5. Discussion

This research project had the following objectives:

- to develop a methodology for an improved early warning system for flood prediction within the Mawddach catchment (discussed in section 5.1),
- to identify environmental options for reduction of flood severity through land use management (discussed in sections 5.2, 5.3),
- to develop a realistic hydrological computer model for the Mawddach catchment which embraces both climatic/hydrological and the various catchment characteristics (discussed in section 5.4).

5.1 Development of a flood forecasting system

Different approaches to flood prediction are possible:

- Reacting to current water flows,
- Reacting to current rainfall by predicting future water flows,
- Predicting future rainfall, and consequently predicting future water flows.

In moving through this sequence, the amount of advance warning possible for a flood event increases, but so does the difficulty of accurate forecasting.

Monitoring of current water flows may provide an accurate prediction of flooding on a timescale of several hours:

It was shown that water depth of the Afon Ty Cerrig in the headwaters of the Afon Wnion provides a very accurate predictor of water depth in Dolgellau 3 hours 30 minutes later (fig.3.40). It would be simple and cost effective to install an automatic river gauge on the Afon Ty Cerrig, transmitting data by telemetry to a flood monitoring centre for Dolgellau.

No simple relationship was found to link waterflows in the headwaters of the Mawddach to future water levels in the lower catchment.

It was observed that a rise in groundwater levels within periglacial valley slope deposits in Coed y Brenin was always a precursor to flooding some 5km downstream around Llanelltyd. It is not thought that the rise in groundwater *in itself* causes flooding – rather that this represents a closing of the slower water transmission pathways through superficial deposits, so that subsequent rainfall has to follow a fast surface runoff route into rivers. Monitoring of groundwater levels in Coed y Brenin could not give advance warning of flood events, but would provide a valuable indicator of the likelihood of further rainfall causing flooding. Local organisations and individuals could therefore be alerted when potential flood risk was high.

Monitoring of current rainfall can provide inputs to a hillslope runoff model for the prediction of flooding, and may extend the period of flood warning to around 6 hours.

Current rainfall patterns over the catchment may be:

- measured directly using raingauges linked by telemetry to a flood forecasting centre,
- determined from analysis of rainfall radar images,
- computed by means of a numerical weather model.

Analysis of frontal rainfall events over the Mawddach catchment has identified two principal rainfall patterns, termed Type A and Type B. To provide the most effective input to a flood model, gauges should be situated at points of rainfall maxima for these patterns. It is suggested that three critically sited gauges could quantify Type A rainfall, at Trawsfynydd, on the upper slopes of Rhobell Fawr and at Pared yr Ychain. Two gauges would be needed to quantify Type B rainfall, at the head of Cwm Mynach and on the upper slopes of Rhobell Fawr. This small array of gauges, equipped with telemetry, should be adequate for synthesis of an overall rainfall distribution pattern for the catchment.

Comparison of indirect methods of rainfall monitoring suggests that numerical weather modelling is currently to be preferred to rainfall radar image interpretation. This is due to the complexity of rainfall generation mechanisms over the mountain catchment and the limited visibility of some of these mechanisms to radar.
A numerical weather model can be run in real time, with regular updates of atmospheric variables from the NCEP GDAS system and error reduction through

observational feedback in a neural network. A rainfall accuracy to within 20% error should be achievable on a 1km grid for frontal storm events.

Prediction of river flows and consequent flooding will depend on accurate hillslope runoff, river routing and overbank discharge models. During the project, various software packages have been assessed individually and as components of an integrated system:

- Hillslope runoff modelling was shown to be critically dependant on soil antecedent moisture conditions.
  Satisfactory results could be obtained using the HEC-1 program for individual storms, but errors were introduced when sequences of storms occurred over a period of a few days. This was due to limitations in the way the program handles soil saturation and drainage through the SCS Curve Numbers method. An alternative hillslope runoff model was developed which employs the van Genuchten function to model soil hydraulic conductivity at different moisture levels. This simulates the processes of soil drainage vertically and down slope, with consequent changes to soil moisture levels over a period of time. The program provided more accurate runoff values than HEC-1 when tested over a sequence of closely spaced storms.
- The software packages GSTARS and River2D were found to work well for the river routing and floodplain overbank discharge components of the model respectively.
- Investigations indicate that neither groundwater resurgence nor tidal flooding have a significant effect on flood risk for the lower Wnion valley around Dolgellau and lower Mawddach valley above Llanelltyd, so may be omitted from a flood warning model for the non-tidal catchment. Groundwater resurgence, whilst locally significant in Coed y Brenin, operates on a longer timescale than hillslope runoff and would not affect river levels until after a flood peak had passed. Tidal flooding is of short duration at the head of the estuary, and tidal peaks were found to have no additive backwater effect on river flows upstream.

Significant problems were identified in predicting flooding from convective thunderstorms. These events, whilst rare, can produce the most serious flood damage in the Mawddach and Wnion catchments. The difficulty arises from the very localised nature of convective cells:

- It is unlikely that the position of a convective cell would correspond with a rain gauge location, so maximum storm intensity has to be estimated from inadequate data.
- Numerical weather models have varying amounts of success in predicting the locations and intensities of convective cells. It is necessary to run multiple models using different convective physics schemes as a means of obtaining a suitable weighted average rainfall distribution for input to a hillslope runoff model, but significant inaccuracies would still be expected.
- It is possible that rainfall radar might have the best chance of accurately determining rainfall intensity during a convective storm, since rainfall production in towering cumulonimbus cloud is readily observable to the radar beam. However, the grid resolution of rainfall radar is not yet adequate to characterise intense rainfall centres whose diameters may be less than 1km.

Prediction of future rainfall with consequent modelling of hillslope runoff and river flows gives the greatest opportunity for advance warning of flood events.

Options for future prediction of rainfall are limited:

- It is possible to extrapolate future rainfall patterns from current patterns, using data from raingauges or rainfall radar. Much will depend on the skill and experience of the forecaster in predicting accurately the spatial movement and temporal evolution of the rainfall system as it crosses the catchment.
- Numerical weather modelling is probably the best option currently available for rainfall forecasting. NCEP GDAS 6-hour predicted atmospheric data may be used in conjunction with a high resolution local model such as MM5 which can incorporate topography and land surface characteristics to accurately simulate microclimate effects. A main area of current research is an effort to improve convective rainfall prediction by weather models.

5.2 Meteorology

From data collected during the project, it appears that rainfall patterns associated with different meteorological events are more complex than previously expected. The generally accepted practice of estimating rainfall across the catchment from interpolation between a small number of raingauges is inadequate, even if an altitude correction factor is applied to the estimates. Rainfall patterns may vary widely between events, and between adjacent valleys during the same event. Within an individual storm the total rainfall may differ by a factor of four or more between different locations within the Mawddach catchment, and zones of highest rainfall do not necessarily correspond with the highest ground.

Sensitivity analysis during modelling has shown that rainfall is the single most important factor controlling flooding in the Mawddach catchment. The area is one of generally low permeability bedrock, and the distribution of superficial deposits, soils and vegetation have only a subsidiary modifying effect on flood events. Obtaining the most accurate forecasts possible of detailed rainfall patterns is crucial to the success of flood forecasting for the rivers Mawddach and Wnion.

An initial task carried out during the project was to determine the spatial variability of rainfall across the region. At the commencement of the project in late 2001, five rain gauges were being operated in or near the Mawddach catchment. The catchment covers an area of approximately 400km^2, with mountainous terrain rising from sea level to over 800m, so the small number of gauges could not provide an adequate representation of rainfall patterns during storms. For the extreme flood event of 3 July 2001, it was apparent that the centre of maximum rainfall lay in the area of the Oernant valley at a considerable distance from any existing rain gauge site.

Over the period of 2002-3, an additional 24 electronic raingauges with data loggers were installed, providing progressively more detailed rainfall distributions for storm events (fig.5.1). Storm isohyets were plotted after each significant period of rainfall, and locations were identified where additional gauges could help resolve ambiguities in the rainfall pattern.

