3.2 Hillslope hydrology

In the following chapters, models are developed for different aspects of the hydrology of the Mawddach catchment. Instrumentation has been installed in six investigation areas within the catchment to provide data for calibration and verification of the models. The data collected may be split into two categories:

- Observations which directly provide parameter values for input to a model, for example: the river discharge at intervals during a storm event,

- Observations which do not directly link to model parameters but provide evidence against which model performance may be progressively refined, for example: the extent of surface saturation on a hillslope during a storm event.

The investigation areas, illustrated in fig.3.13, are:

1. **The upper basin of the Mawddach estuary**. Hydrographs have been recorded at the tidal limits of the rivers Mawddach and Wnion, and within the tidal estuary at Penmaenpool. These recordings are used to investigate river-tidal interactions and will be discussed further in *section 3.6: The Mawddach Estuary.*
2. **The central river system in Coed y Brenin**. A river gauging station is operated in Coed y Brenin by the Environment Agency, who have kindly made data available. The gauging station is at Tyddyn Gwladys, a short distance downstream from the confluence of the Afon Mawddach with its main tributary the Afon Gain. An additional river gauge was installed on the Afon Gain upstream of the confluence so that discharges for the Gain and upper Mawddach sub-catchments could be estimated separately.

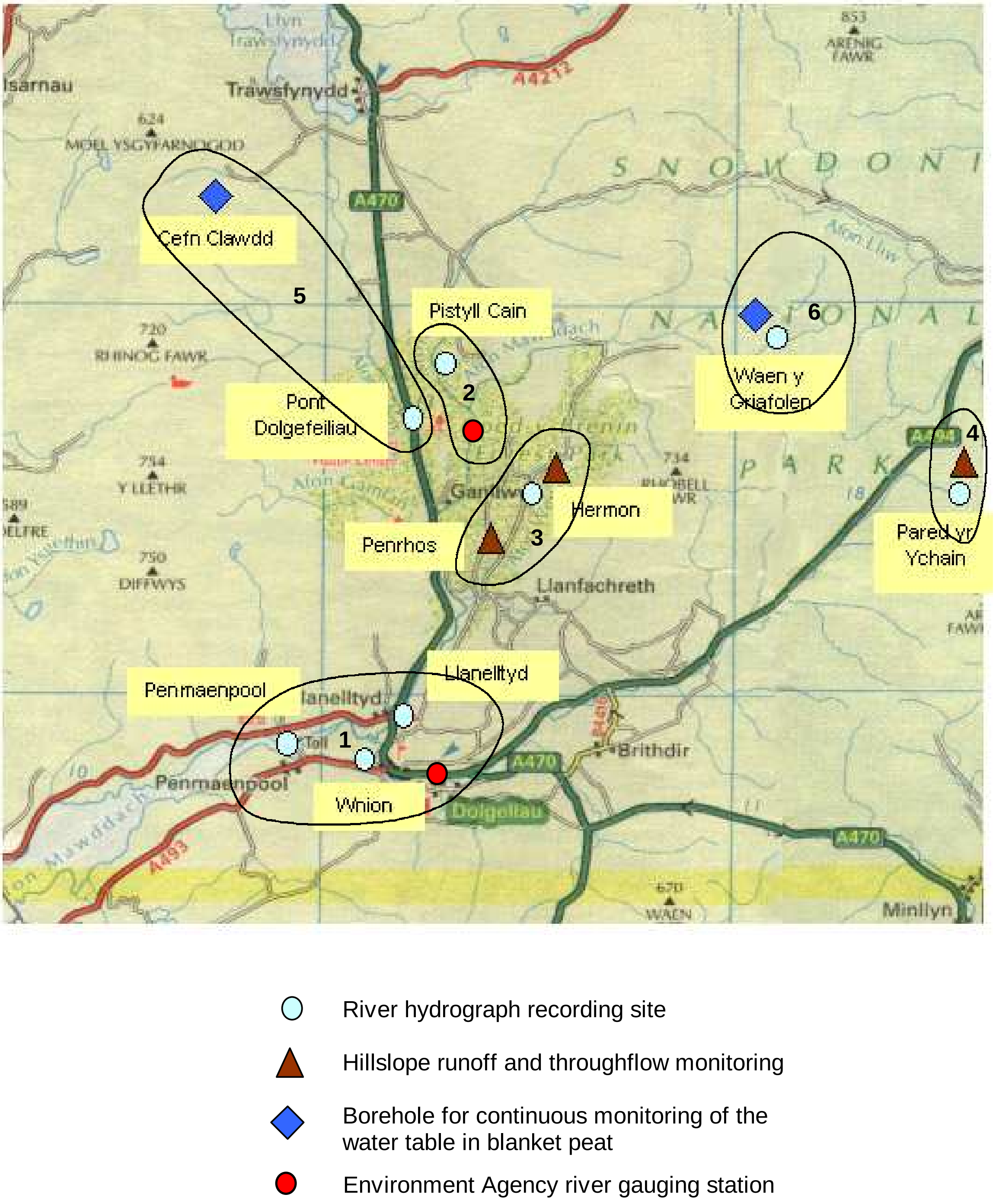


Figure 3.13: Experimental areas and hydrological recording sites

3. **The Afon Wen sub-catchment at Hermon**. The Afon Wen valley is typical of the deeply incised river gorges of Coed y Brenin which have extensive infill of glacial till and periglacial outwash and solifluction deposits. Surface runoff and soil throughflow monitoring sites have been established around the village of Hermon. Data is used to investigate the effects of antecedent drainage conditions on hillslope runoff during storm events . A river gauge has been operated at this location.

   River bed temperatures have also been monitored at Hermon to investigate river-groundwater interaction along the major fracture zone followed by the river. Results are discussed in *Section 3.4: River and floodplain processes.*
4. **Afon Wnion headwaters at Pared yr Ychain**. The Pared yr Ychain valley was selected as typifying the slopes of the Aran mountains which form the headwaters for the Afon Wnion. These slopes are largely covered by glacial till. Surface runoff and soil throughflow monitoring sites were established to investigate hillslope responses during storm events. A river gauge has been operated on the Afon Ty Cerrig at this location.
5. **Afon Eden headwaters at Cefn Clawdd**. The Cefn Clawdd valley was selected as typical of the Afon Eden headwaters of the Trawsfynydd plateau. This area is covered by blanket peat. A borehole was installed for water table monitoring; observations from the site are discussed in *Section 3.5: Peat blanket bogs*. A river gauge has been operated at Pont Dolgefeiliau where the Afon Eden flows south from the Trawsfynydd plateau.
6. **Source of the Mawddach at Waen y Griafolen**. The Mawddach has its source in an extensive peat basin which has been the subject of detailed hydrological monitoring. This work is also discussed in *Section 3.5: Peat blanket bogs.* A river gauge has been operated on the outlet stream from the peat basin.

Tyddyn Gwladys gauging station

A river gauging station is operated by the Environment Agency on the Afon Mawddach at Tyddyn Gwladys in the Coed y Brenin forest (fig.3.14). Flow is measured on a gravel plane-bed reach which has been artificially straightened to reduce turbulence and lateral variations in flow rate. Water depths are measured by float recorder in a stilling well. Calibration of river discharge against stage height is carried out by a propeller flow meter which traverses the river, suspended from a cable. A typical hydrograph of readings for the period September 2002 to July 2003 is shown in fig.3.15. Detailed data sets with 15min reading intervals have been provided by the Environment Agency for storm events of special interest:

- 3 July 2001
- 8 November 2002
- 29 December 2002
- 8 March 2003
- 22 May 2003
- 3-4 February 2004

These hydrographs are illustrated in fig.3.16(a)-(f).

Figure 3.14: Tyddyn Gwladys river gauging station

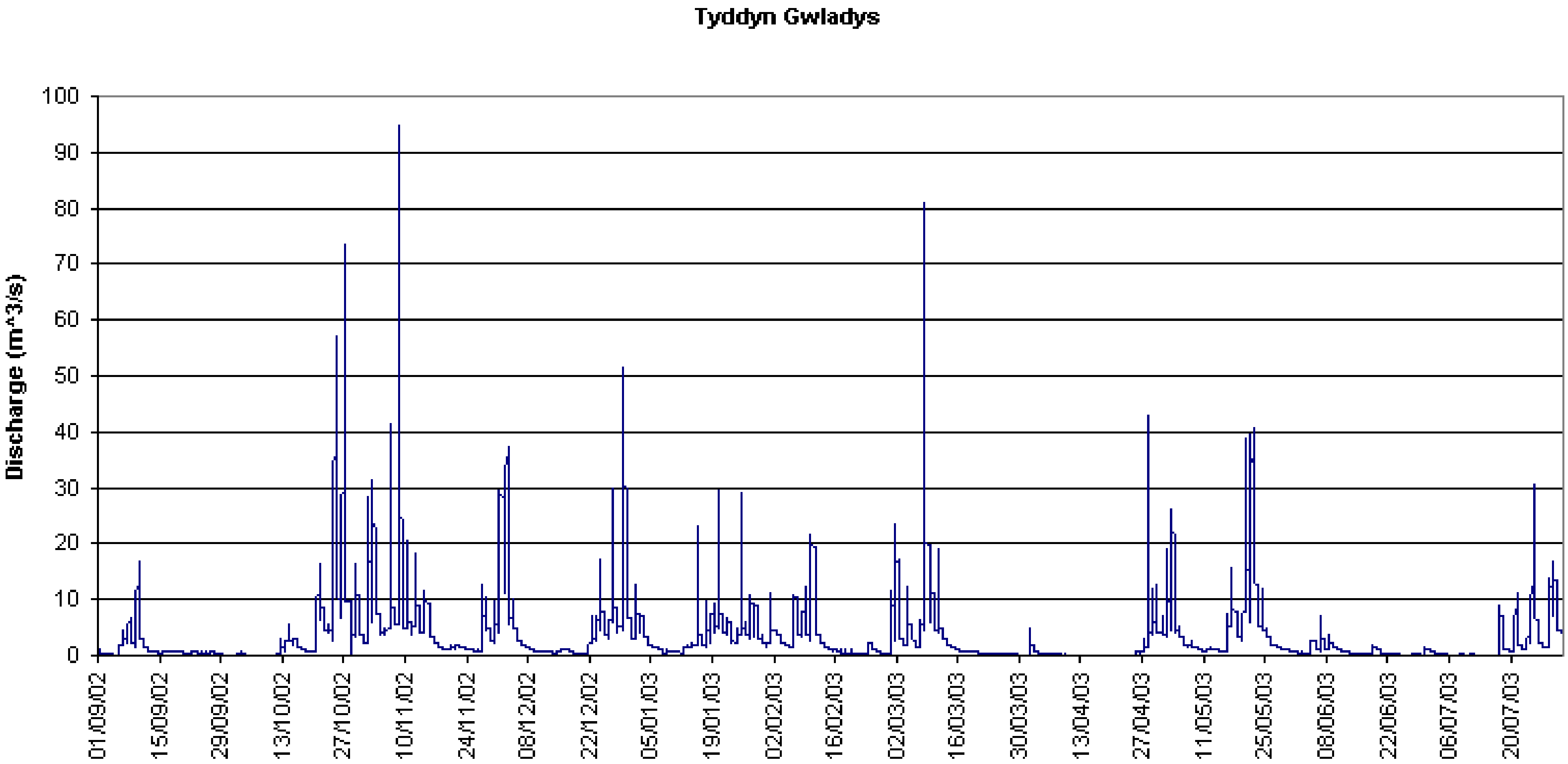


Figure 3.15: Readings for Tyddyn Gwladys river gauging station, Afon Mawddach, for the period September 2002 to July 2003

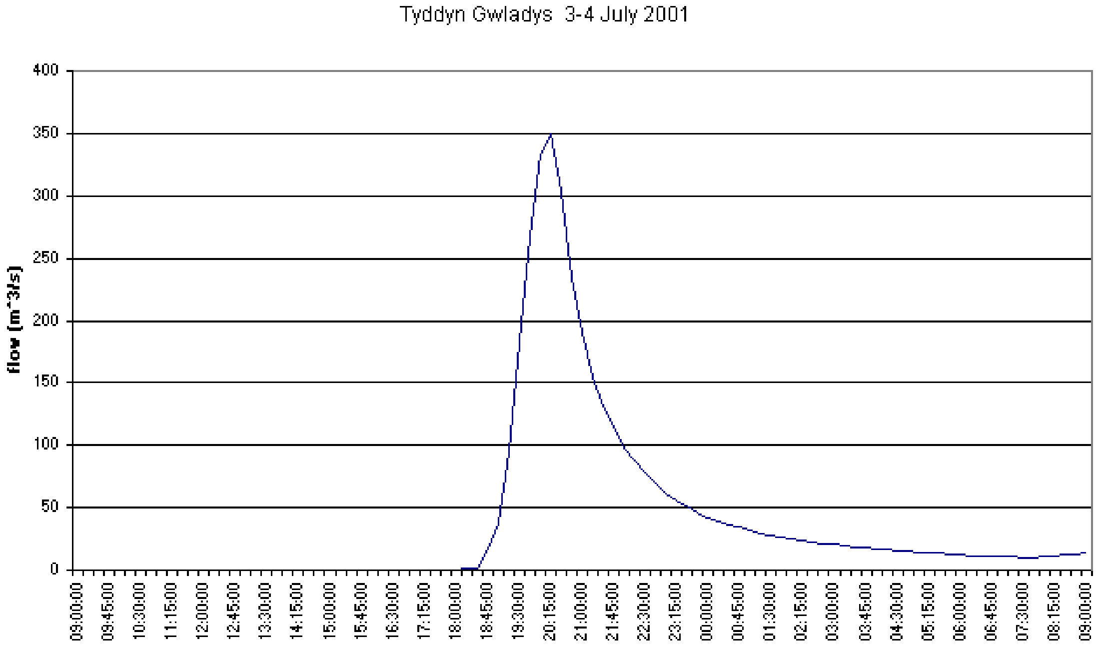


Figure 3.16(a). Hydrograph for the storm event of 3 July 2001, Tyddyn Gwladys

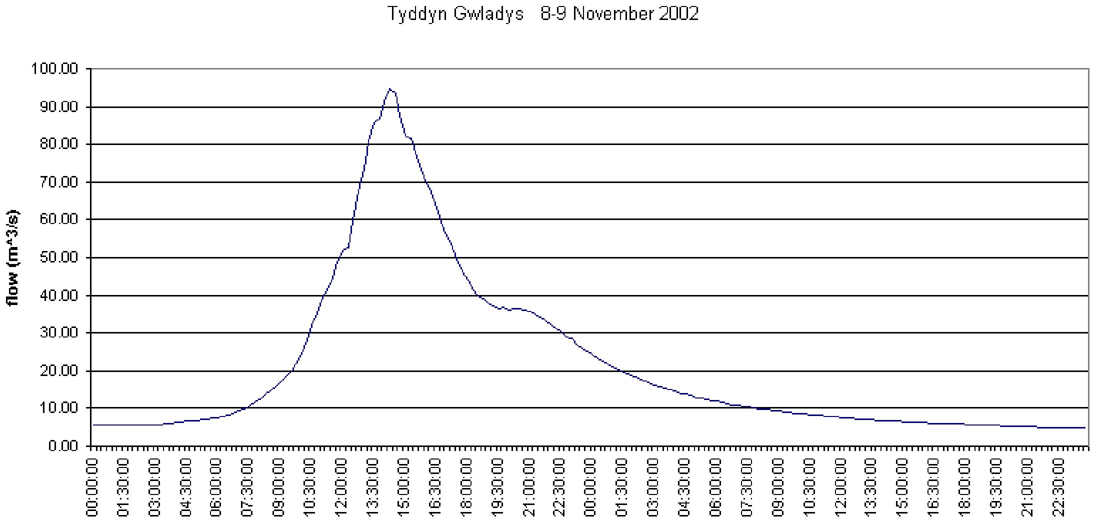


Figure 3.16(b). Hydrograph for the storm event of 8 November 2002, Tyddyn Gwladys

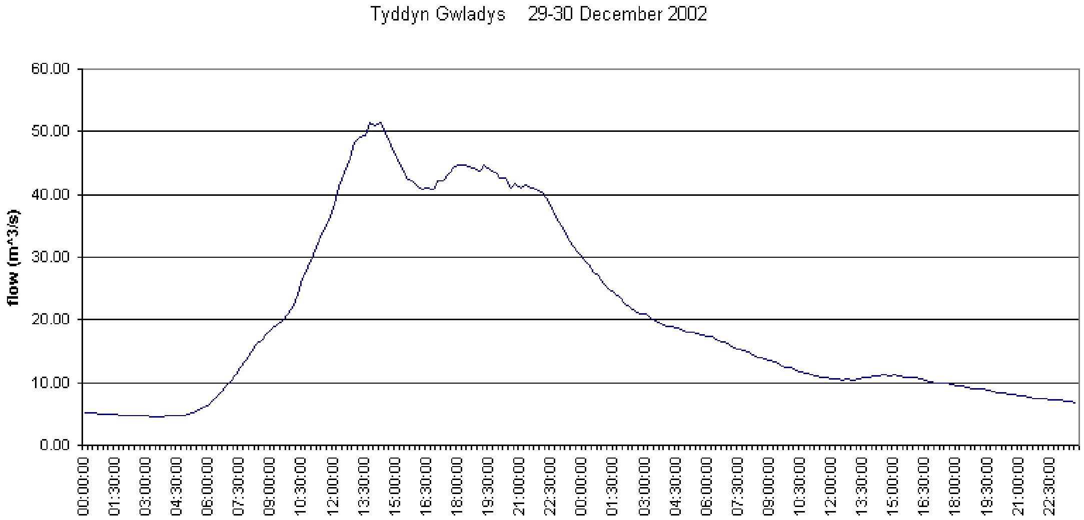


Figure 3.16(c). Hydrograph for the storm event of 29 December 2002, Tyddyn Gwladys

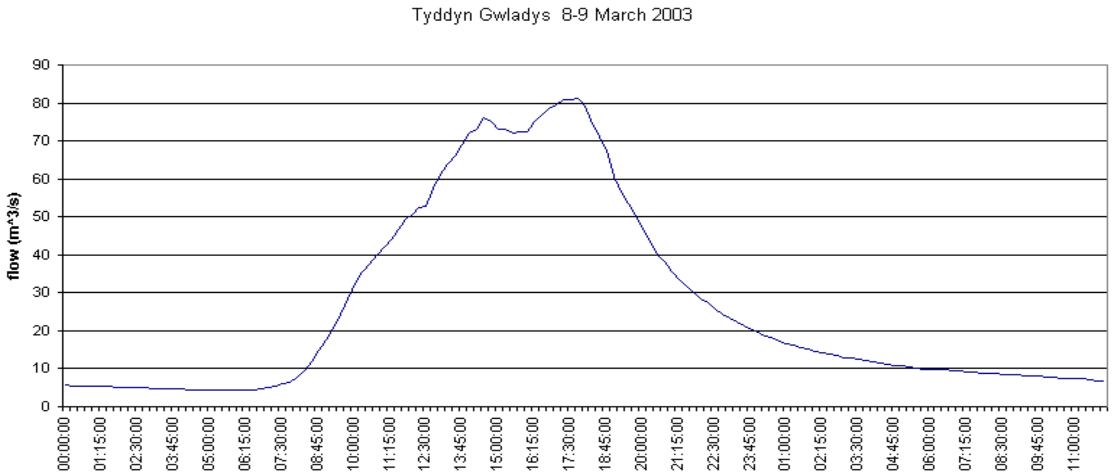

Tyddyn Gwladys 8-9 March 2003

Figure 3.16(d). Hydrograph for the storm event of 8 March 2003, Tyddyn Gwladys

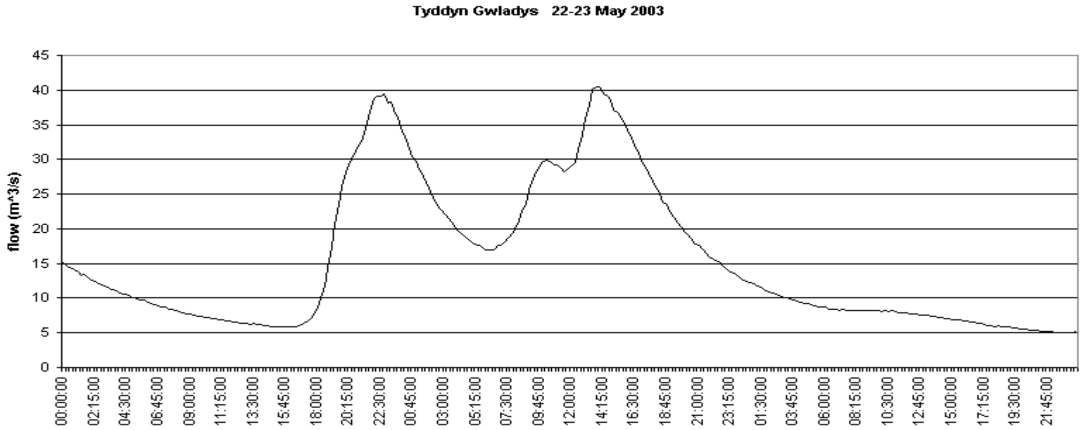

Tyddyn Gwladys 22-23 May 2003

Figure 3.16(e). Hydrograph for the storm event of 22 May 2003, Tyddyn Gwladys

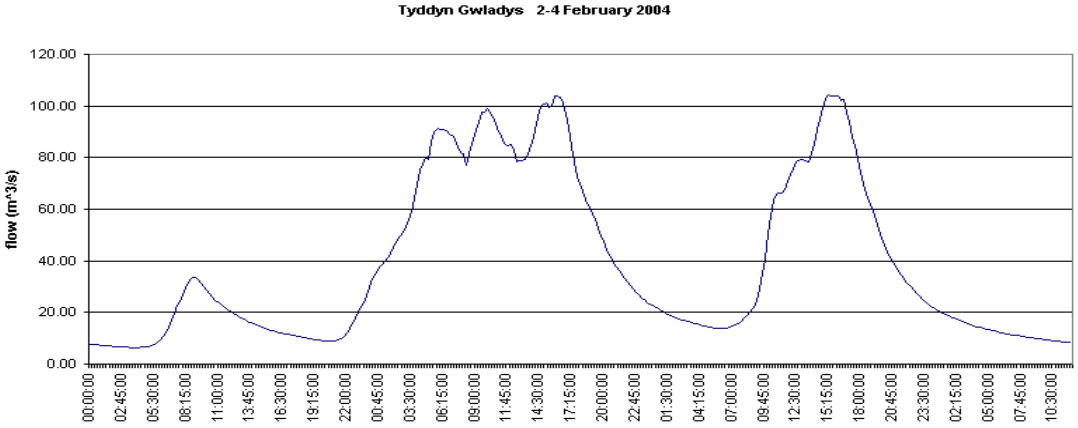

Tyddyn Gwladys 2-4 February 2004

Figure 3.16(f). Hydrograph for the storm event of 3-4 February 2004, Tyddyn Gwladys

The July 2001, November 2002, December 2002 and March 2003 events represent isolated periods of intense rainfall, whereas the May 2003 and February 2004 events represent flooding at the culmination of a sequence of heavy rainfall periods.

Subcatchments and river reaches

For the purpose of hydrological modelling, the Mawddach and Wnion basins above the tidal limits have been divided into a number of subcatchments, each representing a reach of the trunk stream. The twelve reaches of the Mawddach are shown in fig.3.17, and the eight reaches of the Wnion are shown in fig.3.18. The hillslope hydrological characteristics and the nature of the river channels are described further in Appendix B.

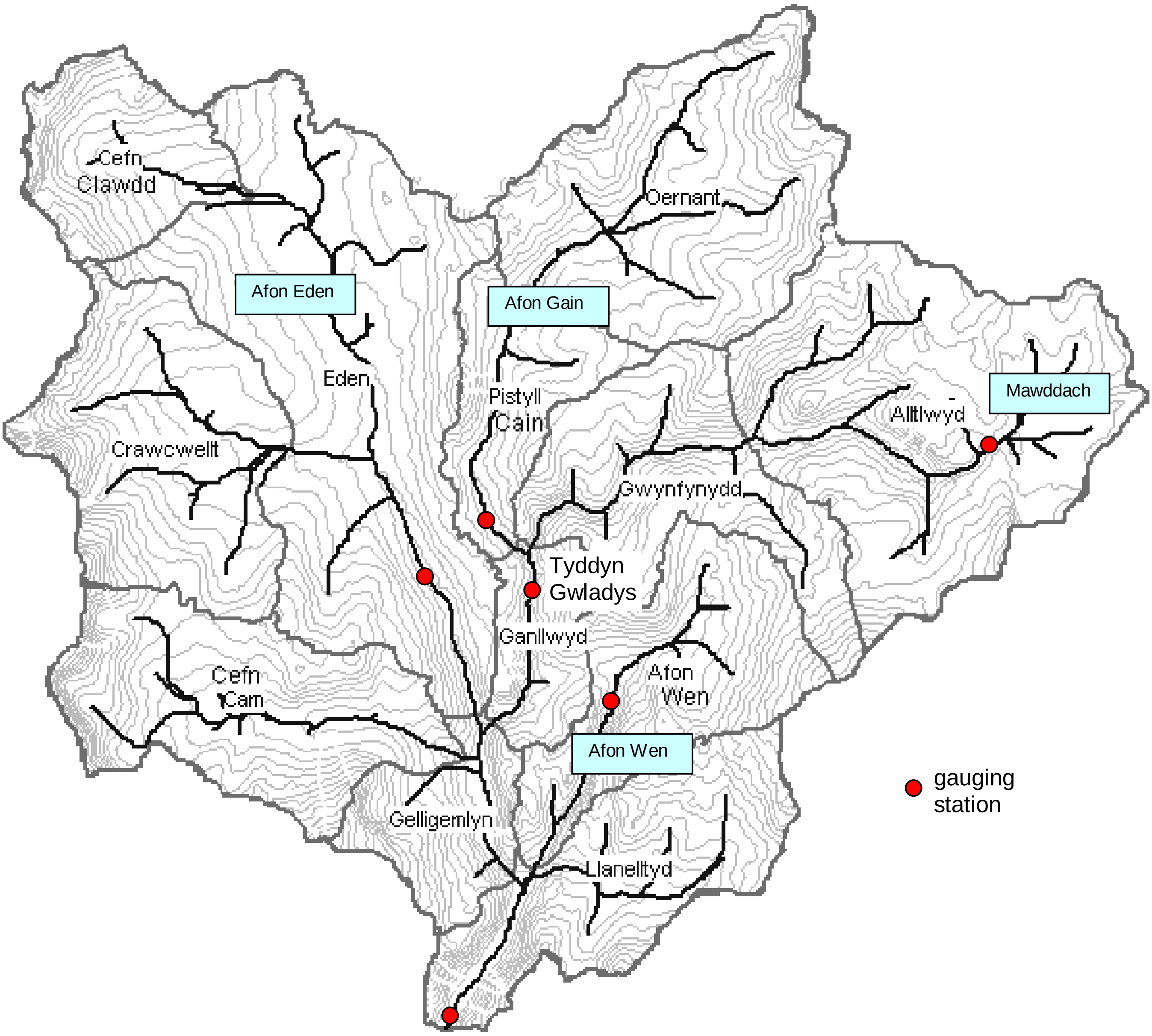


Figure 3.17: Mawddach sub-catchments and river reaches

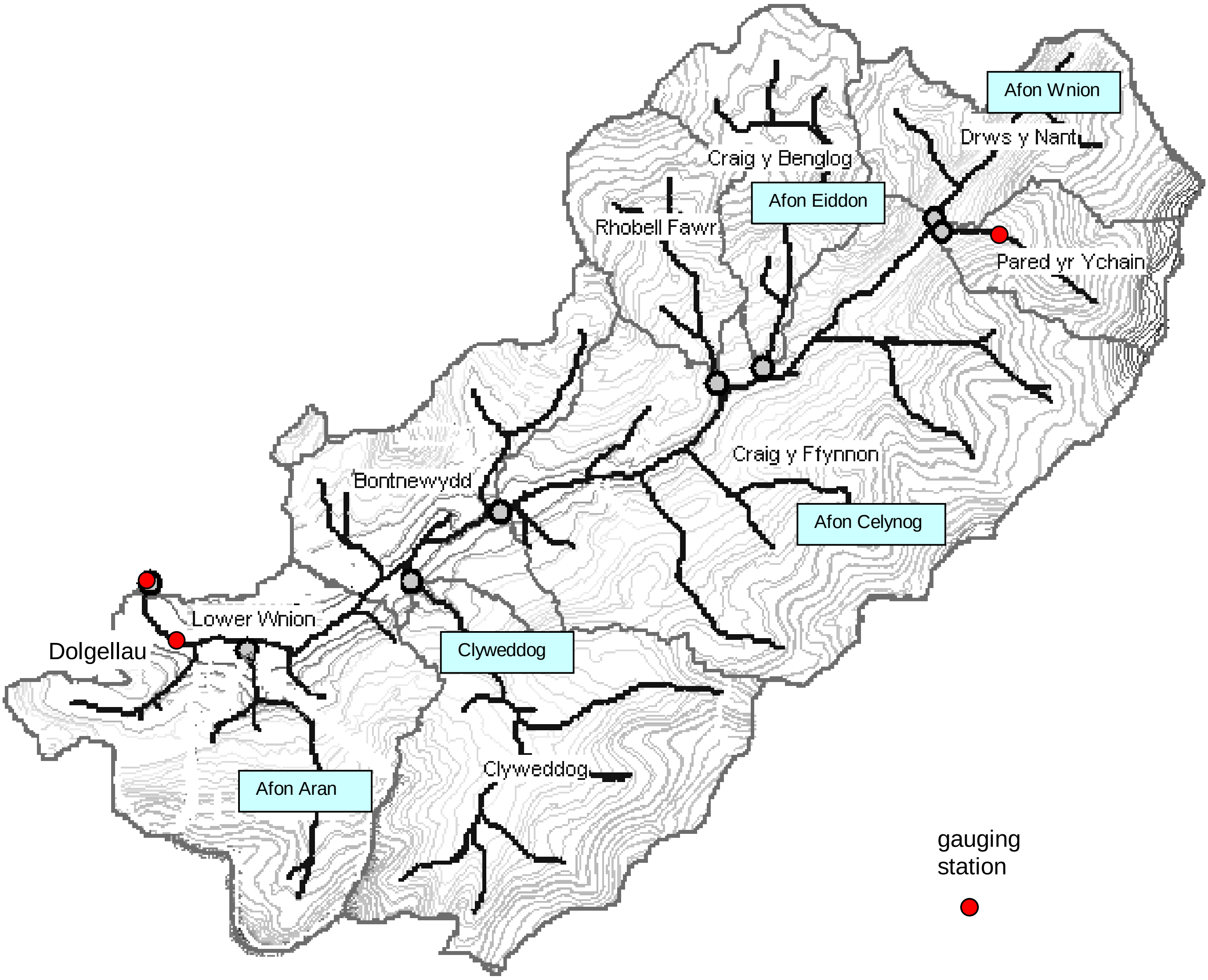


Figure 3.18: Wnion sub-catchments and river reaches

River channel surveying

Calibration of hydrograph sites and modelling of both river routing and sediment transport required the accurate surveying of channel cross profiles at many points throughout the river system. Between 3 and 9 cross-section sites were selected within each of the sub-catchments described in the previous section. The number of cross-sections needed to adequately record channel geometry over the whole river reach was determined by the variability in channel form. At each cross-section site, a survey was carried out by levelling up to points well above any expected flood stage. River bed and bank sediment characteristics were recorded. An estimate of water surface gradient at bankfull discharge was obtained by levelling between the highest points on the banks showing evidence of flood erosion or deposition along the river course.

