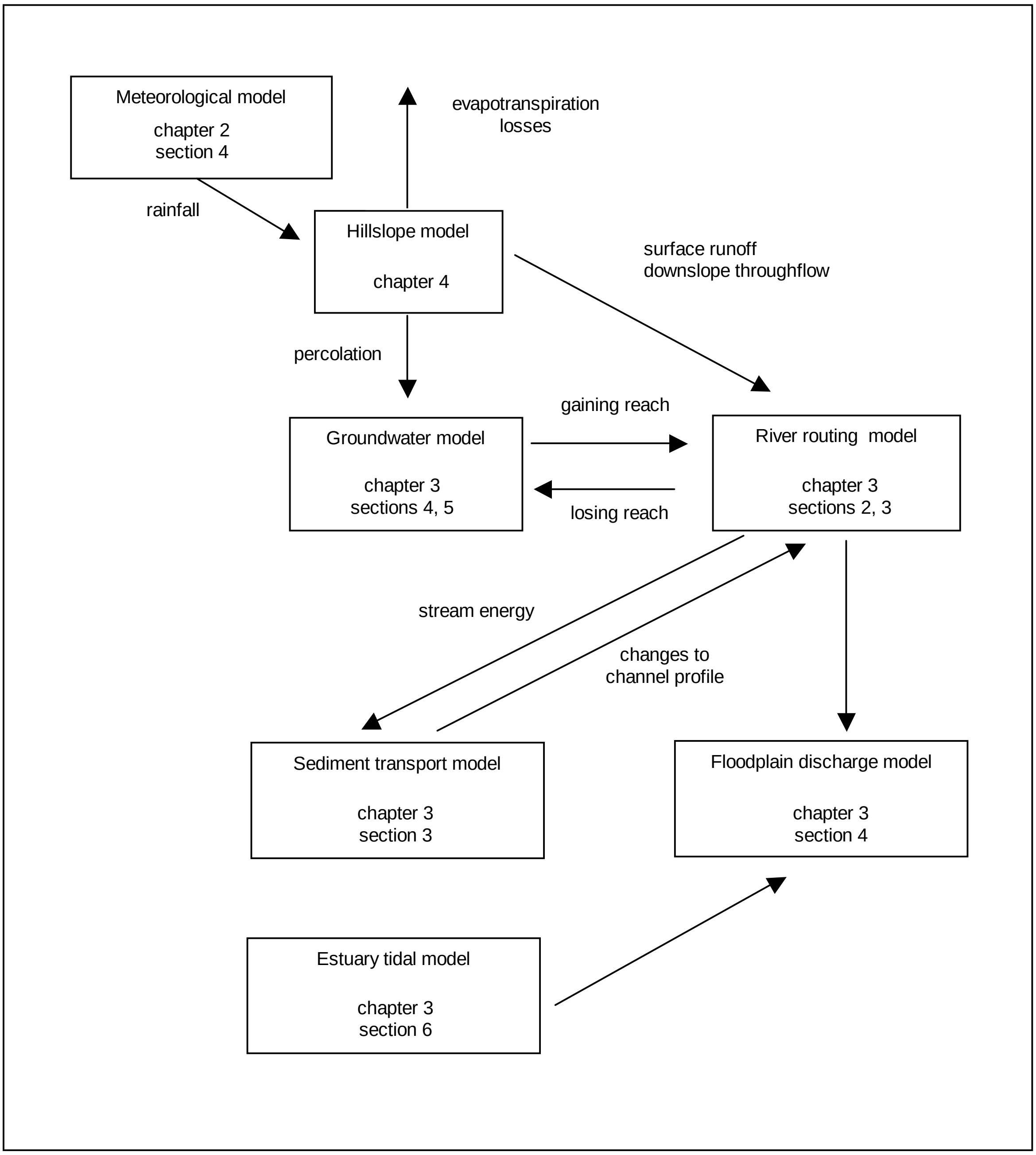


Figure 1.2: Proposed modelling components for the integrated Mawddach flood prediction system

Meteorlogical modelling is addressed first in ***Chapter 2***, followed by hydrological modelling in ***Chapter 3***. Central to the operation of the integrated system is a new hillslope runoff model which will be developed during the project – this is described and evaluated in ***Chapter 4***.

Synopsis of chapters

Flooding in the Mawddach and Wnion catchments examines historical and present day flooding, and discusses possible effects of climate change for the region.