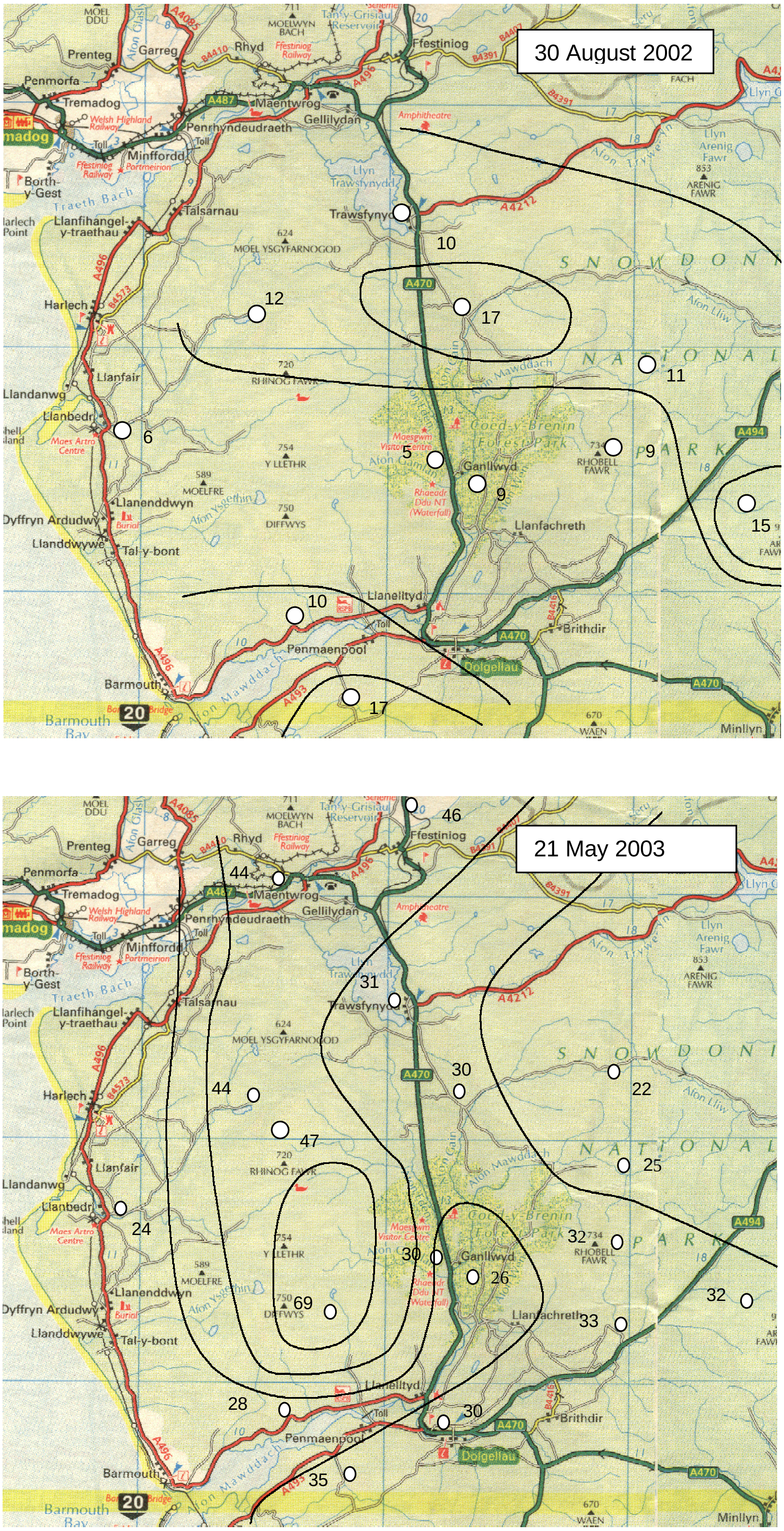


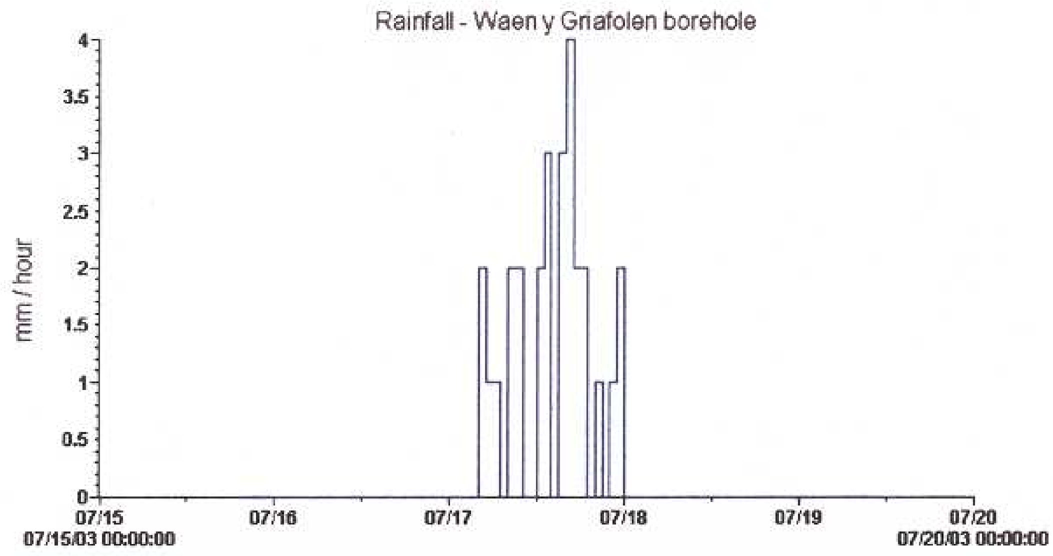
Figure 5.1: Example storm rainfall maps, illustrating the development of the raingauge recording network in the Mawddach catchment over the period 2002-3

Care was taken in the placing of rain gauges. Open country was chosen, to avoid sheltering of gauges by trees or rock outcrops. Instruments were generally attached to fence posts to avoid splashing from the ground surface, and as protection against grazing sheep or goats.

It is possible that wind turbulence around fence posts on open moorland could reduce the volume of water collected by gauges. Practical aspects of raingauge operation are discussed in the Institute of Hydrology report on the Plynlimon instrumented catchment (Institute of Hydrology, 1990). Use of a ground grid of open matting is advocated to reduce turbulance around raingauges. Despite no special precautions of this type for the Mawddach raingauge installations, it is not considered that loss of rainfall through turbulance will have significantly affected the results. It was observed that the heaviest rain storms were not accompanied by very strong winds. Rain loss through turbulance is quoted by Institute of Hydrology (1990) as between 2% and 16% for sites on Plynlimon.

The tipping bucket raingauges and the accompanying electronic data loggers could operate reliably for long periods in the field. In practice, gauges were checked and data downloaded once a fortnight to allow the prompt analysis of each storm event. Very occasionally, loss of data occurred from an individual gauge through a mechanical fault in the tipping bucket mechanism, or through water leaking into the casing of the data logger. The fault was always obvious, and the affected dataset could be excluded from the overall analysis.

Two raingauges were installed in close proximity to one another at the Pared yr Ychain and Hermon soil throughflow experimental sites, to ensure uninterrupted rainfall records for these sites. It was found that the raingauge records were consistent to within 1mm during any specified time period, and the instruments recorded equivalent total storm rainfall values. A discrepancy of 1mm for any time period is to be expected, due to unpredictability in the exact moment of tipping of the collecting spoon of each instrument.



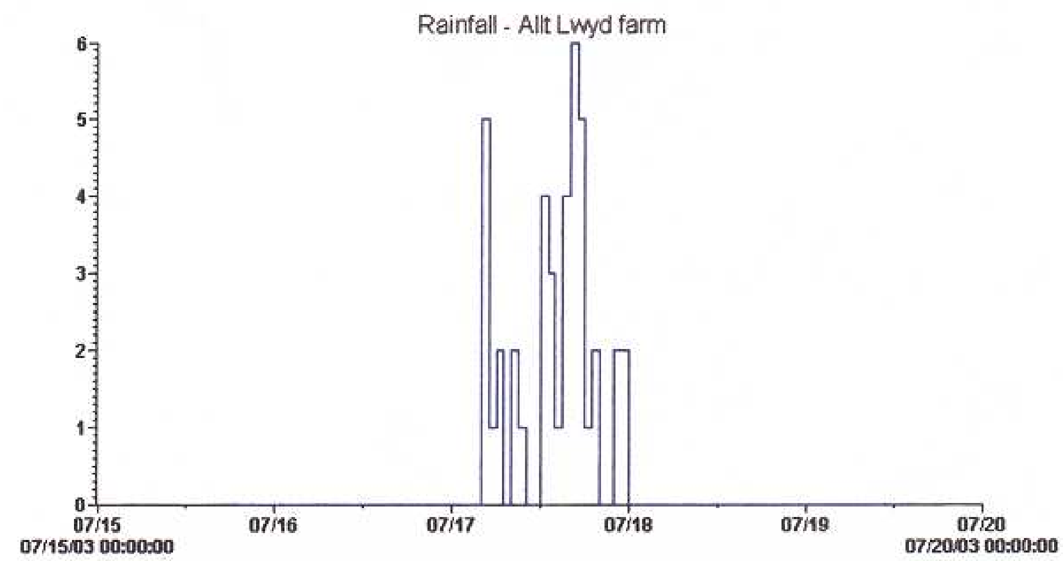


Figure 5.2: Comparison of rainfall at the valley location of Allt Lwyd and the nearby mountain location of Waen y Griafolen

Whilst the focus of the research was to identify regional patterns of storm rainfall, interesting localised topographic effects were also discovered. Raingauges were installed at the head of the Allt Lwyd valley at an altitude of 300m, and at the watertable monitoring site on the Waen y Griafolen blanket bog at an altitude of 425m. The gauges were 2km apart. It was found that rainfall was consistently higher at the valley site than on the adjacent blanket bog plateau. Typical storm rainfall recordings are given in fig.5.2. An explanation may be that the prevailing moist westerly airflow channelled along the Allt Lwyd during storms is forced to rise at the valley head, initiating the condensation of raindrops. A relatively thick layer of moist air infilling the valley then provides conditions suitable for rainfall enhancement by the seeder-feeder mechanism.

Further insight into the microclimate effects of deep valleys within the Mawddach catchment is provided by wind data. Automatic weather stations were operated at Coleg Meirion-Dwyfor in Dolgellau and Aran Hall School, Rhydymain, during the years 2002-3. At both locations, wind direction shows a bimodal distribution up and down valley, with cross-valley winds relatively infrequent. Periods of heavy rainfall are strongly correlated with up-valley winds, as in the example graphs for February 2003. More than 90% of rainfall events during the recording period occurred with winds from the NW in Dolgellau and SW at Aran Hall. During the same period, the airflows at middle troposphere levels show a wide variety of trajectories from the northern, western and southern quadrants.

