3.4 River and floodplain processes

Flooding can have economic consequences in various areas of the Mawddach catchment, but most serious concern is associated with flood risk for the town of Dolgellau, situated on the Afon Wnion near its confluence with the Afon Mawddach at the head of the tidal estuary. Historical floods affecting the town were discussed in Section 1.1. Flood hydrographs were presented in Section 3.2 for two recent flood events, 3 July 2001 and 3-4 February 2004. The volumes of sand and gravel transported and deposited along the Afon Wnion during these events were estimated in Section 3.3. Concerns have been expressed in Dolgellau about the effects of sediment accumulation on flooding, as outlined in the BBC News report of 3 October 2005 (fig.3.112).

A flood risk map (fig.3.113) published by the Environment Agency identifies areas of

- *significant flood risk*, defined as having an annual chance of flooding in any year of greater than 1 in 75, and
- *moderate flood risk* with an annual chance of flooding in any year between 1 in 75 and 1 in 200.

The area designated a significant flood risk is composed of the Wnion valley up to the 10m contour height west of the town, rising to the 15m contour height to the east of the town. This implies a possible flood water depth of approximately 6-8m across the valley floor in the vicinity of the town centre. Modelling will be carried out with the objectives of:

- determining the validity of the Environment Agency flood map under current rainfall and river channel conditions,
- determining a possible worst case scenario for flooding in Dolgellau in response to extreme rainfall,
- determining the effects of sediment accumulation on the extent of flooding.

BBC NEWS

BBC News 24

Last Updated: Monday, 3 October 2005, 16:43 GMT 17:43 UK

Flood fear after river work delay

Part of Dolgellau could face flooding if a river running through the town is not cleared, councillors have claimed.

The seven-arched Bont Fawr in Dolgellau. Pic: Dolgellau.com

The town council says it has repeatedly asked the Environment Agency to clear the river Wnion near Bont Fawr.

The Environment Agency said the work had been delayed until after the fishing season and should be finished by the end of October.

But town councillors say they fear there could be flooding before the work is carried out.

"I'm very worried about the situation," said town councillor Menna Roberts. "We've had floods here before and we don't want anything similar happening again.

"We need the Environment Agency to carry out the work as soon as possible."

A spokesman for the Environment Agency Wales said they were aware that "maintenance work" is needed on the river Wnion to "reduce the risk of flooding in Dolgellau."

The spokesman said: "Conducting the work too soon in the year would have disrupted the river during the fishing season.

Jo Stocks of The Stag Inn said: "We had river water coming up in the toilet and water was running through the pub just before Christmas last year.

"The year before we tried to sandbag it, but that made it worse, so last time we just opened the doors and let the water flow through."

Only part of the pub is flooded each time, so the pub can remain open, and it was not possible to get insurance cover for flood damage.

Figure 3.112: BBC News report on the flood risk for Dolgellau. 3 October 2005

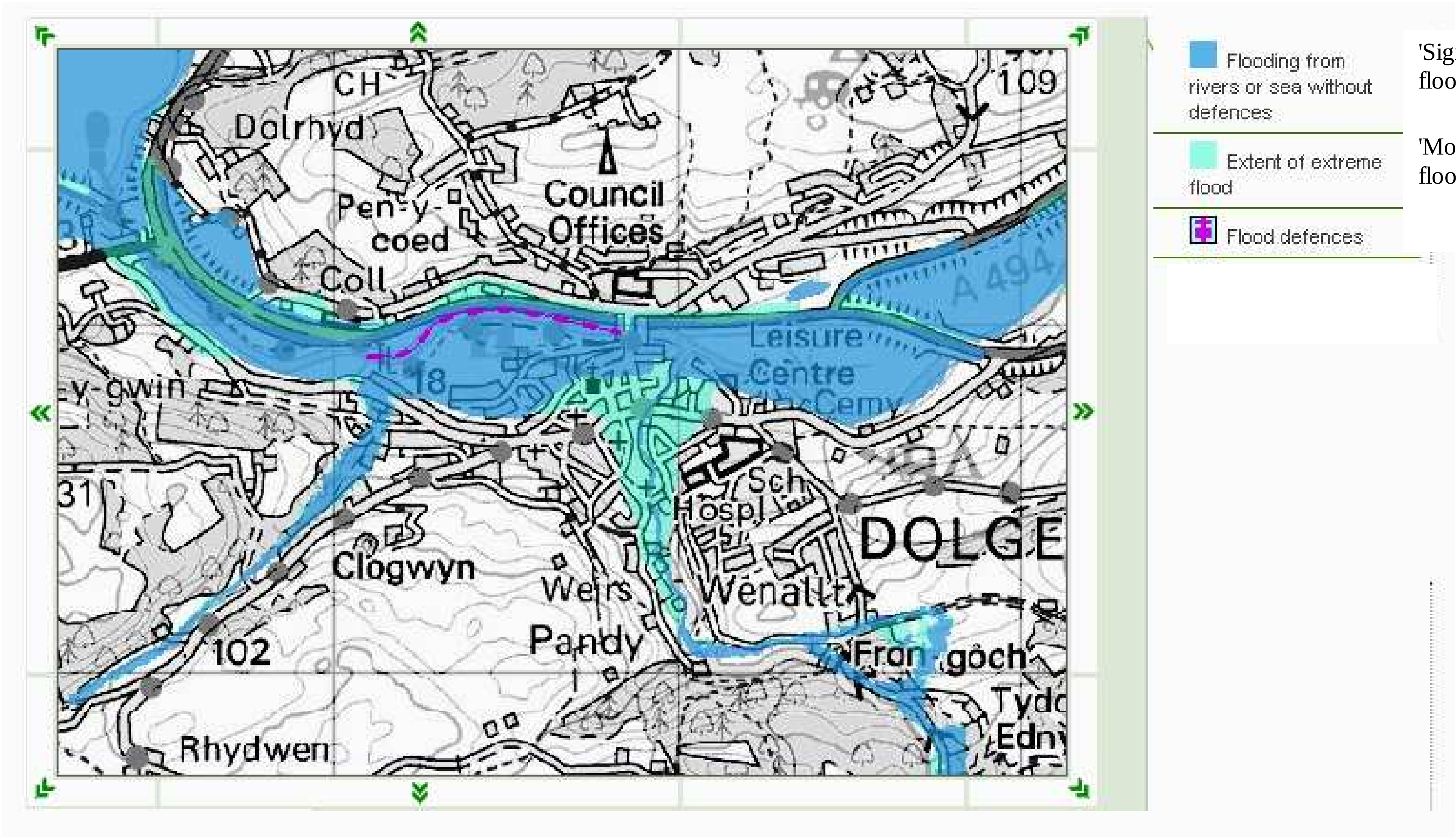


Figure 3.113: Environment Agency flood map: Dolgellau

Dolgellau flood modelling

A practical flood forecasting system should determine the areas of floodplain likely to be inundated during particular flood events and the depths of water to be expected. Tests have been carried out with two different modelling programs capable of providing this information, with a view to selecting the most suitable for inclusion in an integrated flood modelling scheme. The programs examined are:

- RMA2 within the Surface Water Modelling System (King et al., 1997)
- River2D (Steffler and Blackburn, 2002).

Both software packages are depth-averaged finite element models using irregular grids, as described in Section 3.1. Preparation of models proceeds in a similar manner for each package:

A set of elevation data points is first imported. For the Dolgellau model, the floodplain was defined from the Ordnance Survey 25m gridded elevation data set. Additional points were added along the river channel and banks, based on interpolation between surveyed river cross-sections (fig.3.114).

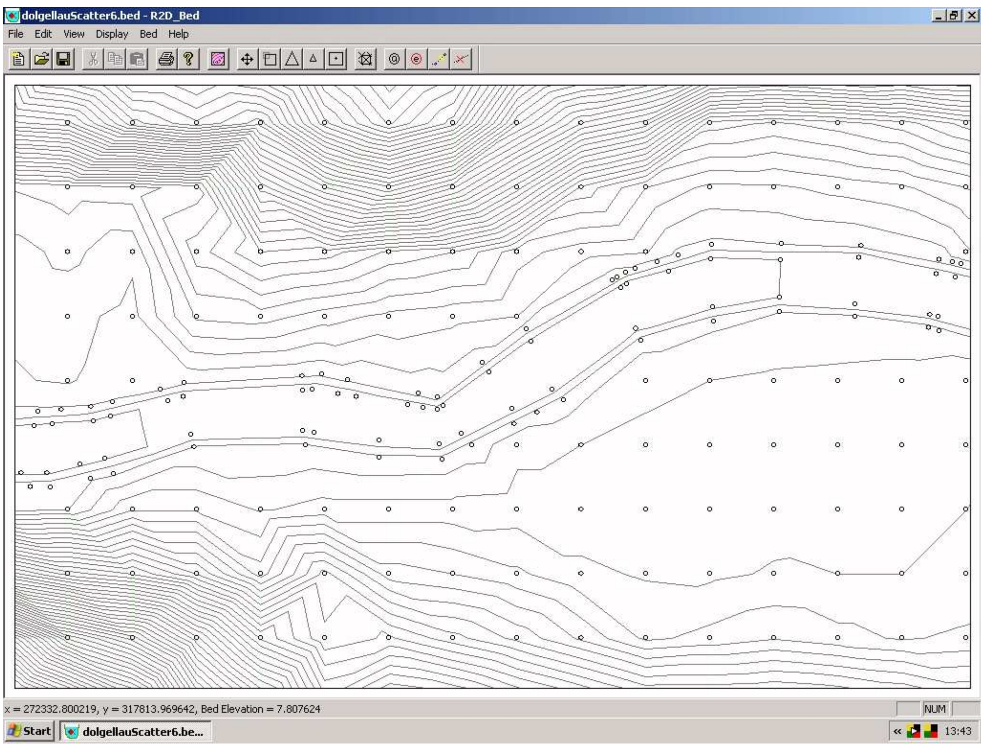


Figure 3.114: 25m gridded elevation point data set used as a basis for Dolgellau floodplain models, augmented by surveyed points along the river channel

The extent of the modelled floodplain area is delimited and a finite element grid is constructed. The River2D program uses triangular elements, whilst RMA2 employs a combination of triangular and quadrilateral elements (fig.3.115). Height values for corner points of the finite elements are interpolated from the elevation data point set.

A compromise has to be made between the accuracy of the finite element mesh and the run time and memory limitations of the computer. Elements of dimension 20m have proved successful for the River2D model, with smaller elements defined in zones of rapid change in elevation such as river banks.