Section 1.2 The Study Area outlines this background against which hydrological models are developed during the project. The Mawddach catchment is an upland area of diverse geology, landforms, soils and natural vegetation. Present and previous human activity within the catchment includes: agriculture, forestry, mining, and the construction of reservoirs for water supply and hydroelectric power. To some extent, all these factors influence hydrological response.

Chapter 2 Meteorology

Section 2.1 Meteorological principles outlines aspects of meteorology relevant to rainfall production over the North Wales area. Theories of midlatitude cyclone development are discussed, and the orographic effects of the mountains considered. The mechanisms of convective rainfall production are examined for thunder storms and extended squall lines.

Section 2.2 Rainfall in the Mawddach catchment reports the results of rainfall monitoring in and around the Mawddach catchment by an array of raingauges. Analyses of storms show that rainfall patterns may vary widely between events, and between adjacent valleys during the same event, depending on the approach directions of weather systems.

Section 2.3 Meteorological modelling examines the fluid dynamics approach taken in modelling the physical processes taking place at different levels of the atmosphere.

Section 2.4 The MM5 modelling system discusses underlying assumptions and mathematical formulation of the high resolution rainfall model for the Mawddach catchment. Storm events are modelled and predicted rainfall distributions are evaluated against field data. A neural network is examined as a method for improving initial rainfall forecasts. Atmospheric processes appearing during the MM5 simulations are compared to theoretical mechanisms for frontal and convective storm events.

Chapter 3 Catchment Hydrology

Section 3.1 Hydrological modelling systems discusses a conceptual model for catchment hydrological processes, and considers different approaches to modelling these processes by computer.

Section 3.2 Hillslope hydrology outlines the collection of field data for use in the calibration and evaluation of the models. The HEC-1 hillslope model is assessed for its suitability within an integrated meteorological/ hydrological model for the Mawddach.

Section 3.3 Sediment movement examines sediment processes within the river system. The valleys of the Mawddach locally have extensive infilling by poorly consolidated glacial and periglacial material. This sediment is easily eroded from riverbanks during storm events. Large volumes of sand and gravel are carried downstream, and may be redeposited within the river system or discharged into the tidal estuary.

Modelling using GSTARS software has been carried out to estimate the volumes of sediment redistributed during particular flood events. Sediment accumulation in the lower reaches of the river system and around the head of the estuary will affect river base levels, with consequences for the extent of future flooding in the area of Dolgellau.

Section 3.4 River and floodplain processes examines the flow of water once it has entered the river system. The Mawddach and its tributaries are dominantly gravel streams with steep gradients, locally flowing over bare rock or forming waterfalls. Modelling of river routing should be able to handle both subcritical and supercritical water flows.

Floodplain inundation can occur at various locations, notably the lower Wnion valley around the town of Dolgellau. Modelling is carried out to assess the likely extent of floodplain inundation in response to different catchment management strategies.

A feature of the middle courses of the Mawddach system is the alignment of river channels along major fracture zones in the bedrock. Fieldwork provides evidence of river–groundwater interaction, with water loss from river channels during dry periods and resurgence during flood events. Groundwater modelling assesses the extent of this interaction.

Section 3.5 Peat blanket bogs examines the hydrological characteristics of upland peat bogs around the headwaters of the Mawddach river system.
A detailed case study has been carried out at Waen y Griafolen, a blanket bog forming the source of the Mawddach itself. Field monitoring of water table levels within the peat, geophysical and auger surveys provide parameters for a MODFLOW groundwater model. River outflows from the peat basin are assessed in relation to possible vegetation changes within the blanket bog.

Section 3.6 The Mawddach estuary considers flood processes around the head of the Mawddach estuary. Salt marsh, reed beds, water meadows and wet woodland areas are naturally flooded at certain tides, and can provide transient storage for flood water. Areas of flood land have been progressively reclaimed for agriculture by the construction of sea walls. An assessment is made of the impact of land reclamation on current and future flooding.

Chapter 4 Integrated catchment modelling

Section 4.1 Integrated meteorological-hydrological models examines the approaches taken by flood modelling systems which obtain rainfall data from meteorological modelling systems. The design is presented for a new hillslope model for use in the Mawddach catchment. This model forms an interface between the MM5 meteorological model, river routing and groundwater components.

The hillslope model is based around the computation of soil hydraulic conductivity in response to varying soil saturation, using the van Genuchten equation.