By the end of 2003, the rain gauge array appeared to be adequate to determine the detailed rainfall distribution patterns for individual storm events. Although each raingauge site needed to be reasonably accessible by four-wheel drive vehicle and mountain path, it was possible to add key upland sites near mountain summits in the Rhinog and Aran mountains. Isohyet maps for storm events appeared as smooth contoured surfaces across the region, with no apparent anomalies in the data.

Three rainfall distribution patterns were identified for storms within the Mawddach catchment:

> In the Type A1 pattern, a zone of high rainfall crosses the Mawddach catchment on a diagonal axis from Trawsfynydd in the NW to Pared yr Ychain in the SE. A single rainfall maximum occurs in the centre of the catchment, around Coed y Brenin and Rhobell Fawr. This pattern is associated with a dominantly west-south-westerly airflow.

> In the Type A2 variant, rainfall maxima are located at the two ends of the axis of high rainfall from Trawsfynydd to Pared yr Ychain . This pattern is associated with a dominantly south-westerly airflow.

Both of these patterns represent situations in which the approaching moist airflow is channelled up the Mawddach estuary and into the Wnion and Mawddach valleys. The locations of maximum rainfall correspond with the closures of the valley systems on the Trawsfynydd plateau and at the head of the Wnion at Drws y Nant. It may be the case that the valley air flow is forced upwards at these points, causing further uplift in unstable middle troposphere layers and initiating rainfall by a seeder-feeder mechanism.

> In the Type B pattern, a zone of high rainfall is oriented north-south along the line of the Rhinog mountain range. This pattern is associated with a dominantly south-south-westerly airflow.

Weather systems approaching from the SSW cross over the Mawddach estuary and Wnion valley, impacting instead on the long ridge of the Rhinog mountain range where rainfall is concentrated.

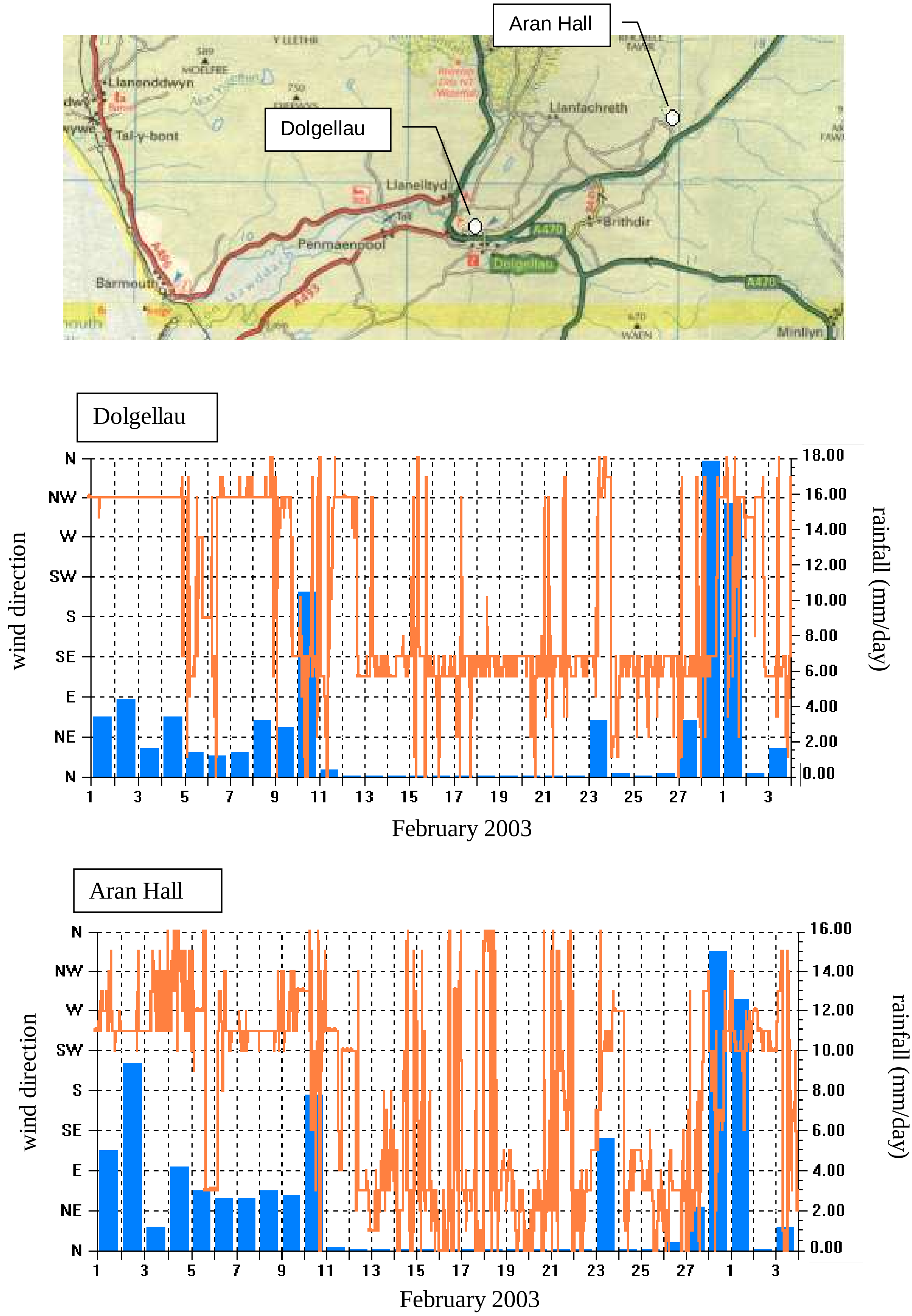


Figure 5.3: Relationship between rain periods and wind direction in the Wnion valley, February 2003

Dominant wind directions may be linked to the orientation of warm fronts. Type A1 rainfall patterns are typically produced by N-S oriented warm fronts. Type A2 patterns are typically produced by NW-SE oriented warm fronts. Type B patterns are typically produced by W-E oriented warm fronts. During an individual rainfall event, the orientation of a front may change as it crosses the Mawddach catchment, leading to a change in rainfall pattern between the early and late stages of the rainfall event. The rainfall patterns generated across the catchment are therefore seen as a complex interaction of mesoscale weather systems with the mountain topography to generate short-lived microclimate effects within individual valleys or over individual mountain blocks.

It is apparent that an axis several kilometres wide of consistently high rainfall exists across the Mawddach catchment from Coed y Brenin, through Rhobell Fawr to Pared yr Ychain. Within this axis, the growth of natural vegetation is exceptionally prolific (fig.5.4). This is the area where catchment management practices can be most effective in controlling downstream flooding whilst at the same time conserving important natural habitats.

Figure 5.4: Localities on the axis of high rainfall across the Mawddach catchment. (above) Forestry plantation at Hermon, with prolific *Polytrichum* moss growth, (middle) Waen y Griafolen blanket bog with *Sphagnum* moss and *Juncus* (soft rush), (below) Pared yr Ychain, with prolific growth of *Vaccinium* (bilberry).

In the high rainfall zone of the Mawddach catchment, it is common to observe clouds of water vapour drifting up hillsides into the forestry plantations (fig.5.5), where the saturated air remains for extended periods, condensing on branches and tree trunks. This mechanism might be termed 'cloud catching'.

Figure 5.5: Mist drifting into forestry plantations. (above) Pared yr Ychain, (below) Hermon

Relative humidity was recorded over a one year period at two sites in forest plantations at Hermon on the high rainfall axis. Results are presented in fig.1.81 of chapter 1. Relative humidity was close to 100% for long periods within the forest. It appears that the damp moss ground vegetation was both maintaining this humidity and benefiting from it to promote growth.

Meteorological modelling

The MM5 model uses global atmospheric gridded data which is available for Internet download from the US National Centre for Environmental Prediction (NCEP) at 6-hourly intervals. Whilst the model gave satisfactory 6 hour rainfall predictions, the accuracy of 12 hour or 24 hour predictions were not investigated. It is anticipated, however, that these longer forecasts would give general indications of developing critical situations.

In the course of the project, various options have been chosen within the MM5 package for cloud microphysics and planetary boundary layer physics schemes, and a combination found which gives best results for the Mawddach model. A neural network was examined as a method for improving initial rainfall forecasts. This could produce a small but useful increase in accuracy.

The general patterns of frontal rainfall are reproduced well, both temporally and spatially. Rainfall distributions obtained from MM5 are in better agreement with field raingauge readings than rainfall radar over the North Wales area. It is difficult to assess the model results with absolute certainty, since they are being compared to a rainfall distribution based on a widely spaced network of raingauges over a region where microclimate effects may be locally significant. Rainfall predictions using MM5 in a 6 hour forecasting mode for frontal events are likely to be in the order of 30% accuracy for individual point values, or 15% accuracy if rainfall averaging across the catchment is allowed.

MM5 proved to have greater difficulty in predicting convective events accurately. Alternative convective physics schemes within the MM5 package gave very different analyses for the 3 July 2001 storm, ranging from a fairly accurate squall line rainfall representation to a complete failure to predict the storm rainfall.