Figure 3.19: Surveying the channel cross section, Afon Gain

Examples of surveyed sections for the Eden subcatchment, and the Llanelltyd subcatchment of the lower Mawddach, are shown in figs 3.20 and 3.21.

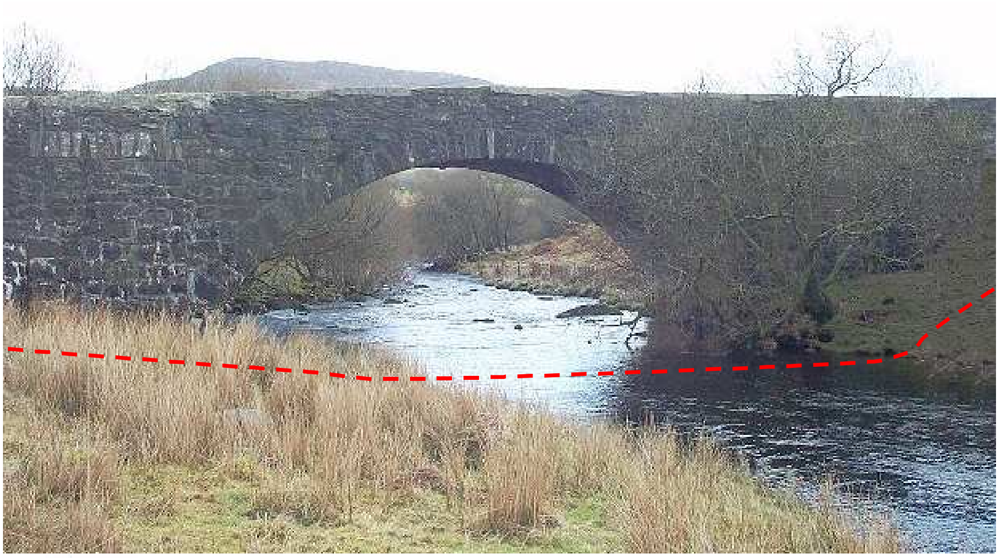


Figure 3.20(a)
(above)
Line of cross section surveyed at Pont y Grible, Afon Eden

(below)
Cross section at Pont y Grible

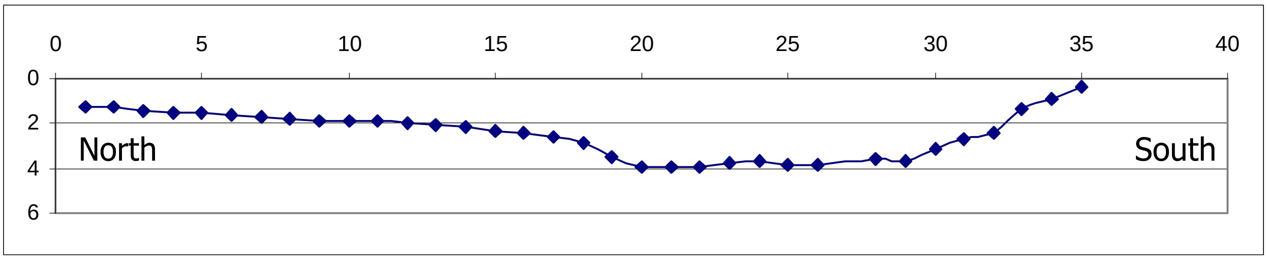


Figure 3.20(b)
(above)
Line of cross section surveyed at Pont Dolgefeiliau, Afon Eden

(below)
Cross section at Pont Dolgefeiliau

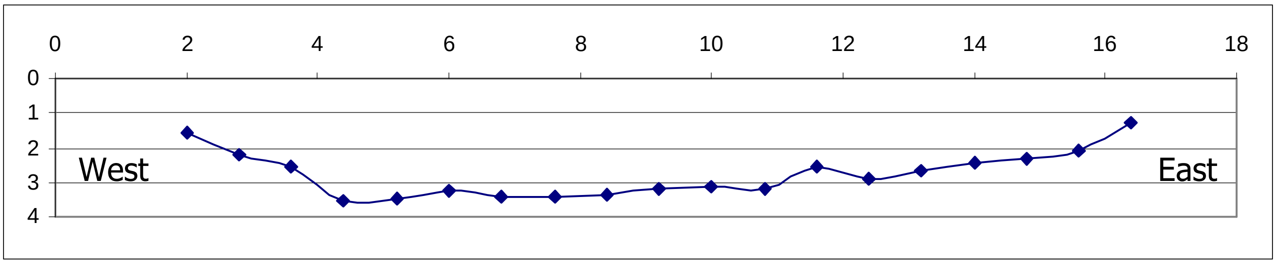
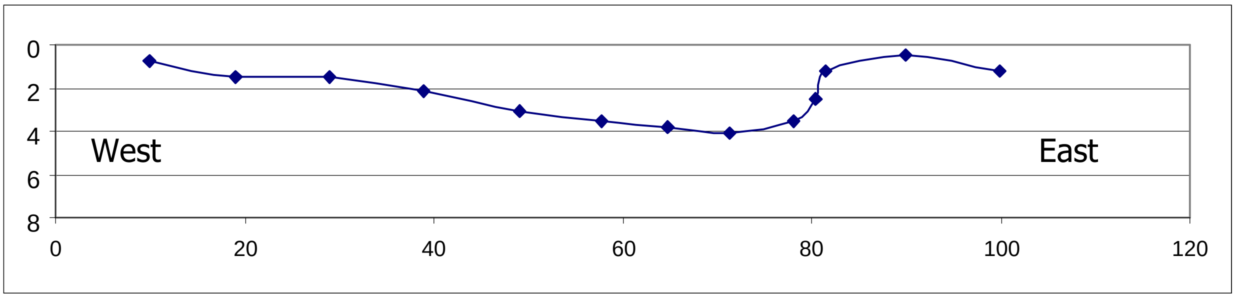


Figure 3.21(a)
(above)
Line of cross section surveyed on the Afon Mawddach north of Cymmer Abbey, Llanelltyd.
photo: Lydia Yates

(below)
Afon Mawddach cross section north of Cymmer Abbey.



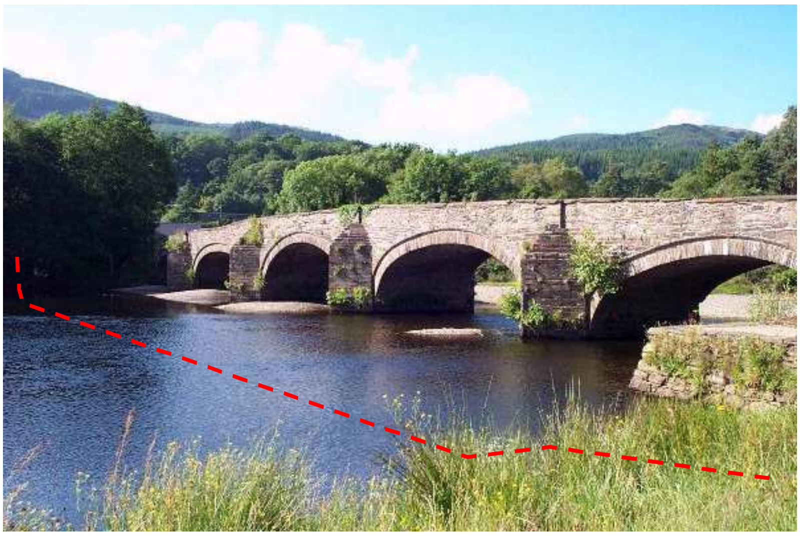
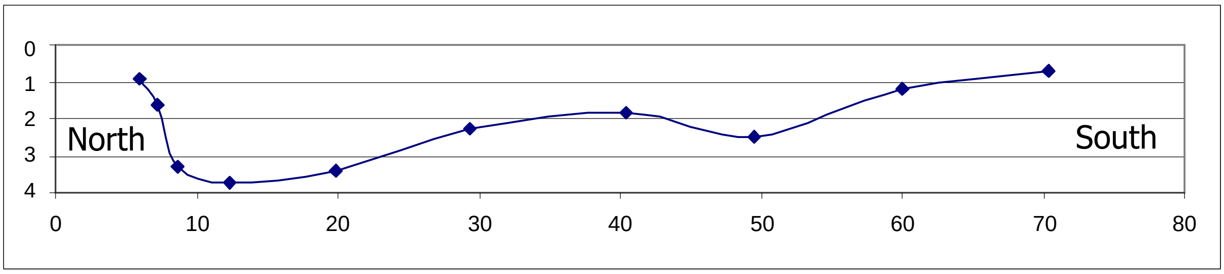


Figure 3.21(b)
(above)
Line of cross section surveyed at Llanelltyd Bridge, Afon Mawddach.

(below)
Cross section at Llanelltyd Bridge.



Hydrograph recording

Prior to this project, only one river gauging site existed at Tyddyn Gwladys on the Mawddach, run by the Environment Agency. Additional hydrograph recording sites were required for river flow data in the Mawddach and Wnion catchments.

The flash flood regimes of the Mawddach river system present severe problems for flow measurement. Binnie and Partners (1985) report that two gauging stations have operated for short periods on the Afon Eden, one upstream of Pont Dolgefeiliau and the other near Ganllwyd. The Pont Dolgefeiliau site was taken out of use after blockage of the stilling well by river sediment, and the data from the Ganllwyd site was considered too inaccurate for publication.

Figure 3.22: The Ganllwyd reach of the Afon Mawddach during low flow and flood conditions.

Practical difficulties in flow measurement may be appreciated by considering fig.3.22 which shows the Ganllwyd reach of the Afon Mawddach during low flow and flood conditions:

- Water levels may rise by 2m or more during flood flow, making it impossible to measure flows manually by entering the river.
- Even where river depths remain relatively shallow during flooding, the water flow can considerably exceed the $2ms^{-1}$ velocity considered to be a safe limit for working in the river.
- Overbank flooding is common, making access to the main channel hazardous during storm events.

Despite these problems, it was considered worthwhile to collect as much flow data as possible from different parts of the river system. Hydrographs were constructed as best-estimates for particular sites, ensuring that these were consistent with overall river flows within the catchment.

Gauges were installed at a series of sites on the Mawddach-Wnion system to provide continuous logging of water depth. Assistance was received from Malcolm Murgatroyd, electronics engineer in Dolgellau, who designed and constructed a number of portable instruments (fig.3.23). These use a pressure sensor, secured to the river bed and connected by heavy duty cable to a module on the river bank housing electronic circuitry, battery power supply and a data logger. Water depth is measured as a function of hydrostatic pressure, with the instrument design compensating for variations in water temperature and atmospheric pressure which might affect river bed readings. In tests at four different river sites under widely differing flow conditions, it was found that water depths were consistently recorded to an accuracy better than 1cm. This level of accuracy was considered adequate for recording on upland streams of steep gradient, where turbulence commonly produces surface oscillations of amplitude 1cm or more. These sites were operated as 'rated sections' and calibrated for river flow as described below.

Recorders were operated during the project (fig.3.13) at:

- Pont Dolgefeiliau, on the Afon Eden
- Pont Gwynfynydd, on the Afon Gain
- Hermon, on the Afon Wen
- Pared yr Ychain, on the Afon Ty Cerrig.
- Llanelltyd, at the tidal limit of the Afon Mawddach
- Pont y Wern Ddu, at the tidal limit of the Afon Wnion
- Penmaenpool bridge, in the upper estuary

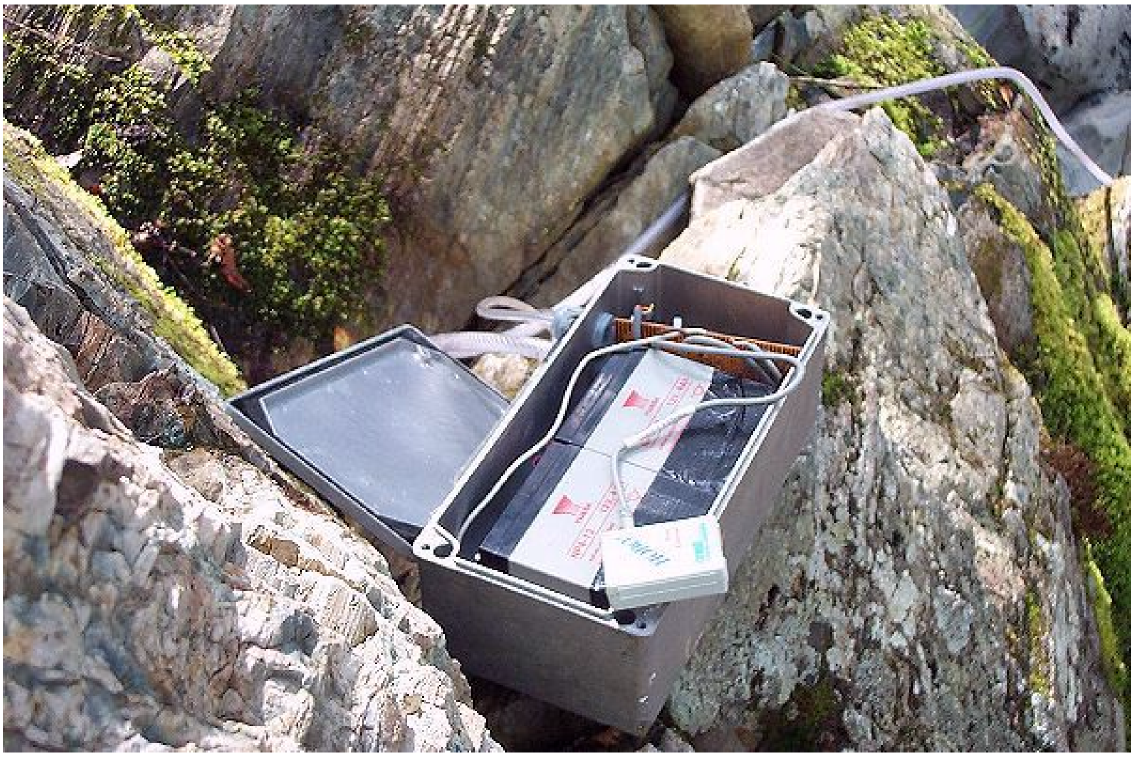


Figure 3.23: Barometric water depth recorder

An example set of water depth recordings is shown in fig.3.24 for the Pont Dolgefeiliau site over the period December 2002 to April 2003. This is based on measurements made at 5min intervals, so the timing of flood peaks may be considered precise.

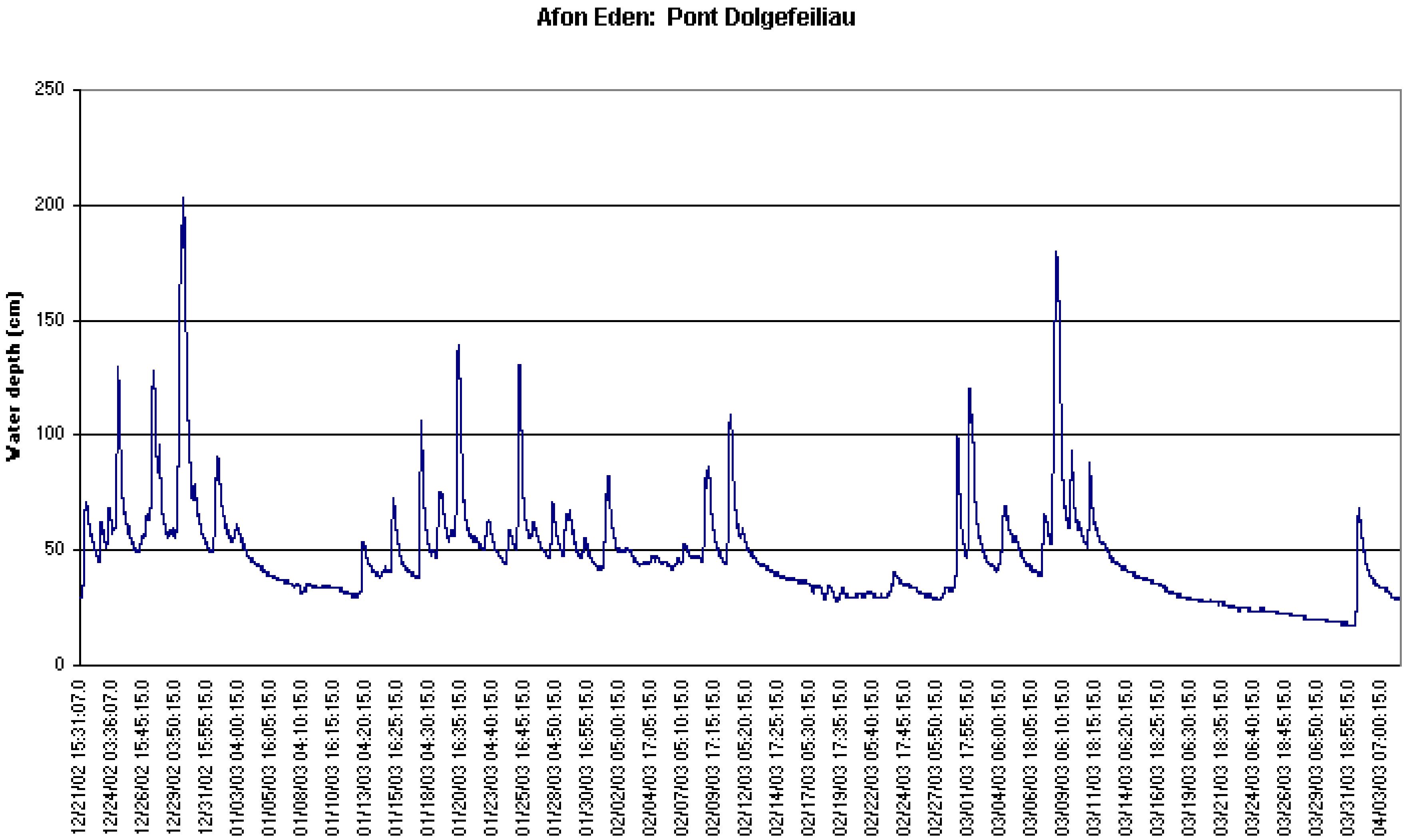


Figure 3.24: Water depth recordings for the Pont Dolgefeiliau site over the period December 2002 to April 2003.

Calibration of river discharge in terms of water depth was carried out by:

- Accurately surveying the channel cross section at the location of the depth recorder,
- Measuring water flow rates at points across the channel during different flow conditions, using a propeller flow meter (fig.3.25).
- Computing river discharge as a product of cross sectional area and flow rate.

Figure 3.25: Propeller flowmeter used in hydrograph site calibration

Under low flow conditions, it was possible to enter the river channel and make a series of flow measurements at measured positions across the channel.

Under flood conditions it was not safe to enter the rivers, so flow measurements were made with the propeller attached to a long metal pole extended from the bank (fig. 3.26). Flow rate was determined by integration over a 10 second interval to reduce perturbations due to turbulence. Three flow measuring points were chosen, which were measured as the centre and quarter-width points of the channel. Flow measurement made at an estimated quarter-depth from the surface. A mean flow velocity for the current river stage was obtained by averaging these values.

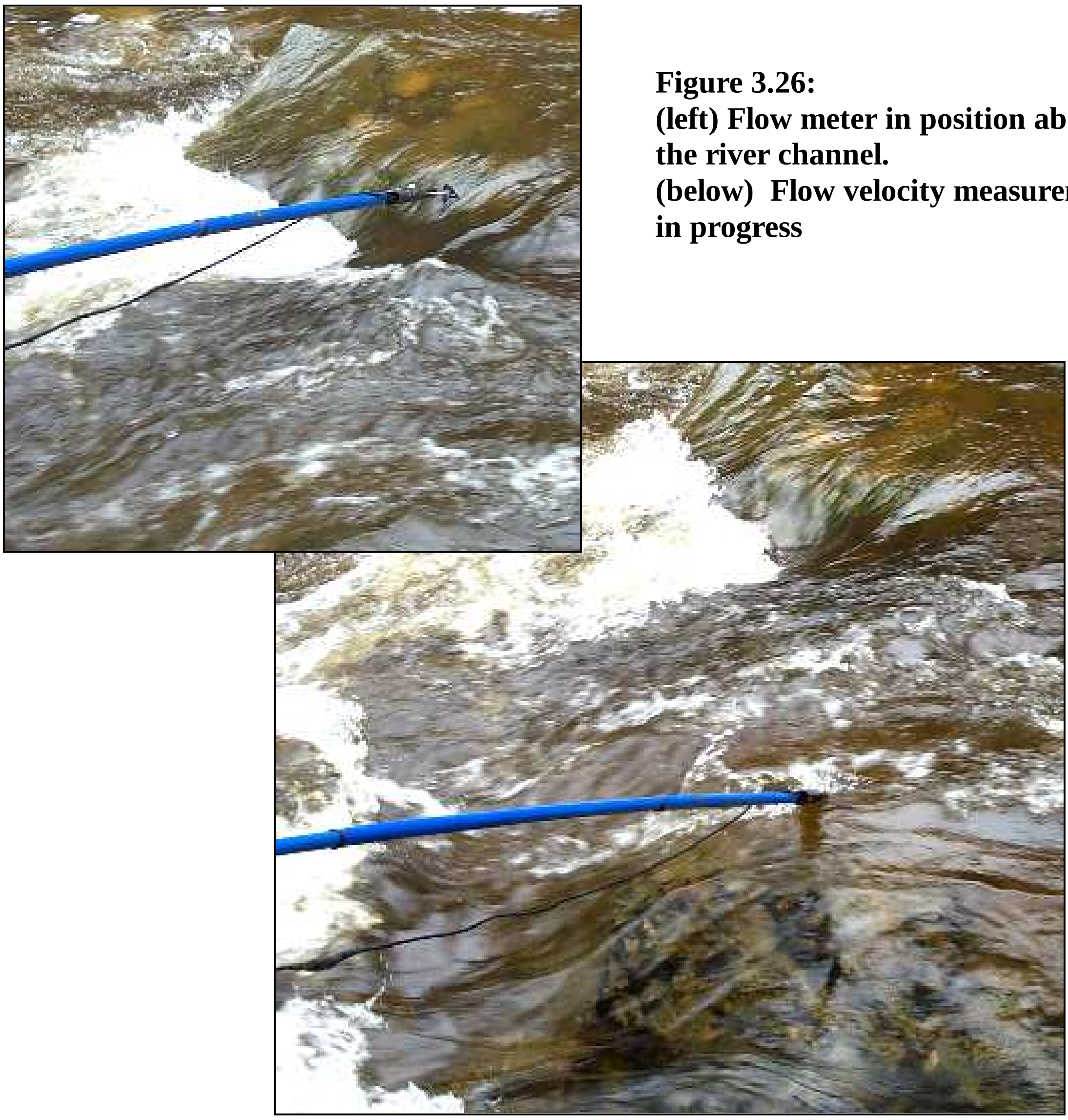


Figure 3.26:
(left) Flow meter in position above the river channel.
(below) Flow velocity measurement in progress

Calibration data for the hydrograph sites is given in Appendix D. The calibrations obtained from flow data are imprecise for a number of reasons:

- Velocity measurements were obtained mainly during low to moderate flow conditions. Adequate data for high flow conditions were difficult to obtain, due to problems in reaching hydrograph sites during the brief intervals of maximum flood discharge, and the difficulty of accessing central sections of the channel when river width was increased during flood conditions.

- Water surface gradient will be elevated upstream during the period of a rising hydrograph and depressed upstream during the period of a falling hydrograph. Flow velocities may therefore vary for the same river depth between the rising and falling limbs of the storm hydrograph due to water surface gradient.
- Sediment processes may significantly influence water velocities. Fig.3.27 illustrates the variability in suspended sediment between flood events on the Afon Eden at the Pont Dolgefeiliau gauging site. A first storm flow after an extended period of dry weather may pick up large quantities of silt and sand grade material from the channel bed and remove this from the river system, leaving a clean gravel bed with different frictional resistance characteristics during subsequent flood events.
- In a mountain stream regime with a predominantly gravel-cobble bedload, significant changes to bed profile may occur during individual flood events due to erosion or deposition.

To augment the measurements of high flow rate and to reduce the errors from field observations, additional theoretical calculations of flood discharge velocities were carried out using two methods, Manning's equation and the Relative Depth method.

Manning's equation:

Bankfull discharge Q is calculated from:

$$Q = \frac{1}{n} A r^{2/3} s^{1/2}$$

where A = cross sectional area at bankfull stage
r = cross sectional area / wetted perimeter
s = water surface downstream slope
n = Manning's roughness coefficient

Suitable values for roughness coefficient **n** can be obtained by comparison of the hydrograph sites with illustrations of calibrated mountain streams provided by Barnes (1967), and Arcement and Schneider(2003) .

8.30am, 07 August 2001

8.30am, 10 August 2001

8.30am, 12 August 2001

Figure 3.27: Example water flows at different river stages, Pont Dolgefeiliau, Afon Eden

Relative depth method (Pethick, 1980):

The channel relative depth F is calculated as:

$$F = \frac{D}{B}$$

where D = average water depth at bankfull

B = average bedload size

A roughness factor R is obtained from the channel relative depth value, using the logarithmic relationship:

$$R = 0.95 \ln(F) + 0.95$$

Bankfull mean velocity is then calculated as

$$V = 8.86\sqrt{D.s.R}$$

where s = water surface downstream slope at bankfull

Determination of water surface downstream slope at bankfull has been relatively easy for the Mawddach river system, as evidence of maximum water levels during the 3 July 2001 flood event is extensively preserved. This evidence includes: debris accumulations (fig.3.28), deposition of sand and gravel on riverbank ledges, and scouring of moss, lichen and bark from trees adjacent to the channel.

Figure 3.28: Debris accumulations around trees, providing evidence of maximum water levels during the July 2001 flood, Afon Mawddach, Gwynfynydd

The methodology for calibration of the hydrograph recording sites equipped with portable water depth recorders was:

- Determine river discharge as a function of water depth under a range of flow conditions by field measurements. Between 9 and 12 sets of flow measurements were obtained at each hydrograph site.
- Determine bankfull depth and compute bankfull discharge using both Manning's equation and the Relative depth method. In practice, these methods were found to agree within 10%.
- Produce provisional calibration curves for the hydrograph sites as a best fit to the observed and calculated discharge values.
- Check the discharge values for consistency across the catchment during the six test flood events. There is a requirement that water volumes are conserved during passage through the river system, allowing for reasonable inflows and river/groundwater interactions.
- If anomalies were identified which appeared to contradict the conservation principle, then minimal adjustments to the calibration curves were allowed: The Environment Agency Tyddyn Gwladys gauging station was considered to be providing accurate discharge values. Storm hydrograph peak flows at sites using portable water depth recorders were required to be consistent with the flows at Tyddyn Gwladys.

After analysis of the test storm events, calibrations were achieved which were considered internally consistent and adequate for use in rainfall-runoff modelling.

Hydrograph sites

Afon Gain

Site description

A hydrograph recorder has been situated in the waterfall pool (fig.3.29) approximately 1km upstream from Pistyll Cain. Flow is measured at the outlet from the pool where the channel is constrained between rock outcrops. Access to the river is from the east bank, with flow measurement possible during low water and flood stages. The channel represents a bedrock reach, with isolated bed cover of cobbles and boulders of 0.5m to 1m median dimension.