Different zones of the floodplain and river channel can be assigned appropriate values of surface roughness. In the case of RMA2, roughness can be entered directly as a *Manning roughness coefficient*. River2D makes use of the parameter *roughness height*, which is a function of Manning roughness coefficient and hydraulic radius. Manning roughness values chosen for the models were:

river channel	0.04
floodplain woodland	0.12
grassland	0.03
urban landuse	0.02

The final stage in setting up the model is to define boundary conditions. Sections of the model boundary may be defined as:

- no-flow boundaries
- flow boundaries, with river discharge defined either by a steady state value or a time series of discharge values (fig.3.116)
- water surface elevation boundaries, with river stage height defined either by a steady state value or a time series of stage heights.

River2D additionally provides an option to calculate water depth at the outlet of the reach using the depth–unit discharge relationship:

$$q = Kh^m$$

with default values of K = 1, m = 1.666.

For the Dolgellau models, inflow discharge from the lower Wnion valley was defined, along with water level at the outlet to the tidal estuary.

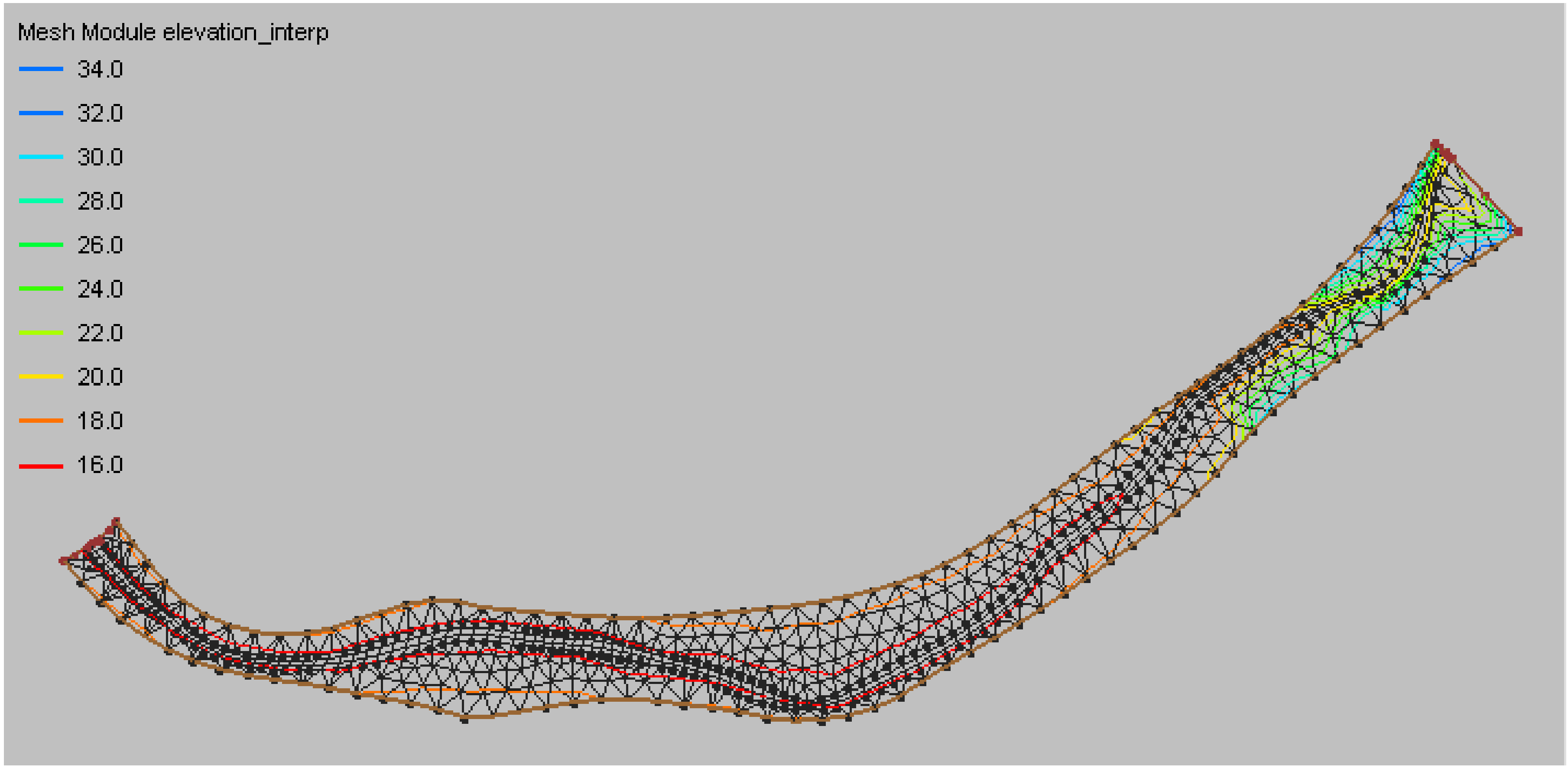


Figure 3.115: RMA2 finite element grid for the Dolgellau flood plain model

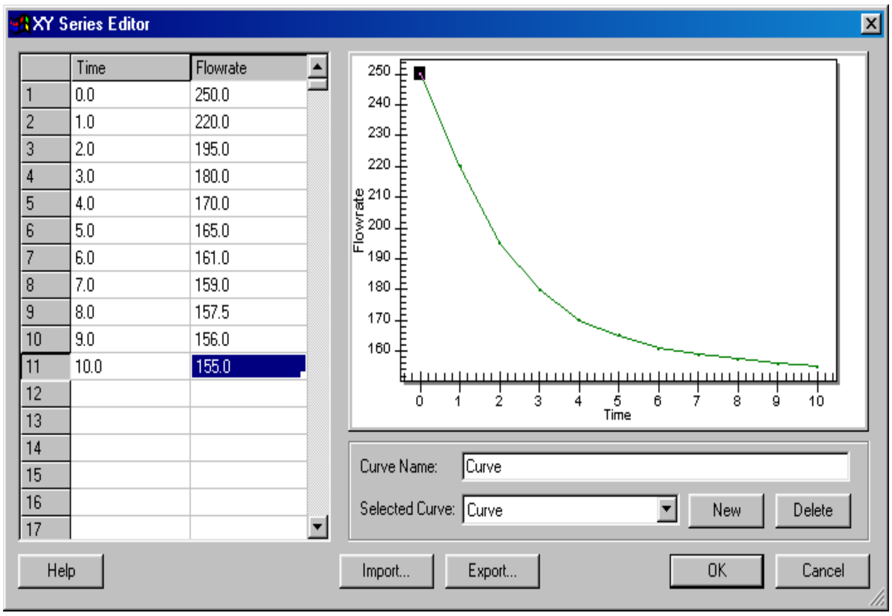


Figure 3.116: Definition of a transient series of inflow rates (m^3/s) for a RMA2 model. Time is measured as a count of 15 minute intervals.

The approach taken to run a model is similar for both the River2D and RMA2 programs. An initial water level is specified above the height of the flood plain, and the model is *'spun down'* by progressively reducing the water level between iteration cycles until normal flow in the river channel is simulated. During this process, drying of finite elements on the floodplain will occur (fig.3.117). Low flow models can be saved and used as starting conditions for flood simulations.

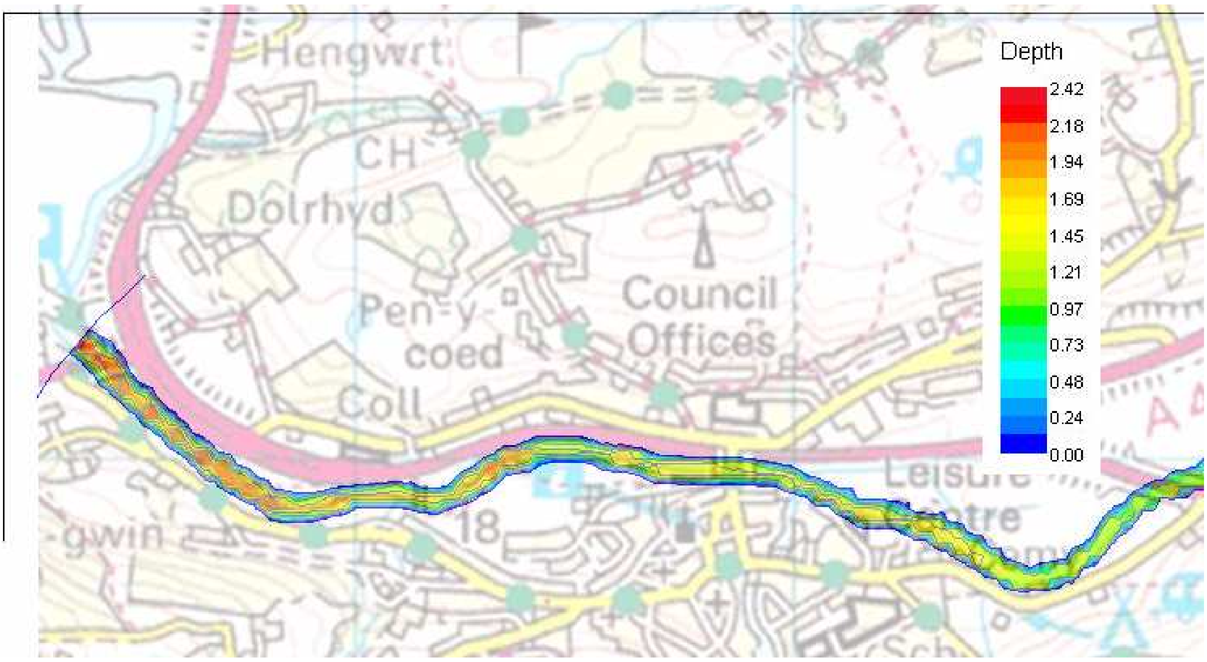


Figure 3.117: River2D model for the Afon Wnion at low flow

A comparison of the functionality of the two programs was carried out by setting up RMA2 and River2D models to simulate a constant flow of $350m^3/s$ for the lower Wnion valley around Dolgellau. This represents an extreme flood with approximately twice the flow rate of a typical annual flood event. Both programs were successful in producing plots of water depth across the Dolgellau floodplain, and results may be compared in fig.3.118.

Close similarities are seen between the patterns of flooding predicted by the RMA2 and River2D programs. Both show widespread flooding of the Marian Mawr playing fields to the west of Bont Fawr. Some differences exist in the extent of flooding of low lying land to the east of the town, with the River2D result appearing more plausible on the basis of field observations of flooding. Predicted water depths across flooded areas are similar for each model.

During the initial experiments with the two programs, numerical stability problems were experienced whilst running RMA2 models. Wetting or drying of the floodplain would cause surface elements to be added or removed from the model. In severe cases, these changes to the model boundary shape induced instability and the model failed to converge. The authors of RMA2 advise that surface elements should have their edges aligned along contours to reduce irregularities in the boundary shape. A *marsh porosity* option is also available, to allow surface elements to be gradually added or removed from the model over a series of iterations. Despite these precautions, instability was still found to occur, and considerable time was spent making minor adjustments to boundary conditions and the finite element grid in order to achieve successful runs.