The Anthes-Kuo scheme corresponded well to the sparse rain gauge data available, and give a rainfall distribution which was largely consistent with field observations of flood damage and maximum river levels. The Grell scheme considerably underestimated rainfall volumes. It may be the case that the Grell scheme is more suited to modelling isolated convective storms rather than structured pre-frontal squall line activity.

Due to the scarcity of convective storms within the Mawddach region, it has not been possible to test whether the convective physics schemes are consistent in their abilities to predict storm rainfall. In view of the uncertainty over the modelling of convective storms, the best approach appears to be an ensemble run when thunderstorm activity is anticipated; multiple models will be run using different convective schemes, with attention paid to the prediction of a convective storm by any individual model. It seems that MM5 is more likely to miss an event than to overestimate rainfall.

A pleasing feature of the MM5 model is its ability as a process model. Diagnostic plots could be obtained to illustrate and explain the structure of frontal storm rainfall and squall line convective events. The model can realistically recreate the valley and mountain microclimate effects which were evident from field monitoring, giving confidence in the accuracy of the atmospheric physics schemes implemented by the model .

Future developments in meteorological modelling

Since the start of the project, considerable developments have taken place in the field of numerical weather prediction in the USA. Several software systems including MM5 were in use, but a decision was taken to combine work into a single model by collaboration between NCAR (National Center for Atmospheric Research) and NOAA NCEP (National Oceanographic and Atmospheric Administration National Center for Environmental Prediction). The new system being developed is WRF, the Weather Research and Forecasting model (Scamarock et al., 2007; Wang et al., 2006).

WRF makes use of many of the physics and mathematics concepts developed in MM5, and extends these to produce a standard software system suitable for both operational weather forecasting and theoretical studies of weather systems. The model can operate on resolutions down to a 1km grid, and can be run in fast parallel processing mode on a wide range of computer systems from stand-alone and networked microcomputers to mainframe computers. An increased range of atmospheric physics modules are being produced for simulating cloud microphysics, cumulus convection, and planetary boundary layer processes. It is recommended that current users of MM5 make a transition to the WRF model where future development efforts will be concentrated.

WRF has many similarities with MM5 in the way that the model domains are set up and ground surface characteristics are initialised. Running the model follows a similar sequence, and output can be displayed graphically in a similar manner to MM5. There should be no technical difficulties in establishing a WRF model for the Mawddach region.

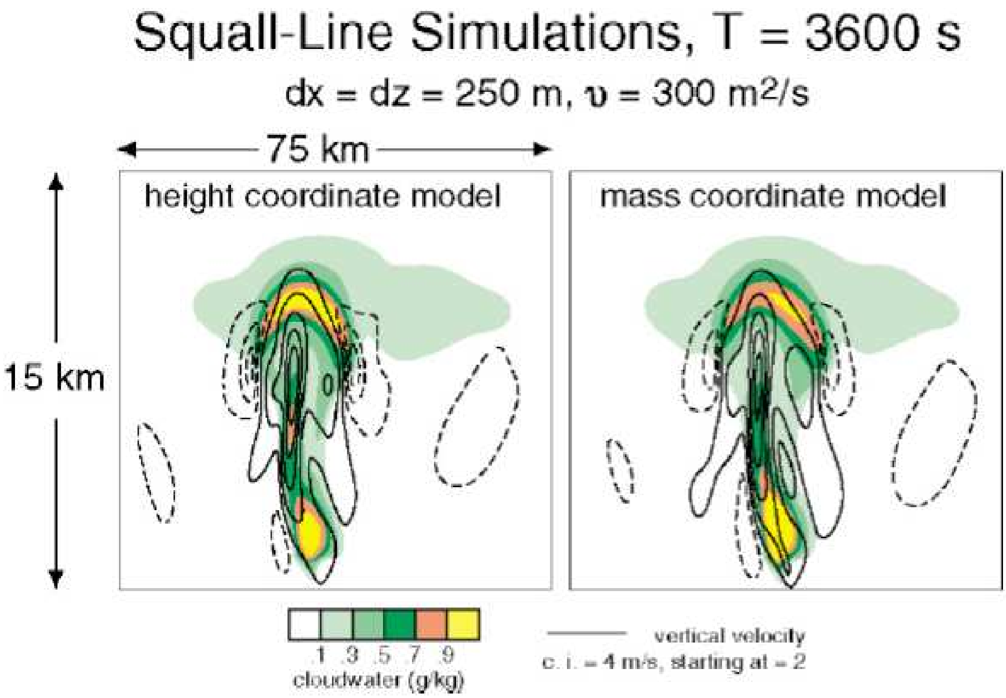
WRF is currently being used as the daily operational weather forecasting system for Shanxi province, China (Chen et al., 2007). The system uses nested grids of 45km, 15km and 5km. It produces forecasts up to 48-72 hours twice a day. The model is initialised using the NCEP global forecast system. The Kain-Fritch cumulus parameterisation scheme has been chosen, and the authors find that it produces acceptably accurate forecasts of rainfall location and amount for summer convective precipitation events.

Various studies have been carried out to compare the forecasting abilities of MM5 and WRF. Deng et al. (2007) compared high-resolution MM5 and WRF weather simulations for the 2006 Torino Winter Olympics in Italy, concluding that there was no significant difference in accuracy between the two models. Ha et al. (2007) compared precipitation forecasts by MM5 and WRF for the Korean Peninsula during the summer monsoon season. They concluded that the accuracy of the two programs was similar, but that an ensemble of the MM5 and WRF models together could produce better forecasts than either single model. Perhaps it is a little early for WRF to have developed the improved physics schemes which should ultimately increase its forecasting accuracy.

The problems of modelling convective rainfall became apparent in the Mawddach MM5 model for the July 2001 storm. Convective modelling is perhaps the most active current area of research in numerical weather forecasting. Redelsperger et al. (2000) and Bechtold et al. (2000) discuss the TOGA-COARE project to investigate and model tropical squall lines. Takemi (2006) examines the modelling of stability and shear in squall-lines using WRF. It is likely that progress will soon be made in developing improved convective schemes for incorporation into the WRF model.

The main advantage of WRF over MM5 lies in its ability to provide a test bed for modelling idealised cases of meteorological processes on a variety of scales. This allows researchers to investigate and understand the physics involved, to identify discrepancies between the model and observed behaviour, and to formulate improvements to the WRF physics code in order to better simulate real weather systems in operational mode. A number of idealised cases have been developed so far, and additional cases are being added. The current cases include two convective examples: a two-dimensional squall line simulation and a three-dimensional supercell simulation (fig.5.6).

2D squall line simulation



3D supercell simulation

Height coordinate model

(dx = dy = 2 km, dz = 500 m, dt = 12 s, 160 x 160 x 20 km domain)

Surface temperature, surface winds and cloud field at 2 hours

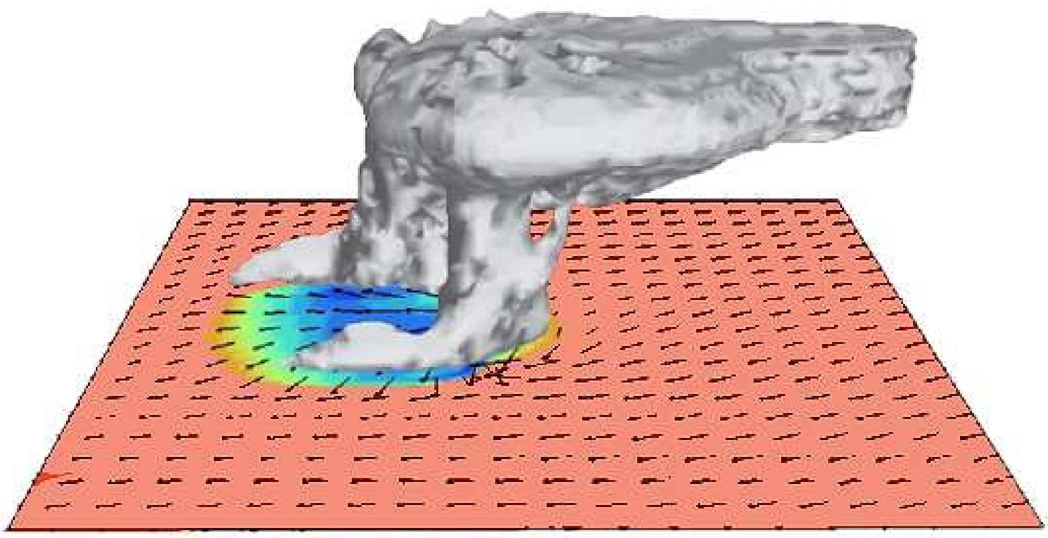


Figure 5.6: Idealised convective case studies for the WRF meteorological model

Progress in accurately forecasting rainfall over North Wales seems to depend on an improved understanding of the interactions of mesoscale weather systems with the mountain topography, which in turn can lead to modifications in the physics schemes used in the meteorological model. The WRF system provides an opportunity to undertake experimental work of this nature.

An example of idealised modelling of the orographic effects of the mountains is the study by Schneidereit and Schär (2000) of the Alpine Piedmont extreme flood of 1994. They use a high resolution mesoscale meteorological model to effectively simulate the effects of the Alpine mountain range on precipitation patterns, thereby gaining insight into the meteorological processes responsible for the storm rainfall. A key feature of the study is that the alpine mountain range is initially modelled as a simplified geometrical shape. Complexities caused by local topography can be eliminated at the first stage of analysis, but can be progressively reintroduced as the model is developed in an increasingly accurate simulation of the real case.