Figure 3.29: Afon Gain hydrograph recording site. The recorder is located on the river bed at point A.

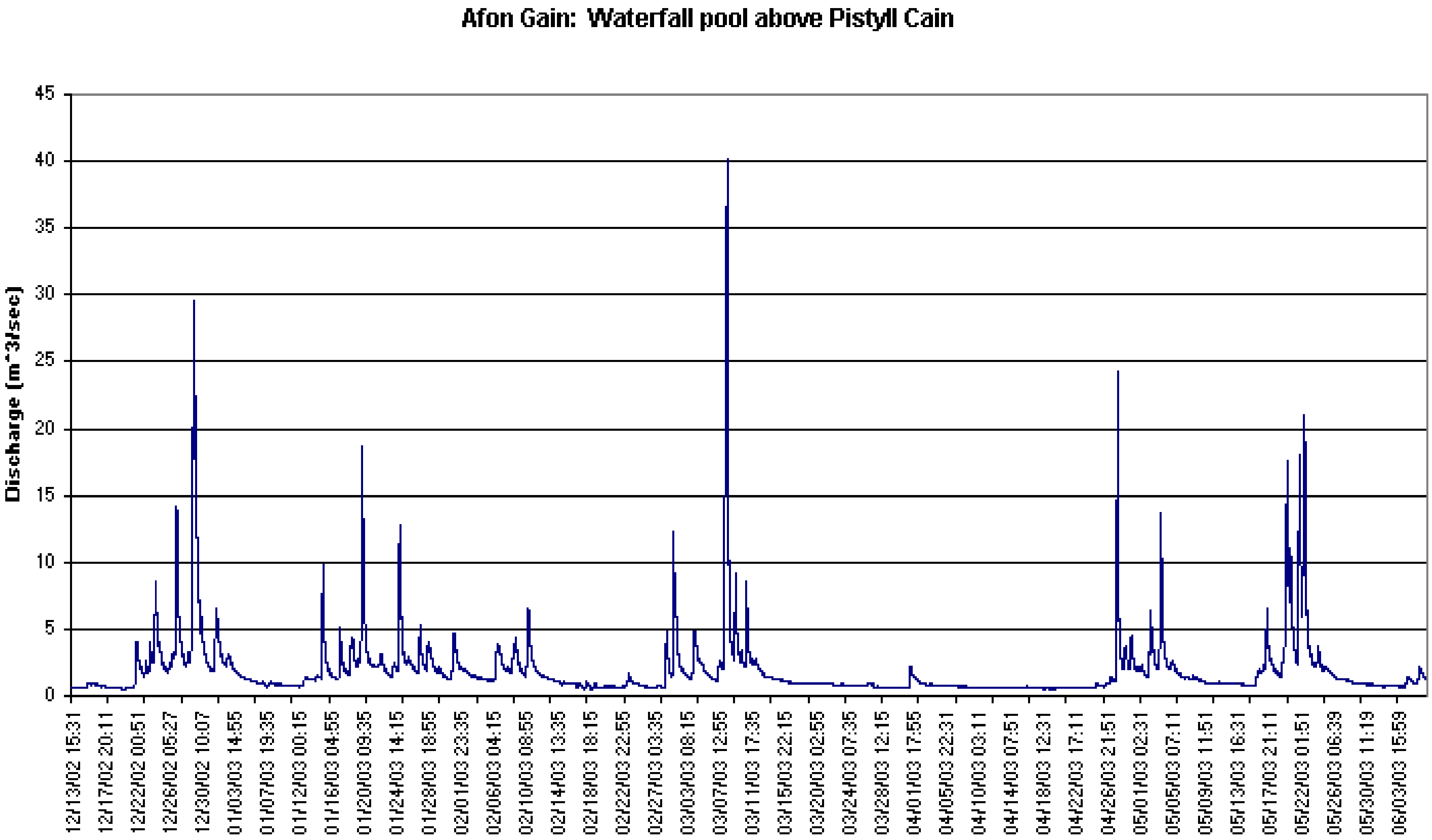


Figure 3.30: Example stage-discharge chart for the Afon Gain hydrograph recording site for the period December 2002 – May 2003.

Pont Dolgefeiliau, Afon Eden

Site description

A hydrograph recorder has been situated approximately 20m downstream from Pont Dolgefeiliau (fig.3.31). Access for the measurement of flow velocities is possible from either bank, except during high flood conditions when the river extends onto the flood plain on both sides. The channel forms a plane bed reach on bedrock, with more than 90% cover of coarse gravel and cobbles in the range 0.1m to 0.5m median dimension.

Figure 3.31: Afon Eden hydrograph recording site. The recorder is located on the river bed at point A.

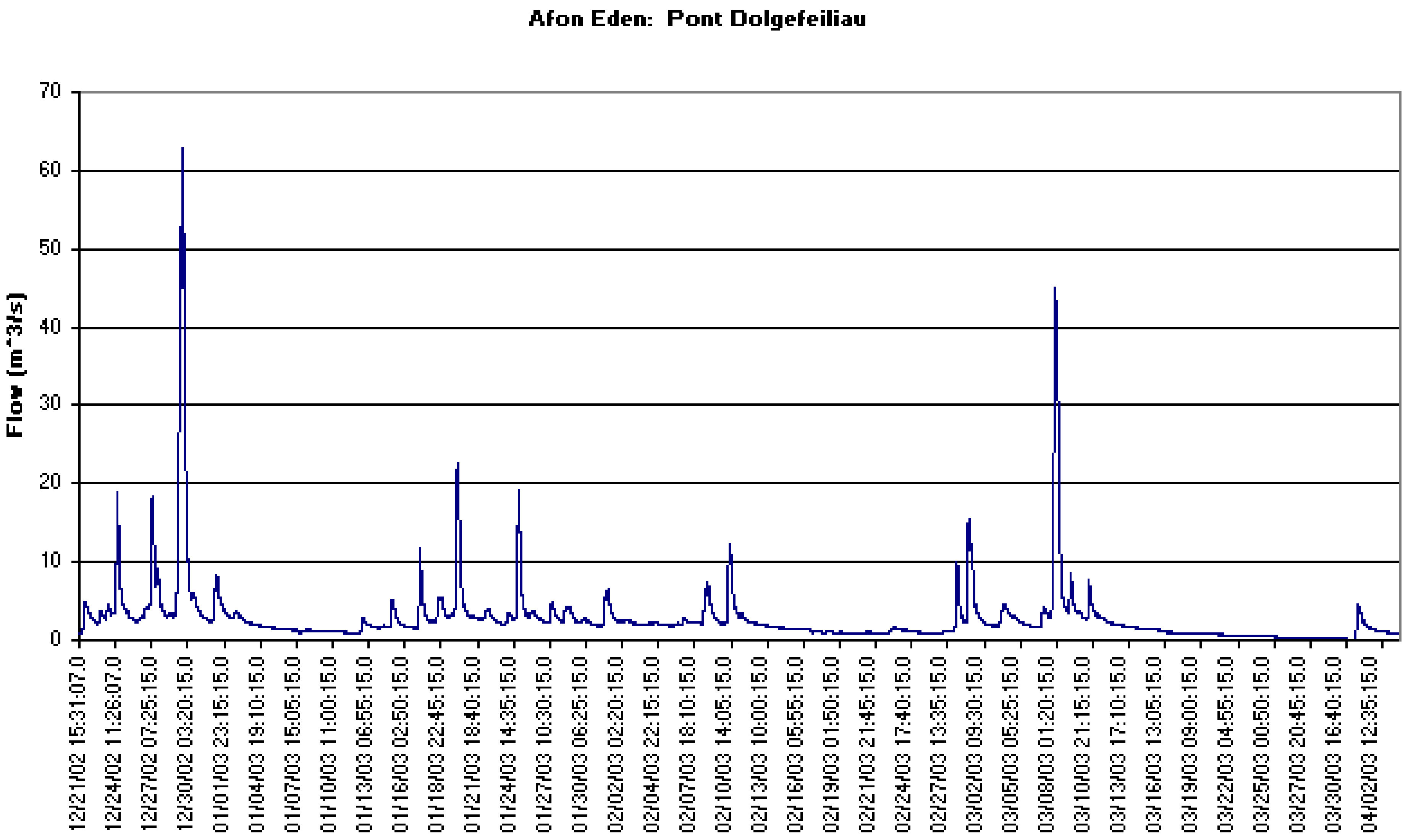


Figure 3.32: Example stage-discharge chart for the Afon Eden hydrograph recording site for the period December 2002 – April 2003

Afon Wen

Site description

A hydrograph recorder has been situated in the waterfall pool (fig.3.33) approximately 0.5km downstream from the village of Hermon. Flow is measured at the outlet from the pool where the channel is constrained between rock outcrops. Access to the river is from the east bank, with flow measurement possible during low water and flood stages. The channel represents a step pool reach, with bed cover of cobbles of 0.1m to 0.5m median dimension.

Figure 3.33: Afon Wen hydrograph recording site. The water depth recorder is located in the pool at location A. Flow is measured at the pool outlet along the section shown in red.

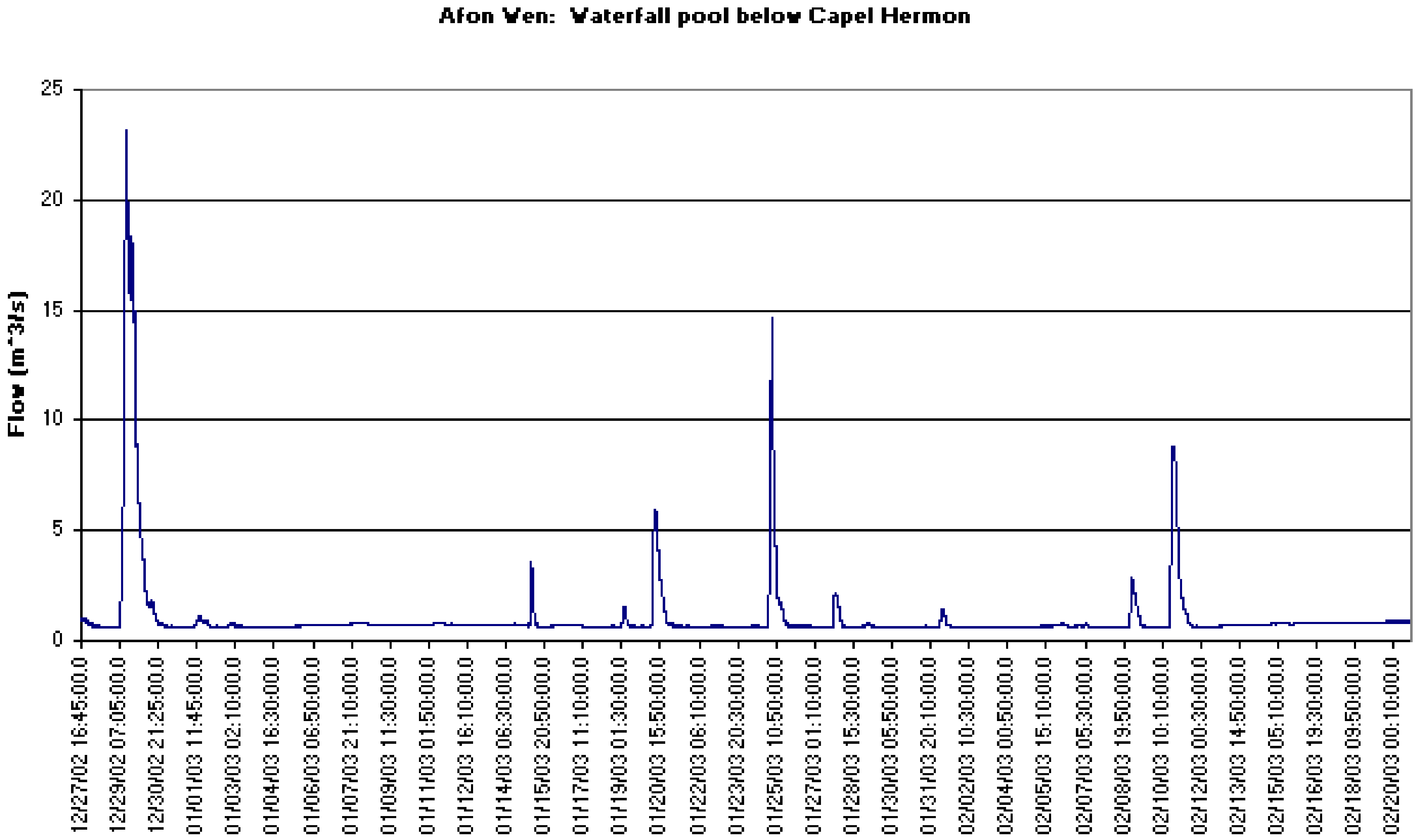


Figure 3.34: Example stage-discharge chart for the Afon Wen hydrograph recording site for the period December 2002 – February 2003

Afon Ty Cerrig

Site description

A hydrograph recorder has been situated in a pool on the Afon Ty Cerrig, a principal headwater stream of the Afon Wnion, at the location shown in fig.3.35. This lies within a forestry plantation at Pared yr Ychain on the slopes of Aran Fawddwy. The channel is composed of cobbles and boulders of 0.5m to 1m median dimension, with a high gradient producing characteristics of a cascade reach. The channel is relatively narrow and confined within incised banks, making it accessible for flow measurement during low flow and flood conditions.

Figure 3.35: Afon Ty Cerrig hydrograph recording site. The recorder is located on the river bed at point A.

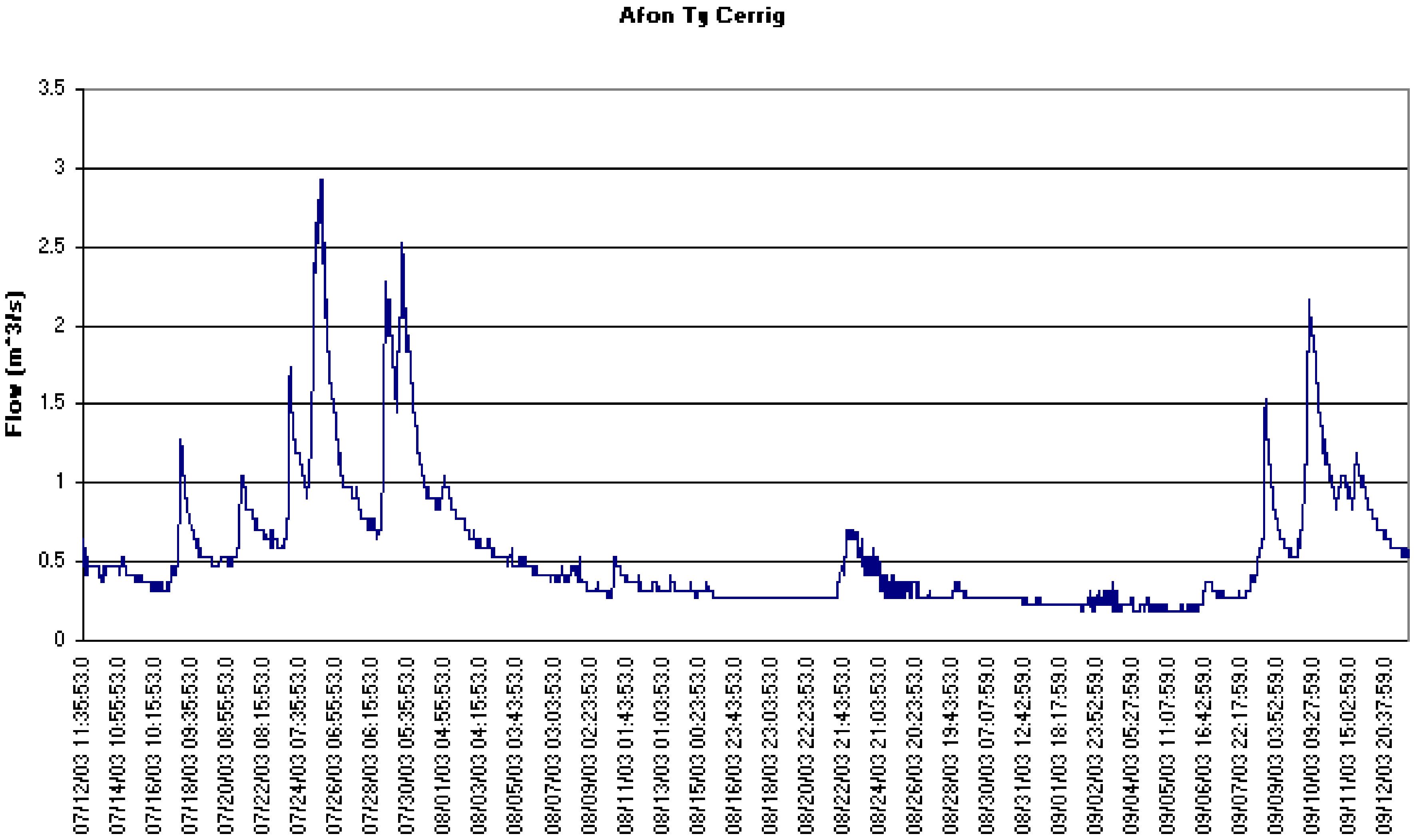


Figure 3.36: Example stage-discharge chart for the Afon Ty Cerrig hydrograph recording site for the period July 2003 – September 2003

Dolgellau

Site description

River stage height data has kindly been supplied by the Environment Agency for the gauging ststion on the Afon Wnion approximately 40m upstream from Bont Fawr, Dolgellau. The gauge is situated on a plane bed reach, with coarse gravel in the size range 0.05m to 0.30m making up most of the bed load.

Figure 3.37: Bont Fawr, Dolgellau, photographed from the Environment Agency river gauging station.

A calibration curve for conversion of river stage(m) to river discharge(m^3s^{-1}) was prepared in a similar manner to the calibration curves for the portable hydrograph recorder sites. The river cross profile was surveyed, and flows measured at points across the river under different stage heights (appendix C). Field measurements were augmented by calculated flow rates for flood conditions when measurement was impractical. The calibration curve function was then used to convert the stage height chart of fig.3.38 to the discharge chart of fig.3.39.

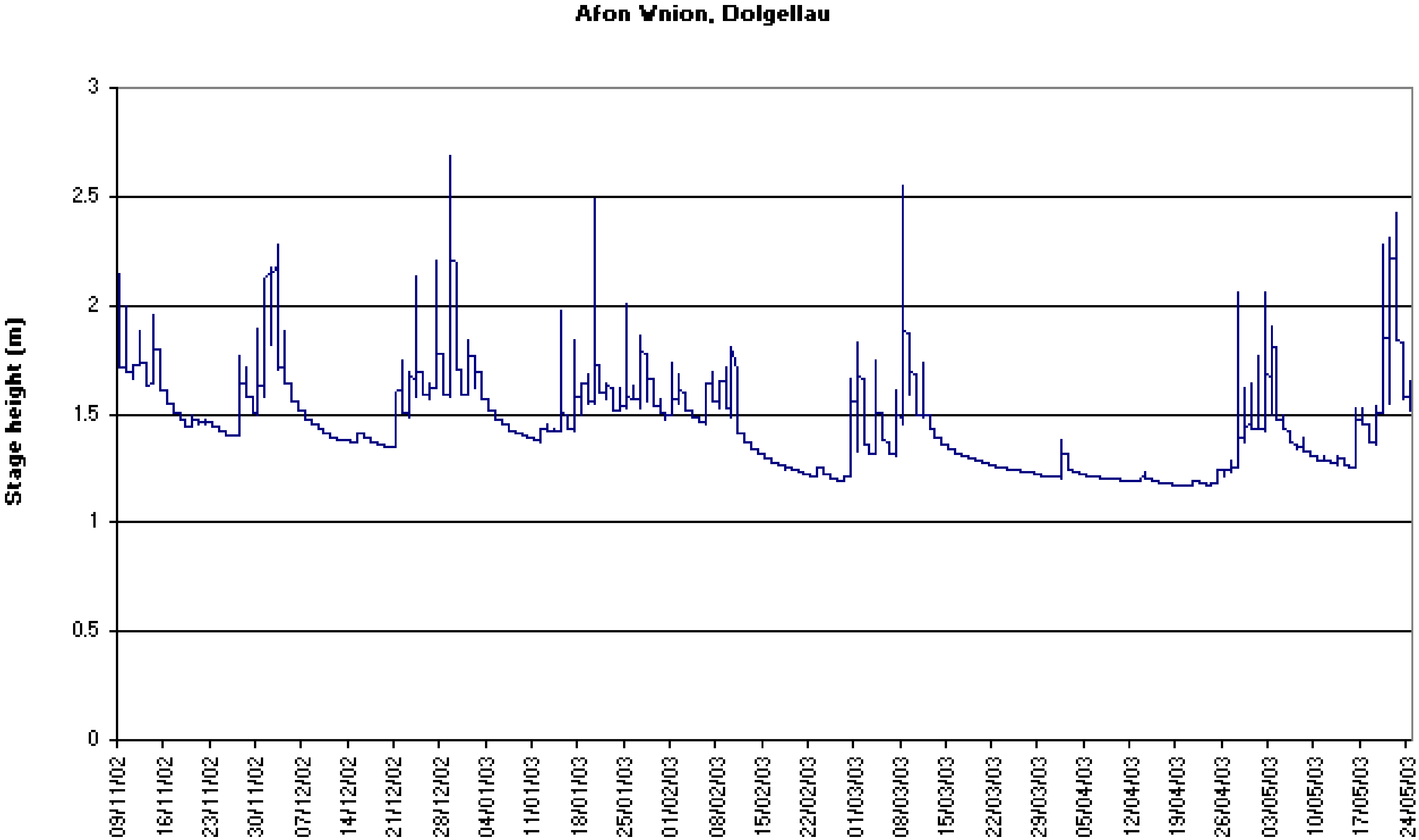


Figure 3.38: Example stage height chart for the Afon Wnion gauging station for the period November 2002 – May 2003

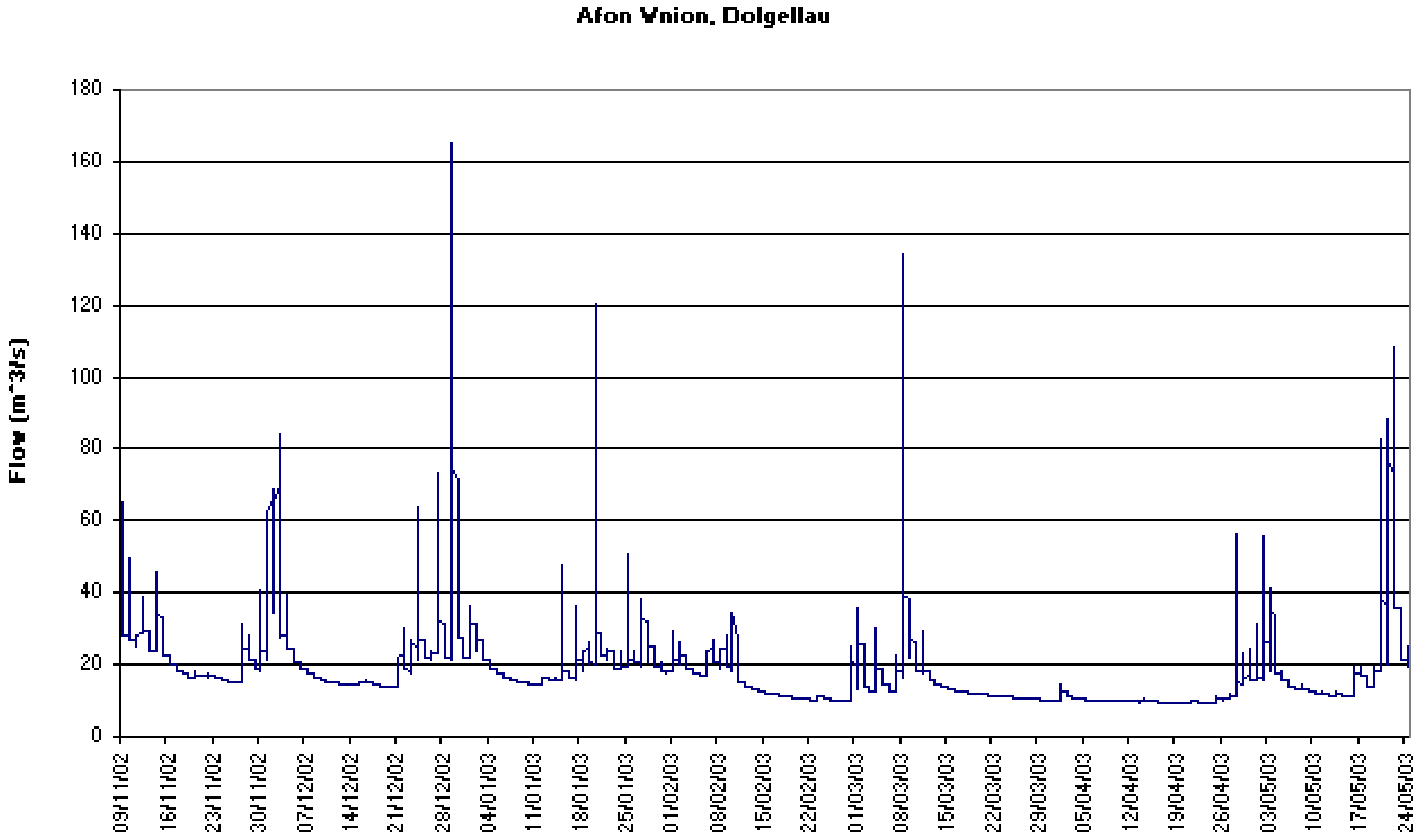


Figure 3.39: Example stage discharge chart for the Afon Wnion gauging station for the period November 2002 – May 2003

Hydrograph correlation

Whilst analysing hydrographs for consitency across the catchment, an interesting result was discovered. Hydrographs recorded at Pared yr Ychain in the source region of the Afon Wnion, and on the Afon Wnion 0.5km west of Dolgellau, can be closely linked by a simple mathematical transformation:

$$\text{water depth in Dolgellau} = \mathbf{A} * \exp(\mathbf{B} * \text{water depth at Pared yr Ychain}) + \mathbf{C}$$

using the empirically determined parameters: $A = 0.05$, $B = 8.2$, $C = -0.15$, as shown in fig.3.40. Parameters were fitted manually by progressive refinement in an Excel spreadsheet and graph. This method was chosen in preference to the use of a statistical package, since tidal spikes present in the Dolgellau hydrograph had to be ignored during curve fitting.

The significance of this result is that the water depth predicted for Dolgellau is 3 hours 30 minutes after the time of the Pont Ty Cerrig hydrograph observation, providing a flood forecasting method of good accuracy. The success of the flood forecasting method appears to be due to two factors:

- Pared yr Ychain lies on the NW-SE axis of high rainfall which crosses the Mawddach catchment. Storm events at Pared yr Ychain therefore have a particularly significant effect on flood levels downstream on the Afon Wnion.
- The Afon Ty Cerrig which is gauged at Pared yr Ychain is typical of the streams draining the slopes of the Aran mountains. These slopes exhibit a high degree of hydrological uniformity over much of the course of the Wnion valley, with similar slope angles, cover by glacial deposits, and grassland vegetation. Hillslope runoff over this large area may therefore have a similar travel time to the Wnion trunk stream, and total flow in the Wnion is a simple scaling of the flow in the Afon Ty Cerrig tributary.

No similar simple relationship between hydrographs was found for the Mawddach sub-catchment. Contributions to total flow from the upper Mawddach, Gain, Eden and Afon Wen may vary greatly in volume and timing between storm events. This unpredicatability can be ascribed to: the variety of rainfall patterns, and local complexity of slopes, landuse and geology, and the different river routing times for flow along the different tributaries.