No stability problems were experienced with River2D. This program provides improved mathematical stability by modelling both river flow and groundwater flow through bank sediments. It is possible to set values for both storativity and infiltration rate. Water surface contours beneath the flood plain appear as a subdued projection of the surface topography. The apparently more realistic flood boundary of the River2D model in fig.3.118 may be explained by the simulation of surface and groundwater interaction. Formulae used to compute surface and groundwater levels are discussed in section 3.1.

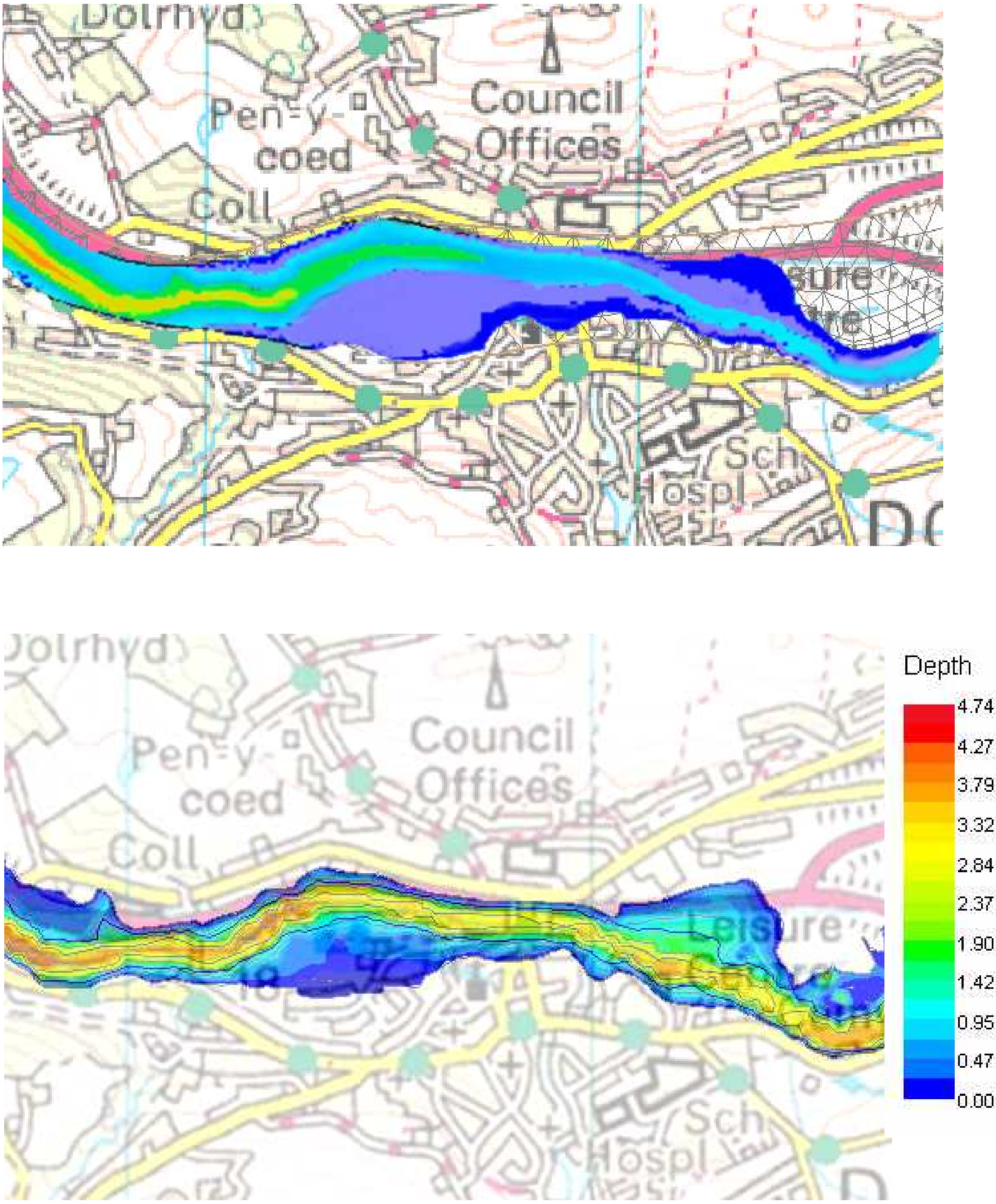


Figure 3.118: Model results for constant river flow of 350m^3/s. (upper) RMA2, (lower) River2D

In view of the reliability and ease of use of River2D, and modelling results which appear equivalent or superior to those of RMA2, it was decided that further work on surface water modelling would be carried out using the River2D program.

Simulation of flood events for the Dolgellau flood plain

Runs of the River2D model were carried out to represent:

- time sequences for the flood events of 3 July 2001 and 3-4 February 2004 using 30 minute time steps,
- steady state inflows of inflows on the Afon Wnion of 100, 150, 200, 250, 300 and 350m^3/s.

It was found that river-groundwater interactions during flood events were sufficiently rapid to maintain equilibrium between river and floodplain water levels between time steps. No hysteresis effects were evident during the rising or falling limbs of the flood hydrographs, and no significant differences were found between flood sequence simulations and steady state simulations for the same instantaneous river inflow rate. The extent of flooding during a storm event could be successfully represented by a single steady-state simulation using the hydrograph peak discharge, considerably simplifying the modelling process.

In interpreting the model, we should note that River2D is calculating an equilibrium between river and groundwater levels in the river banks within a closed surface water system. It is not allowing for large scale removal of river water to groundwater storage or the resurgence of groundwater into river channels under the effects of a positive hydraulic head. However, these effects are not expected to have a significant effect on flooding in Dolgellau since:

- the floodplain is largely underlain by boulder clay deposits, with low permeability as shown by the slow drainage of flood waters from low lying fields following flooding,
- the floodplain has a low gradient and lies close to sea level; the water table is close to the river bed at all times and provides little hydraulic head to drive groundwater exchange,
- modelling carried out later in this section for the Afon Wen indicates that groundwater resurgence occurs on a slow timescale compared to flood discharge along open river channels; groundwater resurgence is unlikely to have any significant effect until after a flood peak has passed.
- Fig.3.119 shows a steady state discharge of 150m^3/s, representing the onset of flooding in the vicinity of Dolgellau, with low lying land to either side of the main A470 by-pass to the west of the town being inundated (fig.3.120).

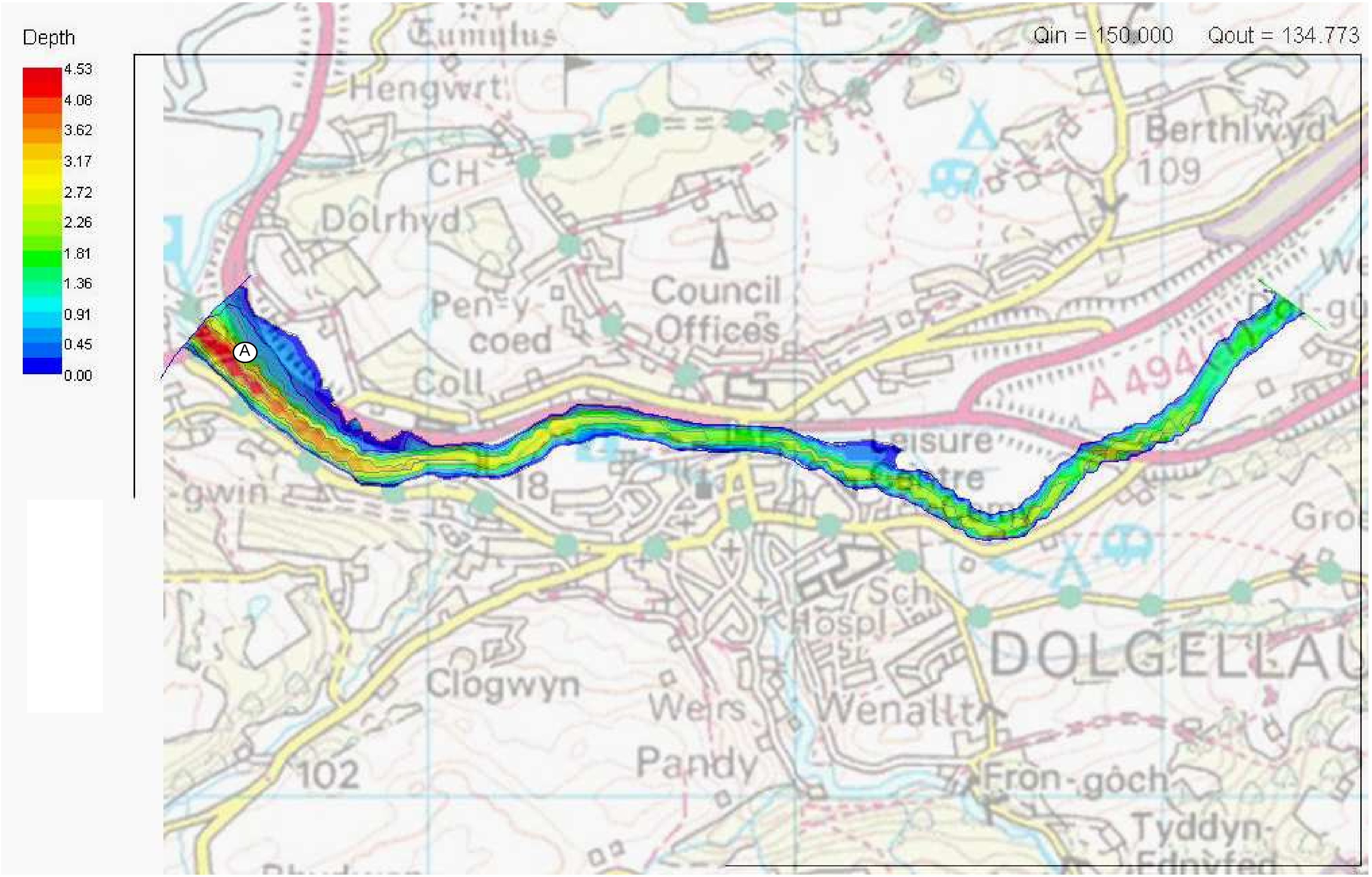


Figure 3.119: River2D simulation of Afon Wnion steady state inflow of $150m^3/s$

Figure 3.120: Flooding on the western outskirts of Dolgellau, looking south eastwards from point A in fig. 3.119. The Afon Wnion lies to the right of the low embankment and line of trees in the middle distance.

Water flow of 200 m^3/s is modelled in fig.3.123. At this river stage, flooding of the Marian Mawr playing fields begins, as represented in the model, with river water entering around the western limit of the flood defence embankments (fig.3.121).

Figure 3.121: Flooding of the Marian Mawr playing fields behind the flood defence embankment of the River Wnion. View west from point A in fig.3.123.