Section 4.2 The Mawddach hillslope model discusses the modular design of the hillslope program and the algorithms for water flow simulation. Kirkby wetness index, geological and land use data are used in computing soil distribution on a 50m grid, to provide hydrological parameters for hillslope infiltration, throughflow and runoff. The stages are outlined for running a model, monitoring hillslope waterflows and obtaining output hydrographs.

Section 4.3 Validation of the hillslope model presents the results of runs of the model for sub-catchments at Hermon, Pared yr Ychain and Waen y Griafolen. The physical realism of the hillslope model and the accuracy of the output generated are assessed against field data collected during storm events in the sub-catchments.

Section 4.4 Results of runs of the integrated model. The elements for an integrated meteorological/hydrological model of the Mawddach catchment which are now in place, and are brought together to create a flood forecasting system. Runs of the model have been carried out for the convective flood event of 3 July 2001 and the frontal storms of 3-4 February 2004 as a means of evaluating the system. The operation of the model in real-time forecasting mode is tested.

Chapter 5 Discussion

Section 5.1 Meteorology examines the field data collected for regional rainfall patterns and microclimate effects within the Mawddach catchment. Different approaches for rainfall forecasting are considered. There is a discussion of the future development of meteorological modelling with the introduction of the WRF modelling system.

Section 5.2 Hydrology assesses the work carried out in the Mawddach catchment to quantify the processes of hillslope runoff, river routing and floodplain overbank discharge, groundwater movement, river sediment deposition and estuary tidal flows. Sources of errors in field data collection are identified. An assessment is made of the software packages used in simulating hydrological processes during the project.

Section 5.3 Catchment modelling evaluates the integrated meteorological / hydrological system developed for flood forecasting in the Mawddach catchment.

Chapter 6 Conclusions and Recommendations

The main findings of the project are summarised. A proposal is made to reduce sediment accumulation in the lower reaches of the Wnion and Mawddach. A scheme is presented for the extension of flood plain forestry as a means of flood reduction. Conservation measures are recommended for blanket bog, salt marsh and estuary wet woodland ecosystems.

The integrated meteorological/hydrological modelling system is advocated for use as an early warning system for flooding on the Mawddach.

Flooding in the Mawddach and Wnion catchments

The Romans settled in the Mawddach region, constructing a large fort at Tomen-y-Mur near Trawsfynydd (Ellis, 1928). From Tomen-y-Mur, a road ran southwards in a straight line down the Ganllwyd valley, but before reaching Llanelltyd it turned abruptly to the east through Llanfachreth and Bont Newydd before returning to its southerly course. This diversion suggests that the Wnion valley near Dolgellau was marshy and liable to heavy frequent flooding during that period.

From the late sixteenth to the early nineteenth century, Dolgellau developed as a prosperous town based on the manufacture of woollen textiles, with abundant water power for textile mills provided by the River Aran (Rhydderch, 1976) . A 19th century illustration (fig.1.3) shows the growth of the town onto the Wnion floodplain.

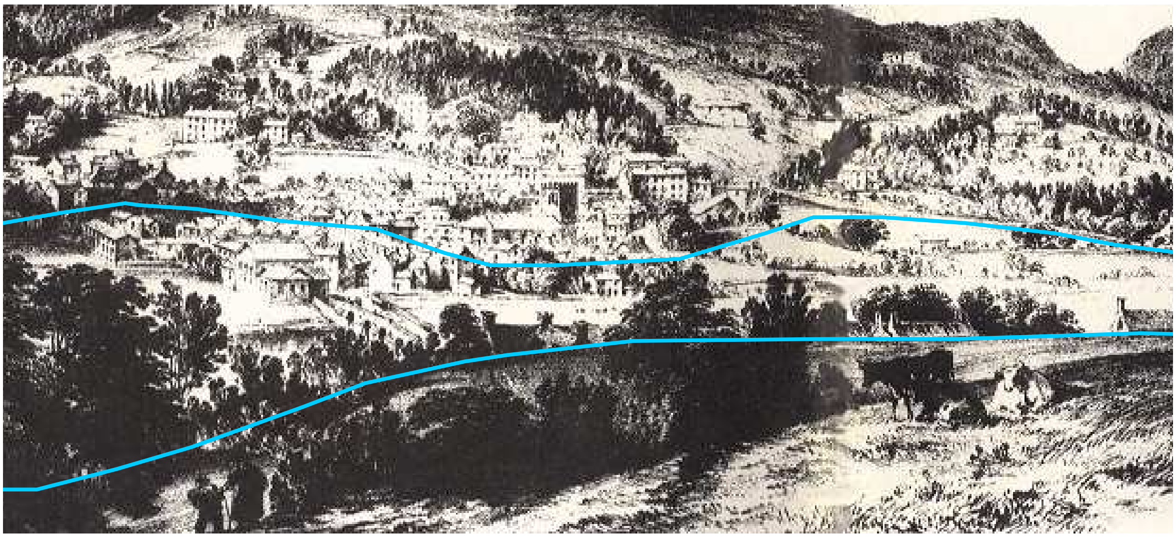


Figure 1.3: Dolgellau in the mid 1800's. The Wnion floodplain is outlined in blue. (based on an illustration from Rhydderch, 1976)