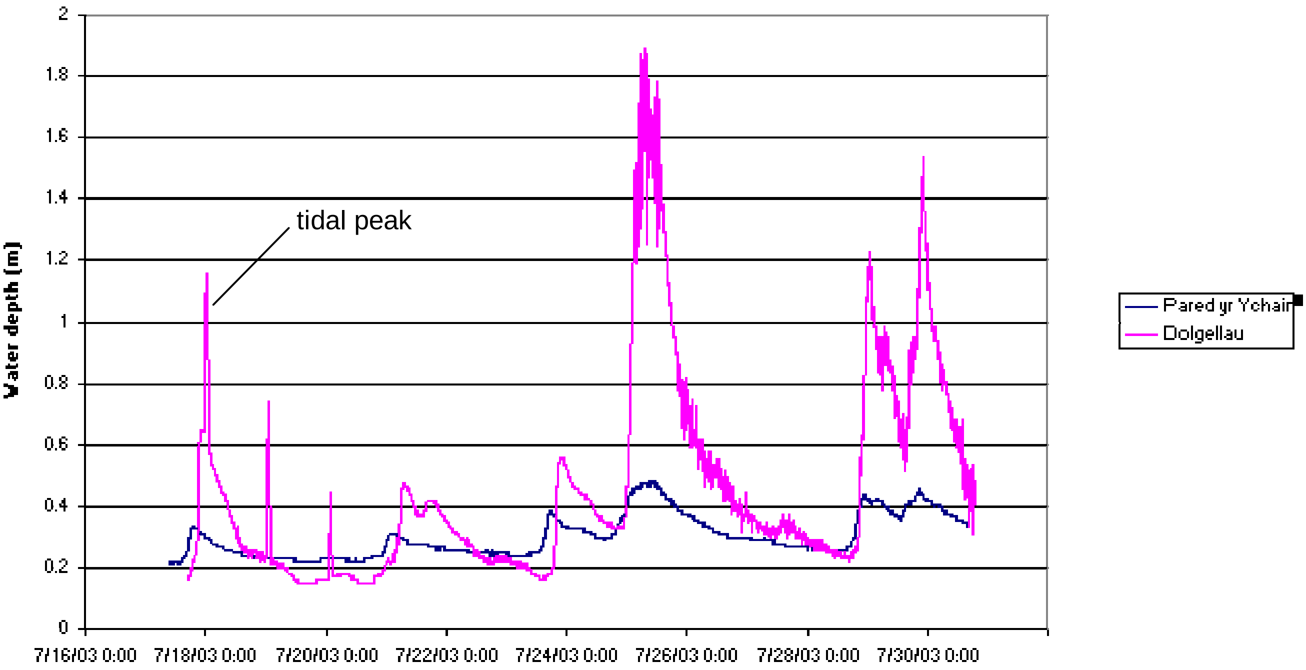


Figure 3.40(a). Original hydrographs recorded for the Afon Wnion

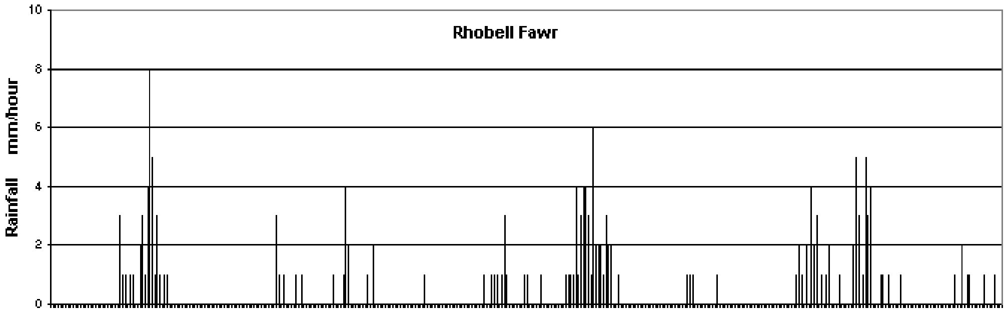


Figure 3.40(b). Rainfall for the period 16 July – 31 July 2003

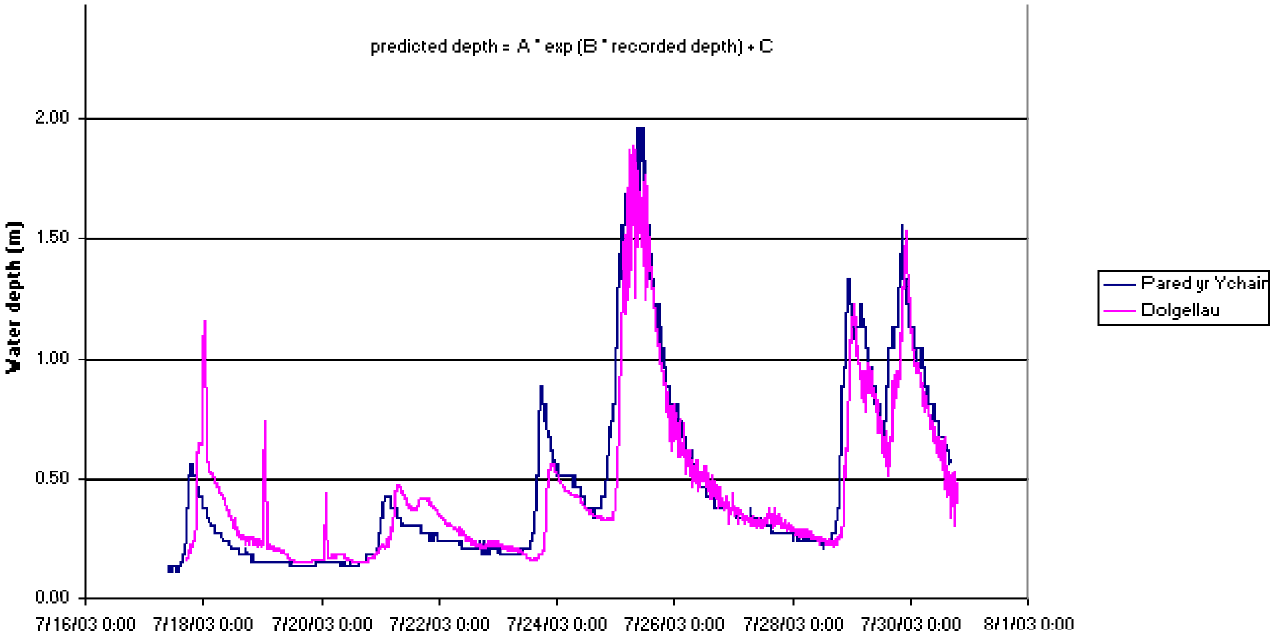


Figure 3.40(c). Hydrographs after transformation of the Pared yr Ychain data

Soil shallow stormflow

Weyman (1973) has studied the downslope flow of water in thick soils. Initial infiltration occurs vertically downwards, with lateral flow developing only within the saturated zone of the soil profile. Low permeability bedrock or low permeability soil horizons are considered essential for initiating lateral flow in the soil. Weyman observes that shallow flow may contribute to storm discharge, and may continue for several weeks after a storm event without further recharge. He states that lateral downslope flow appears to obey Darcy's law for fluid flow through porous media.

Hillslope water flow measurements have been carried out in the source area of the Afon Wnion at Pared yr Ychain, to investigate mechanisms of hillslope hydrology. Three sites have been instrumented to record surface runoff to a depth of 10cm and shallow stormflow (throughflow) at a depth of 1.5m, using a similar construction method to Atkinson (1978) as shown in fig.3.41.

Figure 3.41(a)
Site prepared for instrumentation, showing peat soil on glacial till, Pared yr Ychain

Figure 3.41(b)
Site after installation of water flow recorders and data loggers, Pared yr Ychain

The high rainfall of the area promotes prolific growth of ground vegetation – principally mosses, ferns and grasses amongst a young conifer plantation. An intermediate acidity peat soil is developed to a depth of 20 – 25cm on sandy clay glacial till derived from acid volcanic rocks. Typical results from flow measurements are shown in fig.3.42.

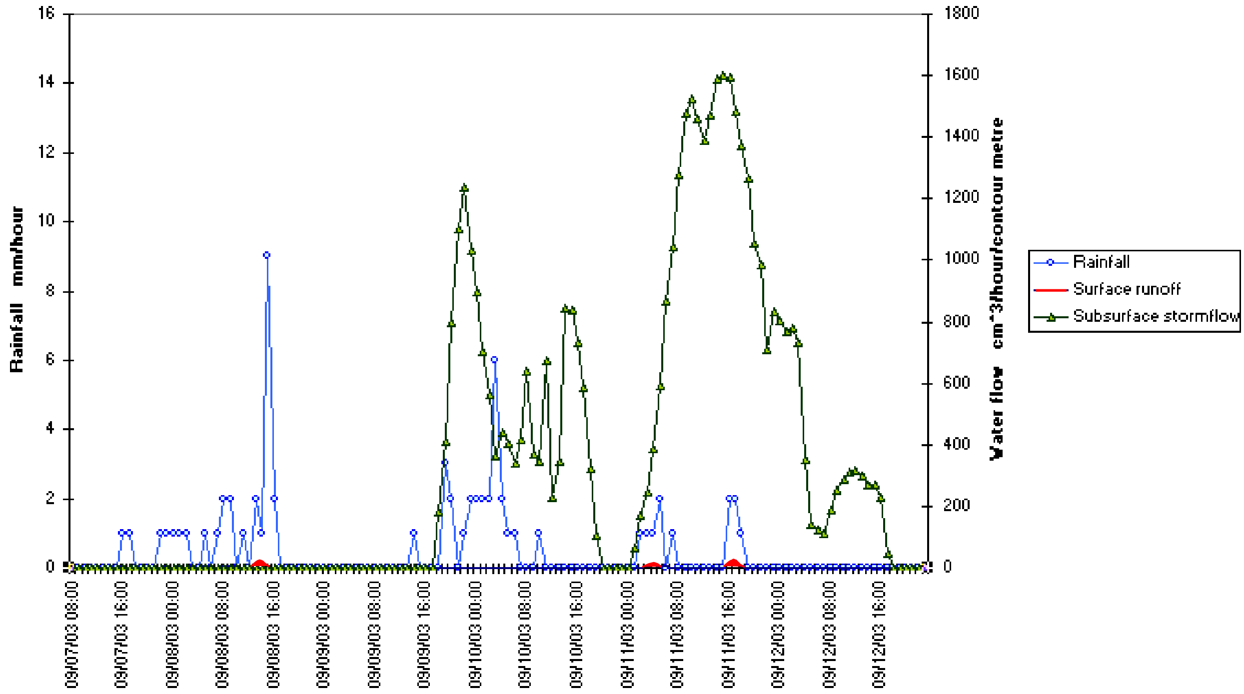


Figure 3.42: Hillslope water flows at Pared yr Ychain, 7 - 12 September 2003

It is found that volumes of hillslope water flow are strongly controlled by antecedent conditions. Nearly all downslope movement of water occurs as stormflow within the glacial till, with insignificant amounts of surface runoff recorded. This may be due to the absorbent effect of ground vegetation and ready availability of pathways for routing of water downwards through the thin peat layer. Streams are deeply incised into the glacial deposits of the Aran slopes, and shallow throughflow is discharged through the banks of channels during storm events.

It is significant that large volumes of sub-surface stormflow occur some four to six hours after the onset of heavy rainfall, which may be too late to directly influence flood peaks downstream. Stormflow can, however, continue for up to two days after rainfall and may control antecedent base flow levels for subsequent storm events. A series of rainfall events within a few days of one another in September 2003 are seen to produce progressively greater volumes of shallow stormflow, as the subsoil becomes saturated and the watertable is raised.

Further insight into the importance of antecedent conditions comes from another soil throughflow experimental site set up at Tir Penrhos, near Hermon in the Afon Wen valley (fig.3.43). This site is on a valley slope overlain by a thick succession of periglacial deposits in which 1.5m of scree overlies solifluction material and fluvial sands and gravels.

Figure 3.43:
Surface runoff and soil throughflow monitoring site, Tir Penrhos, Hermon

Example data for surface runoff and soil throughflow is presented in fig.3.44. At Tir Penrhos, ground vegetation below mixed woodland is poorly developed. Surface runoff is relatively high in comparison to the Pared yr Ychain sites. Permeability of the periglacial scree at shallow depth is high, so throughflow is not recorded for the majority of rainfall events. At these times, the water table lies deep in the scree layer below the level of monitoring. A prolonged period of heavy rain can, however, cause the water table to rise, generating a very high volume of shallow throughflow for the discharge point at the base of the experimental site.

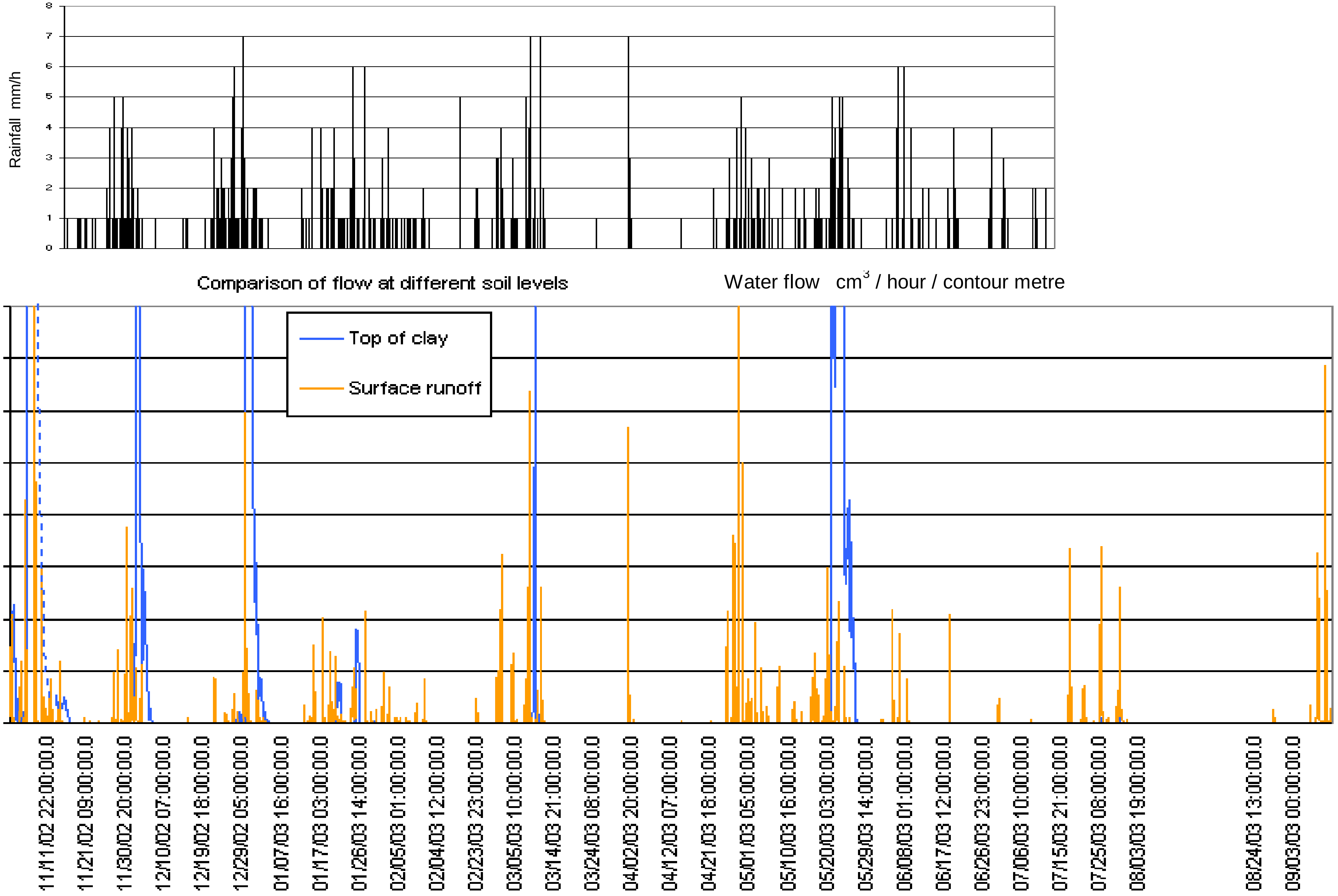


Figure 3.44: Surface runoff and soil throughflow monitoring at Tir Penrhos, November 2002 – September 2003

Results from the Tir Penrhos experiment are particularly interesting because the instances of high volumes of shallow throughflow correspond exactly with periods of extensive flooding of agicultural land around the head of the Mawddach estuary, some 5km downstream.

It is conjectured that under normal conditions:

- Glacial and periglacial deposits on the valley sides are unsaturated, and allow downwards percolation of soil water into groundwater storage.
- Due to the stepped profiles of the Mawddach and its tributaries, the water table lies below the river bed over a majority of reaches within the middle courses of the rivers in Coed y Brenin. Water may be lost through the river beds into groundwater storage.
- Groundwater is released into rivers over several days following rainfall. This timescale is too slow to affect the flood peak of a storm event.

After a prolonged period of heavy rainfall, hydrological conditions change:

- Glacial and periglacial deposits on the valley sides become saturated to a shallow depth. Downwards percolation into groundwater storage can no longer maintain drainage, and there is a rapid increase in downslope water transfer by shallow stormflow. Water is readily released through the banks of streams, and quickly enters the river routing system.
- The water table rises below the main channels, and groundwater is released through the streambed to increase river flow.
- Further rainfall follows fast surface runoff pathways, contributing to the buildup of a flood peak downstream.

Monitoring of subsurface throughflow below hillslopes in Coed y Brenin may provide early warning of the saturation conditions needed to initiate flooding downstream.

Watershed Modelling System

A first step in producing flood models for the Mawddach and Wnion subcatchments has been the use of the HEC-1 semi-distributed model, described previously in section 3.1 (fig.3.6). The model uses rainfall estimates to simulate infiltration, surface runoff and river routing processes. Synthetic hydrographs can be generated for selected points within the channel network.

Clear limitations of HEC-1 are:

- loss of infiltration water from the model completely,
- the modelling of sub-catchments with uniform hydrological properties, a situation which does not accurately represent the small scale variations in slope, geology, vegetation and soil types observed in the field.

Despite these simplifying factors, HEC-1 is found to produce acceptable hydrograph simulations for individual storm events. The hydrographs generated can provide input to sediment transport models as described in section 3.3, and to floodplain inundation models as described in section 3.4. HEC-1 may be taken as a baseline against which the performance of more sophisticated hydrological models should be judged.

Before running the HEC-1 model, data files must be generated to represent the hydrological properties of the catchment, the geometry of the river network, rainfall sequence, and the mathematical options selected to simulate infiltration, surface runoff and river routing (Goldman and Ely, 1990). These files may be prepared manually and input in alphanumeric format using a text editor, but the process is greatly simplified by the use of data preparation software based on GIS techniques. The Watershed Modelling System (Brigham Young University, 2004) has been used for this purpose in the current project. The WMS program additionally provides post-processing facilities for graphical display of the river network incorporating output hydrographs at selected points.

Setting up a hillslope runoff model

A HEC-1 model is developed by dividing the overall catchment into a series of basins which may be considered hydrologically homogeneous. Rainfall, infiltration and surface runoff will be averaged across each basin. Twelve sub-catchments were chosen above the tidal limit for the Mawddach, and eight sub-catchments were chosen for the Wnion. The sub-catchments are described in appendix B, and are outlined in figures 3.17 and 3.18.

A digital elevation model is first loaded into the program, then used to define the river channel network and sub-catchment boundaries (fig.3.45). For the Mawddach and Wnion catchments, a 50m gridded DEM provided by the Centre for Ecology and Hydrology has proved suitable.

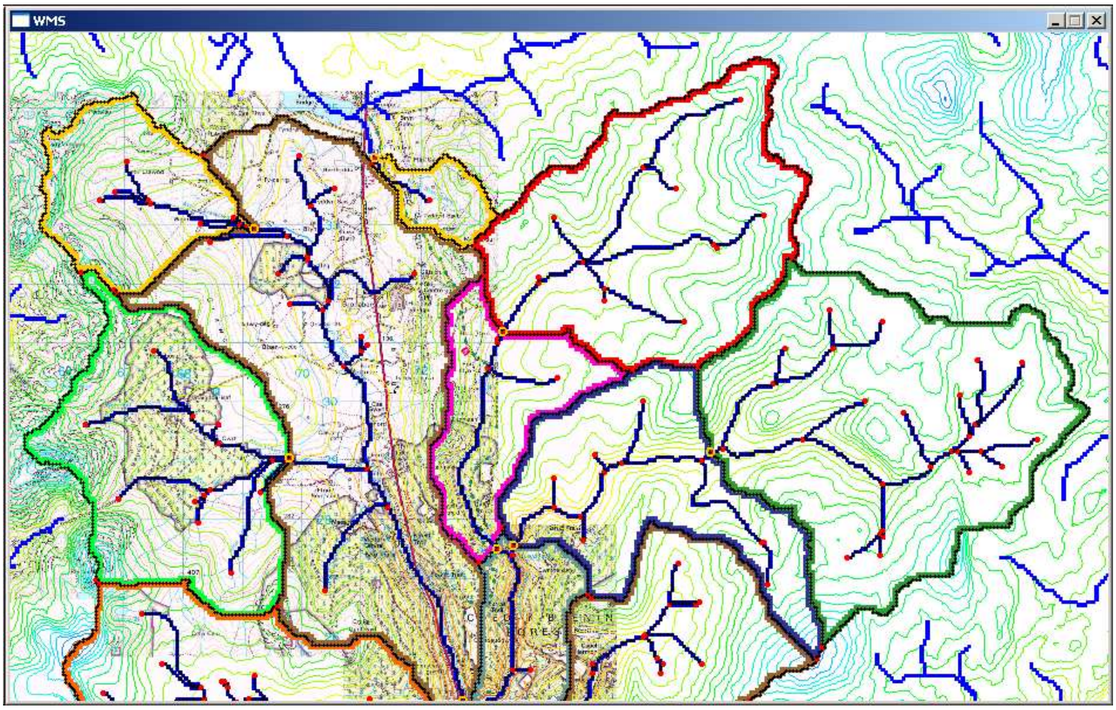


Figure 3.45: Construction of the Watershed Modelling System model for the upper Mawddach. Topographic contours, the stream network and sub-catchment boundaries and have been determined geometrically from the digital elevation model.

The digital elevation model is now converted to a Triangulated Irregular Network to simplify the calculation of the basin parameters required by the HEC-1 program. Triangles are constructed to conform with the stream courses and basin boundaries previously defined, in order to maximise the accuracy of the model (fig.3.46).

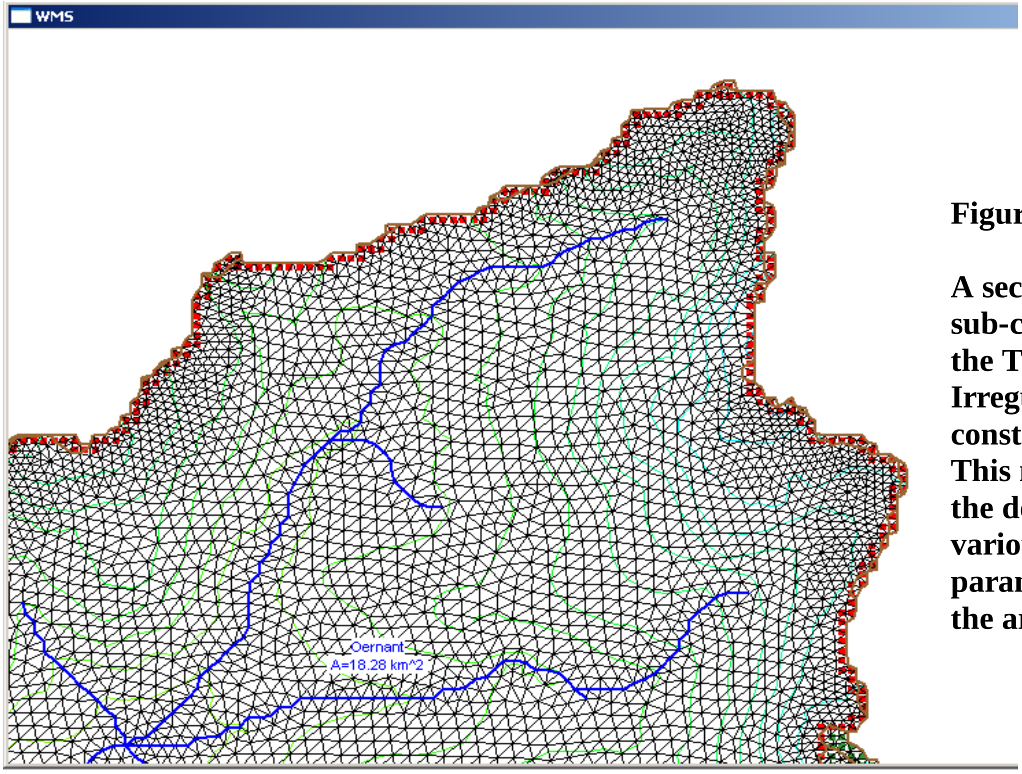


Figure 3.46:

A section of the Oernant sub-catchment, showing the Triangulated Irregular Network constructed by WMS. This network is used in the determination of various basin parameters, including the area value shown.

Soil and landuse overlays

An option available in HEC-1 is to determine infiltration rates by the SCS Curve Numbers method (fig.69). This option has proved successful when used in the Mawddach model.

Before using the Curve Numbers method, it is necessary to provide information on the types and distribution of soils and vegetation within the catchment. This is done by setting up separate overlays, as in the land use example of fig.3.48 below.

- Land use has been divided into the main categories of natural vegetation and agricultural use identified earlier in section 1.2 and displayed in fig.1.88.
- Soils are categorised on a four-point scale from: dry (type A) to wet (type D). Four curve numbers A to D are allocated to each land use category, as shown in Table 3.1. A curve number may then be selected from this group, depending on whether the soil is: dry, moderately dry, damp, or wet.
- Soils developed on well jointed Cambrian grit would belong to a drier group than those on poorly drained shales or basalts.
- The soils of the whole region belong to drier categories in the summer than in winter months.

The procedure for curve number allocation is illustrated in fig.3.47 for a hypothetical area of sub-catchment:

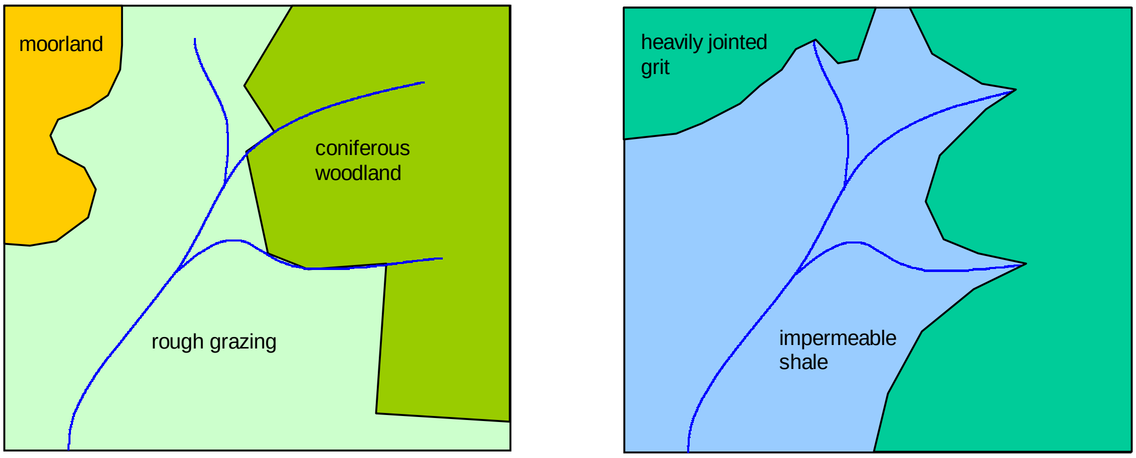


Figure 3.47(a). Land use and geology overlays.

Land use and geology overlays are superimposed in the model to identify zones with unique combinations of land use/geology. Curve Numbers are allocated according to the land use categories in Table 3.1. The soil moisture class (A-D) chosen depends partly on geology and partly on antecedent soil moisture conditions. For example, soils on freely draining grits are allocated class B during periods of low rainfall, but class C after a previous period of wet weather. Naturally damper soils on impermeable shales are allocated class C during periods of low rainfall, but class D after a previous period of wet weather.