Flooding of the low lying land to the west of the town becomes deeper and more extensive, as in the model. Fig.3.122 shows flood water entering fields near Coleg Meirion-Dwyfor by overtopping the river banks.

Figure 3.122: Flooding of fields bordering the Afon Wnion near Coleg Meirion-Dwyfor. View south from point B in fig. 3.123.

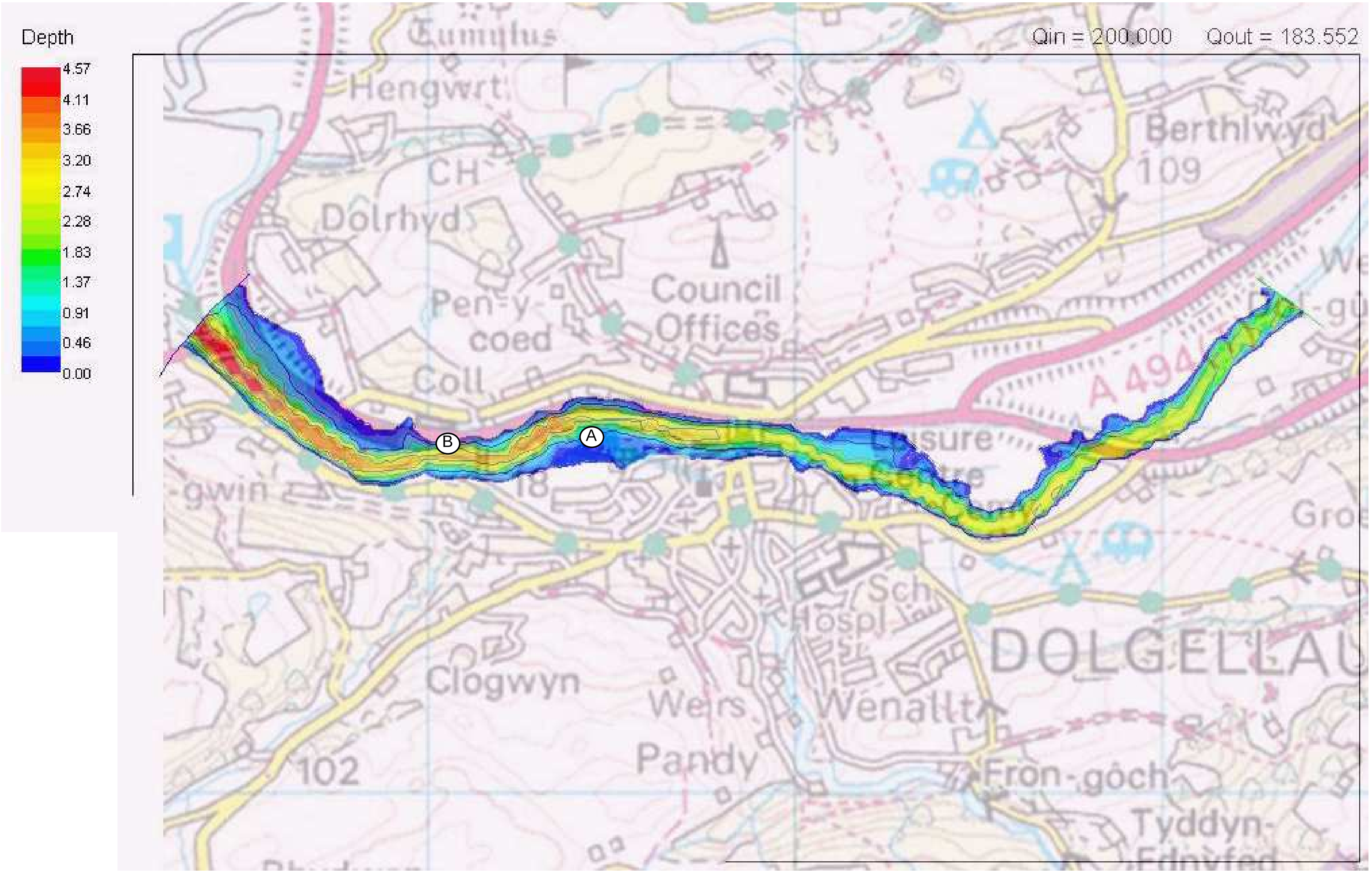


Figure 3.123: River2D simulation of Afon Wnion steady state inflow of 200m^3/s

At water flows above 200m^3/s, properties in the town of Dolgellau are under threat from flooding. Fig.3.126 models a flow of 300m^3/s where flooding would have extended to roads in the vicinity of Bont Fawr (fig. 3.124). The A470 main road may become impassable at its lowest point alongside the river due to the inability of drainage pumps to cope with the inflow of flood water (fig.3.125).

Figure 3.124: Flooding in the town car park alongside Bont Fawr, Dolgellau. View west from point A in fig. 3.126

Figure 3.125: Flooding of the A470 road alongside Bont Fawr, Dolgellau. View west from point B in fig. 3.126

Flooding within the town would commence with the cellars of properties in Bridge Street, eventually reaching street level (point C on the model of fig. 3.126). At a flow of 300m^3/s the town's industrial estate would be at risk (point D on the model).

From the investigations carried out with River2D, it is concluded that the model can provide realistic estimates of the extent and depth of flooding around Dolgellau if an accurate storm hydrograph prediction for the Afon Wnion is available.

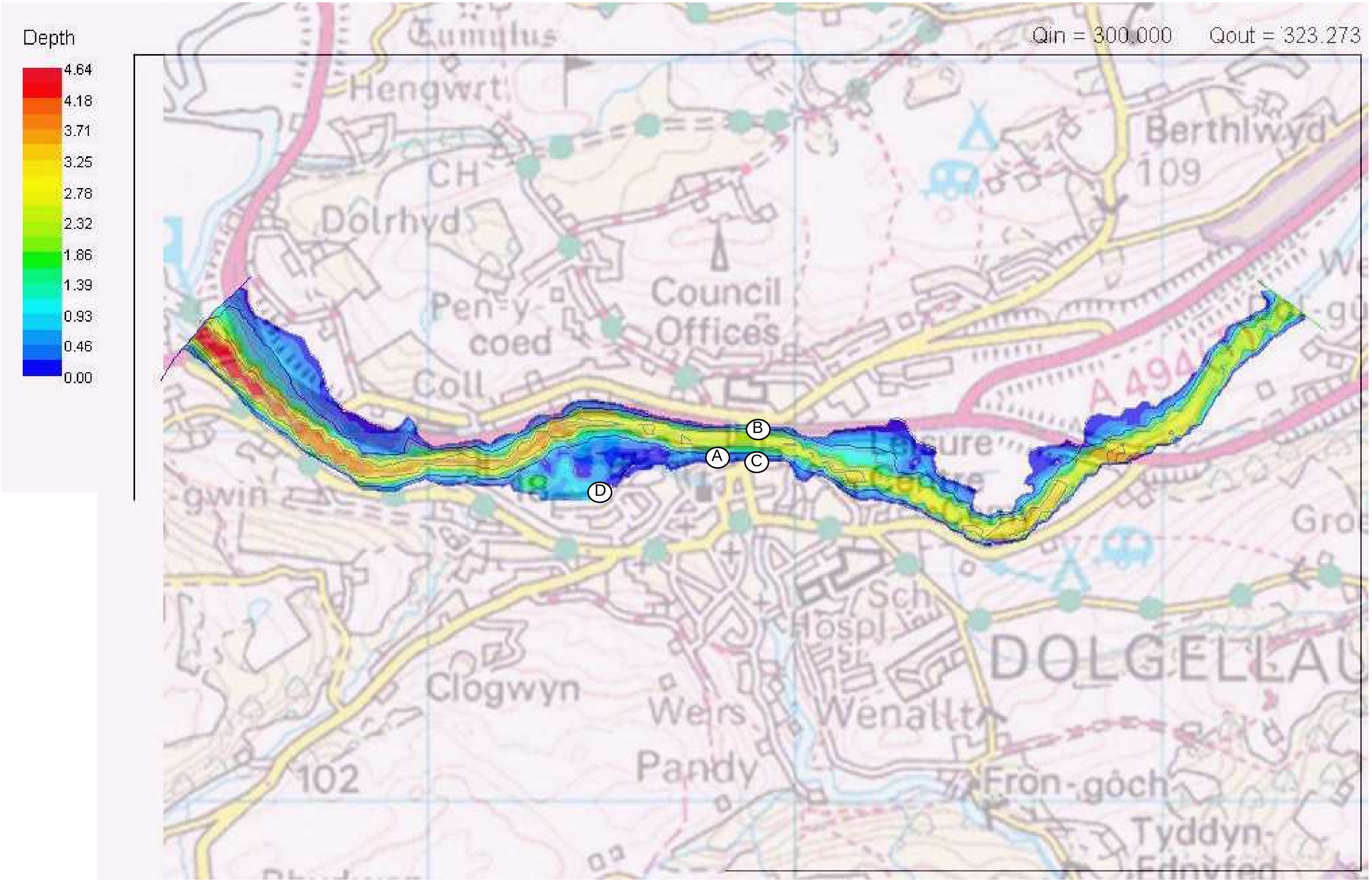


Figure 3.126: River2D simulation of Afon Wnion steady state inflow of 300m^3/s

For the next phase of modelling, a worst case scenario was selected in which a series of convective rainfall cells of intensity similar to the 3 July 2001 storm event were situated above the Middle Wnion valley in the area of Rhydymain. A run of the HEC-1 hillslope runoff model was carried out with storm total rainfall values of 80mm at Drws y Nant and Llyn Cynnwch, and a total rainfall of 120mm at Rhydymain to represent the centre of the storm. Rainfall was concentrated intensely over a 3 hour period in a similar pattern to the July 2001 event. A synthetic hydrograph for flow on the Afon Wnion entering Dolgellau is given in fig.3.127. This indicates a flow maximum of approximately 450m^3/s.