The Great Western Railway opened a line from Bala to Dolgellau in 1868, with the Cambrian Railway continuing the link from Dolgellau to Barmouth in 1869. From its inception, the railway route along the Wnion valley and the Mawddach estuary was susceptible to river and tidal flooding. A report for the Rail Safety and Standards Board (JBA Consulting, 2004) on the Impact of Scour and Flood Risk on Railway Structures cites a bridge failure on the Afon Wnion, Dolgellau, in July 1880. The Priority Rating assigned to this incident is High, based on the seriousness of damage and the frequency of flood events of similar magnitude. The exact location of the bridge is not stated, but is likely to be the structure near the tidal limit of the Wnion, west of the town, shown in fig.1.4 during flood conditions.

Figure 1.4: Disused railway bridge at the tidal limit of the River Wnion, Dolgellau. This is likely to be the site of the 1880 bridge failure.

Archive photographs illustrate a number of flood events affecting the town of Dolgellau during the 20th century. Particularly serious was the storm of September 19, 1922 when shops were flooded and extensive damage occurred to Bont Fawr, the main road bridge over the River Wnion (figs 1.5, 1.6).

Figure 1.5: Flooding in Bridge Street, Dolgellau, September 19, 1922
(photo: Richard Morgan collection)

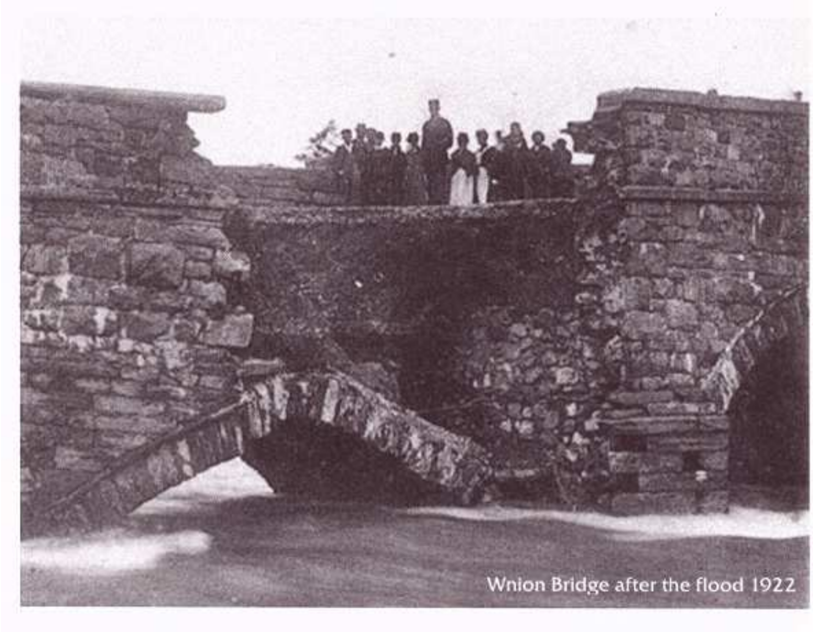


Figure 1.6: Damage to Bont Fawr, Dolgellau, September 19, 1922. (photo: Richard Morgan collection)

Figure 1.7: Dolgellau flood of December 12, 1964
(photo: Gwynedd County Council Archives Service)

Another serious flood (fig.1.7) on December 12, 1964 prompted the Town Council to order the construction of a one-mile flood defence wall along the River Wnion (fig.1.8). This wall has protected the town well from subsequent floods, but has come close to overtopping in recent years.

Figure 1.8: Flood defence wall alongside Bont Fawr.
Flood event of 4 February 2004.

The head of the Mawddach estuary is reached a short distance downstream from Dolgellau. Reclamation of farmland has been carried out by the construction of earth embankments around some areas of former reed beds and salt marsh, and the excavation of drainage ditches (fig.1.9).

Figure 1.9: Land reclamation at the head of the Mawddach estuary. Earth embankments are marked in red, and drainage ditches in blue.