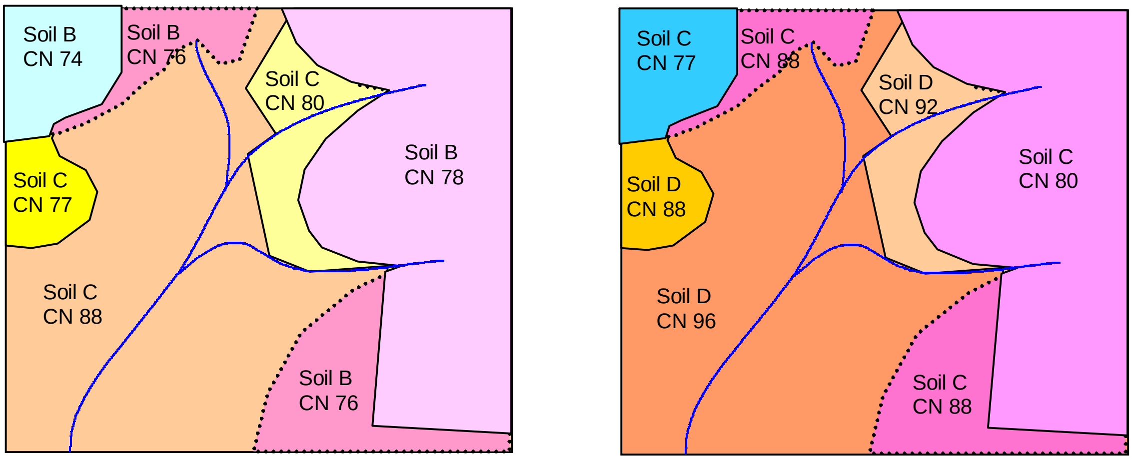


Figure 3.47(b). Allocation of Curve Numbers (left) dry antecedent conditions, (right) wet antecedent conditions

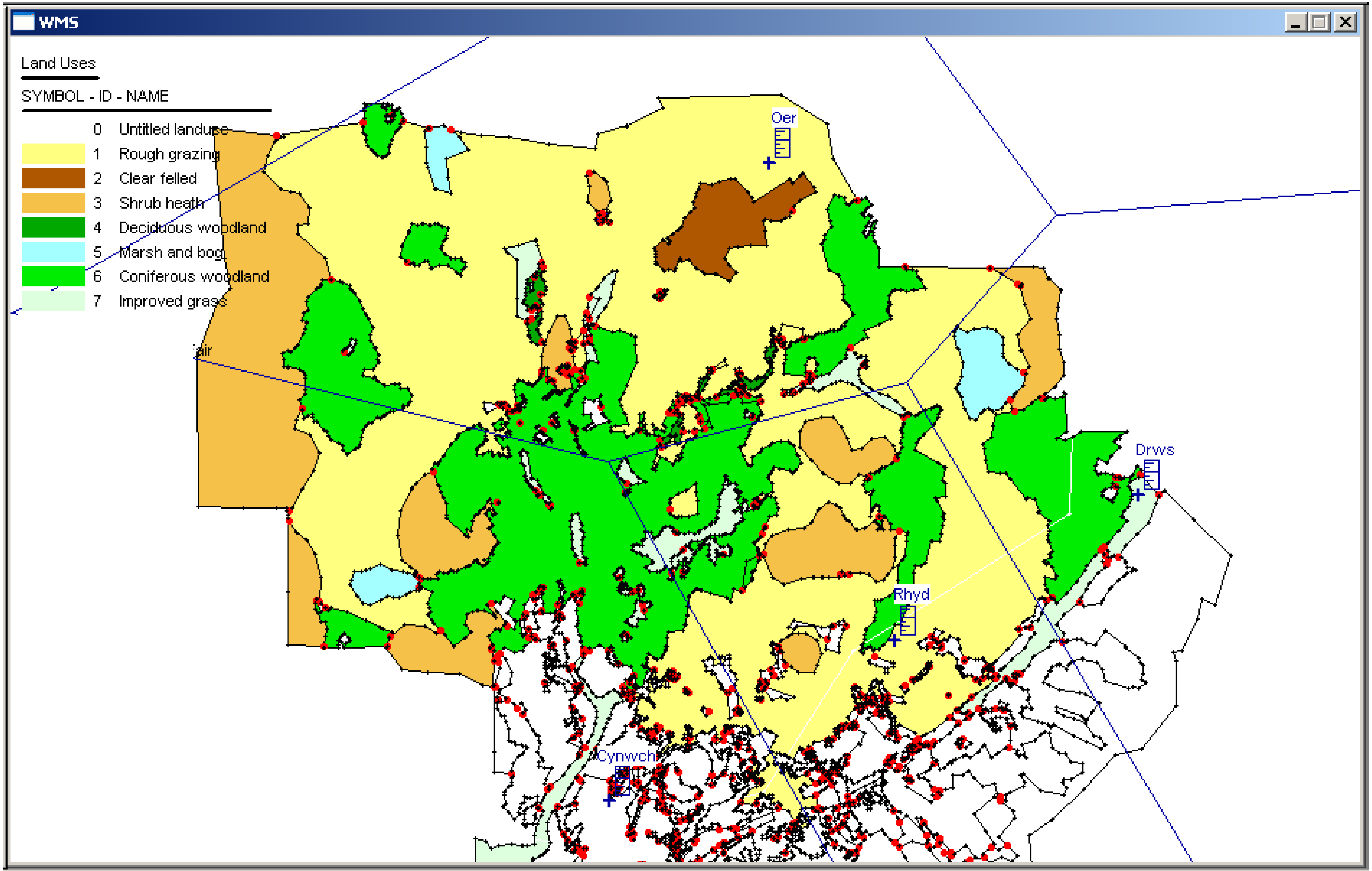


Figure 3.48: Land use overlay for the WMS Mawddach model

The partition of rainfall between infiltration and surface runoff is determined by the equation:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}$$

using Imperial units, where Q is runoff (inches), P is cumulative rainfall during the storm event (inches), and S is the soil moisture deficit (inches). A parameter termed the *Curve Number,* CN, is related to S by the equation

$$S = \frac{1000 - 10CN}{CN}$$

Example graphs for different curve numbers are shown in fig.3.49. Qualitatively, this indicates that runoff increases during a storm event as the soil becomes increasingly saturated, and that zones of high curve number experience more runoff, and correspondingly less infiltration, than zones of low curve number.

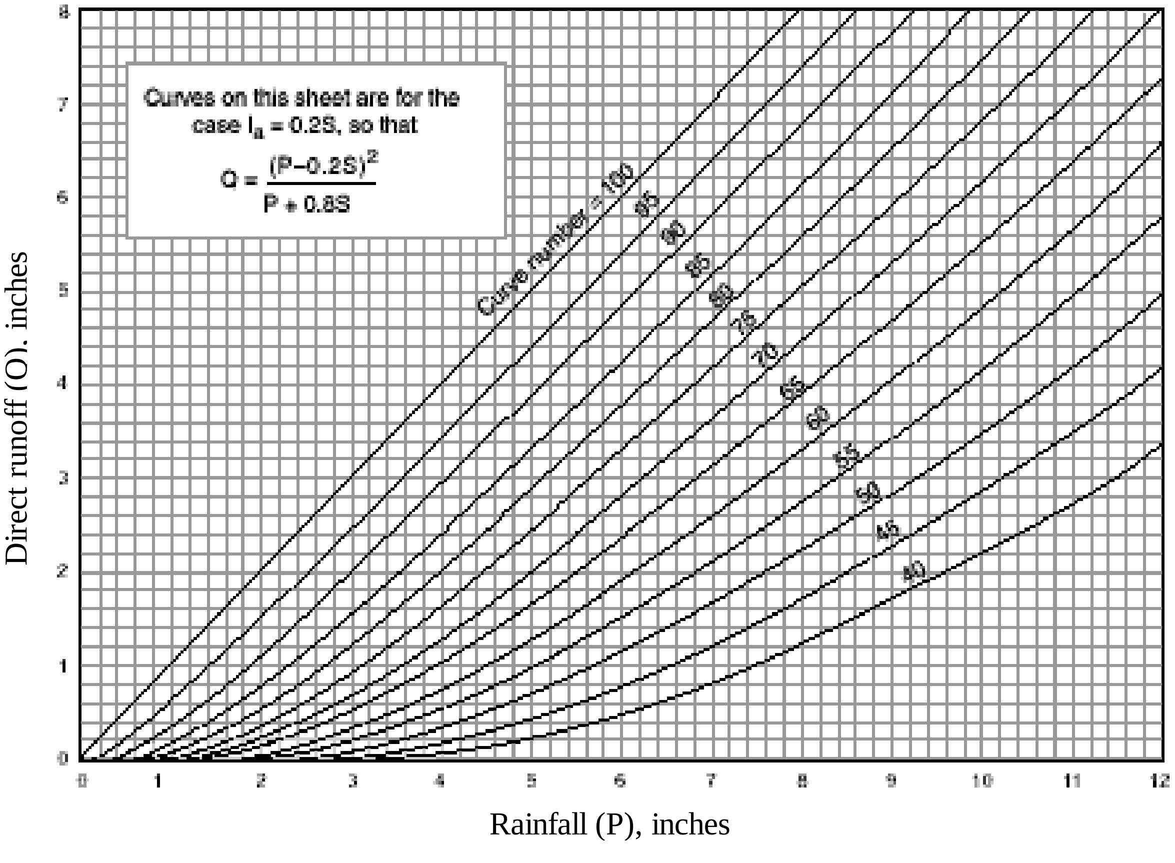


Figure 3.49: Soil Conservation Service curve number chart

Curve numbers are computed by superimposing vegetation and soil overlays, and using a table to determine values for different soil/vegetation combinations. Experimentation has led to the following values providing consistent results for storm events in the Mawddach catchment:

Land use category	Soil A	Soil B	Soil C	Soil D
Rough grazing	68	76	88	96
Heather moorland	70	74	77	88
Coniferous woodland	76	78	80	92
Deciduous woodland	76	78	83	92
Improved grassland	82	85	88	96
Clear felled	90	92	92	98
Bog and marsh	83	84	87	96

Table 3.1. SCS Curve Numbers used in the Mawddach catchment model

An alternative approach to computing soil infiltration in the HEC-1 model uses the Green-Ampt equation. Experiments have been carried with this method, but it was found that the SCS Curve Numbers approach provides more consistent results, with a simpler facility for incorporating antecedent soil moisture conditions.

Rainfall

To simulate water flows during a storm event, it is necessary to provide a time sequence of rainfall for one or more stations across the catchment. Where multiple raingauge stations are used, the program is able to construct interlocking Thiessen polygons around each station to represent the zones of applicability for each gauge. Rainfall values can be computed for each sub-basin by averaging adjacent raingauge readings, weighted in proportion to the Thiessen polygon coverage within the sub-basin. Fig.3.50 shows Thiessen polygons constructed for raingauge stations active around the Mawddach catchment at the time of the July 3, 2001 flood event.

Fig.3.51 illustrates the method of setting up a rainfall sequence to represent storm rainfall at a gauge site. The time interval between readings is chosen, in this case 15mins, and cumulative rainfall is entered for each specified time as a fraction of the total storm rainfall at that gauge site. It then just remains to enter the storm rainfall total for the gauge site.

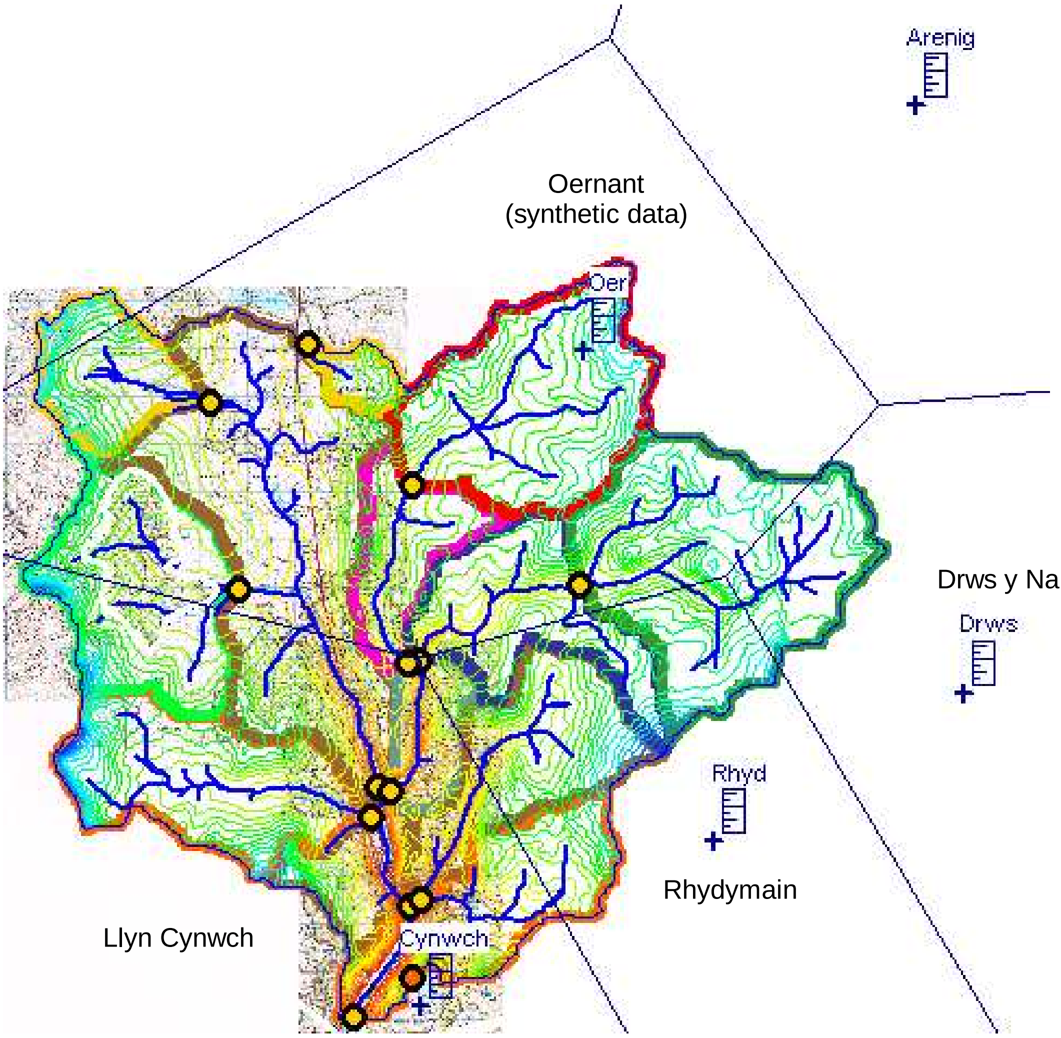
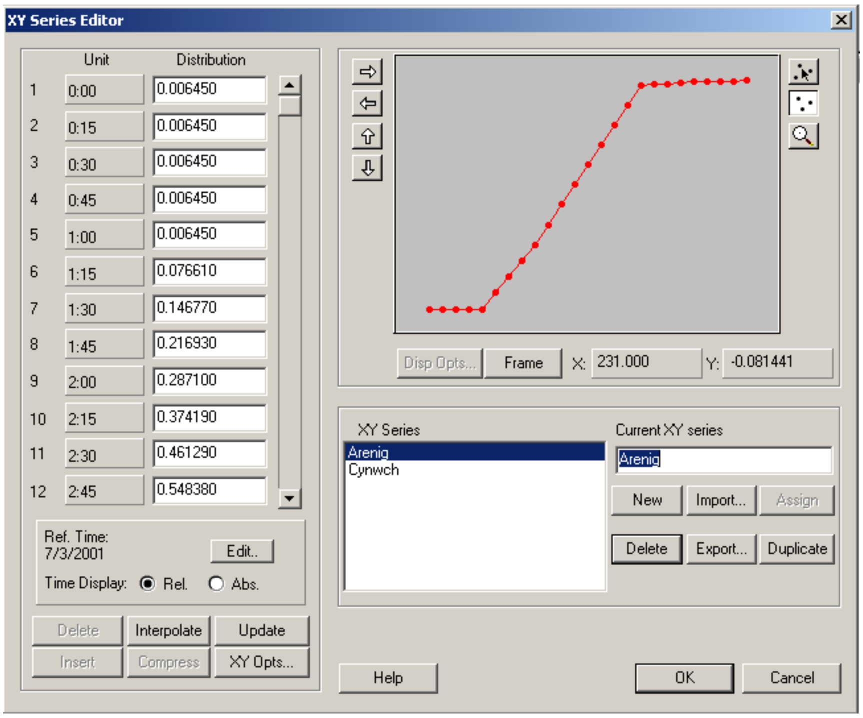


Figure 3.50: Construction of Thiessen polygons for the Mawddach sub-catchment



	Unit	Distribution
1	0:00	0.006450
2	0:15	0.006450
3	0:30	0.006450
4	0:45	0.006450
5	1:00	0.006450
6	1:15	0.076610
7	1:30	0.146770
8	1:45	0.216930
9	2:00	0.287100
10	2:15	0.374190
11	2:30	0.461290
12	2:45	0.548380

Ref. Time:
7/3/2001
Time Display: ● Rel. ○ Abs.

X: 231.000 Y: -0.081441

XY Series
Arenig
Cynwch

Current XY series
Arenig

Figure 3.51: Setting up a storm rainfall sequence for a raingauge station

Overland flow

Rainfall not lost from the model as infiltration is treated as quickflow. This term may be taken to include both surface water sheet flow and shallow fast soil throughflow down hillslopes. Before running a HEC-1 model, the method to be used for computing overland flow must be chosen. The model provides both a Unit Hydrograph method and a Kinetic Wave method for overland flow.

The mathematical basis of the Kinematic wave method was outlined in section 3.1 above, and is discussed by Bevan (2001). The Kinetic Wave method treats the drainage system as composed of three orders of flow path:

- First order flow occurs across strips of hillslope, as at locations A. No permanent stream channels of this order are present.
- Second order flow occurs through feeder channels, as at locations B. Permanent channels are present, though they may be dry between storm events. These channels are too small to form part of the mapped river system.
- Third order flow occurs in river channels as at C. This flow is handled by river routing methods, and does not form part of the surface runoff calculation.

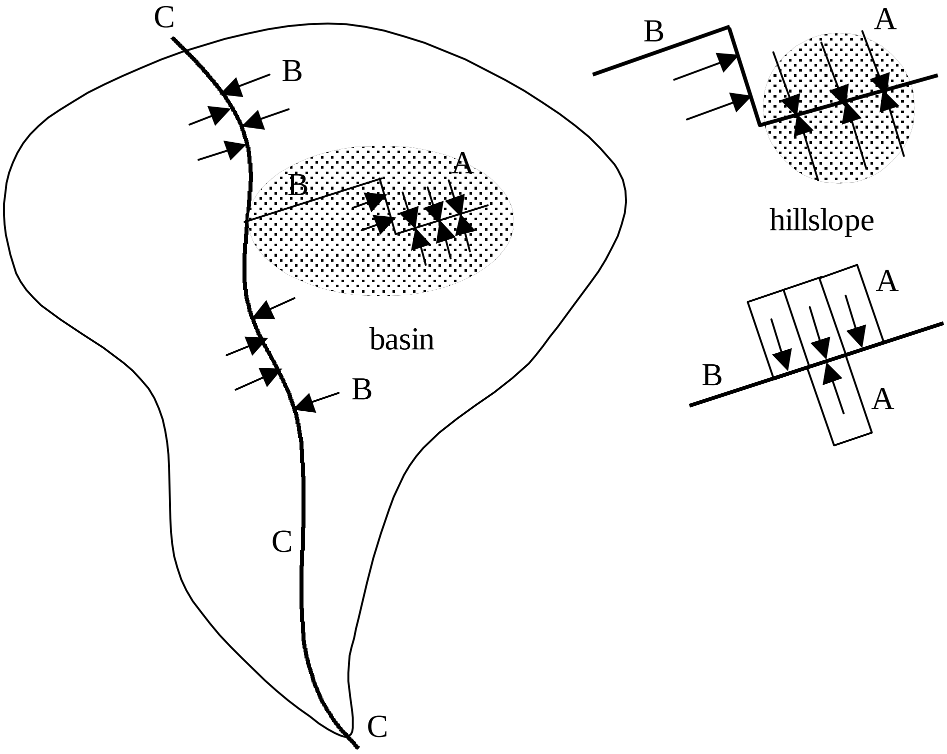


Figure 3.52: Orders of surface water flow modelled by WMS HEC-1

In order to determine flow volumes using the Kinetic Wave equations, the HEC-1 program carries out separate processing of the first order overland flow planes and the second order collector channels. In each case, the data required for calculations are:

- mean flow distance
- mean slope
- Manning roughness

Additionally, the mean cross section shape of the collector channels must be specified.

Experiments were carried out using the Kinetic Wave method for storm events in the Mawddach catchment. Whilst it was possible to produce results in close agreement with recorded hydrographs for single storm events, there was difficulty in obtaining a single set of hillslope parameters which produced consistent results for different storms. Consequently, the alternative method of Unit Hydrographs was selected for the Mawddach HEC-1 model.

Unit Hydrograph methods

The Unit Hydrograph methods operate on the principle that runoff during storms is additive. For a given area of hillslope,

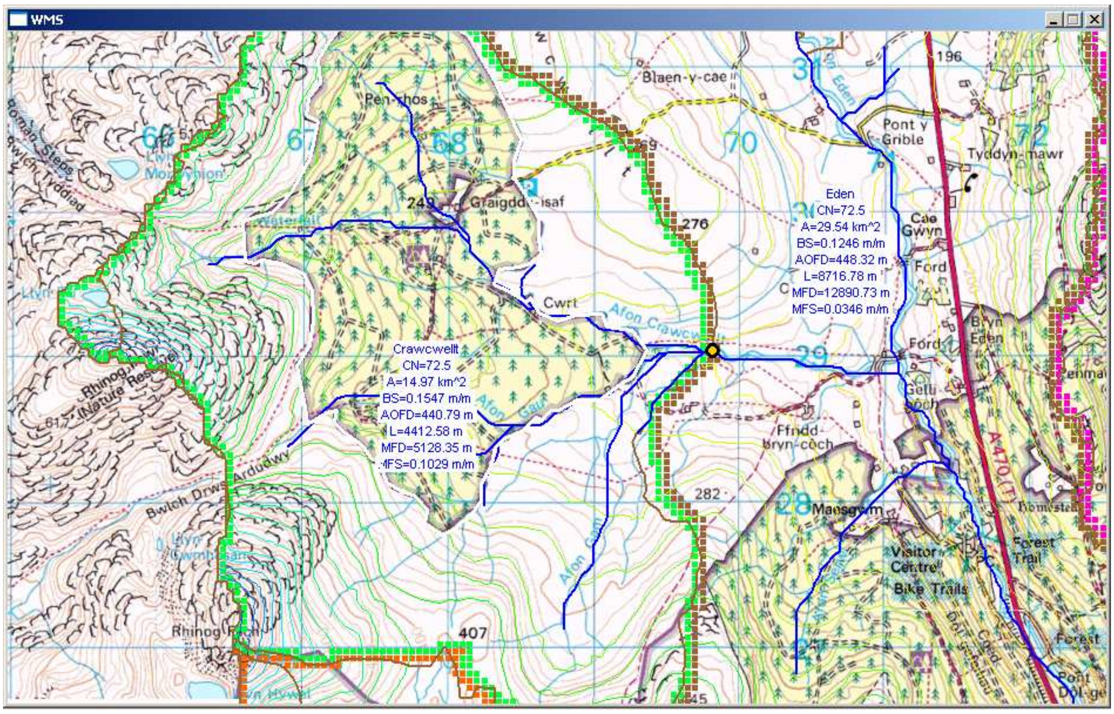
- a storm of 20mm/h produces twice as much runoff as a storm of 10mm/h,
- a storm of duration 2 hours produces twice the runoff of a storm of 1 hour with the same rainfall intensity.

Runoff from different sub-catchments and time intervals can therefore be added in a simple way, allowing for the time of routing waterflows downstream between sub-catchments.

Unit Hydrograph methods depend on obtaining a mathematical relationship between the runoff produced by unit rainfall in one time interval, and geometric characteristics of the sub-catchment. From the various linking equations available, the Espey Rural method has proved successful for the Mawddach model. This equation makes use of the mean stream length and stream slope to compute the time for peak flow from the sub-catchment after the commencement of storm rainfall. The equation for the Espey Rural method is:

$$\text{time to peak flow} = 2.65 \times (\text{stream length})^{0.12} \times (\text{stream slope})^{-0.52} \text{ minutes}$$

The required measurements, amongst others, are determined automatically by the WMS software (fig.3.53).



Crawcwellt
CN=72.5
A=14.97 km^2
BS=0.1547 m/m
AOFD=440.79 m
L=4412.58 m
MFD=5128.35 m
MFS=0.1029 m/m

Eden
CN=72.5
A=29.54 km^2
BS=0.1246 m/m
AOFD=448.32 m
L=8716.78 m
MFD=12890.73 m
MFS=0.0346 m/m

Figure 3.53: Illustration of basin parameters computed geometrically for two of the Mawddach sub-catchments: A area, BS basin mean slope, AOFD average overland flow distance, L basin length, MFD mean flow distance, MFS mean flow slope

River routing

River routing in the HEC-1 model can be carried out by various methods including the Muskingham and Muskingham-Cunge equations, and the Kinematic Wave equation. In each case, the downstream water flow volume is determined from the channel distance and flow velocity, with flow velocity being calculated as some function of channel slope, channel shape and Manning's roughness. In practice it was found that the model was relatively insensitive to the choice of routing method, with all giving similar routing times. The Muskingham method, requiring the least parameters, was therefore chosen for the Mawddach HEC-1 model.

Model output

After preparation of input data files is complete, the model may be run and output files are generated.

The HEC-1 model operates on a series of sub-catchments, linked upstream in a branching tree pattern (fig.3.54). When the model is run:

- hillslope flows are generated for each sub-catchment for each time interval,
- the hillslope flows are routed to the outflow of the sub-catchment,
- riverflows entering the head of the sub-catchment are routed downstream and combined with the hillslope flows at the outlet,
- the combined riverflow is then made available to the next sub-catchment downstream at the start of the next time interval,
- riverflows are combined at confluence points and routed downstream.

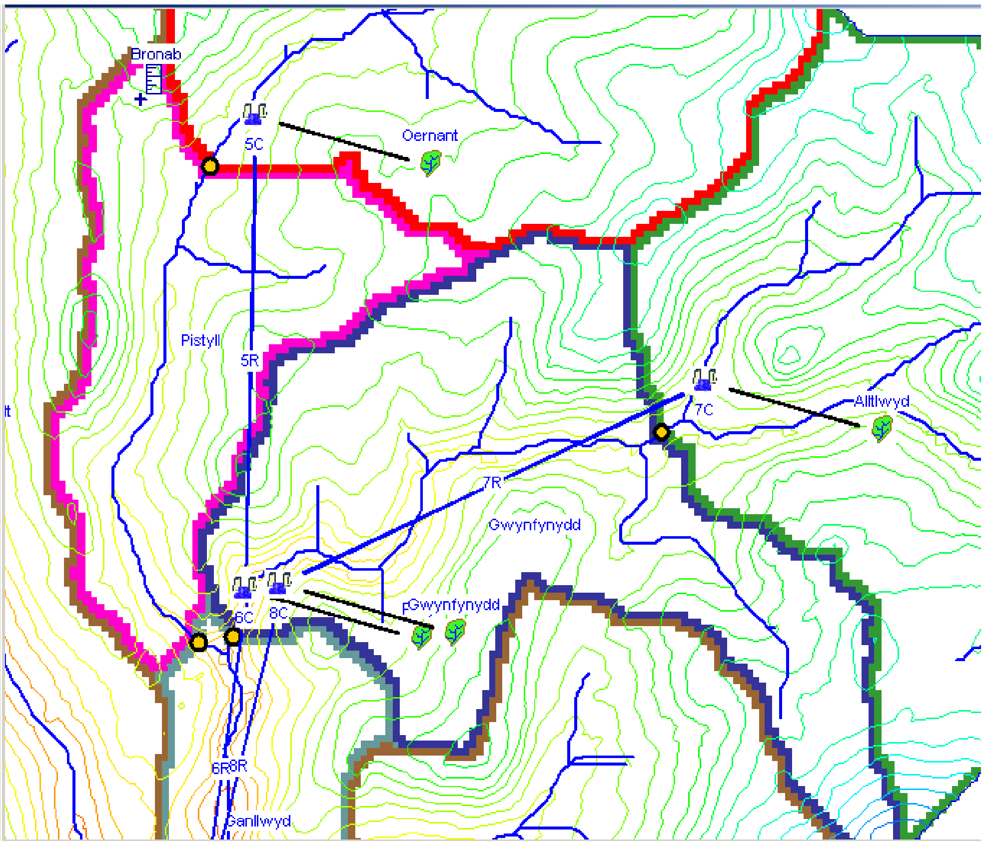


Figure 3.54: River routing diagram produced by WMS for the upper Mawddach. Green 'basin' symbols represent hillslope runoff from individual sub-catchments, Blue lines represent downstream routing directions, and 'flume' symbols represent points at which synthetic hydrographs have been generated by the model.

Results of model runs

Runs were carried out for the example rainfall events discussed earlier in section 2.4:

- Squall line convective storm: 3 July 2001
- Frontal storms: 8 November 2002, 29 December 2002, 8 March 2003, 21-22 May 2003, 3-4 February 2004

The HEC-1 model was set up and configured to simulate the extreme storm event of 3 July 2001 associated with a squall line of convective thunderstorm cells across the Mawddach catchment. The storm was active between 16:00 h and 22:00 h.

At the time of the July 2001 storm, five raingauges were providing hourly totals within or close to the Mawddach catchment. From the pattern of river levels, it is likely that the zone of maximum storm rainfall lay within this ring of stations, over the mountainous terrain around Moel Oernant.

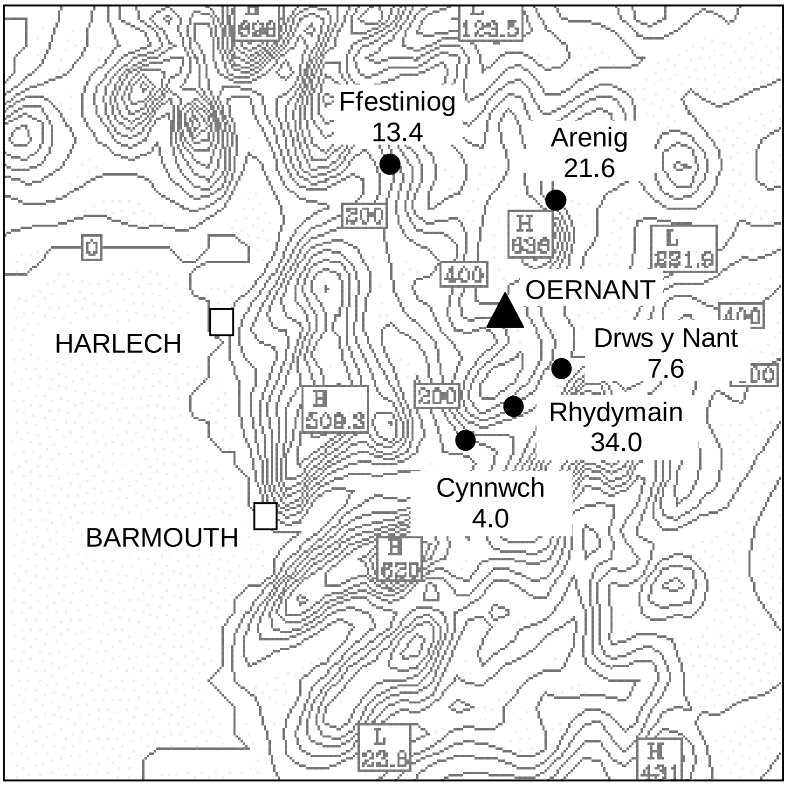


Fig. 3.55: Rain gauge sites, showing totals (mm) for the period 18:00–19:00 h, 3 July 2001

The MM5 mesoscale meteorological model has been used to obtain further insight into rainfall intensities and distribution during the storm (cf section 2.4). Modelling correctly identifies the north-south orientation of the squall line (fig.2.113). Localised convective cells with maximum rainfall intensities during the storm of between 45 and 70 mm h^{-1} are produced.