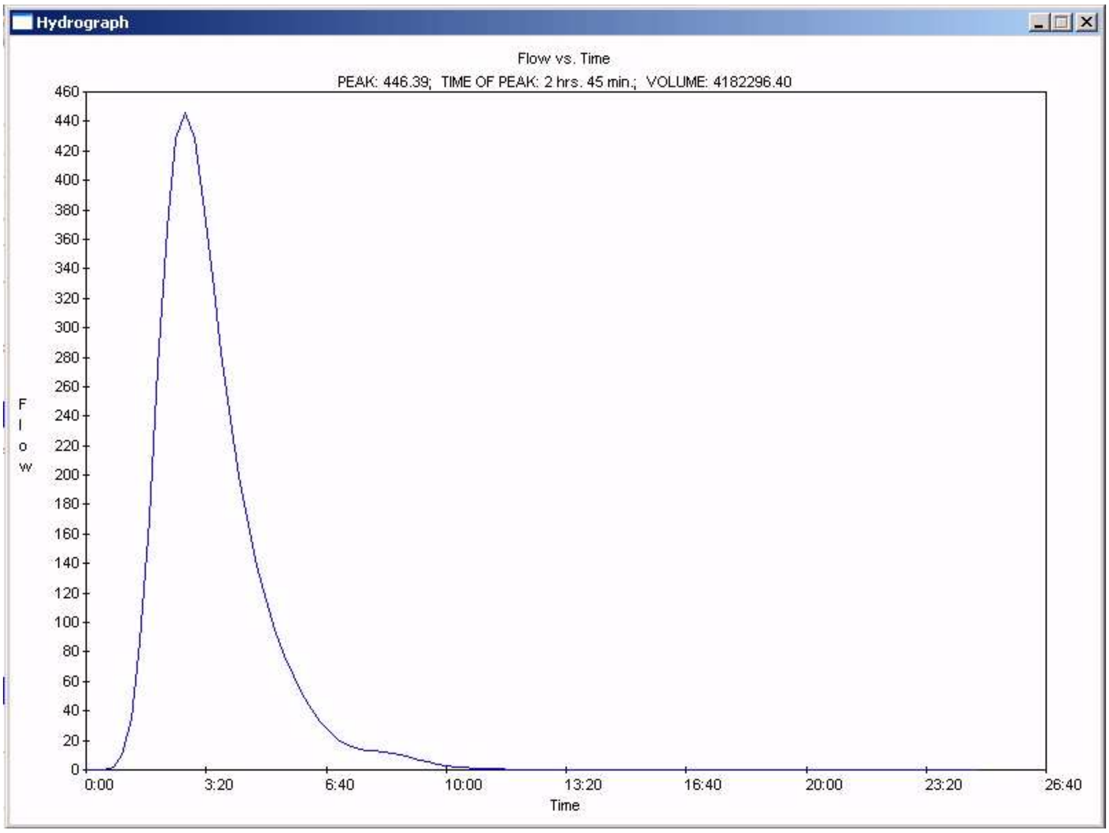


Figure 3.127: Hypothetical maximum flood hydrograph for the Afon Wnion entering the town of Dolgellau. Flow shown as m^3/s.

A feature of the Environmental Agency flood map (fig.3.113) is the implication of possible extensive flooding from the Afon Aran tributary, which descends steeply into the town from its source at Llyn Aran below the escarpment of Cader Idris. To investigate this possibility, a HEC-1 hillslope runoff model was set up for the Aran sub-catchment (fig. 3.128). A similar worst case scenario was modelled, with a convective storm over Cader Idris producing total rainfall of 120mm over a 3 hour period. The modelled synthetic hydrograph at the Afon Wnion confluence is shown in fig.3.129, where the maximum flow reaches approximately 45m^3/s.

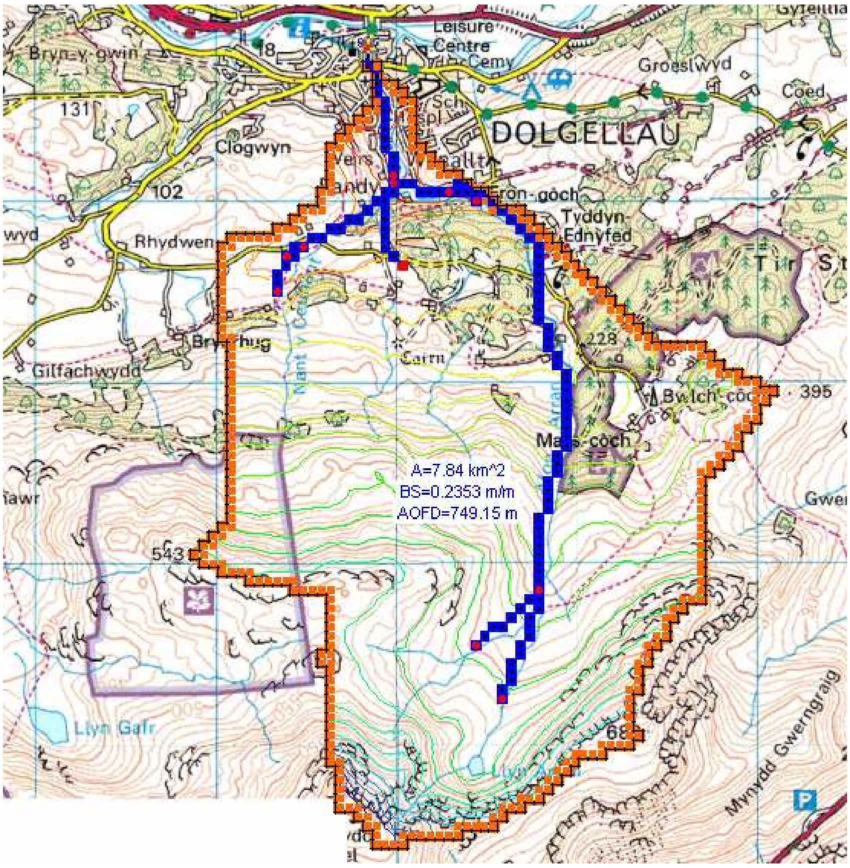


Figure 3.128: HEC-1 hillslope runoff model for the Aran sub-catchment.

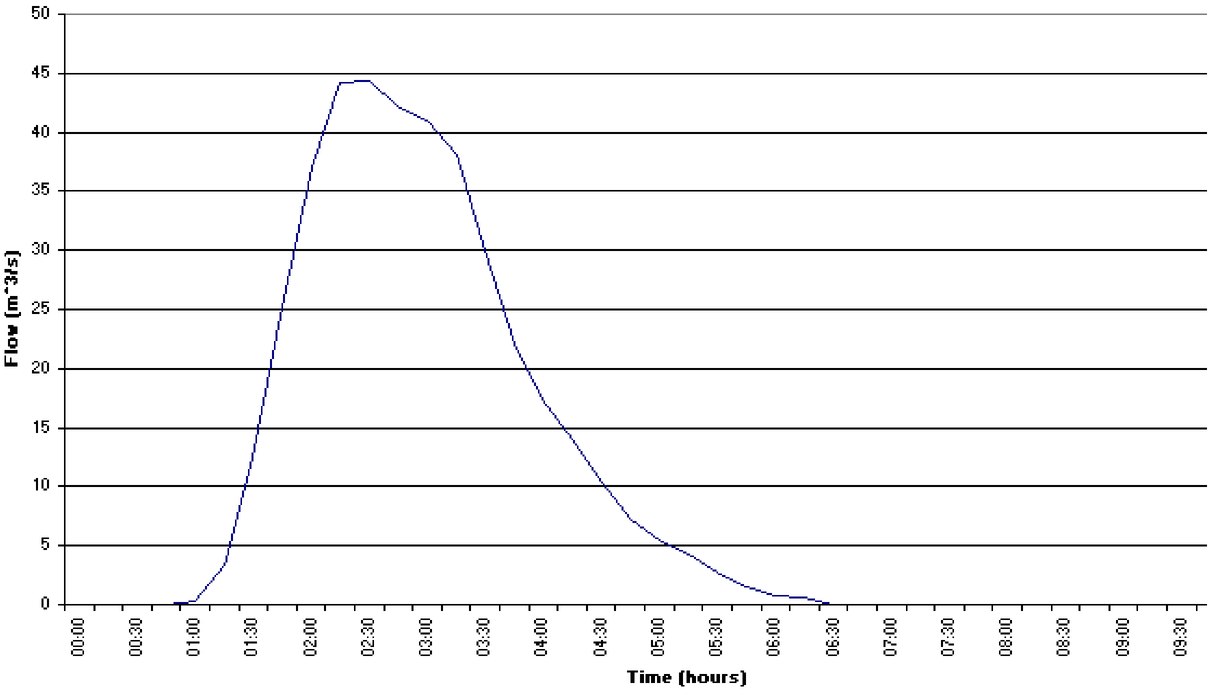


Figure 3.129: Extreme flood hydrograph for the Afon Aran, Dolgellau

A River2D model was run which combines an inflow of $445m^3/s$ on the Afon Wnion and $45m^3/s$ on the Afon Aran. The flood plain map generated is shown in fig.3.130. More extensive flooding of the low lying areas of the town adjacent to Bont Fawr and the Marian Mawr fields is evident, with further inundation of agricultural land in the lower Wnion valley to the east of the town. The industrial estate is at risk, along with properties in Bridge Street. A scenario similar to the 1964 Dolgellau flood (fig.1.7) is predicted. The model shows zones of high groundwater in the Eldon Square area which may affect cellars of properties. With the exception of properties immediately bordering the Afon Aran, no significant flooding from this stream is expected.

From experiments with River2D, it is concluded that the Environment Agency flood exaggerates the flood risk for the Wnion valley in the Dolgellau area. In particular, the map overestimates the extent of flooding within the centre of the town even under the most extreme conceivable flood scenario. In particular, the apparent flood risk from the Afon Aran tributary seems to be largely unfounded. This exaggeration of flood risk may have an adverse effect on costs of property insurance for local residents.