The enclosed fields may be susceptible to both river and tidal flooding. A graphic account is provided by a Snowdonia National Park information panel alongside the estuary at Penmaenpool:

> "The fields you can see looking across towards the estuary were covered by the tide until the middle of the 19th century. Farmers transformed the land from saltings into pasture by building a wall and carrying soil onto the land by horse and cart. The wall was breached by a very high tide in 1927, carrying a farmer and his cattle into the woods above the road. The fields were not reclaimed until 1978, when the tidal defence wall was rebuilt."

The railway running along the southern shore of the estuary was regularly affected by tidal flooding, with the undermining of engineering structures occurring relatively frequently. Incidents at Arthog station (fig.1.10) are reported by Hambley, Bodlander and Southern (1991):

> "Arthog station consisted of a wooden platform and building... Severe flooding in 1927 washed away an iron bridge adjacent to the station. Its replacement withstood a similar flood in 1938 during which the stationmaster Mr W.T.Edwards clung to the ground frame levers for several hours as flood waters swirled around him. He was later able to climb onto the roof of a hut before finally being rescued by boat."

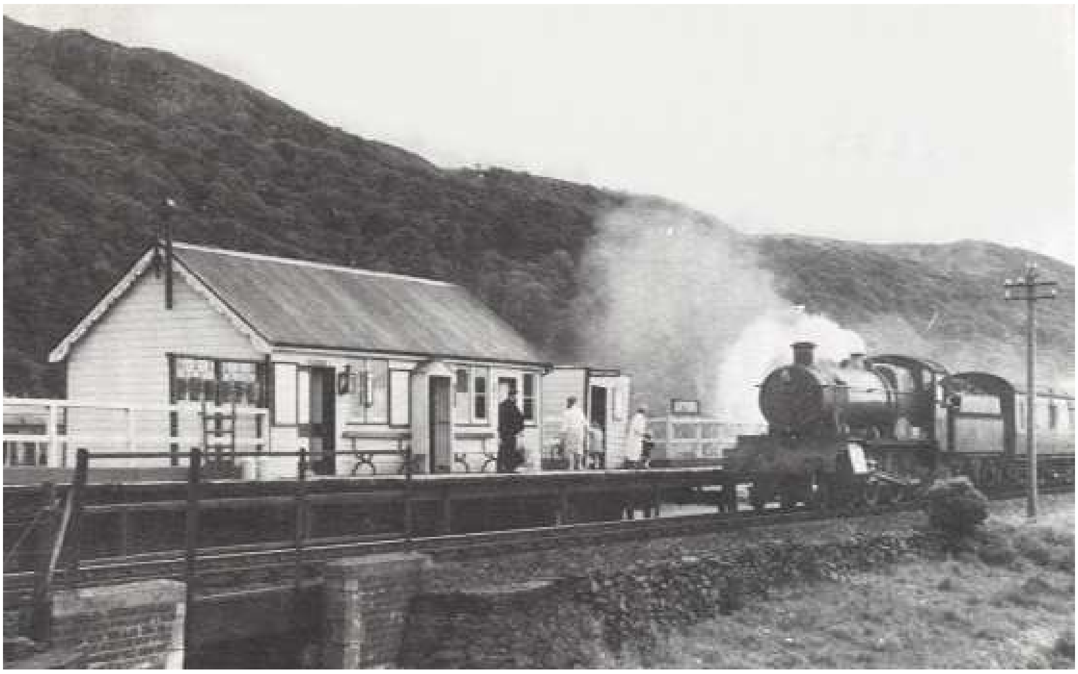


Figure 1.10: The former railway station at Arthog
(photo: Hambley, Bodlander and Southern , 1991)

The upper reaches of the Mawddach and Wnion river systems drain mountains and moorland, often in areas of impermeable rock. These streams are susceptible to a flash flood regime, with river levels rising rapidly after the onset of storm rainfall (fig.1.11).

Figure 1.11:
Illustration of variations in discharge on the River Gain at Pistyll Cain.
Above: typical condition after a dry summer month.
Left: river in spate during the February 2004 flood.

The most serious flood event recorded for the upper Mawddach occurred on July 3, 2001. Up to 120mm of rain fell during a three hour period from convectional thunderstorms along a squall line (Mason, 2002). This event caused damage to buildings, washed away bridges and roads, and disrupted communications and farming activities over a wide area between Trawsfynydd, Dolgellau and Llanuwchllyn. The extent of surface runoff is shown in figs 1.12 and 1.13.