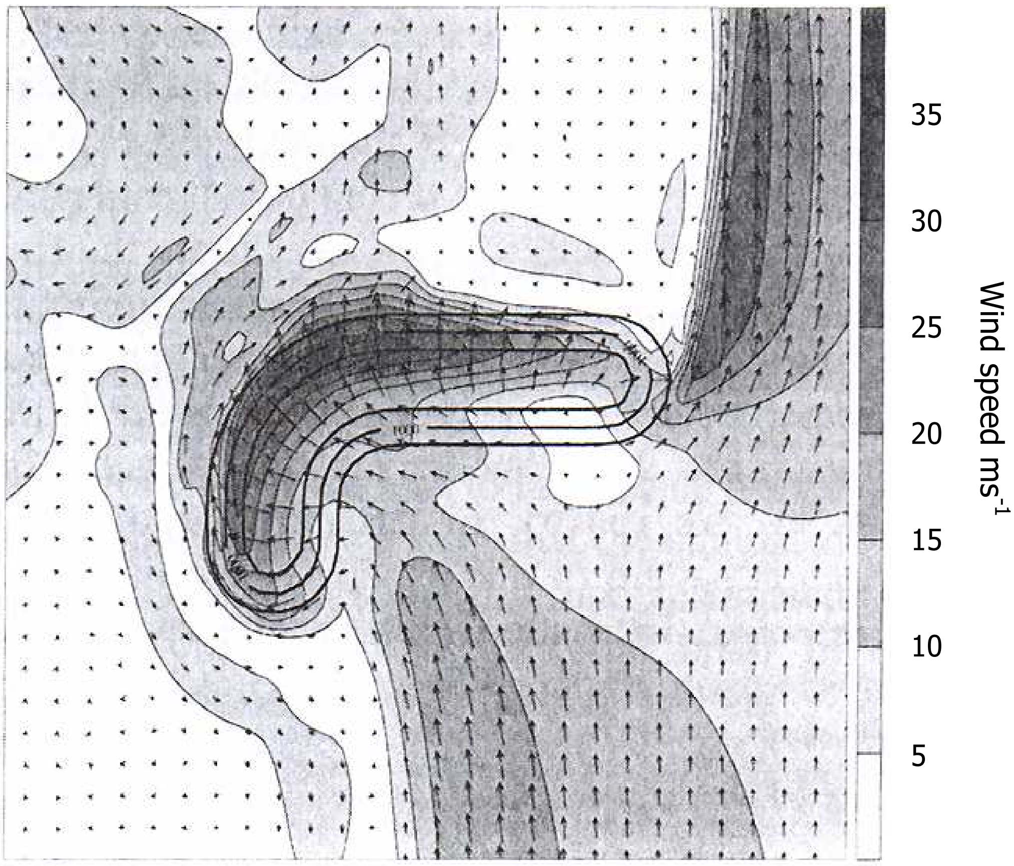


Figure 5.7: Example result from the idealised Alpine model of Schneidereit and Schär (2000)

5.3 Hydrology

A principal objective of the project was to gain an understanding of the hydrological processes operating in the Mawddach catchment, as a basis for developing a flood forecasting model and to help in identifying management options which could reduce the severity of flood events. It was anticipated that a compromise would be necessary when developing the model, between including all possibly relevant hydrological aspects of the catchment, and producing a system to run reasonably reliably on a time scale suitable for operational flood forecasting.

A starting point for field investigations was the examination of run-off and throughflow processes. This was done by the construction of a series of hillslope waterflow monitoring sites which were operated during the period 2002-3.

River hydrograph data was essential to the calibration and validation of hydrological models. At the commencement of the project, one hydrograph recording station was operating on the Afon Mawddach at Tyddyn Gwladys, and one on the Afon Wnion in Dolgellau. It was necessary to augment this data with hydrographs for other points within the river system, and a search was made for a suitable hydrograph recording instrument which could operate on steep and fast flowing mountain reaches. After initial experiments with an ultrasonic device proved unreliable, a good solution was found in the barometric water depth recorder developed by Malcolm Murgatroyd. Hydrographs were recorded at a further six locations around the Mawddach catchment.

The deep river gorge topography of Coed y Brenin suggested the possibility of groundwater resurgence through river bed gravels during and after storms, which may have some effect on flood events. To investigate this theory, a river bed temperature monitoring experiment was carried out for six months during 2003 on the Afon Wen at Hermon.

Reconnaissance surveys of the Mawddach catchment identified a number of areas of peat blanket bog with the largest, Waen y Griafolen, forming the source area for the

Mawddach itself. It was expected that these areas of peat would act as significant water absorbing stores which would gradually fill over the wetter winter months and drain down slowly over the drier summers. Boreholes fitted with electronic water level recorders were established at Waen y Griafolen, and at Cefn Clawdd in a blanket bog at the foot of the Rhinog escarpment, in order to examine changes in water table over the course of a year.

A main focus of the modelling was to determine the timing and extent of overbank flooding in the lower valleys of the Wnion and Mawddach, particularly in so far as it affects the town of Dolgellau. It was of interest that flood plain forestry has been advocated as a method of enhancing temporary water storage and reducing the severity of peak flooding downstream. Opportunities may exist for re-establishing floodplain wet woodland in the lower Mawddach and Wnion valleys, and an evaluation of possible schemes became a part of the project. In order to calibrate floodplain models for different land use scenarios, field mapping was carried out at three locations on the Mawddach where peak flood levels from the July 2001 flood could be readily identified.

Over the course of the project, it became increasingly apparent that large volumes of sediment were being eroded, transported and re-deposited within river system during flood events. This material ranges in size from fine sand to coarse gravel and cobbles. Concern had been expressed in Dolgellau at the large accumulations of sediment in the area of Bont Fawr which were thought to increase flood risk for the town. This material is periodically removed by the Environment Agency, but accumulations soon re-appear. Modelling of sediment movement was carried out for two major flood events on the Mawddach and Wnion, and field evidence collected to assess the accuracy of the model.

The coastal nature of the catchment allows for the further complication of river-tidal interactions. At the commencement of the project, it was expected that high tides might combine with flood flows on the rivers Wnion and Mawddach to produce exceptionally severe flooding around the head of the estuary. To test the extent of river-tidal interaction, a series of hydrographs were recorded within the estuary and at the river tidal limits.

Hillslope runoff

It was expected that hydrological modelling of the Mawddach catchment would present a considerable challenge. Events since the Devensian ice retreat have left a mosaic of glacial, periglacial and recent deposits with contrasting hydrological properties on an already complex pattern of bedrock. Subsequent agricultural and forestry practices have further modified soil profiles.

Field observations provide ample evidence of the operation of both shallow throughflow and surface overland flow processes during storm events (fig.5.8). Release of throughflow at rock outcrops and cuttings is common, and may continue for long periods after a rainfall event. Wet flush areas are frequently found at the bases of hillslopes where water is released to surface overland flow during storm events.

In order to quantify the hillslope processes operating in the catchment, a series of experimental sites were constructed on hillslopes of differing parent material: boulder clay till at Pared yr Ychain and periglacial sands, solifluction deposits and scree at Hermon. The design of the monitoring sites is described in chapter 3 above.

The experimental site at Tir Penrhos, Hermon, was cut into a thick succession of sandy solifluxion deposits flanking the valley side and now forested. Moderate volumes of surface runoff were recorded during each rainfall event, but throughflow down to a depth of 1.6m below the surface was generally absent. Only after a series of heavy and closely spaced storm events did throughflow appear, but then in great quantities which were beyond the recording limits of the tipping bucket gauge in use. It was of great significance that these periods of heavy throughflow corresponded exactly with periods of flooding of the lower Mawddach valley some 8km downstream. It appears that saturation of the substantial quantities of periglacial valley deposits in the middle course of the Mawddach is a necessary antecedent condition for flooding Once these deposits can no longer deeply absorb and slowly release rainwater, a switch occurs to a fast shallow stormflow and surface runoff mechanism. Subsequent rainfall rapidly enters surface watercourses to create a downstream flood peak.

Figure 5.8:
Examples of sub-surface throughflow and overland flow.
(left) Throughflow in ranker soil released over a rock outcrop, Pared yr Ychain. Flow is continuing after a period of four weeks in summer with no rainfall.
(below) Hillslope locations around Rhobell Fawr where surface water flows emerge after rainfall. These wet flushes are marked by *Juncus* soft rush.

An opportunity exists for instrumenting a soil throughflow site in the Coed y Brenin area, as a means of predicting the precursor conditions for flooding during the next rainfall event.

Three sites were established around the village of Hermon to monitor surface runoff only for hillslopes of different land use: conifer plantation, clear felled hillside, and grassland. Results are presented in chapter 1. The most striking feature of this investigation was the contrast in soil profile between the forest and clear felled sites. It is apparent that a thick forest brown earth, originally present at both sites, was washed out from the felled area over a short period after the trees were harvested. This is likely to have followed the die-off of the moss ground vegetation in dry conditions. The increased runoff rates observed for the clear felled hillside in comparison to the forest appear to be directly related to the differences in soil profile, with reduced absorption capacity resulting from the soil erosion process.