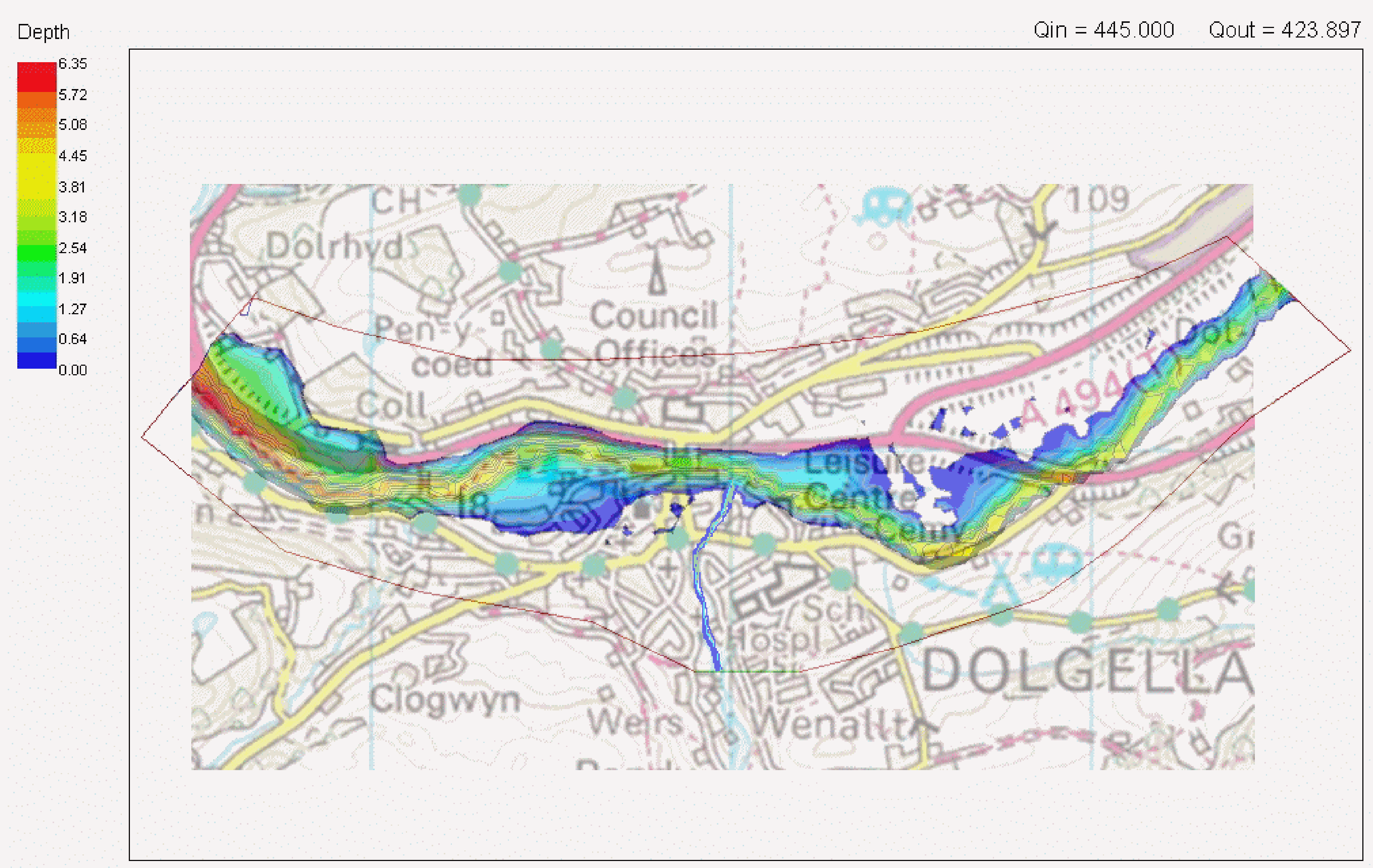


Figure 3.130: River2D simulation of worst case flooding scenario for the Afon Wnion, Dolgellau

A final investigation was carried out to examine the effects of substantial sediment deposition within the Wnion river channel. In section 3.3, sediment modelling was carried out for the two major flood events of July 2001 and February 2004. Estimates were obtained for volumes of *sand and fine gravel* and *medium gravel to cobble* size fractions deposited along a 3km reach of the Afon Wnion extending from above Dolgellau, through the town to the Marian Mawr playing fields. Deposition volumes during a time step were computed as the volumes of sediment within the water flow which exceeded the current transport capacity of the river.

Interpretation of the flood deposition data is difficult without more detailed sedimentological studies, but some assumptions can be made:

- the *sand-fine gravel* grade of material may be expected to be washed downstream in the river channel and lost from the reach in the days or weeks following a flood event. This is evident from the normal coarse gravel bedload grade of the lower Wnion.
- sand and fine gravel washed over the banks onto the agricultural land of the floodplain would be stabilised by vegetation and become part of the soil profile. Significant amounts of overbank deposits are indeed observed following flood events on the lower Wnion.
- *medium gravel-cobble* grade material would remain within the river channel and move slowly downstream, accumulating in favourable locations such as the basin downstream of Bont Fawr.

Flood event	**Deposition (m^3) along the Lower Wnion 1 reach**		**Estimated thickness of residual gravel accumulation (m) along the 3km reach, across a 40m riparian zone**
	coarse sand and fine gravel	**medium-coarse gravel and cobbles**	
3 July 2001	140 000	30 000	0.25
3-4 February 2004	140 000	180 000	1.5

Table 3.5. Estimates of coarse sediment deposition along the Afon Wnion through Dolgellau during major flood events

Rough estimates of the depth of stable *medium gravel to cobble* deposition during the two modelled flood events are given in table 3.5. These calculations assume an average width of 40m for the river and adjacent riparian zone where deposition may take place during flood flow conditions. Accumulations of up to 1.5m of gravel during the prolonged flood sequence of 3-4 February 2004 are consistent with observations of the river channel through Dolgellau before and after the flood. The considerable gravel deposition during the February 2004 event will be a consequence of the long duration of high flow conditions, allowing several days' downstream movement of coarse sediment by rolling and saltation processes at the channel bed.

Under normal circumstances, unstable gravel accumulations might be expected to continue slowly downstream and be lost from the lower Wnion reach before the next major flood event. If, however, the accumulation of immobile coarse gravel at the head of the Mawddach estuary is sufficient to significantly raise the river base level, the reduction in channel gradient upstream could inhibit gravel movement. This issue will be examined further in Section 3.6: *the Mawddach Estuary.*

Modelling was carried out with the River2D program to investigate the effects of permanently raising the bed level of the Afon Wnion by gravel accumulation. Adjustments were carried out to the finite element mesh to simulate accumulation of 1.0m of sediment within the channel along the reach between the Dolgellau leisure centre and Coleg Meirion-Dwyfor.

Results are shown in fig.3.131 for an input flow rate of $200m^3/s$. Comparison with fig.3.123 for the same input flow rate indicates a significantly larger area of flooding. Water depths adjacent to the river are generally shallow, but the effect would be to cause substantial disruption to road traffic in the area of the town around Bont Fawr. Accumulation of additional gravel in the river channel should be considered a serious potential flood risk.

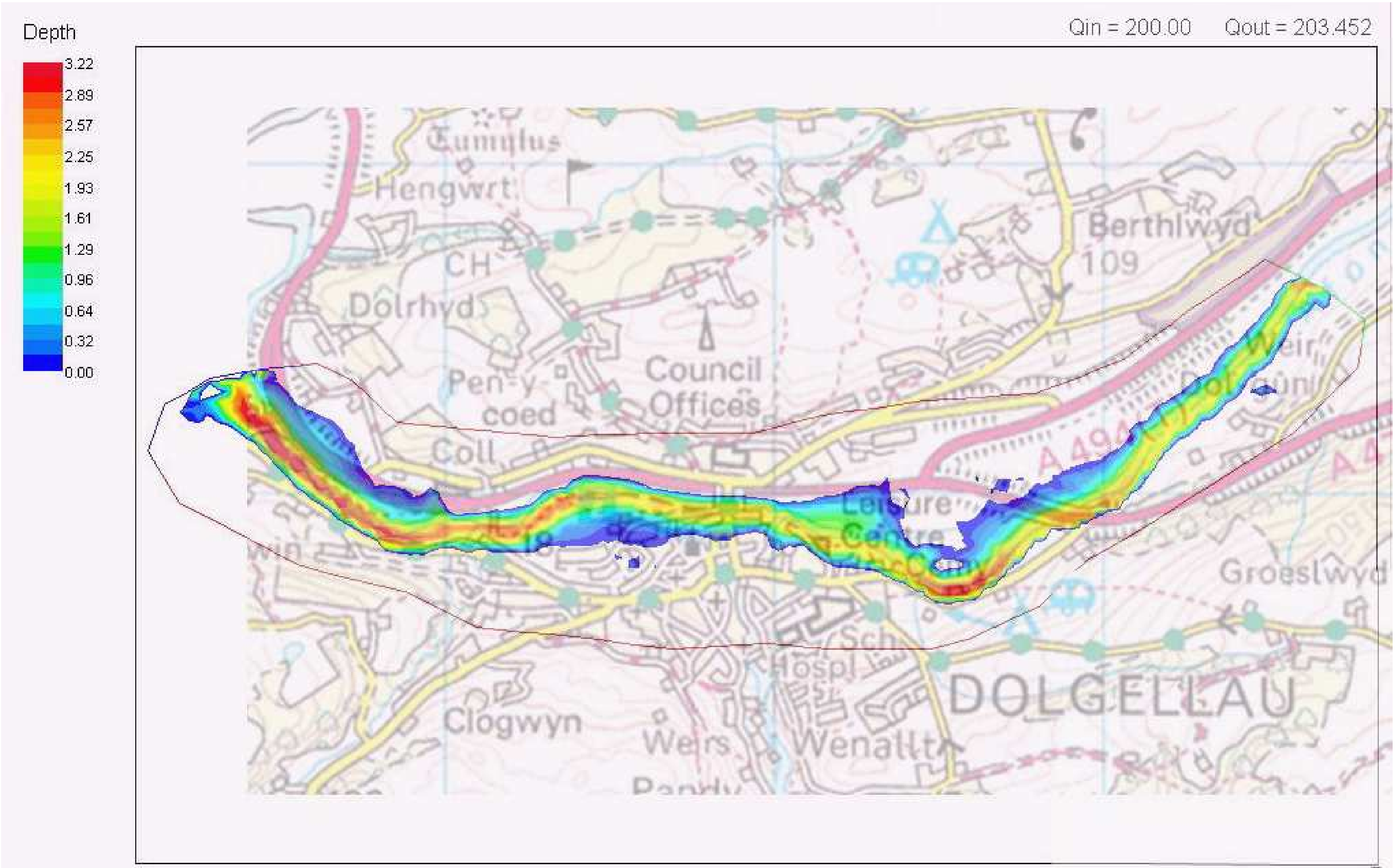


Figure 3.131: River2D simulation of 200m^3/s for the Afon Wnion, Dolgellau, assuming accumulation of an additional 1.0m of gravel along the channel bed throughout the reach. Actual water depth above the accumulated gravel is shown.

Effects of floodplain forestry on water flow

Rigid vegetation within the path of a water flow will induce turbulence. A measure of the ratio of inertial forces to viscous forces is the Reynolds number. For low Reynolds number, the flow past an obstruction is linear, but becomes increasingly turbulent as the Reynolds number increases (Open University, 1984). Water flow through dense floodplain woodland will exhibit Reynolds numbers in excess of 10^3 (Fischer-Antze et al., 2001).