Figure 1.12: Infiltration-excess overland flow occurring during the July 2001 flood event, Cwm Prysor. The storm occurred after a hot summer's day, with extremely high intensity rainfall falling on dry ground.
photo: Robert Chilton

Figure 1.13: Flood water which disrupted traffic on the Bala to Trawsfynydd road, Cwm Prysor. July 2001 flood.
photo: Robert Chilton

Figure 1.14: Bridge destroyed on the River Gain

Figure 1.15: Bridge damage at Abergeirw

Figure 1.16: Forestry road undermined, Coed y Brenin
photo: Robert Chilton

Figure 1.17: Bank erosion endangering buildings, Ferndale
photo: Robert Chilton

Examples of damage to infrastructure during the July 2001 flood are shown in figs 1.14 to 1.17. A total of 27 bridges were recorded by Gwynedd County Council as being damaged during the flood event, some of which were washed away completely or beyond repair.

To summarise current flood risks for the Mawddach catchment:

- Flooding can endanger livestock on farmland adjacent to rivers or the estuary.
- Flooding can lead to the undermining of roads and destruction of bridges, with potential danger to life.
- Flooding can cause damage to properties, either through direct flooding or by the undermining of foundations by river bank erosion.

Improved advance warning of flooding could allow preparations to be made by farmers, the highway authority and property owners to minimise danger and loss. Advance warnings must, however, be reliable. False alarms may lead to warnings being ignored in a real emergency. The design of an improved and reliable flood warning model for the Mawddach catchment is the first objective of this research.

Within the Mawddach catchment, flooding has occurred throughout historical times with a number of very severe events occurring during the past 100 years. A consensus of scientific opinion suggests that climate change is occurring along the Atlantic margins of western Europe, and is likely to continue in coming decades. Studies carried out for the areas of Wales (Jones et al., 2007) and Norway (Skaugen et al., 2003) both draw similar conclusions:

- a seasonal shift in rainfall patterns is occurring, with drier summers and wetter winters,
- there is no large change in total annual rainfall, but more extreme storm events are occurring due to higher available energy in the atmospheric circulatory system.
- within the overall weather patterns, large variations occur in mountainous areas due to local microclimate effects.