Inaccuracies in the model are likely to be positional, rather than in intensity. Random processes operating within a squall line make it difficult to predict the exact location where a convective cell will develop. On the basis of field evidence, the centres of convective cells should be displaced approximately 12 km northwards to lie over the southern Arenig plateau. A hypothetical rainfall distribution at Moel Oernant close to the centre of the storm can then be constructed (Table 3.2). The Moel Oernant synthetic data is included in the HEC-1 hydrological model which follows.

	Ffestiniog	Arenig	Drws y Nant	Rhydymain	Llyn Cynnwch	Oernant
15:00-16:00	0.2	0.4	0	0	5.6	0
16:00-17:00	23.6	0	0	6.2	21.6	20
17:00-18:00	7.4	17.4	11.4	19.8	13.6	25
18:00-19:00	13.4	21.6	7.6	34	4	40
19:00-20:00	16	21.4	29.4	25.8	1.2	35
20:00-21:00	0.6	0.8	0	0	0	0
21:00-22:00	0	0.4	0.2	0.2	1.8	0
storm total	61.2	62	48.6	86	47.8	120

Table 3.2. Hourly rainfall totals and total storm rainfall (mm) during the 3 July 2001 storm event.

The relative timing of rainfall is illustrated in fig.3.56. This shows the storm moving slowly across the catchment from Llyn Cynnwch in the west to Drws y Nant in the east, a distance of 15km in 3 hours. The cumulative rainfall curves, along with the storm rainfall totals for each location, were used to set up raingauge inputs for the HEC-1 model.

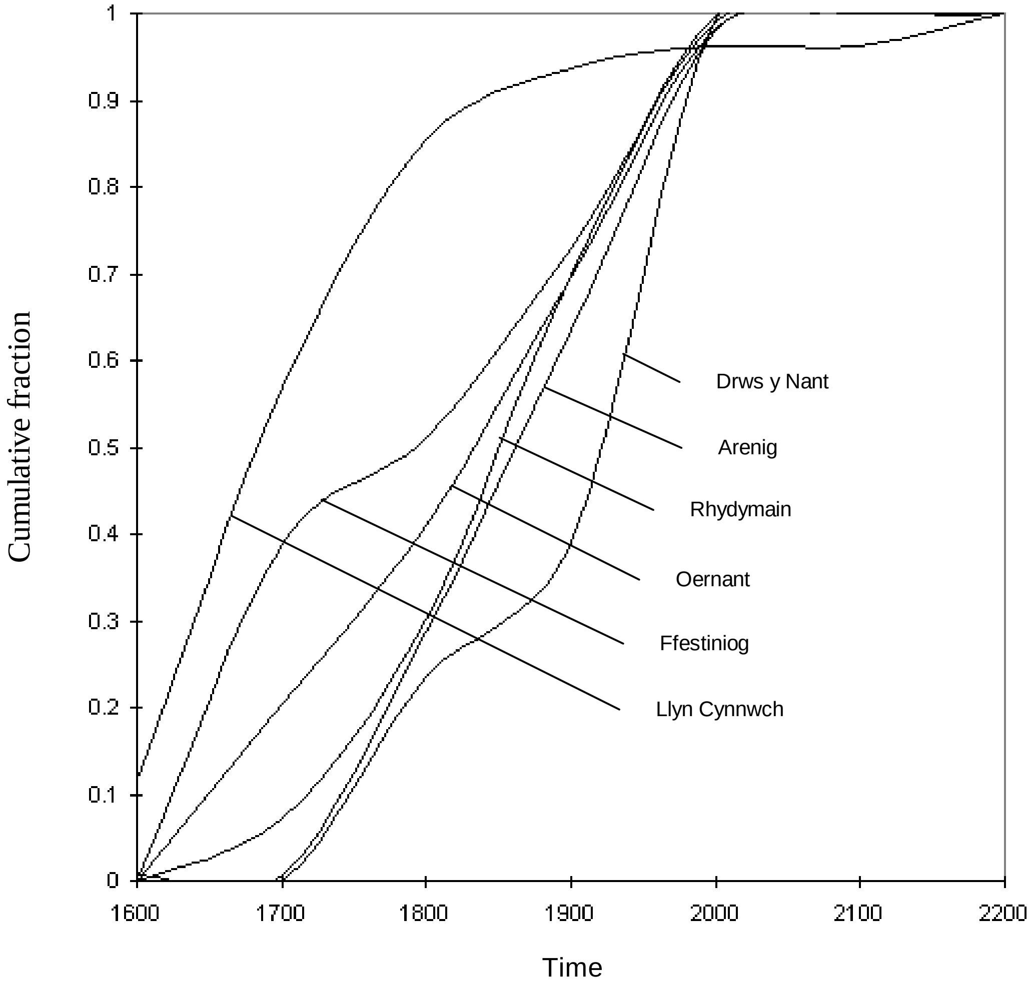


Figure 3.56: Cumulative curves for rainfall at gauge sites during the 3 July 2007 storm event

Runoff was determined in HEC-1 by the unit hydrograph Espey Rural method, with precipitation losses estimated by SCS curve numbers. This storm event occurred at the end of a dry summer period, so the model assumes soil moisture level A (dry) over the Cambrian grit outcrop and B (moderately dry) across the remaining Cambrian shales and Ordovician shales and volcanics. Rainfall was applied over the model area according to the Thiessen polygon method, weighted according to the area of the sub-catchment covered by each polygon, including estimated gauge totals for the Oernant site in Table 1. River routing then used the Muskingham equation.

Synthetic hydrograph results are presented for the Tyddyn Gwladys gauging station (fig.3.57) and the Bont Fawr gauging station, Dolgellau (fig.3.58), with recorded hydrographs for comparison.

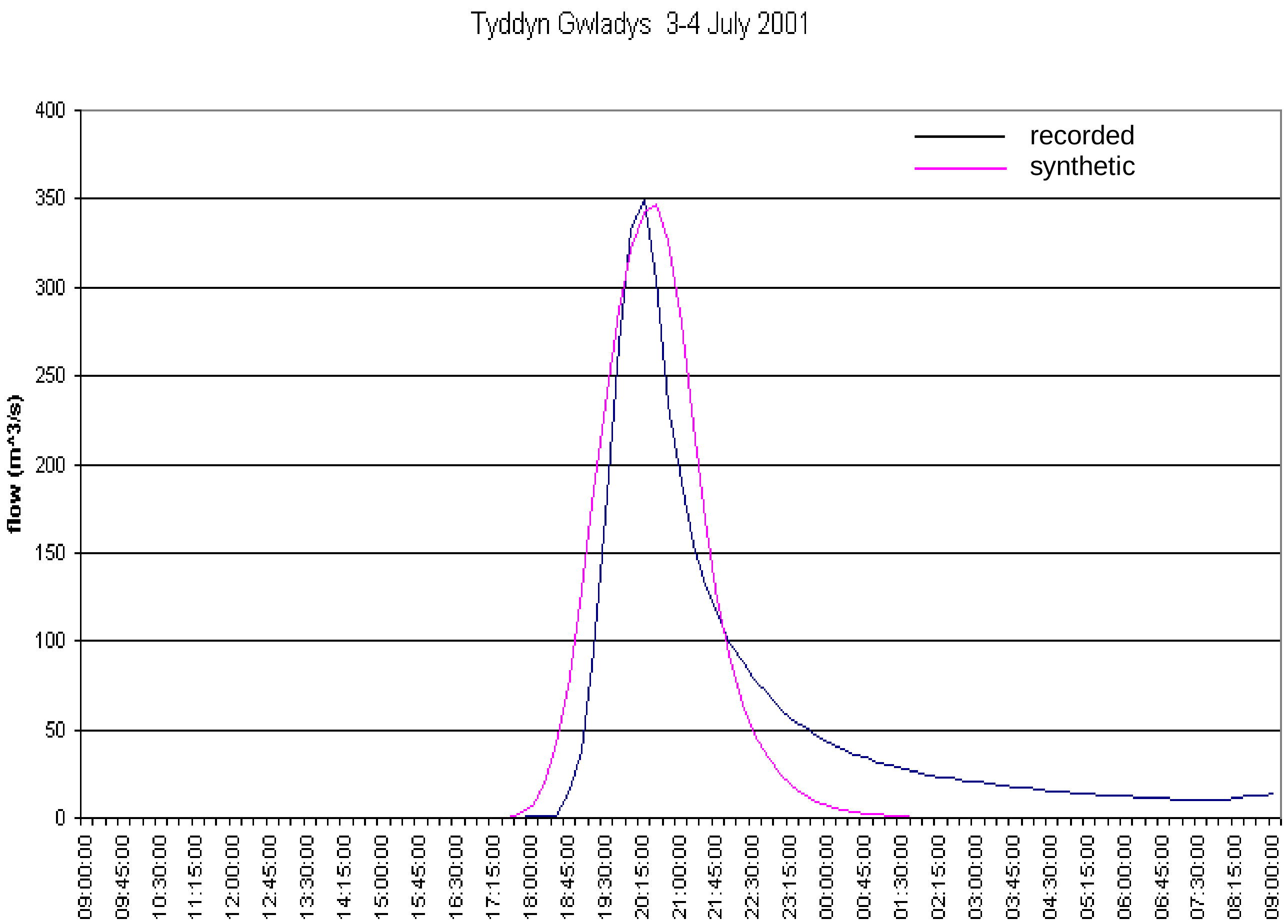


Figure 3.57: Comparison of recorded and synthetic hydrographs: Tyddyn Gwladys gauging station, 3 July 2001

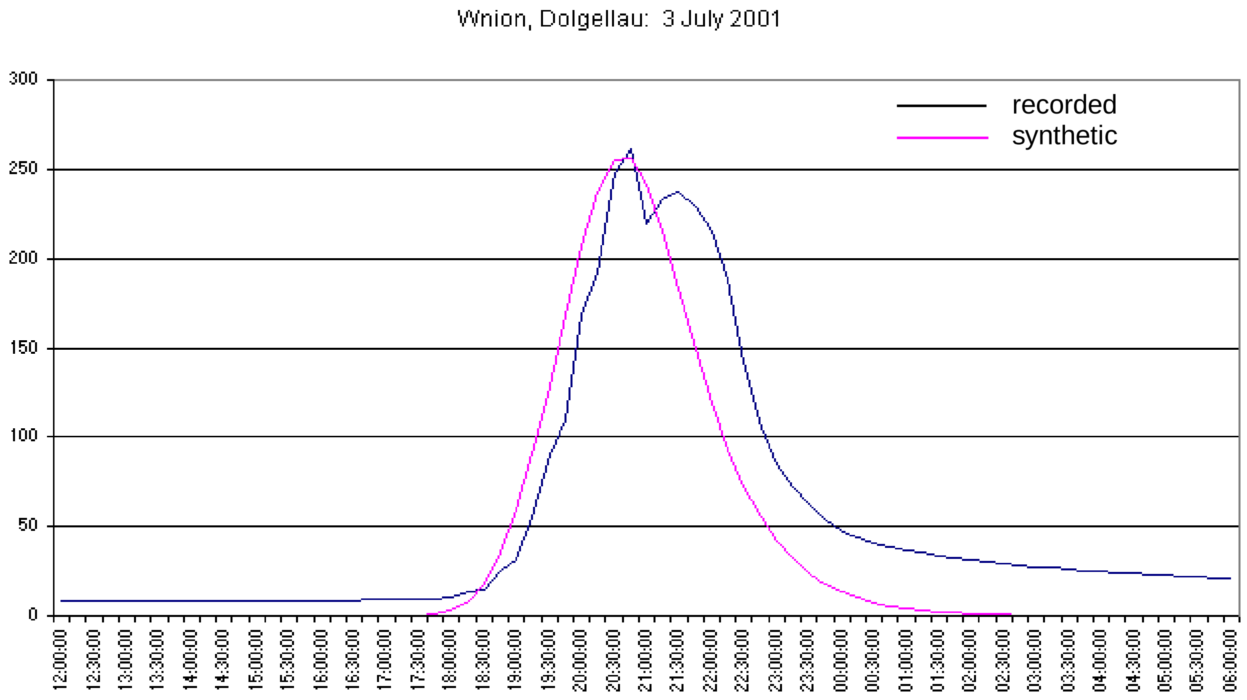


Figure 3.58: Comparison of recorded and synthetic hydrographs: Bont Fawr gauging station, Dolgellau, 3 July 2001

At Tyddyn Gwladys, a maximum flow of 340 $m^3 s^{-1}$ was recorded at 19:00 h. The modelled hydrograph has a rising limb in reasonable agreement, but the falling limb drops off too steeply at the end of the rainfall event. A likely explanation is the temporary groundwater storage of storm water which is released over the following 24 hours to produce the long tail of the recorded hydrograph. This flow is not represented in the simulation, since rainwater infiltrating to groundwater storage is lost from the HEC-1 model. The identification of fast storm runoff and slower base flow volumes from the hydrograph pattern is discussed by Linsley, Kohler and Paulhus (1988), and Wittenberg and Sivapalan (1999).

The hydrographs for the Wnion in Dolgellau show a similar relationship, with the simulated curve falling off too steeply and not representing the slow release of groundwater to the river system after the storm event. A further feature of note is the double peak present on the recorded hydrograph which is not produced by the model. Experience has shown that errors in hydrograph recording are most likely to occur around peak flows, when hydraulic pressures are greatest. If we assume, however, that the recording is accurate then a plausible explanation would be a sequence of two high intensity convection cells operating during the storm, sending successive waves of water down the river. The limited coverage of raingauges for the Wnion sub-catchment would have been insufficient to show the rainfall pattern in this amount of detail during the storm event. The operation of multiple convective cells within the squall line is consistent with both the Fovell and Tan theoretical model (figs 2.31-2.32), and the MM5 results from modelling the storm (fig.2.113).

One purpose of carrying out the HEC-1 simulation of the July 2001 flood event was to generate synthetic hydrographs for the ungauged outlets of the twelve Mawddach sub-catchments and eight Wnion sub-catchments. Results graphs are shown in figures 3.59 and 3.60. This hydrograph data is to be used as input to a GSTARS sediment transport model in section 3.3 below. It is appreciated that the tails of the synthetic hydrographs do not accurately represent the extended period during which the release of groundwater will affect river level. However, since a majority of sediment erosion and entrainment is likely to occur at high river discharges, the HEC-1 hydrographs were considered adequate for use in the sediment model. Subsequent evaluation of results of the sediment modelling indicates that this assumption was reasonable.

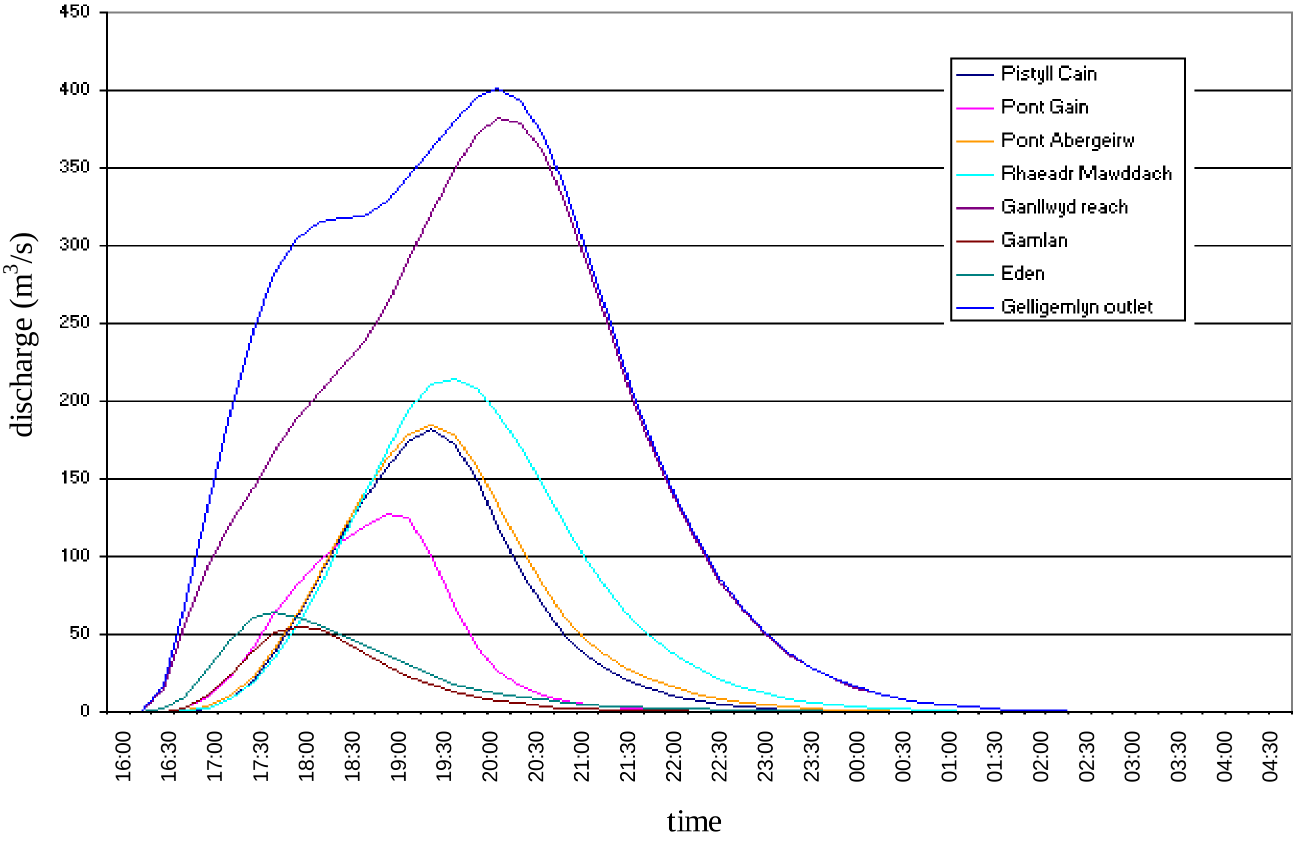


Figure 3.59: 3-4 July 2001 flood event: hydrographs for Mawddach sub-catchments

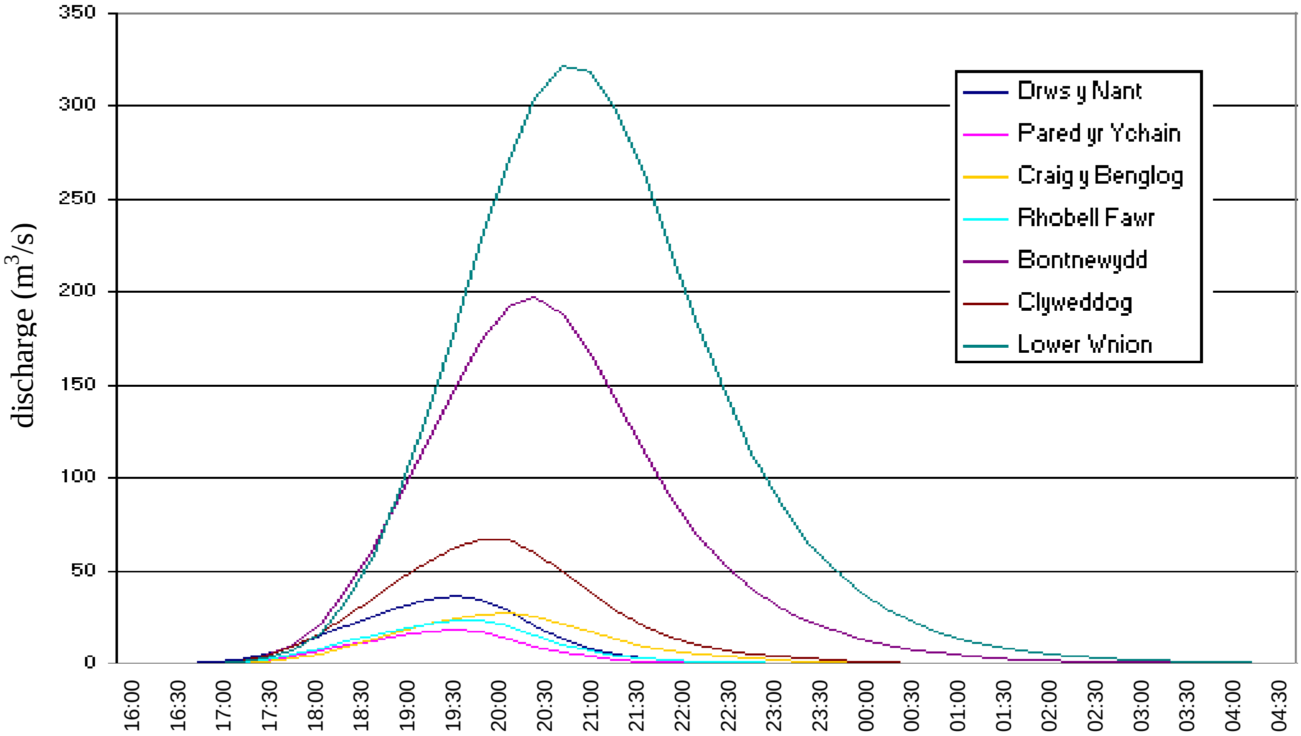


Figure 3.60: 3-4 July 2001 flood event: hydrographs for Wnion sub-catchments

Frontal storms

Runs of the HEC-1 Mawddach and Wnion sub-catchment models were carried out for a series of storms associated with frontal rainfall. With the exception of an event on 8 March 2003, these storms have all been analysed in section 2.2 and rainfall modelling carried out in section 2.4 above.

Simulation methods and parameters used in this set of HEC-1 models were identical to the 3 July 2001 case study, with the exception of:

- Rainfall: Data was available for a more numerous set of rain gauges, as shown in table 3.3. For each station, this table gives: three-hour rainfall totals(mm), cumulative storm rainfall(mm). In addition, cumulative rainfall fractions are calculated for use in the HEC-1 model.

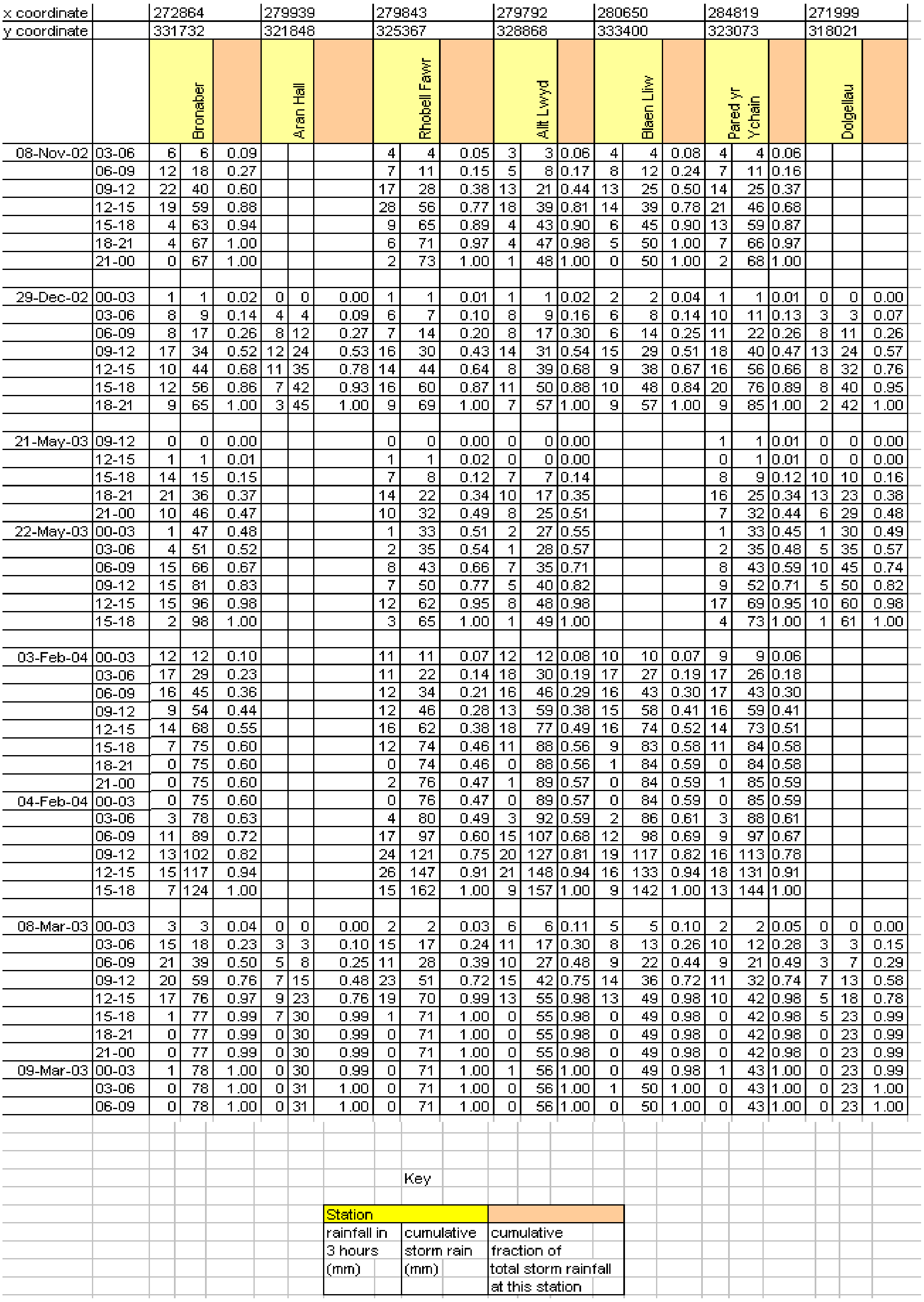
- Soil characteristics: For the storms occurring during the wetter winter months between November and March, soil moisture level C (damp) was used for the Cambrian grit outcrop, and moisture level D (wet) was used for the Cambrian shale and Ordovician shale and volcanic outcrop areas. For the May storm event, the assumed soil moisture levels were reduced to B (moderately dry) for the Cambrian grit outcrop and moisture level C (damp) for the other areas of the catchment.