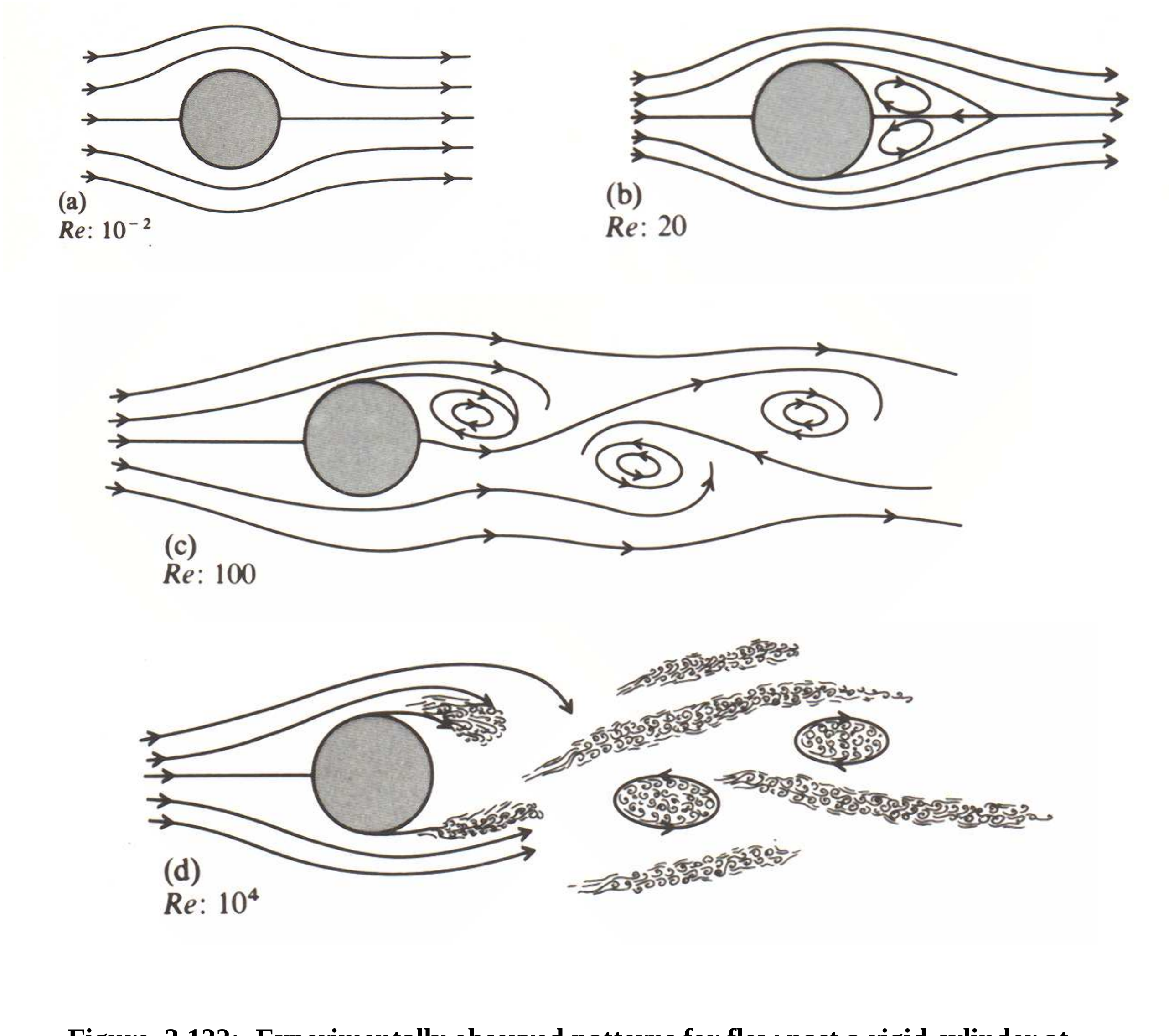


Figure 3.132: Experimentally observed patterns for flow past a rigid cylinder at different Reynolds numbers (after Open University, 1984)

The effects of tree stems within a water flow are complex, but will include:

- reducing downstream flow velocity through conversion of linear kinetic energy into turbulent motion,
- causing deflection of flow, reducing the down-valley flow component and increasing the cross-valley component.

During the rising limb of a flood hydrograph, the expected consequences are that:

- water outflow volume from a forested reach will be reduced, and
- the depth of water within the flood plain forest will be increased

in comparison to grassland. The floodplain forest can provide enhanced temporary storage capacity, with water being released during the falling limb of the hydrograph. The consequent reduction of the flood peak downstream may be sufficient to prevent the overtopping of river banks or flood defences (Thomas and Nisbet, 2004).

In order to quantify the effects of floodplain forestry in modifying water flows, either a theoretical or an empirical approach may be taken. Fischer-Antze, Stoesser, Bates and Olsen (2001) have developed mathematical models for idealised flow through arrays of rigid cylinders representing tree stems. The model describes steady one dimensional flow in direction x:

$$\frac{\partial u_i}{\partial x_i} = 0$$

where u is velocity, and uses the Navier-Stokes equation combined with the continuity equation:

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_i} = \frac{1}{\rho}\frac{\partial}{\partial x_i}\left(-P\delta_{ij} - \rho u_i u_j\right) - F_i$$

where:	U	time averaged velocity
	t	time
	ρ	water density
	P	pressure

The first term on the right-hand side of the equation represents laminar flow, with the second term F_i representing external forces of gravity and frictional drag.

The frictional drag component due to submerged rigid vegetation can be written as:

$$F_{D,i} = \rho \frac{U_i^2}{2} C_D \lambda$$

where C_D is a drag coefficient which can be taken as 1.0 for Reynolds numbers above 10^3. The vegetative coefficient λ is defined as:

$$\lambda = \frac{D}{s \cdot l}$$

where D is tree stem diameter, and s and l are the horizontal dimensions of a cell containing the tree (fig.3.133):

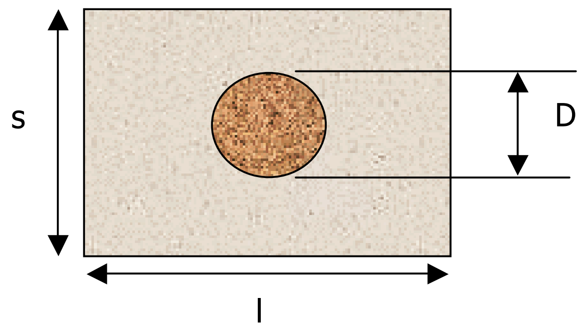


Figure 3.133: Determination of vegetative coefficient

Fischer-Antze et al. (2001) showed that the addition of the single turbulence term to equations for laminar water flow was sufficient to model the effects of flood plain forestry, making the modelling complete river reaches under different vegetation conditions relatively straightforward. Further mathematical treatments, verified by laboratory experiments, are given by Cui and Neary (2002), and Vionnet, Tassi and Martín-Vide (2004).

An investigation will be carried out to predict the effects of introducing floodplain woodland into the lower Wnion valley upstream from the town of Dolgellau. The River2D program has proved successful for floodplain modelling, and offers functions for simulating the presence of flood plain forestry through two mechanisms:

- by specifying roughness height, which allows for flow resistance over the ground surface,
- by specifying depth averaged eddy viscosity coefficients within the water.

The theoretical work of Fischer-Antze et al. supports this approach as being adequate to model resistance effects of water flow through an array of trees.

Calibration of the flood plain forestry models

Where flood plain forest can control flooding, this is seen as environmentally preferable to hard engineering works such as the construction of concrete or masonry flood defence walls. The type of planting advocated by the Forestry Commission for flood control is alder, willow and birch. Opportunities also exist for restoring native species to riparian zones, such as: oak, ash, black poplar, elm, and lime. Planting of floodplain woodland may be undertaken as a combination of flood control and nature conservation aimed at increasing species diversity. Typical flood plain woodland is shown in fig. 3.134 under flood conditions.

Figure 3.134: Wet woodland alongside the Afon Wnion downstream of Dolgellau. This area, dominated by willow, is inundated by floods several times annually.

As a first step in examining floodplain forestry scenarios in the Wnion valley, it was necessary to determine appropriate values for roughness height and eddy viscosity coefficients for wet woodland. Investigations were carried out in conjunction with the MSc Environmental Forestry project of Jerome O'Connell, Bangor University (O'Connell, 2004) . Two sites were selected on the Ganllwyd reach of the Afon Mawddach within the forested area of Coed y Brenin:

- the Tyddyn Gwladys reach, extending for 500m downstream from the Environment Agency gauging station,
- Cefn Deuddwr, at the confluence of the Afon Eden with the Afon Mawddach.

At each site, clear evidence was available to allow mapping of the maximum extent and maximum elevation reached by flood waters during the 3 July 2001 storm event. This evidence consisted of sand and gravel deposits on the floodplain, accumulations of forestry debris, and the height of erosion of mosses and lichens from the trunks of trees in the path of the flood waters.

The Tyddyn Gwladys river section is largely a bedrock reach with cobble and gravel accumulations along the banks. A substantial bench exists on the western side of the valley, eroded in a former meander before the river moved to its present course by further down cutting (fig.3.135). The river banks, bench and the break of slope behind are wooded with a mixture of semi-natural native broadleaf species and planted conifers (fig.3.136).

Figure 3.135: Afon Mawddach at the Tyddyn Gwladys forest site. View downstream with the flat bench forming the far bank.

Figure 3.136: *Bench alongside the Afon Mawddach at the Tyddyn Gwladys site. Flood debris from the July 2001 event can be seen against the trunks of mature conifers.*

The Cefn Deuddwr site lies about 2km downstream from Tyddyn Gwladys. This is again a heavily forested area with a mixture of native broadleaves and planted conifers (fig.3.137). The site consists of a low bench between the rivers Mawddach and Eden. Shortly after entering, the Afon Mawddach descends by approximately 4m over a substantial waterfall (fig.3.138).

Figure 3.137: Cefn Deuddwr forestry site, looking downstream on the Afon Mawddach. Flood level during the July 2001 event was approximately 2.5m above the grass bank in the right foreground. The viewpoint is the left end of the bridge shown in figure 3.138.

Figure 3.138:
Cefn Deuddwr forestry site, looking upstream on the Afon Mawddach. The rock face alongside the waterfall is visible beneath the bridge.

Figure 3.139: Flood debris from the July 2001 event caught against a tree, a short distance upstream from the waterfall in fig. 3.138

Use of the Ordnance Survey 25m gridded data was not considered to be sufficiently accurate for the detailed modelling of the two forestry sites, so field surveying was carried out by levelling. Heights were determined relative to a local datum at each site. Positions were determined by the construction of triangles of survey points extending outwards from a survey baseline (fig.3.140).

Figure 3.140: Surveying in progress at Cefn Deuddwr on the Afon Mawddach

The relative height measurements and positional data were checked for accuracy around closed loops. After acceptance, the data was transferred to the River2D_Bed utility for the construction of triangulated networks (fig.3.141) and generation of contour maps (fig.3.142).