Figure 1.18 (right): Annual rainfall totals (mm), Trawsfynydd

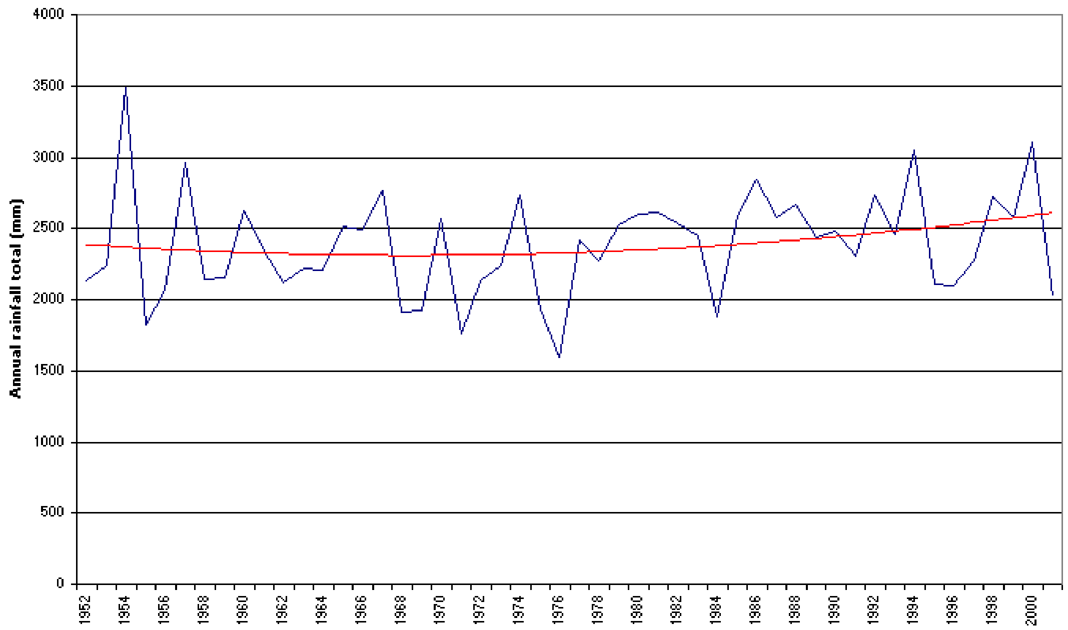
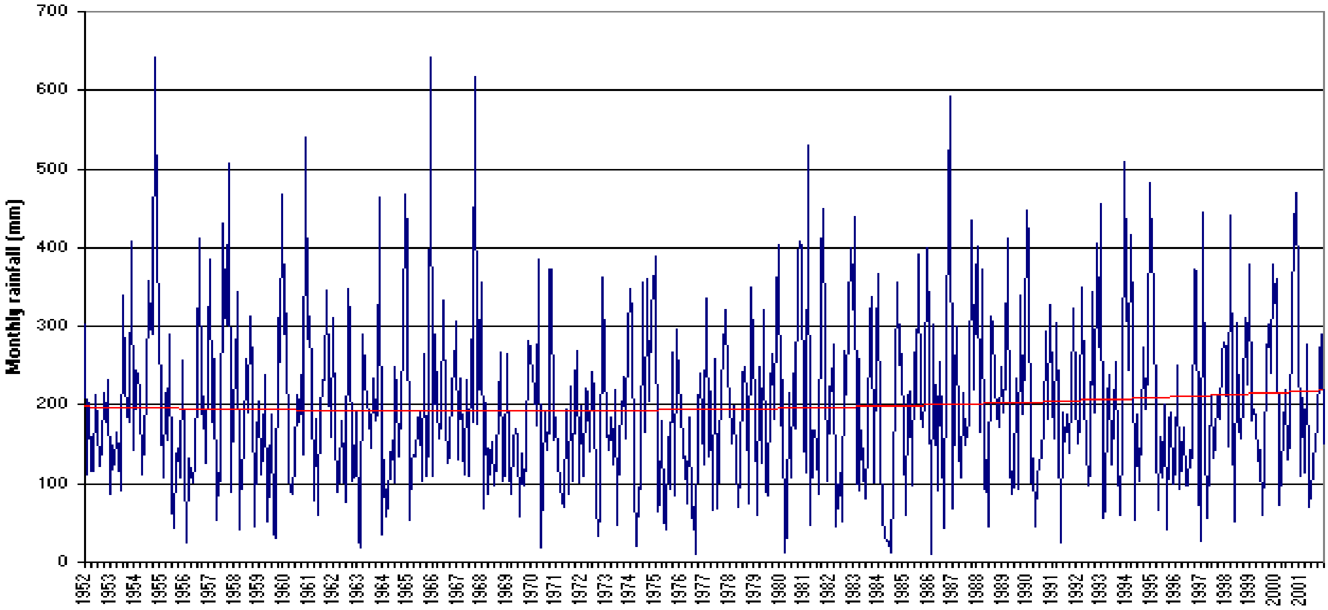