x coordinate		258800			264700			265000			268300			268200			272687			273982			270700		
y coordinate		327000			331500			318200			315600			322700			324518			323936			336000		
		Llanbedr			Cwm Bychan			Caerdeon			Erw Wen			Cwm Mynach			Ganllwyd			Tir Penrhos			Trawsfynydd		
08-Nov-02	03-06	4	4	0.11	5	5	0.08	7	7	0.13	7	7	0.11				5	5	0.07	5	5	0.07	6	6	0.11
	06-09	10	14	0.37	13	18	0.29	11	18	0.35	9	16	0.25				12	17	0.25	11	16	0.23	12	18	0.34
	09-12	12	26	0.68	18	36	0.57	17	35	0.67	18	34	0.53				21	38	0.56	23	39	0.56	18	36	0.68
	12-15	10	36	0.95	20	56	0.89	11	46	0.88	16	50	0.78				18	56	0.82	20	59	0.84	11	47	0.89
	15-18	1	37	0.97	2	58	0.92	2	48	0.92	3	53	0.83				6	62	0.91	7	66	0.94	2	49	0.92
	18-21	1	38	1.00	5	63	1.00	2	50	0.96	5	58	0.91				6	68	1.00	4	70	1.00	3	52	0.98
	21-00	0	38	1.00	0	63	1.00	2	52	1.00	6	64	1.00				0	68	1.00	0	70	1.00	1	53	1.00
29-Dec-02	00-03	1	1	0.03							1	1	0.02				0	0	0.00	1	1	0.02	2	2	0.03
	03-06	5	6	0.16							7	8	0.14				7	7	0.12	6	7	0.12	10	12	0.16
	06-09	4	10	0.27							7	15	0.27				9	16	0.28	7	14	0.23	8	20	0.27
	09-12	12	22	0.59							20	35	0.63				18	34	0.59	16	30	0.50	19	39	0.52
	12-15	9	31	0.84							9	44	0.79				9	43	0.74	10	40	0.67	9	48	0.64
	15-18	6	37	1.00							9	53	0.95				10	53	0.91	14	54	0.90	18	66	0.88
	18-21	0	37	1.00							3	56	1.00				5	58	1.00	6	60	1.00	9	75	1.00
21-May-03	09-12				1	1	0.01	0	0	0.00	0	0	0.00	1	1	0.01	0	0	0.00	1	1	0.02	0	0	0.00
	12-15				0	1	0.01	0	0	0.00	0	0	0.00	0	1	0.01	1	1	0.02	0	1	0.02	1	1	0.01
	15-18				12	13	0.13	10	10	0.14	10	10	0.14	16	17	0.11	6	7	0.11	5	6	0.10	8	9	0.13
	18-21				23	36	0.35	10	20	0.29	13	23	0.32	35	52	0.35	11	18	0.28	12	18	0.31	16	25	0.36
	21-00				8	44	0.42	8	28	0.41	12	35	0.49	18	70	0.47	11	29	0.45	8	26	0.45	6	31	0.44
22-May-03	00-03				2	46	0.44	1	29	0.42	1	36	0.51	2	72	0.49	1	30	0.47	1	27	0.47	1	32	0.46
	03-06				5	51	0.49	7	36	0.52	7	43	0.61	9	81	0.55	2	32	0.50	2	29	0.50	2	34	0.49
	06-09				26	77	0.74	14	50	0.72	12	55	0.77	20	101	0.68	9	41	0.64	7	36	0.62	11	45	0.64
	09-12				10	87	0.84	5	55	0.80	6	61	0.86	12	113	0.76	7	48	0.75	6	42	0.72	10	55	0.79
	12-15				15	102	0.98	12	67	0.97	6	67	0.94	30	143	0.97	14	62	0.97	13	55	0.95	13	68	0.97
	15-18				2	104	1.00	2	69	1.00	4	71	1.00	5	148	1.00	2	64	1.00	3	58	1.00	2	70	1.00
03-Feb-04	00-03	4	4	0.12	14	14	0.13	7	7	0.12	14	14	0.12	12	12	0.10	11	11	0.11				13	13	0.08
	03-06	0	4	0.12	12	26	0.25	4	11	0.18	13	27	0.23	12	24	0.21	11	22	0.21				18	31	0.20
	06-09	6	10	0.30	13	39	0.37	8	19	0.32	14	41	0.36	14	38	0.33	13	35	0.34				17	48	0.31
	09-12	2	12	0.36	5	44	0.42	3	22	0.37	9	50	0.43	8	46	0.40	6	41	0.39				11	59	0.38
	12-15	3	15	0.45	5	49	0.46	4	26	0.43	8	58	0.50	8	54	0.47	7	48	0.46				12	71	0.46
	15-18	0	15	0.45	4	53	0.50	1	27	0.45	8	66	0.57	8	62	0.54	7	55	0.53				13	84	0.55
	18-21	0	15	0.45	0	53	0.50	0	27	0.45	0	66	0.57	0	62	0.54	0	55	0.53				0	84	0.55
	21-00	0	15	0.45	1	54	0.51	0	27	0.45	0	66	0.57	0	62	0.54	0	55	0.53				2	86	0.56
04-Feb-04	00-03	0	15	0.45	0	54	0.51	0	27	0.45	0	66	0.57	0	62	0.54	0	55	0.53				0	86	0.56
	03-06	0	15	0.45	6	60	0.57	4	31	0.52	4	70	0.61	7	69	0.60	4	59	0.57				7	93	0.60
	06-09	6	21	0.64	17	77	0.73	10	41	0.68	12	82	0.71	16	85	0.74	12	71	0.68				18	111	0.72
	09-12	3	24	0.73	10	87	0.82	6	47	0.78	11	93	0.81	10	95	0.83	11	82	0.79				16	127	0.82
	12-15	7	31	0.94	12	99	0.93	9	56	0.93	13	106	0.92	12	107	0.93	15	97	0.93				16	143	0.93
	15-18	2	33	1.00	7	106	1.00	4	60	1.00	9	115	1.00	8	115	1.00	7	104	1.00				11	154	1.00
08-Mar-03	00-03	5	5	0.25	5	5	0.20	4	4	0.25	6	6	0.17	8	8	0.17	7	7	0.12	5	5	0.09	7	7	0.08
	03-06	4	9	0.45	4	9	0.36	3	7	0.44	7	13	0.36	9	17	0.36	11	18	0.32	10	15	0.26	20	27	0.29
	06-09	3	12	0.60	4	13	0.52	3	10	0.63	11	24	0.67	11	28	0.60	14	32	0.56	13	28	0.48	30	57	0.61
	09-12	3	15	0.75	5	18	0.72	3	13	0.81	5	29	0.81	9	37	0.79	14	46	0.81	17	45	0.78	19	76	0.82
	12-15	5	20	1.00	7	25	1.00	3	16	1.00	7	36	1.00	9	46	0.98	11	57	1.00	12	57	0.98	16	92	0.99
	15-18	0	20	1.00	0	25	1.00	0	16	1.00	0	36	1.00	0	46	0.98	0	57	1.00	0	57	0.98	0	92	0.99
	18-21	0	20	1.00	0	25	1.00	0	16	1.00	0	36	1.00	0	46	0.98	0	57	1.00	0	57	0.98	0	92	0.99
	21-00	0	20	1.00	0	25	1.00	0	16	1.00	0	36	1.00	0	46	0.98	0	57	1.00	0	57	0.98	0	92	0.99
09-Mar-03	00-03	0	20	1.00	0	25	1.00	0	16	1.00	0	36	1.00	1	47	1.00	0	57	1.00	0	57	0.98	1	93	1.00
	03-06	0	20	1.00	0	25	1.00	0	16	1.00	0	36	1.00	0	47	1.00	0	57	1.00	1	58	1.00	0	93	1.00
	06-09	0	20	1.00	0	25	1.00	0	16	1.00	0	36	1.00	0	47	1.00	0	57	1.00	0	58	1.00	0	93	1.00

Key

Station		
rainfall in 3 hours (mm)	cumulative storm rain (mm)	cumulative fraction of total storm rainfall at this station

Table 3.3: Storm event rainfall recorded at gauge sites in and around the Mawddach catchment



x coordinate		272864			279939			279843			279792			280650			284819			271999		
y coordinate		331732			321848			325367			328868			333400			323073			318021		
			Bronaber			Aran Hall			Rhobell Fawr			Allt Lwyd			Blaen Lliw			Pared yr Ychain			Dolgellau	
08-Nov-02	03-06	6	6	0.09				4	4	0.05	3	3	0.06	4	4	0.08	4	4	0.06			
	06-09	12	18	0.27				7	11	0.15	5	8	0.17	8	12	0.24	7	11	0.16			
	09-12	22	40	0.60				17	28	0.38	13	21	0.44	13	25	0.50	14	25	0.37			
	12-15	19	59	0.88				28	56	0.77	18	39	0.81	14	39	0.78	21	46	0.68			
	15-18	4	63	0.94				9	65	0.89	4	43	0.90	6	45	0.90	13	59	0.87			
	18-21	4	67	1.00				6	71	0.97	4	47	0.98	5	50	1.00	7	66	0.97			
	21-00	0	67	1.00				2	73	1.00	1	48	1.00	0	50	1.00	2	68	1.00			
29-Dec-02	00-03	1	1	0.02	0	0	0.00	1	1	0.01	1	1	0.02	2	2	0.04	1	1	0.01	0	0	0.00
	03-06	8	9	0.14	4	4	0.09	6	7	0.10	8	9	0.16	6	8	0.14	10	11	0.13	3	3	0.07
	06-09	8	17	0.26	8	12	0.27	7	14	0.20	8	17	0.30	6	14	0.25	11	22	0.26	8	11	0.26
	09-12	17	34	0.52	12	24	0.53	16	30	0.43	14	31	0.54	15	29	0.51	18	40	0.47	13	24	0.57
	12-15	10	44	0.68	11	35	0.78	14	44	0.64	8	39	0.68	9	38	0.67	16	56	0.66	8	32	0.76
	15-18	12	56	0.86	7	42	0.93	16	60	0.87	11	50	0.88	10	48	0.84	20	76	0.89	8	40	0.95
	18-21	9	65	1.00	3	45	1.00	9	69	1.00	7	57	1.00	9	57	1.00	9	85	1.00	2	42	1.00
21-May-03	09-12	0	0	0.00				0	0	0.00	0	0	0.00				1	1	0.01	0	0	0.00
	12-15	1	1	0.01				1	1	0.02	0	0	0.00				0	1	0.01	0	0	0.00
	15-18	14	15	0.15				7	8	0.12	7	7	0.14				8	9	0.12	10	10	0.16
	18-21	21	36	0.37				14	22	0.34	10	17	0.35				16	25	0.34	13	23	0.38
	21-00	10	46	0.47				10	32	0.49	8	25	0.51				7	32	0.44	6	29	0.48
22-May-03	00-03	1	47	0.48				1	33	0.51	2	27	0.55				1	33	0.45	1	30	0.49
	03-06	4	51	0.52				2	35	0.54	1	28	0.57				2	35	0.48	5	35	0.57
	06-09	15	66	0.67				8	43	0.66	7	35	0.71				8	43	0.59	10	45	0.74
	09-12	15	81	0.83				7	50	0.77	5	40	0.82				9	52	0.71	5	50	0.82
	12-15	15	96	0.98				12	62	0.95	8	48	0.98				17	69	0.95	10	60	0.98
	15-18	2	98	1.00				3	65	1.00	1	49	1.00				4	73	1.00	1	61	1.00
03-Feb-04	00-03	12	12	0.10				11	11	0.07	12	12	0.08	10	10	0.07	9	9	0.06			
	03-06	17	29	0.23				11	22	0.14	18	30	0.19	17	27	0.19	17	26	0.18			
	06-09	16	45	0.36				12	34	0.21	16	46	0.29	16	43	0.30	17	43	0.30			
	09-12	9	54	0.44				12	46	0.28	13	59	0.38	15	58	0.41	16	59	0.41			
	12-15	14	68	0.55				16	62	0.38	18	77	0.49	16	74	0.52	14	73	0.51			
	15-18	7	75	0.60				12	74	0.46	11	88	0.56	9	83	0.58	11	84	0.58			
	18-21	0	75	0.60				0	74	0.46	0	88	0.56	1	84	0.59	0	84	0.58			
	21-00	0	75	0.60				2	76	0.47	1	89	0.57	0	84	0.59	1	85	0.59			
04-Feb-04	00-03	0	75	0.60				0	76	0.47	0	89	0.57	0	84	0.59	0	85	0.59			
	03-06	3	78	0.63				4	80	0.49	3	92	0.59	2	86	0.61	3	88	0.61			
	06-09	11	89	0.72				17	97	0.60	15	107	0.68	12	98	0.69	9	97	0.67			
	09-12	13	102	0.82				24	121	0.75	20	127	0.81	19	117	0.82	16	113	0.78			
	12-15	15	117	0.94				26	147	0.91	21	148	0.94	16	133	0.94	18	131	0.91			
	15-18	7	124	1.00				15	162	1.00	9	157	1.00	9	142	1.00	13	144	1.00			
08-Mar-03	00-03	3	3	0.04	0	0	0.00	2	2	0.03	6	6	0.11	5	5	0.10	2	2	0.05	0	0	0.00
	03-06	15	18	0.23	3	3	0.10	15	17	0.24	11	17	0.30	8	13	0.26	10	12	0.28	3	3	0.15
	06-09	21	39	0.50	5	8	0.25	11	28	0.39	10	27	0.48	9	22	0.44	9	21	0.49	3	7	0.29
	09-12	20	59	0.76	7	15	0.48	23	51	0.72	15	42	0.75	14	36	0.72	11	32	0.74	7	13	0.58
	12-15	17	76	0.97	9	23	0.76	19	70	0.99	13	55	0.98	13	49	0.98	10	42	0.98	5	18	0.78
	15-18	1	77	0.99	7	30	0.99	1	71	1.00	0	55	0.98	0	49	0.98	0	42	0.98	5	23	0.99
	18-21	0	77	0.99	0	30	0.99	0	71	1.00	0	55	0.98	0	49	0.98	0	42	0.98	0	23	0.99
	21-00	0	77	0.99	0	30	0.99	0	71	1.00	0	55	0.98	0	49	0.98	0	42	0.98	0	23	0.99
09-Mar-03	00-03	1	78	1.00	0	30	0.99	0	71	1.00	1	56	1.00	0	49	0.98	1	43	1.00	0	23	0.99
	03-06	0	78	1.00	0	31	1.00	0	71	1.00	0	56	1.00	1	50	1.00	0	43	1.00	0	23	1.00
	06-09	0	78	1.00	0	31	1.00	0	71	1.00	0	56	1.00	0	50	1.00	0	43	1.00	0	23	1.00

Key

Station		
rainfall in 3 hours (mm)	cumulative storm rain (mm)	cumulative fraction of total storm rainfall at this station

Table 3.3: Storm event rainfall recorded at gauge sites in and around the Mawddach catchment

8 November 2002

A comparison between the recorded and modelled hydrograph for Tyddyn Gwladys is shown in fig.3.61. As in the case of the July 2001 convective storm, there is reasonable agreement in the ascending limb and peak of the hydrograph. The descending hydrograph limbs of both the field data and the model show a step. A second period of increased rainfall is not evident from the gauge data in table 3, so this feature is likely to represent the relative delays of waterflows on the upper Mawddach and Gain in reaching the Tyddyn Gwladys site. Although HEC-1 performs correctly qualitatively, the model again shows an excessively rapid fall in river level after the storm event because it ignores processes of groundwater storage and release.

The program provides a facility for entering a value of constant river base flow which will be added to the calculated storm discharge, offsetting the synthetic hydrograph upwards. Realistic base flows have been applied in the cases which follow.

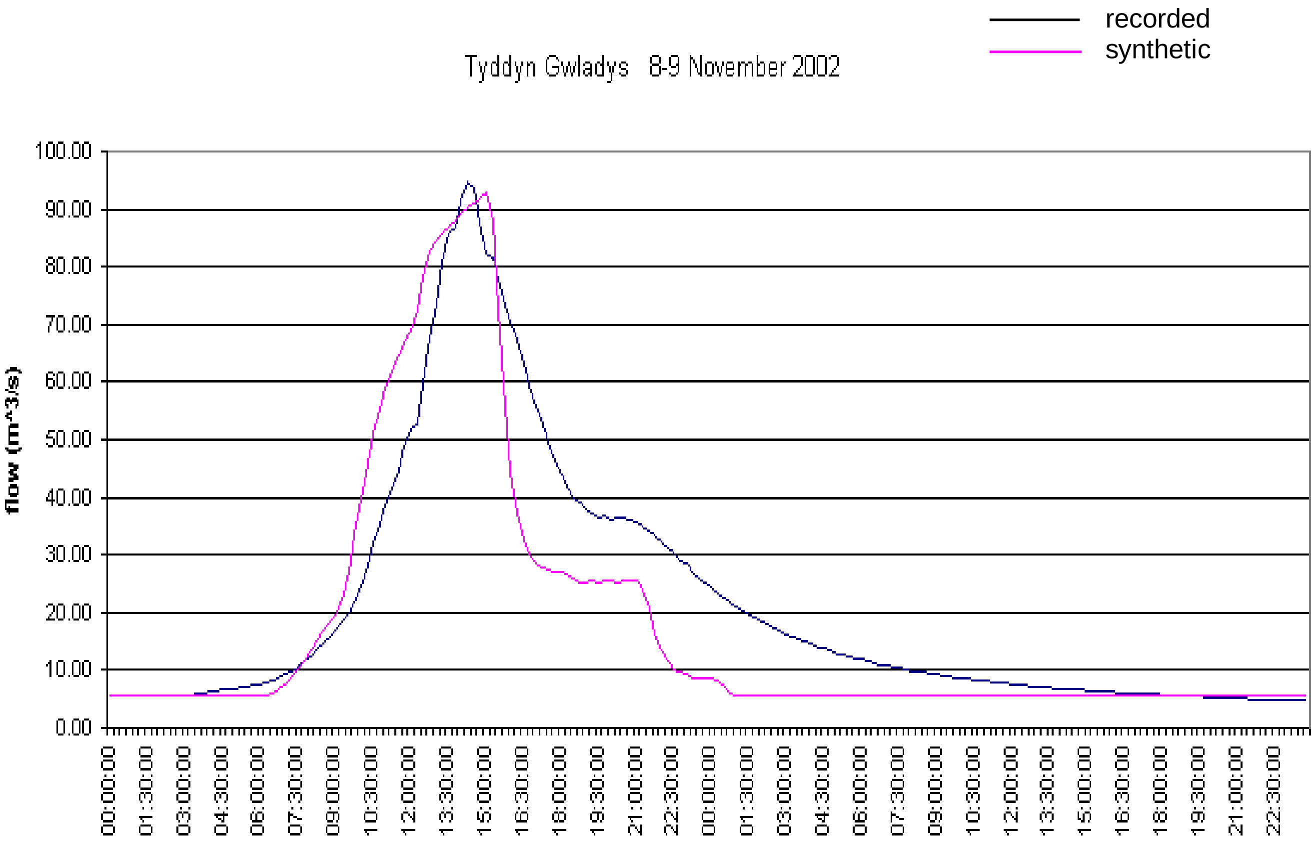


Figure 3.61: Comparison of modelled and recorded hydrographs for Tyddyn Gwladys, Afon Mawddach, 8 November 2002

29 December 2002

Hydrographs for four recording sites are given in figs 3.62-3.65, with HEC-1 synthetic hydrographs for comparison.

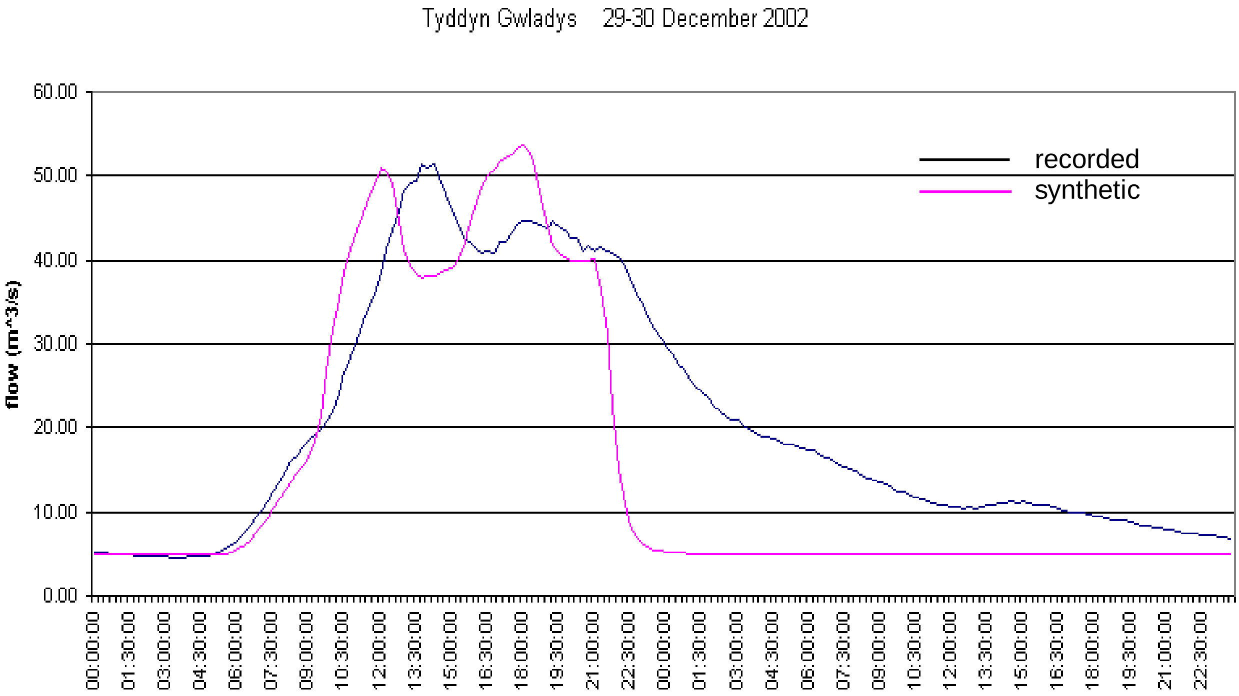


Figure 3.62: Comparison of modelled and recorded hydrographs for Tyddyn Gwladys, Afon Mawddach, 29 December 2002

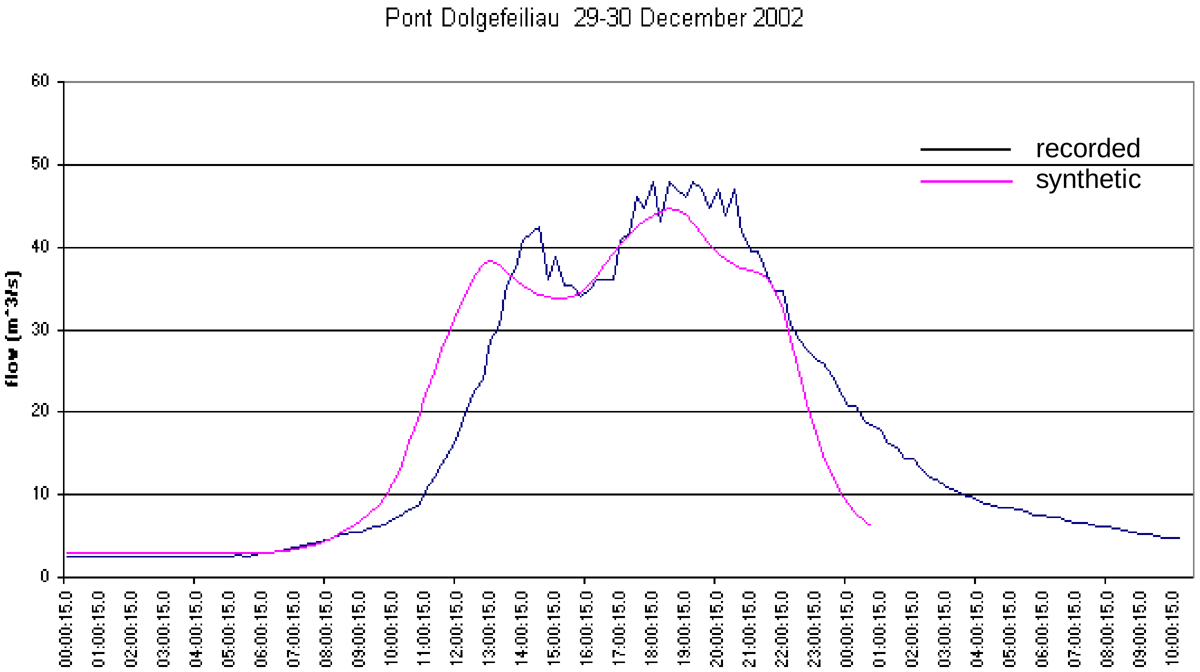


Figure 3.63: Comparison of modelled and recorded hydrographs for Pont Dolgefeiliau, Afon Eden, 29 December 2002

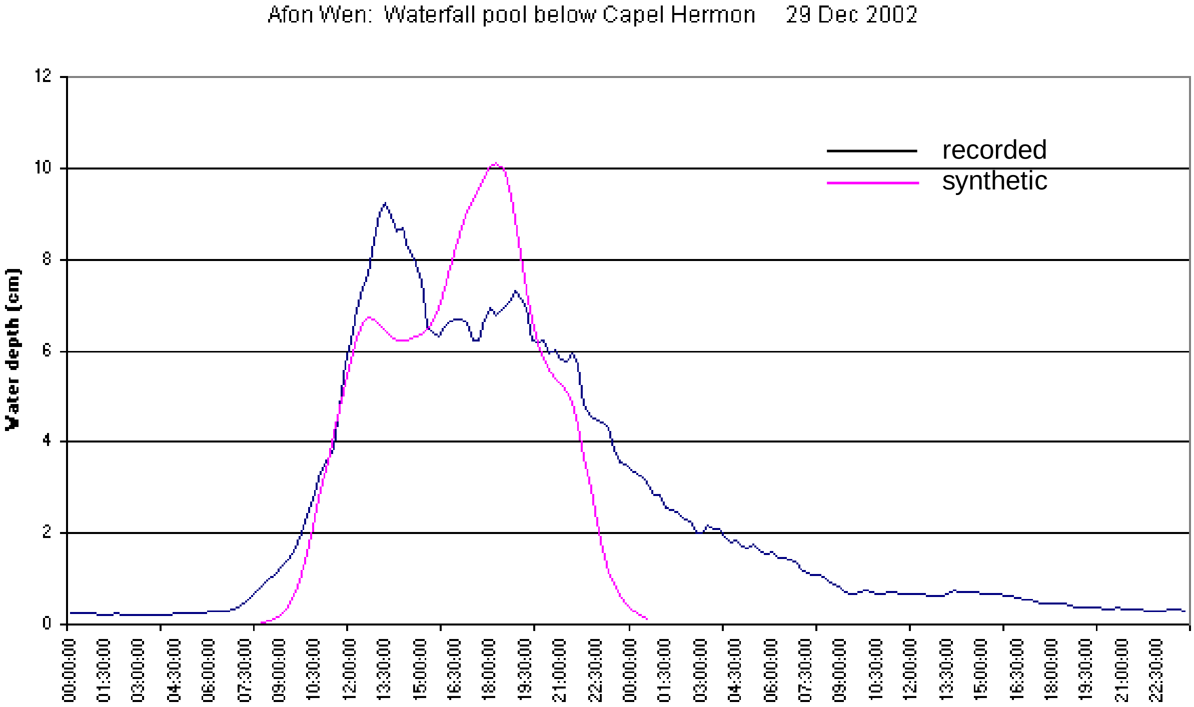


Figure 3.64: Comparison of modelled and recorded hydrographs for Hermon, Afon Wen, 29 December 2002

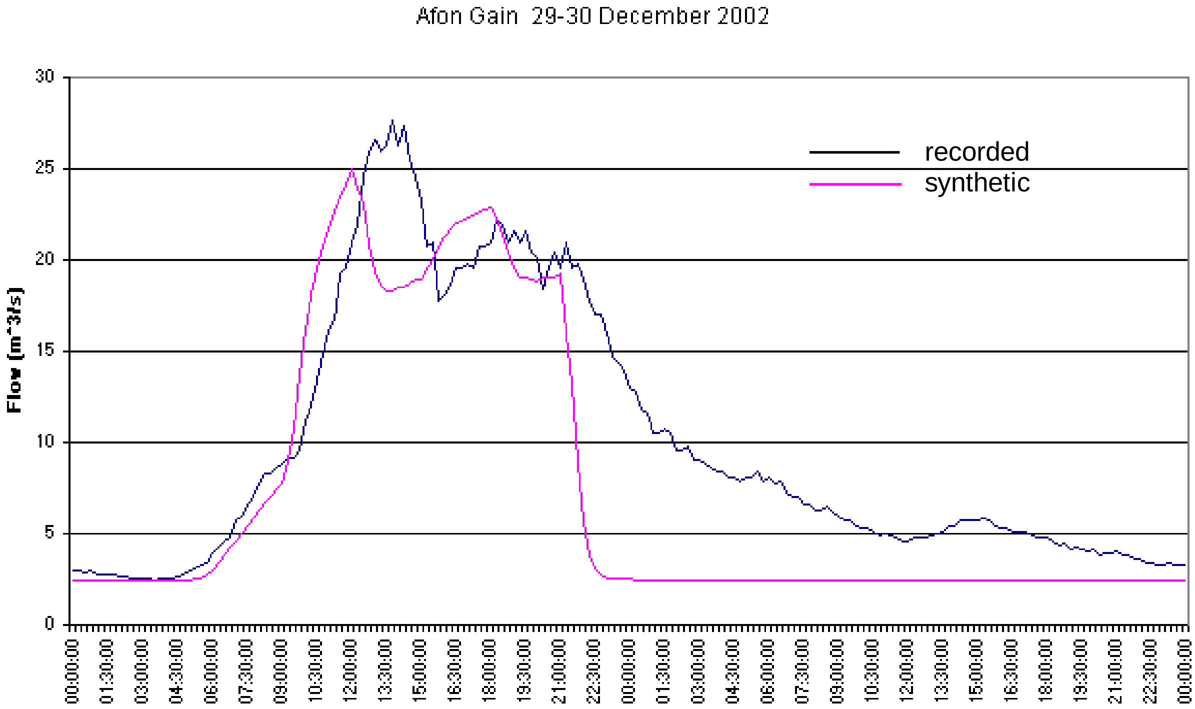


Figure 3.65: Comparison of modelled and recorded hydrographs for the Afon Gain near Pistyll Cain, 29 December 2002

The modelled hydrographs in each case show good correspondence with the rising limbs and time to peak of the field data but, as in previous examples, the falling limbs are excessively steep. It may be significant that this effect is most pronounced for hydrograph sites in the steeply descending gorge sections of the Mawddach, Gain and Afon Wen where resurgence of groundwater following the peak of a flood event might be expected. Field evidence of this process is presented in section 3.4 below. The discrepancy is less pronounced at Pont Dolgefeiliau in the wider floored Eden valley.

8 March 2003

The intense storm of 8 March 2003 was centred on the village of Trawsfynydd, with a band of heavy rainfall extending to the south east as shown in fig. 3.66. This represents a type A rainfall event in the classification of section 2.2.