Runoff from the grassland increased significantly in comparison to the forest site after a crop of grass was cut from the field for silage during the summer. It was unexpected that such a minor and normal agricultural activity could have a noticeable affect on hydrological processes, and makes it doubtful that the precise calibration of a hydrological model for a dynamic landscape is ever possible.

Soil throughflow sites were constructed at Pared yr Ychain in glacial till, with collecting points at the surface and at a depth of 1.6m. During construction, the glacial till appeared to be very hard and compact grey clay containing pebbles and rocks of varying sizes, and it was anticipated that little or no throughflow would be possible through this material. It was with great surprise, therefore, that substantial amounts of throughflow were recorded during almost every storm event: often exceeding the volume of surface runoff by a factor of ten or more. On closer examination it was found that the glacial till was derived from acid igneous rock, and has a substantial sand fraction accounting for its permeability when wet. It seems that scientists should be cautious in ascribing hydrological properties on the basis of map descriptions alone.

After a series of closely spaced rainfall events, the flow through the Pared yr Ychain till was so great that it exceeded the recording rate of the gauge in use. Modifications were made to the throughflow collection system, so that the flow was equally divided amongst nine outflow tubes. Only one fraction was measured (fig.5.9). This arrangement provided a satisfactory method of estimating total throughflow at the site.

Figure 5.9: Modifications carried out to throughflow monitoring sites at Pared yr Ychain by the introduction of a flow divider to increase measurement capacity.

Substantial difficulties exist in measuring hillslope throughflow. The sites could not be excavated down to bedrock due to the thickness of the superficial deposits, and substantial volumes of hillslope throughflow would have been passing beneath the collecting point. Flow paths may also be disturbed by construction, with the possibility of water being drawn to the collection point from adjacent bands of the hillside. Nevertheless, the experiments have provided a valuable understanding of throughflow processes and produced some unexpected and important results which have consequences for hydrological modelling. From a quantitative point of view, the experiments provided evidence for the relative volumes of throughflow and surface runoff for different storm events, and provided an estimate of the timescale over which the throughflow and runoff processes would continue after the storm event.

River flows

Hydrograph recording was undertaken at six sites in the Mawddach and Wnion catchments to augment the data available from the Environment Agency gauging stations at Tyddyn Gwladys and Dolgellau:

- An adequate coverage of storm hydrographs was needed for calibration and validation of the hillslope runoff models used in the project, so additional hydrograph recording sites were chosen on the middle courses of the Afon Gain, Afon Wen and Afon Eden.
- Hydrographs were recorded during the investigation of particular hydrological processes within the catchment: monitoring the outflow from the Waen y Griafolen blanket bog, monitoring the river flow at the Pared yr Ychain hillslope runoff experimental site, and investigating river-tidal interactions at the head of the Mawddach estuary.

Hydrographs have been produced by barometric water depth recording. The measurement technique depends on a series of stages. A relationship is first found between the water depth at the recording point and the voltage output by the instrument. A surveyed cross section of the channel is used to determine the cross-sectional area of the water flow for the particular water depth. The final stage is to estimate the flow velocity, and thereby calculate the river discharge (m^3/s).

It was found that a stable linear relationship existed between water depth and output voltage, allowing depth to be recorded with confidence to the nearest centimetre.

Valley and channel cross-profile surveying was carried out at times of low water when it was safe to enter the river with surveying equipment. Points were recorded at intervals of 0.5m across the channel, with more frequent spacing where breaks of slope occurred. In mountain rivers, there is a real possibility of the river cross profile changing between or during storm events. Sites were chosen where the bed and banks appeared relatively stable, and cross-profiles were resurveyed on several occasions. In practice, no significant changes in cross section occurred at the hydrograph sites during the recording periods.

The greatest uncertainty arises from the measurement of flow velocity in the river channel. A propeller flow meter was used for measurement, and appeared to be accurately calibrated by the manufacturer to a tolerance of better than 0.1m/s. However, the actual measurement of flow within the river could present serious practical difficulties:

- Water velocity would vary significantly at different points within the cross section. Flows were not necessarily stable, with flow velocity changing at the same point over short time periods through turbulence. Under low flow conditions it was possible to largely overcome these difficulties by taking multiple recordings of flow at different points across the width and depth of the channel, and by integrating the flow measurement over a period of 30 seconds to eliminate short interval perturbations in the flow.
- Under conditions of storm flow, difficulties in flow measurement became much more severe. It is generally not safe to enter the mountain rivers of the Mawddach catchment when they are in flood. Water depth and velocity can increase dramatically, and overbank flooding can make access to the recording sites difficult. A technique was developed for lowering the propeller flowmeter into the channel by means of a long metal pole, then making a series of readings at different positions across the channel. Velocity values were often obtained which varied by a factor of four or more across the flow, so there must be significant uncertainty in data collected under flood conditions.

In order to evaluate the quality of the data obtained in the field, additional theoretical calculations of flow velocities were made using Manning channel roughness and slope equations. It was found that a reasonable agreement between field data and theoretical flow rates existed, and satisfactory calibration curves for each hydrograph site were constructed.

There was still some concern as to the accuracy of the hydrograph data, so results for individual storm events were correlated with the hydrographs recorded at the Tyddyn Gwladys gauging station. This site operates at a section of artificially straightened river channel within a plane bed reach, giving a good degree of accuracy in both water depth measurements and river stage – flow velocity calibration. The Tyddyn Gwladys measurements were accepted as correct, and the project hydrograph calibrations were adjusted as necessary to ensure consistency within the river flow system. Only minor adjustment of the Afon Gain and Afon Wen calibrations were necessary, with the Afon Eden calibration appearing satisfactory for each storm event.

In general, a natural river cross section had to be accepted for the hydrograph recording site, and the consequent complexities in flow patterns accepted. The single exception was at the outlet stream of the Waen y Griafolen peat bog, where it was possible to create a V-notch weir from rocks in order to facilitate flow measurement (fig.3.207).

Hydrograph recorders were equipped with data loggers which stored output voltages at intervals of 5 minutes. Clocks were synchronised electronically between the data loggers to within a couple of seconds. The response of the instruments was almost instantaneous when water levels changed. Considerable confidence could therefore be placed on the relative timings of flood hydrograph peaks for the different gauging points within the river system. This provided a valuable check on the suitability of the river routing functions in the hydrological models.

Groundwater effects

There is widespread evidence of the importance of shallow throughflow in superficial deposits during storm events in the Mawddach catchment, so it was of interest to investigate whether water flow through bedrock could also play a part in flood events. A number of major fault lines control the orientation of river reaches within Coed y Brenin, and may provide conduits for groundwater resurgence at times of elevated water table.

Experimental investigation of groundwater resurgence was carried out by river bed temperature monitoring in the Afon Wen at Hermon. River bed gravel was excavated, and a metal bar was used to penetrate through the river sediment until bedrock was encountered at a depth of 1.5m. Plastic tubing carrying an electronic temperature probe was threaded down to the rock interface. River gravel was repacked around the tubing, taking care not to allow direct channel flow by bending the route taken by the tube. A second tube carrying a temperature probe was emplaced in gravel on the upper surface of the river bed. Both instruments were connected to a data logger which recorded temperatures at 5 minute intervals using the same clock. A check on calibration of the temperature probes prior to installation showed that they were consistent with one another, and appeared accurate to within 1 degree C in comparison to an alcohol thermometer.

Results from the river bed temperature experiment are reported in chapter 3. The experimental results are consistent with a MODFLOW groundwater model for the Afon Wen valley, suggesting that groundwater release can increase storm river flows by between 5% and 10% in the deeply incised valleys of the Mawddach and its tributaries in Coed y Brenin. However, this water release occurs over a period of 12 to 24 hours. This is largely after the peak storm river flow has passed, and it is concluded that groundwater release has a negligible effect on the peak discharge during storm events.

The river bed temperature monitoring experiment was very limited in its scope, but gave interesting results. The technique could be extended to other river reaches where bedrock faulting or topography suggest that storm water resurgence is likely. The gorge sections of the Gain and Mawddach within Coed y Brenin would be appropriate sites for further work.

Groundwater resurgence has been modelled using MODFLOW. This program is based on Darcy's flow equation, and is intended primarily for use in models of permeable strata such as sandstones.

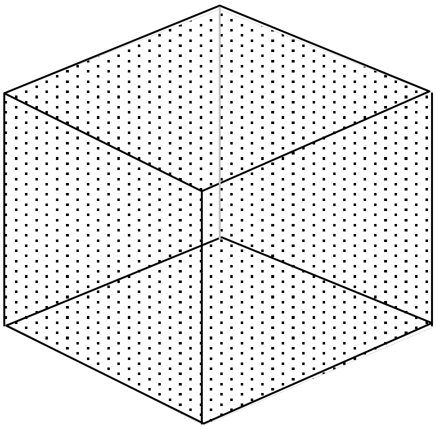


Figure 5.10(a). Theoretical model of permeable material with interconnecting pore spaces, as used by MODFLOW

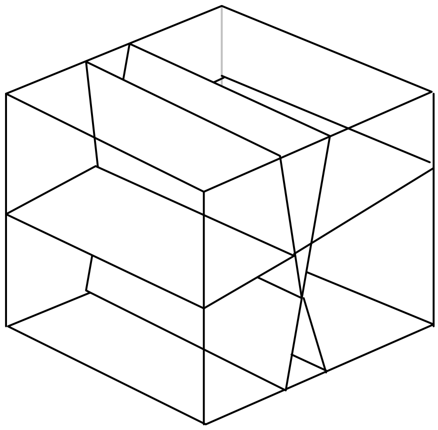


Figure 5.10(b). Theoretical model of fractured impermeable material with groundwater flow planes intersecting cell boundaries, as used in the Svensson (2001) model

A more sophisticated representation of flow through fractured hard rock is provided by the model of Svensson (2001). The model treats the bedrock as a solid substrate intersected by a fracture system connecting the faces of cells. Flow through the cell is determined from

$$Q = K\Delta h \sum \frac{HW}{L}$$

where a sum is obtained of the height (H), width (W) and length (L) dimensions of fractures intersecting the cell boundaries. A constant thickness h and hydraulic conductivity K is assumed for the fracture planes. This approach appears promising as a means of modelling water flows within the Mawddach fault zones, where the orientation and density of fractures could be estimated from well exposed rock outcrops in the gorge sections of the rivers.