Figure 1.19 (below): Monthly rainfall totals (mm), Trawsfynydd



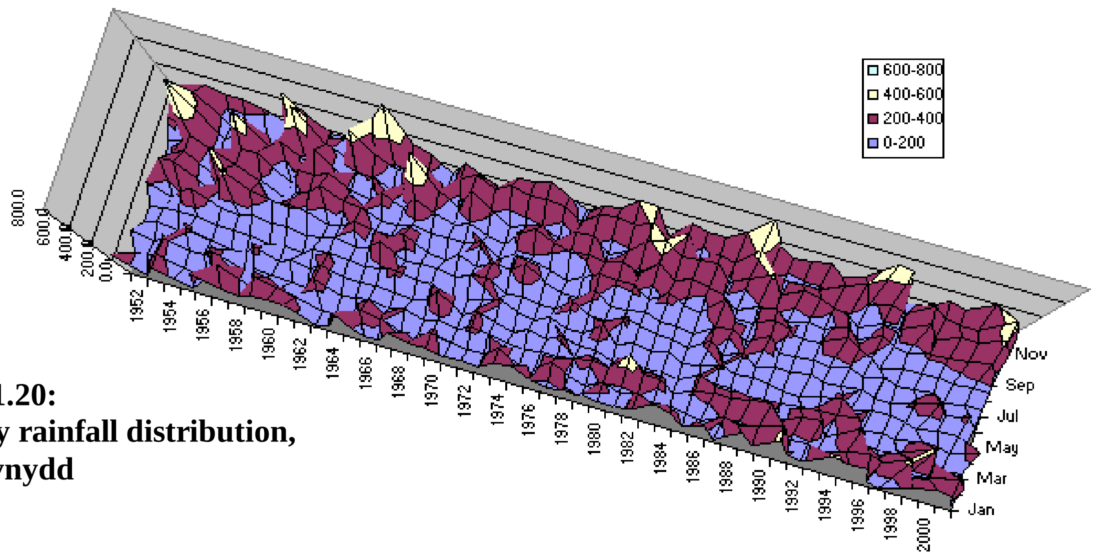


Figure 1.20: Monthly rainfall distribution, Trawsfynydd

A complicating factor is the influence of the North Atlantic Oscillation and the El Niño Southern Oscillation (Daultrey, 1996). Under certain circumstances these global circulatory effects can produce winters with particularly high precipitation in western Britain.

Rainfall data for the period 1952-2001 collected at Graig Ddu Ganol, near Trawsfynydd in the Mawddach catchment, are consistent with these conclusions

- Fig.1.18 shows considerable variation in total annual rainfall, with an upwards trend noticeable since the early 1970's.
- Fig.1.19 shows similar large variations in total monthly rainfall, with the most extreme wet months occurring in the 1950's and 1960's. However, an upwards trend in mean monthly rainfall is again observed since the early 1970's.
- Fig.1.20 suggests that a seasonal shift in rainfall pattern is occurring. Wet periods with monthly rainfall > 200mm in the 1950's typically occurred from July to January, whereas the annual wet period in the late 1990's was typically from September to March – a forwards progression of two months.

These lines of evidence suggest that the flood risk within the Mawddach catchment is likely to remain at its current high level for the present century and may increase further. Possible increases in river flows in response to global warming are addressed by Arnell (2003). Attention to long term environmental management of the catchment to minimise risk of flood generation is therefore justified. This aspect forms the second objective of the research. Two particular issues of interest locally are:

- the effects of river gravel deposition on flood risk
- the effects of forestry in controlling flood discharge.

Concern has been raised in Dolgellau at the accumulation of river gravel in the vicinity of Bont Fawr (figs 1.21-1.23). Fears have been expressed that sediment may constrict river flow through the bridge arches, leading to overtopping of the flood defence wall. Responsibility for maintaining a clear river channel lies with the Environment Agency (Environment Agency Wales, 1999) who regularly remove large quantities of gravel from the area around the bridge, but reaccumulation may occur as the result of a single flood event.

Figure 1.21:
Bont Fawr, Dolgellau, after gravel clearance.

Figure 1.22:
Bont Fawr, Dolgellau, showing gravel reaccumulation.

Figure 1.23:
Work in progress to clear gravel from the Bont Fawr area.

Woodlands form an important component of the natural vegetation of the Mawddach catchment. Riparian broadleaf woodlands survive along many of the river courses (fig.1.24) , and wet woodland is characteristic of floodplain areas around the head of the estuary (fig.1.25). Natural woodland has been greatly augmented by the extensive forestry plantations of Coed y Brenin and the Wnion valley around Rhydymain.

Figure 1.24: Natural riparian woodland alongside the Afon Eiddon, a tributary of the Wnion.

Figure 1.25: Wet woodland alongside the River Wnion at the head of the estuary. Photographed during the February 2004 flood event.

In recent years, interest has increased in the use of flood plain forestry as a means of flood control as an alternative to hard engineering structures (Thomas and Nisbet, 2004). This application of forestry will be examined during the modelling project.

Hypotheses

Preliminary investigation of the Mawddach catchment has revealed considerable complexity in the hydrological processes that are operating. These processes need to be considered whilst developing the conceptual model on which computer applications will be based:

- Wide variations in rainfall seem to occur across the catchment during individual storm events. These variations may not be entirely related to altitude.
- A number of river sections are aligned along major geological faults, and it is suspected that surface water - ground water interactions may occur through the fracture zones.
- Considerable thicknesses of glacial and periglacial materials infill river valleys. These materials vary greatly in hydrological properties, from low permeability clays to freely draining scree, and may have a controlling influence on infiltration and runoff during storm events.
- The headwaters of several major tributaries originate in extensive peat blanket bogs. The water storage properties of these peat deposits may have an influence on storm river discharges.
- Forestry management practices can affect hillslope runoff, and need to be considered in developing a model.
- Tidal and river interactions at the head of the estuary during flood events may influence the extent of flooding. This effect should be analysed.
- Some water is diverted out of the Mawddach catchment by a canal system to augment the water supply to the Maentwrog hydroelectric power station. The extent of this flow should be considered in the development of a water budget for the catchment.