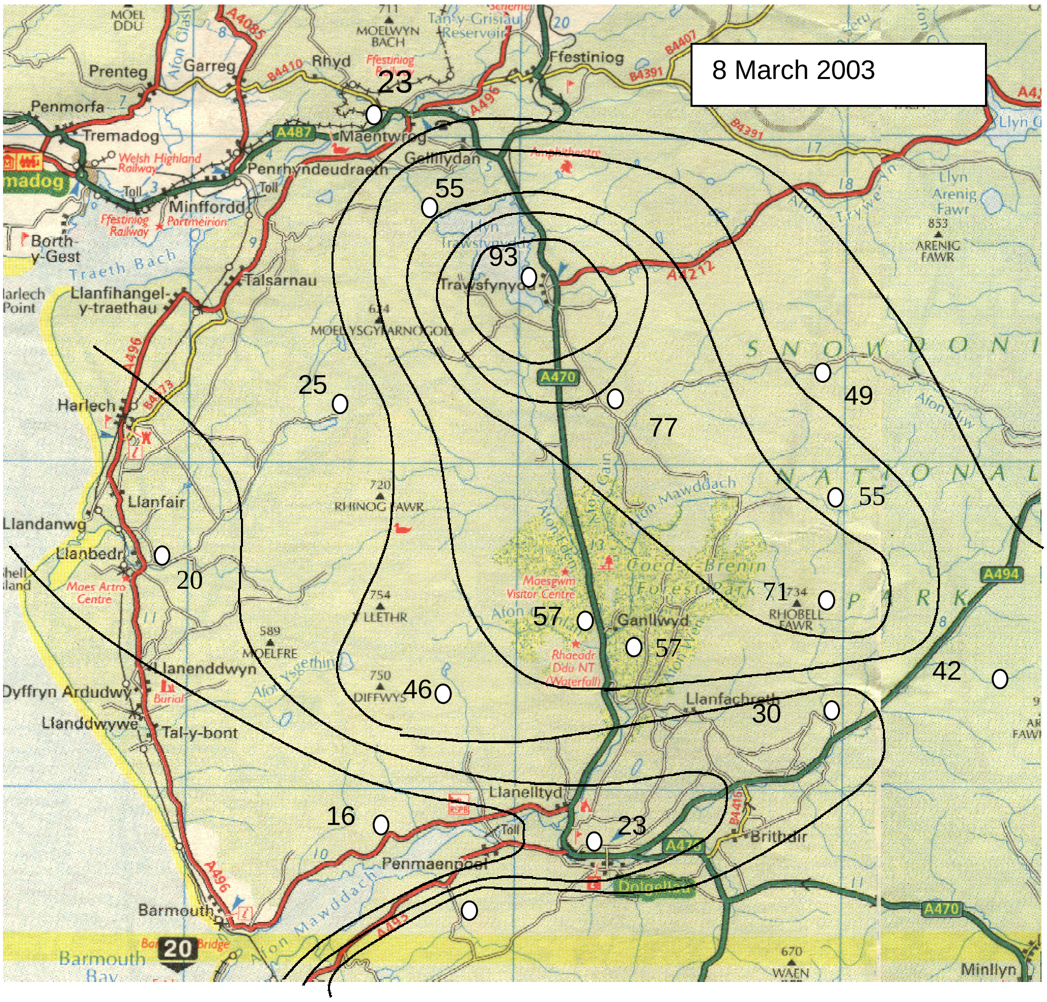


Figure 3.66: Total storm rainfall(mm), 8 March 2003

Hydrographs are available for three river sites for the 8 March 2003 storm, as shown in figs 3.67-3.69.

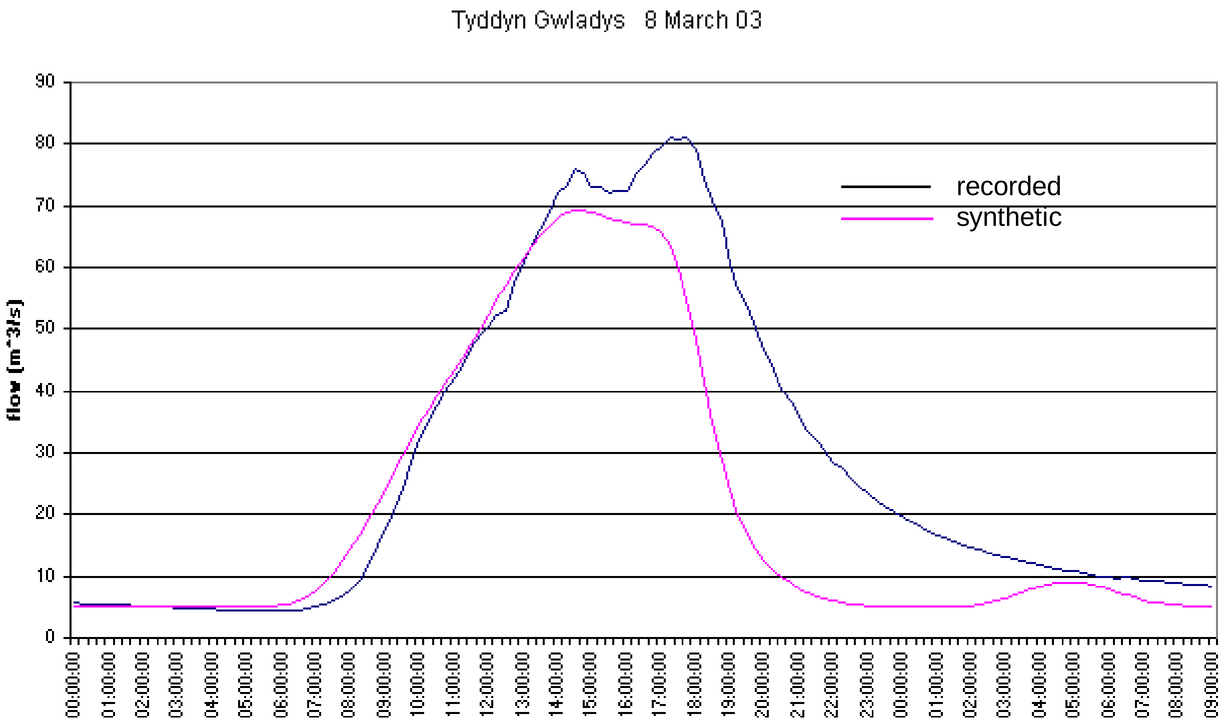


Figure 3.67: Comparison of modelled and recorded hydrographs for Tyddyn Gwladys, Afon Mawddach, 8 March 2003

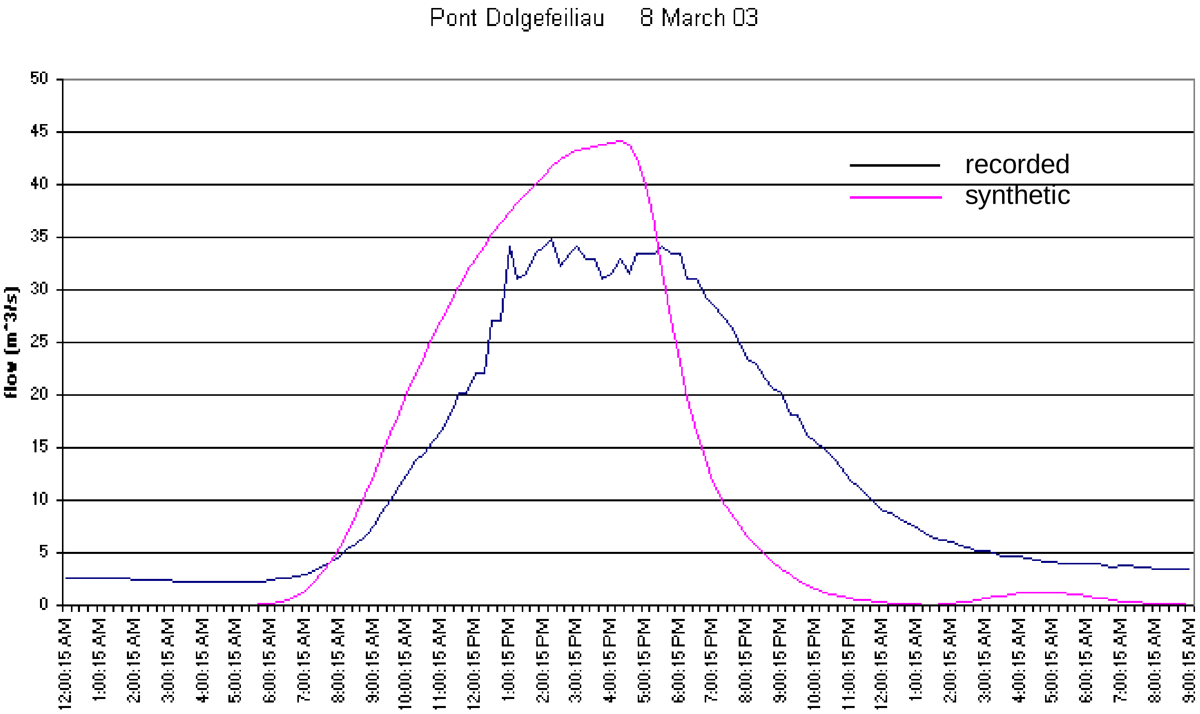


Figure 3.68: Comparison of modelled and recorded hydrographs for Pont Dolgefeiliau, Afon Eden, 8 March 2003

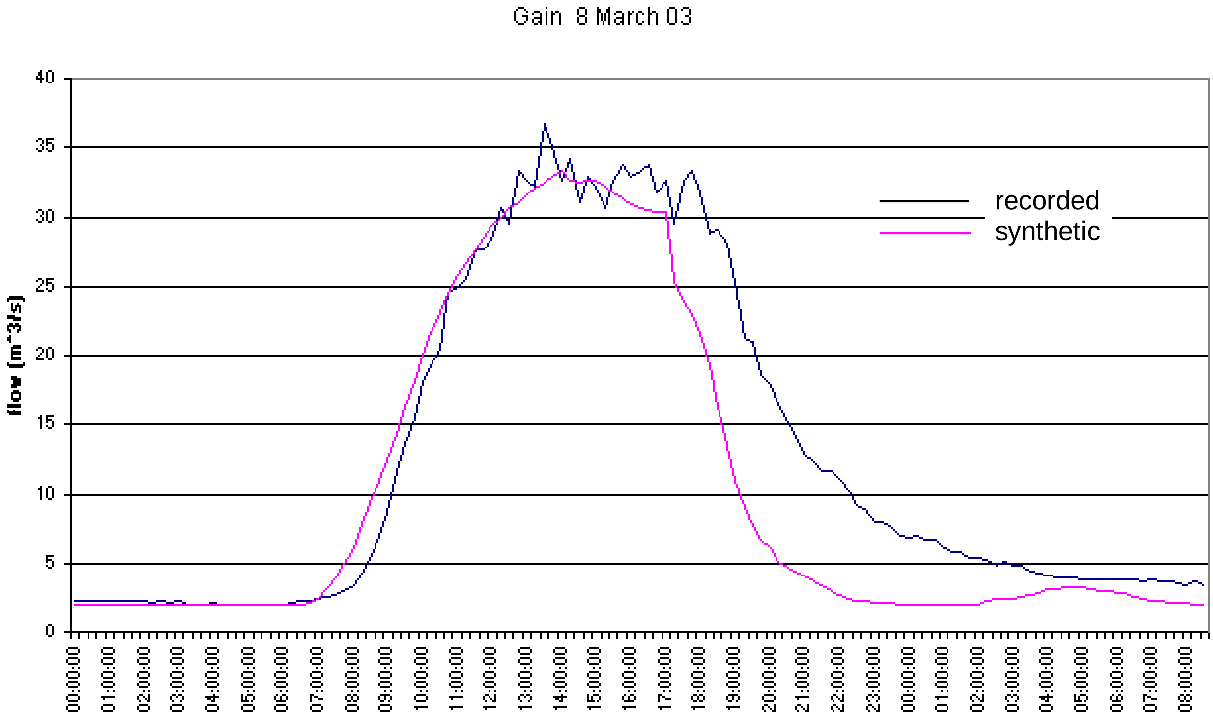


Figure 3.69: Comparison of modelled and recorded hydrographs for the Afon Gain near Pistyll Cain, 8 March 2003

Modelled hydrographs for Tyddyn Gwladys and Pistyll Cain give reasonable approximations for the rising hydrograph limbs and flow maxima. As expected, the falling limbs descend too rapidly due to lack of groundwater resurgence.

The model result for Pont Dolgefeiliau on the Afon Eden is unusual in significantly over-estimating the flood peak. This is the only occasion on which this type of error was observed during the modelling of simple storm events. A likely explanation lies in the very localised nature of the rainfall distribution. A rapid fall-off in rainfall total occurs over the Rhinog mountain range and the Crawcwellt plateau to the south of Trawsfynydd. It may be the case that the Thiessen polygon method has overestimated rainfall for the Eden sub-catchment. A distributed rainfall model such as MM5 which provides rainfall forecasts for each 1km grid square might be expected to provide a more accurate result than averaging rainfall between widely separated rain gauges.

21-23 May 2003

The rainfall event of 21-23 May 2003 differs from previous examples in being a pair of storms occurring on successive days. Three hydrograph records are available for this period, as shown in figs 3.70-3.72.

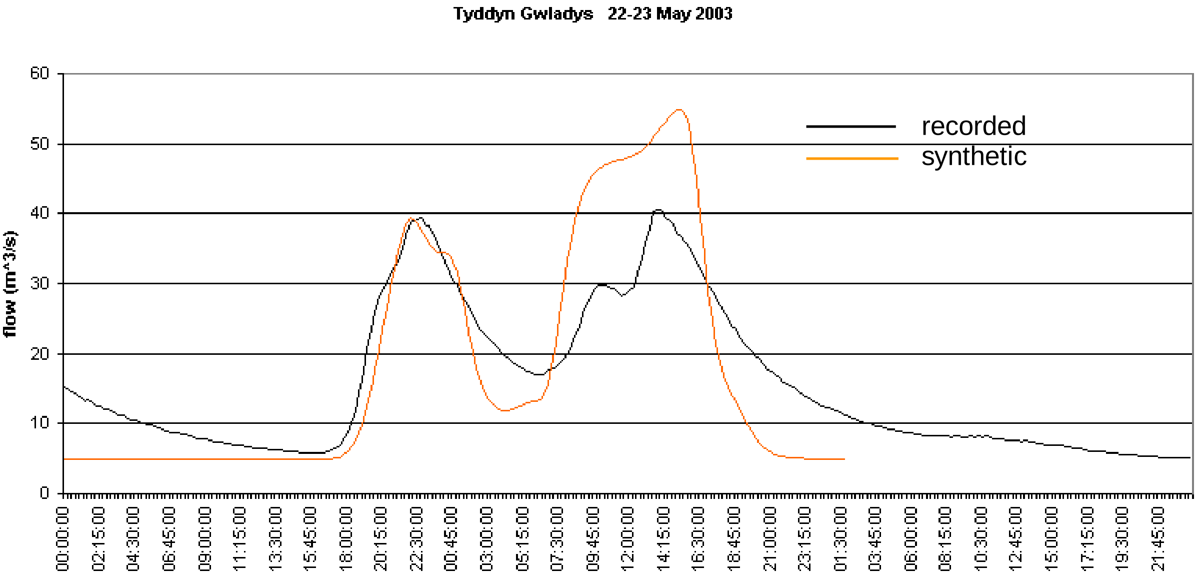


Figure 3.70: Comparison of modelled and recorded hydrographs for Tyddyn Gwladys, Afon Mawddach, 21-23 May 2003

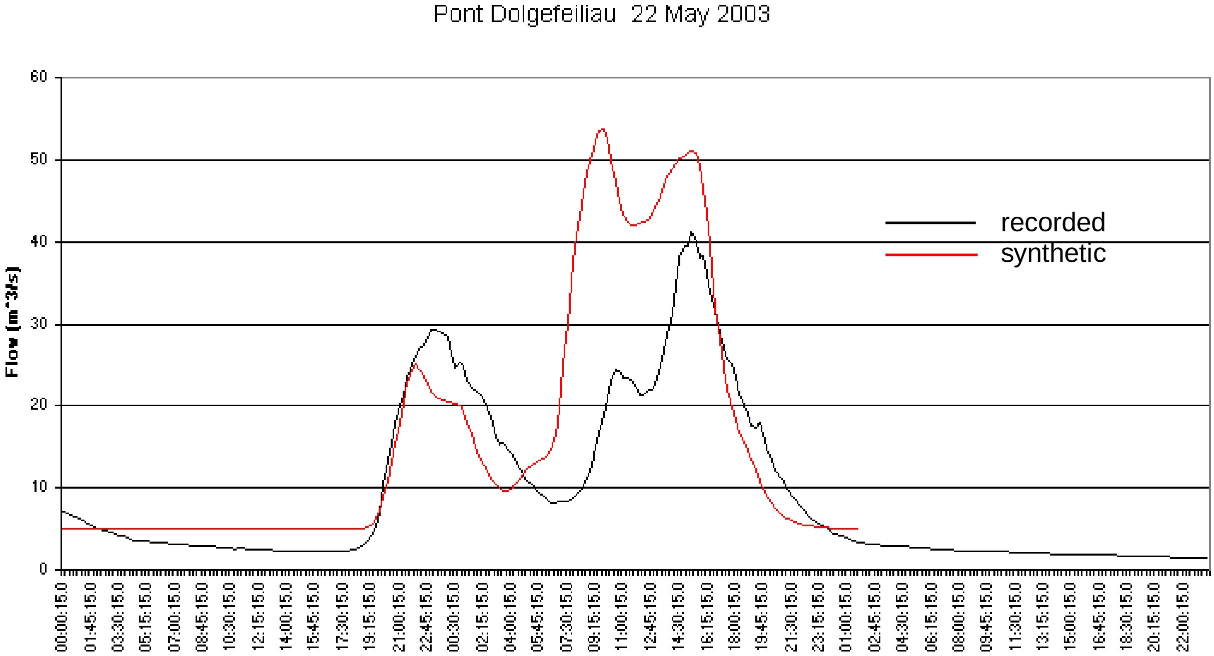


Figure 3.71: Comparison of modelled and recorded hydrographs for Pont Dolgefeiliau, Afon Eden, 21-23 May 2003

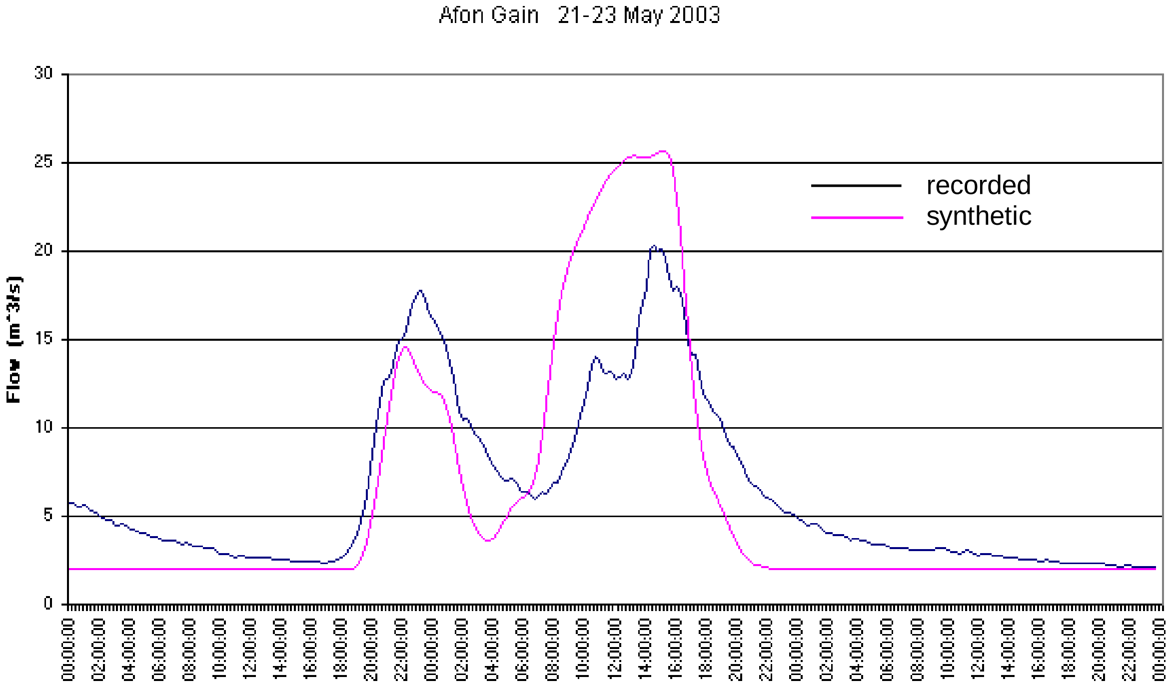


Figure 3.72: Comparison of modelled and recorded hydrographs for the Afon Gain near Pistyll Cain, 21-23 May 2003

A significant feature of each of the hydrographs is that the second storm peak is significantly overestimated by the HEC-1 model. This appears to be a result of the method used to determine infiltration rate based on total cumulative rainfall since the commencement of the rainfall event. The method assumes no recovery of soil water storage capacity during the interval between storms. The HEC-1 model appears to lose accuracy when modelling closely separated rainfall sequences.

3-4 February 2004

Another pair of closely spaced rainfall events occurred during the period 3-4 February 2004, as discussed previously in sections 2.2 and 2.4. A comparison of the recorded hydrograph at Tyddyn Gwladys and the HEC-1 modelled hydrograph is shown in fig.3.73. As in the May 2003 example, the second flood peak is overestimated by the model, but the extent of the error is less than in the May case. A likely explanation is that less recovery of storage capacity would occur during the colder and wetter February period, so the mathematical basis of the model is closer to reality.

The HEC-1 hydrographs generated for sub-catchments of the Mawddach and the Wnion (fig.3.74) are used in a sediment transport model in section 3.3 below.

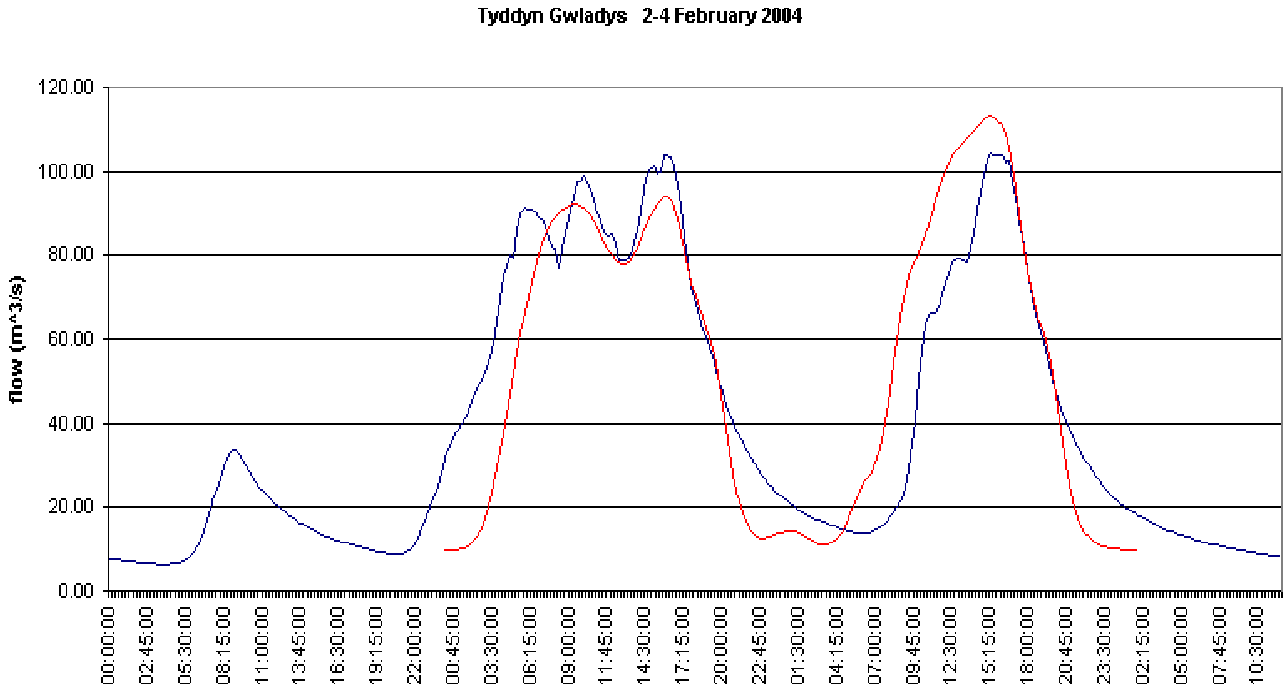


Figure 3.73: Comparison of modelled and recorded hydrographs for Tyddyn Gwladys, Afon Mawddach, 2-4 February 2004

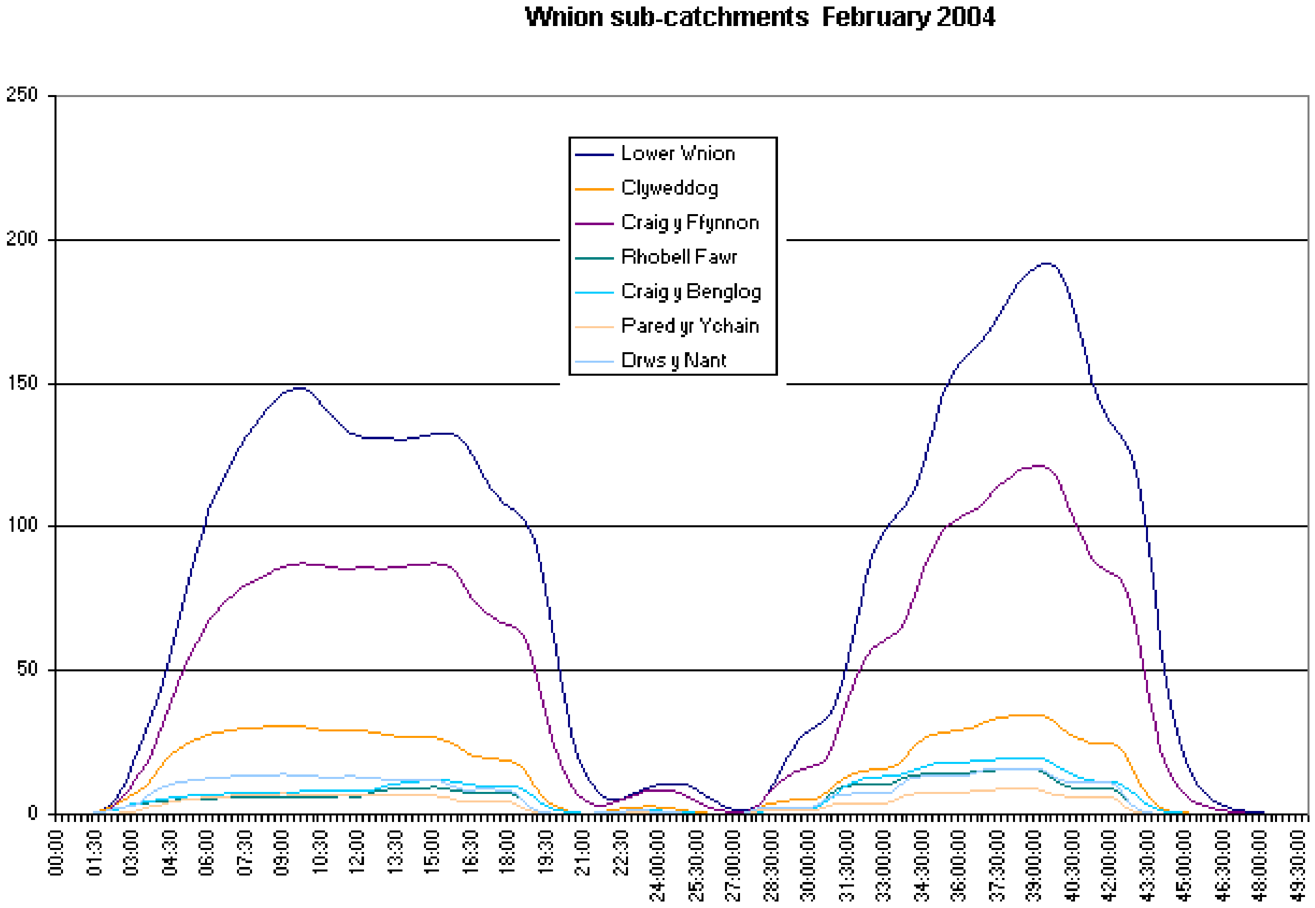


Figure 3.74: Hydrographs generated by theHEC-1 model for sub-catchments of the Afon Wnion, storm events of 2-4 February 2004

Summary

- Field data has been collected from sites within the Mawddach catchment for use in calibrating and validating hydrological models. This data includes measurements of river flows and hillslope runoff.
- Hydrograph data has also been made available by the Environment Agency for the Tyddyn Gwladys gauging station on the Afon Mawddach in Coed y Brenin.
- For the purpose of hydrological modelling, the Mawddach above the tidal limit has been divided into twelve sub-catchments and the Wnion has been divided into eight sub-catchments. A number of river cross-sections have been surveyed within each sub-catchment.
- Hydrographs have been produced for six sites within the river system by barometric water depth recording. Calibration for river discharge has been carried out by a combination of direct flow measurements and theoretical calculations using flow formulae.
- Within the Wnion sub-catchment, a relationship was found between the hydrograph for a headwater stream and the hydrograph at the river mouth with a time delay of 3 hours 30 minutes. No similar relationship could be found for hydrographs in the Mawddach sub-catchment.
- Hillslope runoff and shallow storm flow measurements were made at sites in the Wnion and Mawddach sub-catchments. During storm events, the volumes of shallow subsurface downslope flow greatly exceeded surface runoff. Periods of very high subsurface hillslope flow corresponded exactly with times of flooding downstream near the head of the Mawddach estuary.
- The HEC-1 hydrological model within the Watershed Modelling System has been used to model a variety of convective and frontal storms 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.

- In order to model storm events at different times of the year with different soil antecedent moisture conditions, a simple adjustment of soil moisture categories can be made within the SCS curve number system.
- 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. It would be necessary to specify the antecedent soil moisture condition through selecting an appropriate SCS Curve Numbers parameter: A (dry), B (moderately dry), C (damp) or D (wet). This could be chosen, for example, by examination of throughflow sites at key locations in the gorge sections of the Mawddach system in Coed y Brenin.
- The integrated meteorological/hydrological model to be developed in Chapter 5 addresses the limitations of HEC-1 identified above, and attempts to overcome these to allow the modelling of multiple-storm sequences.
- Limitations with the Curve Numbers method for specifying soil properties will be addressed by using a method based on the Hydrology of Soil Types (HOST) classification (cf. figs 1.65-66).