Peat blanket bogs

The project investigated the hydrological characteristics of upland peat bogs by carrying out a detailed survey at Waen y Griafolen at the headwaters of the Mawddach.

The study began with geophysical and auger surveys to determine the stratigraphy and depositional history of the blanket bog. Results are reported in chapter 3. Two contrasting peat types were found: older peat which is highly humified and gelatinous in texture, and younger peat which has an open texture of undecomposed plant material. The older peat forms the higher areas of the blanket bog, with the younger peat infilling a relict river channel system incised into the upper surface plateau surface of the bog.

A sample of tree root was collected from a palaeosoil at the base of the older peat and sent for dating by the Radiocarbon Accelerator Unit, Oxford University. An age was obtained of 8905 ± 45 years before the reference year AD 1950, placing the date of first peat accumulation as shortly following the retreat of the Devensian valley glaciers. By correlation with other peat locations, it is likely that the channel system containing the younger peats was cut during a wet climatic period at 2 800b.p.

Water levels in the peat were monitored over a period of 12 months using a central borehole with continuous water level recording, augmented by a ring of eight dip wells around the margins of the bog.

The site chosen for the central borehole was on a plateau surface of older humified peat with heather vegetation. The borehole casing consisted of a 2 metre length of 4 inch diameter plastic tubing, perforated with small holes over its full length. The lower end of the pipe was closed to prevent entry of gelatinous peat. The pipe was emplaced in a hole drilled by auger. The borehole was equipped with a barometric depth recorder of the type used for river hydrograph recording. The instrument was found to read accurately to within 1cm. Readings were collected over the 12 month period without interruption, and no problems were experienced the equipment.

A tipping bucket raingauge and data logger were installed on a low wooden post adjacent to the borehole.

The array of dip wells consisted of 1.5 metre plastic tubes of 1.5 inch diameter, perforated with small holes over their full length. These were inserted into holes drilled by auger. Water levels in the dip well tubes were read manually approximately one month.

The water table at the borehole was found to rise by approximately 1cm per hour during a storm event. The peat could become totally saturated in the course of a couple of days heavy rainfall following a long period of dry weather. This lack of long term storage capacity was a considerable surprise. Following rainfall, the water table showed a slow linear fall of approximately 1cm per day over the subsequent dry period. It was apparent that the older peat areas quickly became saturated with pools of standing water appearing during rainstorms. Runoff appears slow due to the very gentle slopes of the central area of the bog.

The outflow stream from Waen y Griafolen was monitored during the survey period. Outflow remained almost constant for long periods between rainfall events, and may be attributed to deep penetration of streams into the low permeability gelatinous older peat which releases water slowly and steadily.

During storm events, water accumulates in the channel system infilled by younger peat. This wet mass of mosses, rushes and sedges acts as a reservoir, regulating water flow out into the river system. An array of shallow ploughed drainage ditches were cut on the surface of the older peat in the mid 20^{th} century with the intention of producing improved grazing, but these have been largely ineffective in draining the bog. The ditches locally increase the rate of surface flow into the incised channel system, but flow through the younger peat appears to control overall discharge to the outlet streams. Modelling using MODFLOW has suggested that a loss of the younger peat and reversion to open gravel river channels would almost double the peak storm discharge from the blanket bog.

Floodplain overbank discharge

A central objective of the project was to determine the relationship between river flows and the extent of flooding in the lower Mawddach and Wnion valleys, particularly around the town of Dolgellau.

Photographic evidence was collected for a series of flood events of different severity in Dolgellau during the project. The extents of flood plain inundation were related to flow rates of the Afon Wnion. Models were constructed for the lower Wnion valley using River2D software and gave predicated flood patterns around the town of Dolgellau consistent with field observations.

It seems possible to accurately predict the extent of flooding in Dolgellau during a storm event based only on an accurate forecast of flow rate for the Afon Wnion. Flooding of low lying fields begins at a flow rate of $150m^3s^{-1}$. Flood waters enter the Marian and Bont Fawr areas of the town at a flow rate of $200m^3s^{-1}$. At a flow rate of $300m^3s^{-1}$, the road system is disrupted and buildings close to the river will be flooded. In a worst-case scenario for Dolgellau, the shopping area of Bridge Street, the Industrial Estate and the area around the Leisure Centre would be inundated. However, the section of the town considered to be at any conceivable risk from flooding is substantially less than the area marked on the Environment Agency Flood Map.

A number of authors, for example Peterken and Hughes (1995) and Thomas and Nisbet (2004) advocate the planting of wet woodlands on floodplains as a means of enhancing flood water retention and reducing peak flood river flows downstream. It was of interest to determine whether such a method could be used to reduce flood risk for the town of Dolgellau.

Limited data is available concerning the hydrological effects of floodplain forests. It is likely that water flow modelling based simply on the ground surface roughness of the woodland will be oversimplified, failing to take into account the turbulence created by the upstanding tree trunks and branches within the flow. The River2D model provides an opportunity to add lateral turbulence, but it was necessary to determine an appropriate value for this coefficient. An opportunity to undertake this calibration came from a study of two floodplain areas in Coed y Brenin where wet woodland had been inundated during the July 2001 Mawddach flood, leaving clear evidence of maximum flood levels.

Detailed surveying of the Coed y Brenin floodplains at Tyddyn Gwladys and Cefn Deuddwr was carried out by levelling and triangulation, including detail of the channel bed and floodplain to beyond the maximum extent of flooding. Floodplain models were constructed with River2D software and simulations of the July 2001 flood were run, using recorded hydrograph data from the Tyddyn Gwladys gauging station. It was then possible to adjust floodplain ground roughness and lateral turbulence parameters in order to obtain a best fit between the modelled river boundary and the known maximum extent of flooding.

Modelling was carried out to evaluate two possible flood plain forestry schemes in the Wnion valley as a means of reducing flood risk in Dolgellau. A lower basin scheme between Dolgellau and Dolserau would have minimal benefits and is not considered feasible. An upper basin scheme between Dolserau and Bontnewydd could substantially reduce peak flood flows on the Afon Wnion by up to $50m^3s^{-1}$. The scheme may provide a cost-effective and environmentally preferable alternative to flood defence engineering works within the town.

River sediment

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. There is concern in Dolgellau that the accumulation of river gravel may increase the risk of flooding in the town. It was important, therefore, to investigate river gravel deposition as part of this project.

The GSTARS program was chosen for sediment transport modelling. Two flood events on the Afon Mawddach and Afon Wnion were selected for analysis: the intense short duration flood of 3 July 2001, and the less severe but extended flood sequence of 3-4 February 2004. The intention was to determine the relative volumes of sediment transported, and to assess the likely extent of deposition along the Dolgellau reach of the Afon Wnion as a result of the flood events.

In order to configure a GSTARS sediment model, it is necessary to obtain channel cross profiles and sediment size distribution data for each representative reach of the river system. The Mawddach above the tidal limit was divided into twelve sub-catchments, and the Wnion into eight sub-catchments. Over a period of time, around eight cross-sections were surveyed by levelling within each of the sub-catchments. At points along each cross-section, estimates were made of the percentages of different size fractions of sediment in the river bed or banks. Results of the modelling are reported in chapter 3.

The program was surprisingly successful in simulating the locations and extents of erosion and deposition which occurred during the July 2001 flood event, giving confidence that sediment transport was being computed realistically.

The peak rates of sediment discharge estimated by the GSTARS model are approximately one hundred times greater for the July 2001 flood, in comparison to the February 2004 flood. This is consistent with field observations of exceptional river bank erosion to a height well above normal flood levels, and extensive deposition of fine sediment across agricultural land in the lower valley of the Mawddach. It must be taken into account, however, that the February 2004 flood continued for approximately ten times the duration of the July 2001 flash flood, so the overall movement of sediment was considerable. Floods approaching the magnitude of the February 2004 event are an annual occurrence within the Mawddach catchment. Over a period of time, the volume of sediment redistributed by annual river processes may be equal to, or greater than, the volumes of sediment redistributed during rare extreme events.

It is evident that significant amounts of gravel and finer sediment can be deposited along the river section through Dolgellau in the course of a single storm event. Modelling indicated that the prolonged sequence of storms in February 2001 could deposit over 1m of gravel in the course of one week. Gravel deposition raises the river bed level and increases flood risk. Deposition of 1m of gravel generates a similar increase in flood risk to a $50m^3s^{-1}$ increase in river flow rate.

The problem of gravel deposition in Dolgellau ought to be given serious attention. The current strategy of removing gravel periodically from the area of Bont Fawr is probably not adequate, since accumulation along the whole length of the lower Wnion will inevitably increase the river bed level throughout the town. Alternative proactive approaches are:

- to limit gravel supply by stabilising river banks which are cutting into soft glacial and periglacial deposits,
- to intercept gravel by means of weirs upstream of the town.

Tidal estuary

At the initial planning stage of the project, it was suspected that interaction between tidal and river flows could be potentially important in increasing the severity of flooding around the head of the Mawddach estuary and upstream towards Dolgellau. Hydrograph recordings were carried out in order to test this theory.

Water depth recorders were operated at Penmaenpool bridge, and close to the tidal limits on the rivers Mawddach and Wnion at the head of the estuary. Results are reported in chapter 3.

It was of considerable surprise that there appears to be no interaction at all between tidal and river flows. Tidal peaks travel up the estuary and beyond the confluence of the Mawddach and Wnion rivers with no change in water height. Flood peaks travelling down the rivers can, in turn, pass through tidal peaks without any apparent effect. Both perturbations in water level continue in upstream or downstream motion as if the other were not present. The answer to this apparently counter-intuitive situation seems to be the difference in mechanisms causing the perturbations. River flood peaks represent a general elevation of the water surface which gradually builds and declines over a period of several hours caused by a change in the water supply rate. The tidal peak, however, is a locally advecting gravity wave on the water surface travelling with a velocity of several metres per second. The celerities of the two waveforms are so different that no interaction can occur.

Although no additive effect occurs between river and tidal flows, it is still possible that an exceptionally high tidal peak could cause flooding around the head of the estuary. It is known that land reclamation has occurred in the upper estuary basin in historic times, and is still continuing on a small scale at the present day. It was considered important to evaluate the possible effects of further land reclamation of tidal flows in the upper basin.

Modelling of a scenario with additional reclamation of tidal marshes was carried out using River2D software, with the results reported in chapter 3. No increase in tidal peak was found to accompany land reclamation. The land reclamation did, however, have consequences in restricting the outflow of river floodwaters during storm events, and would worsen the effects of river flooding in the lower valleys of the Mawddach and Wnion.

The modelling of sediment transport during floods on the Mawddach and Wnion has been discussed. Large volumes of sand and gravel are carried downstream, and may be discharged into the tidal estuary. It appears that gravel becomes immobile a short distance downstream of the tidal limit, and large gravel banks are accumulating at this point. Gravel deposition around the head of the estuary increase river base levels. This in turn will reduce river gradients and flow velocities in the lower valleys of the Wnion and Mawddach, accelerating the rate of sediment deposition in these areas. The practical consequence of this observation is that gravel originating in the Mawddach sub-catchment may have on effect on future flood risk for Dolgellau, in addition to gravel originating in the Wnion sub-catchment.

The River2D program has been satisfactory for most of the work on floodplain modelling in this project, but has limitations in simulating the inundation areas of enclosed reclaimed land which lie below river level. For further detailed hydrological modelling of the upper estuary basin, it may be desirable to use a program specifically designed to simulate the effects of overtopping of sea walls during flood events. A suitable choice might be the two dimensional flood plain flow model of Beffa and Connell (2001).

5.4 Catchment modelling

Field investigations indicated that the main components of a conceptual flood model for the Mawddach catchment are: surface runoff, lateral flow at shallow depth, transfer between surface water and groundwater stores, river routing, and overbank flooding.

An objective of the project has been to establish a methodology for an integrated meteorological/hydrological model of the Mawddach catchment. It was considered essential to use a process modelling approach, in order that model parameters could be related to observable characteristics of the catchment and to allow the testing of alternative catchment management options.

In the course of the project, a series of software packages simulating different stages of the hydrological cycle have been examined and evaluated. A starting point was the HEC-1 hydrological model within the Watershed Modelling System. This program has performed well in simulating a variety of flood events over the Mawddach catchment. Synthetic hydrographs produced by HEC-1 were evaluated against field recordings for each storm event. It was possible to select values for infiltration, hillslope runoff and river routing functions which give consistently accurate simulations of flood peak flows and times to flood peak for different storms.

Limitations of HEC-1 have been demonstrated. The model assumes infiltration water is lost from the model, leading to an inability to model the slow release of stored groundwater back into rivers during the period following a storm. Consequently the receding limbs of the modelled hydrographs are found to be too steep. Where storm events follow in rapid succession, the model fails to recover soil moisture capacity. Saturation of increasingly large proportions of the catchment are assumed, and subsequent storm hydrograph peaks are overestimated. Notwithstanding the above limitations, HEC-1 could provide a basis for a reliable flood forecasting model for simple isolated storm events if provided with suitable rainfall forecasts from a model such as MM5.

River routing within the Mawddach catchment must take account of variations in flow regimes of mountain streams. 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. It was found that the specialist river package GSTARS could handle river routing well, in addition to its main function as a sediment transport model.

Crucial to a flood forecasting system is the provision of a floodplain model which can predict the extent and depth of overbank flooding in response to storm events. Several floodplain models were examined; of these, River2D proved to be the most mathematically stable in modelling the changing boundary of the river channel during flood events.

Initially it was considered that a groundwater component would be needed in the overall integrated system being developed for the Mawddach catchment. In particular, it was thought that groundwater modelling would be needed for areas of deep blanket peat, and also to represent river resurgence in the gorge sections of the Mawddach and its tributaries in Coed y Brenin.

Both fieldwork and simulations using the MODFLOW groundwater model suggest that the large peat blanket bogs of the Mawddach catchment rapidly become saturated during storm events, and most storm water flows occur by shallow throughflow or surface runoff.

Riverbed resurgence during storm events was shown to occur in the Afon Wen gorge, and by implication also occurs in the deeply incised valleys of the Mawddach and Gain. The volumes of water being released from bedrock appear to be relatively small, and are released over a long time period after the main peak of flooding has passed. It was therefore considered unnecessary to incorporate a regional groundwater model into the integrated flood forecasting system.

Investigations of tidal processes operating at the head of the Mawddach estuary indicate that no tidal effects on river flow will be experienced above the tidal limits at the Mawddach – Wnion confluence. It therefore appears unnecessary to incorporate a tidal flow model into the flood forecasting system.

The design of an integrated model could now proceed. For mesoscale basins of the size of the Mawddach, detailed rainfall distributions and detailed land surface characterisations are both required. The MM5 model had been configured and was producing satisfactory rainfall forecasts, so could provide the meteorological component of the system. Meteorological models, including MM5, have been successfully incorporated into hydrological systems and provide more accurate rainfall distributions than interpolation between widely spaced raingauge sites.

The full hydrological analysis of the catchment could be carried out by two different approaches: the development of a single integrated model, or the linking of a series of specialist models to generate an integrated system. Suitable specialist programs had already been identified for the river routing and overbank flooding components. In addition, an interface program would be required to link the rainfall and river routing components, and to handle surface runoff and shallow throughflow processes.

Digital elevation data was available with a spacing of 50m and could provide a grid basis for the hillslope model. Infiltration and downslope throughflow could be modelled by Darcy's equation and surface runoff modelled by the Kinematic wave equation. The model makes use of the van Genuchten function to determine soil hydraulic conductivities at different levels of saturation.

A major difficulty in modelling a large and complex catchment like the Mawddach is the determination of soil hydraulic parameters on a sufficiently detailed scale. It is impractical to collect this data by soil mapping in the field, and it has been shown that air photography does not provide a sufficiently accurate means of delimiting soil hydrological zones.

An automated approach to soil mapping has been developed in the hillslope program. An assumption is made that the principal factors affecting soil hydrological properties are water flows, parent material and vegetation. The Kirkby index provides a means of assessing the likely wetness of a soil site, and can be combined with digitised geological and vegetation data to generate a soil classification according to the HOST system. The soil HOST class in turn allows hydrological properties to be allocated to the soils of each map grid square.

The integrated system, incorporating MM5, the hillslope model, GSTARS and River2D, has been tested for the flood events of 3 July 2001 and 3-4 February 2004. The model was run by distributed processing on a group of twelve networked microcomputers, and produced output sufficiently quickly to be operationally useful.

The hillslope model was calibrated satisfactorily by adjustment of the soil depths and hydrological properties of the HOST soil classes. The model appears to correctly handle fast surface runoff and slower throughflow, and is able to model changes in antecedent conditions over dry and wet periods. This overcomes the inability of HEC-1 to simulate multiple storm events correctly.

An improvement to the realism of the model would be to distinguish the effects of additional classes of vegetation on soil development and surface runoff. In particular, it may be appropriate to separate dwarf shrub heath from grassland, and to model forestry plantations at different stages of growth.

Modifications may be needed to the soil classification scheme to distinguish boulder clay till with different parent materials and differing hydrological properties.

Evapotranspiration has not been treated explicitly in the model, but is implicitly included with groundwater losses. By calibrating the hillslope model against river flows for known storm events, overall water loss from the hillslope system has been satisfactorily modelled from the perspective of flood forecasting. However, some losses allocated to groundwater recharge should actually have been allocated to evapotranspiration, with a consequent overestimate of groundwater recharge. The error is not thought to be large, but this is an aspect that will be addressed during further development of the integrated model.