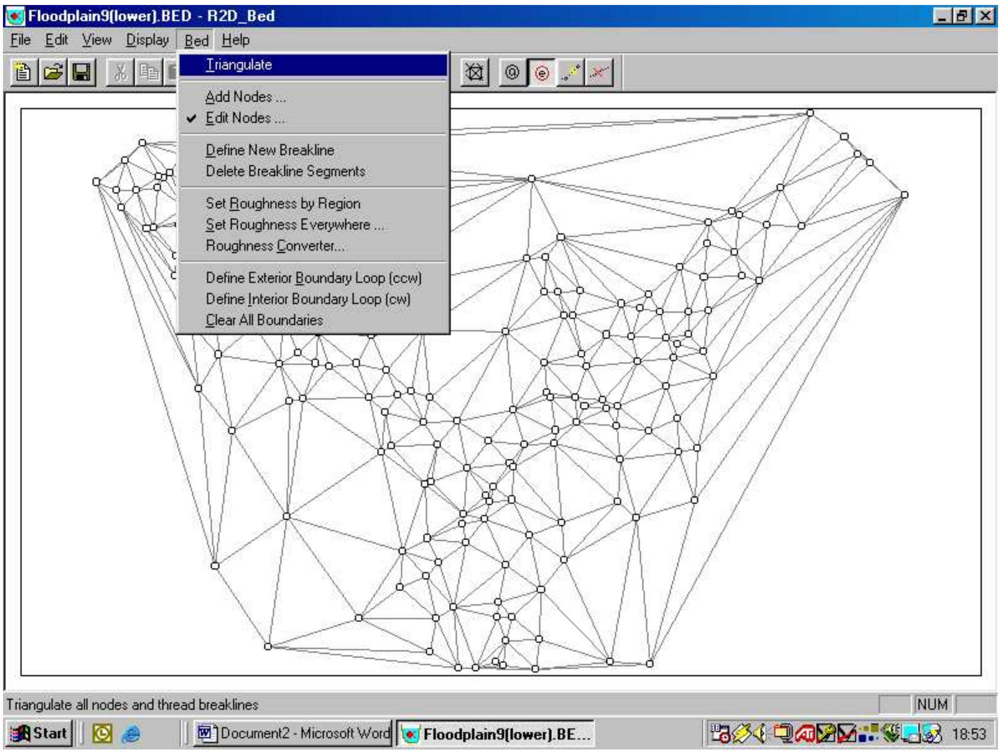


Figure 3.141: Triangulated irregular network of surveyed points at the Cefn Deuddwr site.

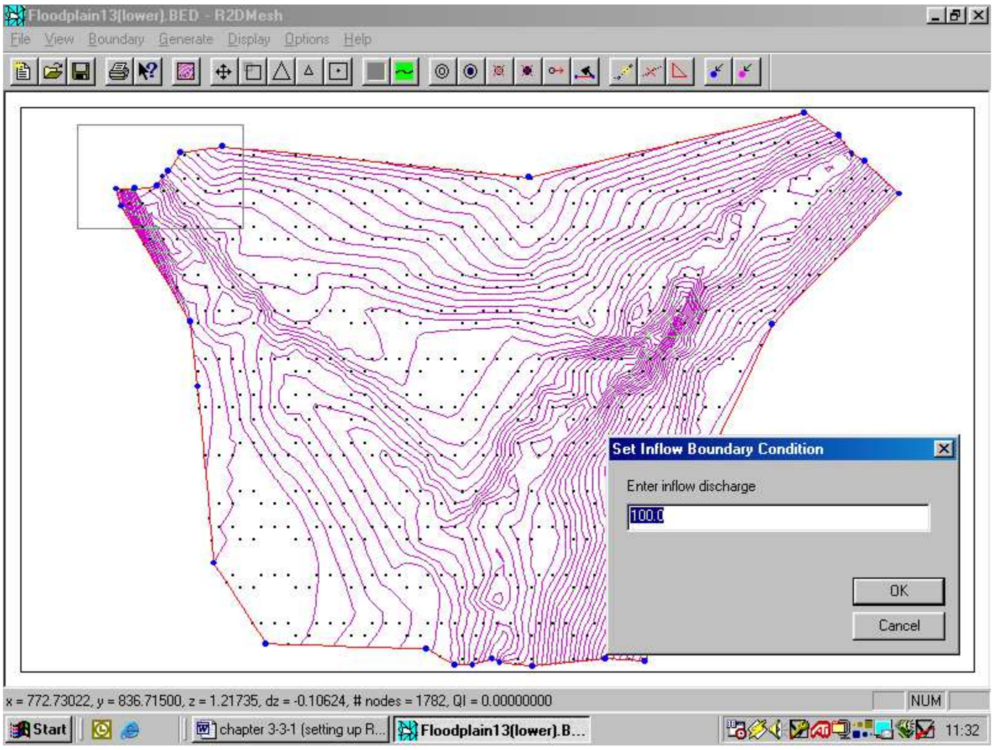


Figure 3.142: Generation of a contour map for theCefn Deuddwr site. An input file for the River2D simulation is being prepared by definition of the model boundary, input flow rates for the rivers Mawddach and Eden, and outlet river stage height.

Surface roughness values for the models were determined accurately by Jerome O'Connell by measuring the diameters of trees within sample plots of the survey areas. Vegetation density values were obtained using the relation:

$$Veg_d = \frac{\sum n_i d_i}{wl}$$

where	Veg_d	vegetation density
	n	number of trees within a trunk diameter range
	d	mean of trunk diameter range
	w	width of sample plot
	l	length of sample plot

Manning roughness was computed from the formulae of Arcement and Schneider (2003):

$$n = n_0 \sqrt{\left(1 + Veg_d \cdot C^*\right)\left(\frac{1}{n_0}\right)^2 \left(\frac{1}{wlR}\right) h^{4/3}}$$

where	n_0	boundary roughness
	C^*	effective drag coefficient
	R	hydraulic radius, equal to water depth on the floodplain

The boundary roughness n_0 is obtained from tables, and allows for various descriptive hydrological characteristics of the flood plain including: the basal soil, surface irregularities, ground vegetation, sinuosity of the flood plain and obstructions present. The effective drag coefficient C^* is obtained from the graph of fig.3.143.

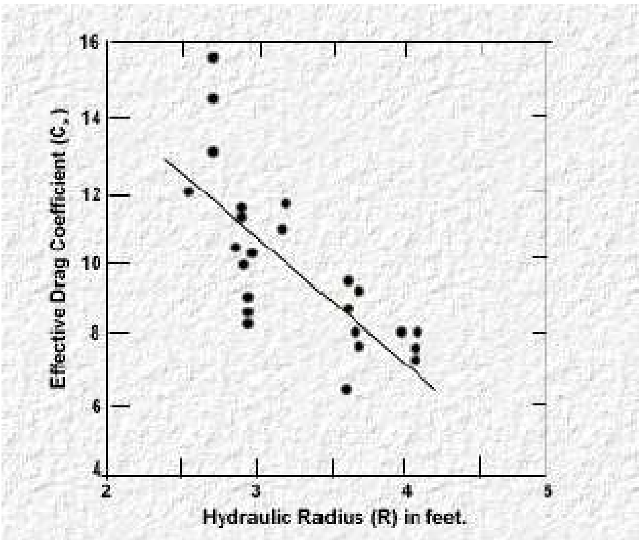


Figure 3.143:
Graph for estimation of effective drag coefficient for wide flood plains. The plotted points have been obtained by analysis of flood events with known values of Manning's roughness coefficient n.

Manning roughness values computed by O'Connell for the forestry sites are shown in table 3.6:

Site	Sample plot	Manning n
Tyddyn Gwladys	A	0.146
	B	0.163
	C	0.049
	D	0.061
	upper river channel	0.058
	lower river channel	0.072
Cefn Deuddwr	A	0.065
	B	0.101
	C	0.147
	D	0.130
	Mawddach gorge channel	0.08
	Afon Eden channel	0.07
	Lower Mawddach channel	0.039

Table 3.6. Computed values of Manning roughness coefficient n for the case study forestry sites. Locations of sample plots are shown in figures 3.144 - 3.145.

Manning roughness values were converted to roughness heights for entry into the River2D model, as shown in figs 3.144 - 3.145. The model input files were completed by defining the model boundary, river flow and stage heights.

Positions of maximum water levels during the July 2001 flood event were plotted on the contour maps of the two forestry sites before running the simulations. Steady state simulations were carried out with the water flow on the Afon Mawddach set to the flood hydrograph maximum recorded by the Tyddyn Gwladys gauging station. Additionally, the flow on the Afon Eden at Cefn Deuddwr was set to the maximum of the synthetic flood hydrograph generated by the HEC-1 model.

The model uses the eddy viscosity coefficient ν_t to simulate turbulent shear stresses according to the relation

$$\tau_{xy} = \nu_t \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right)$$

where τ_{xy} transverse turbulent shear stress

U, V velocity components in x and y directions respectively

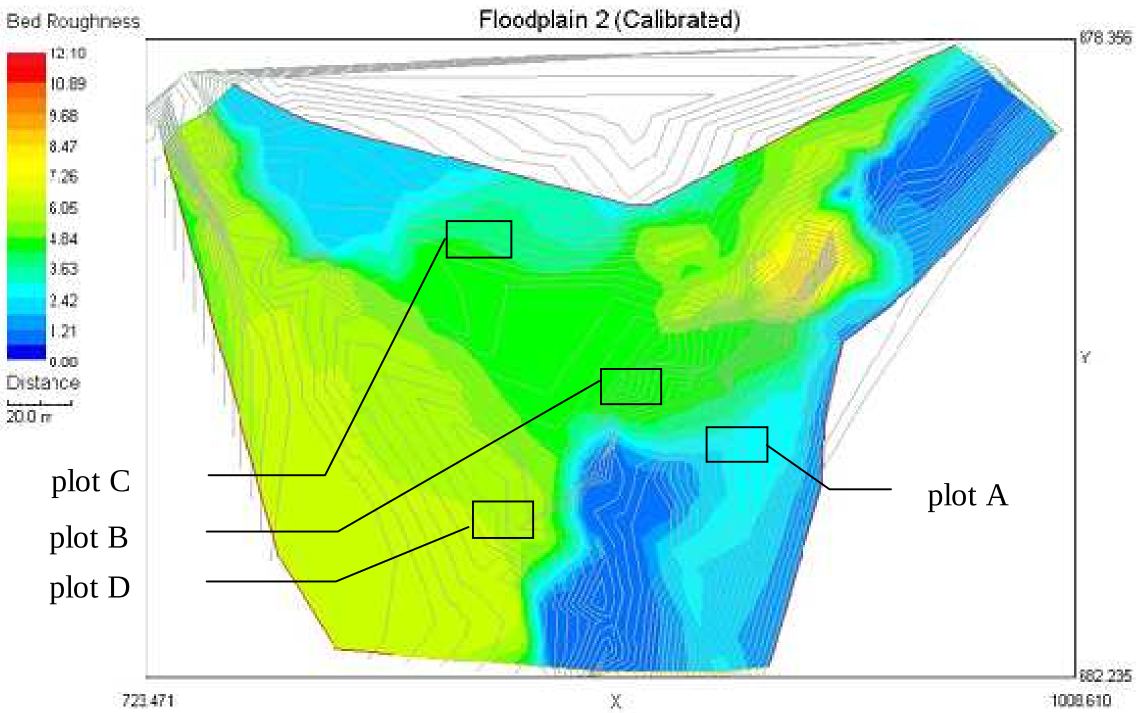


Figure 3.144: Roughness height calibration for the Cefn Deuddwr floodplain (after O'Connell, 2004)

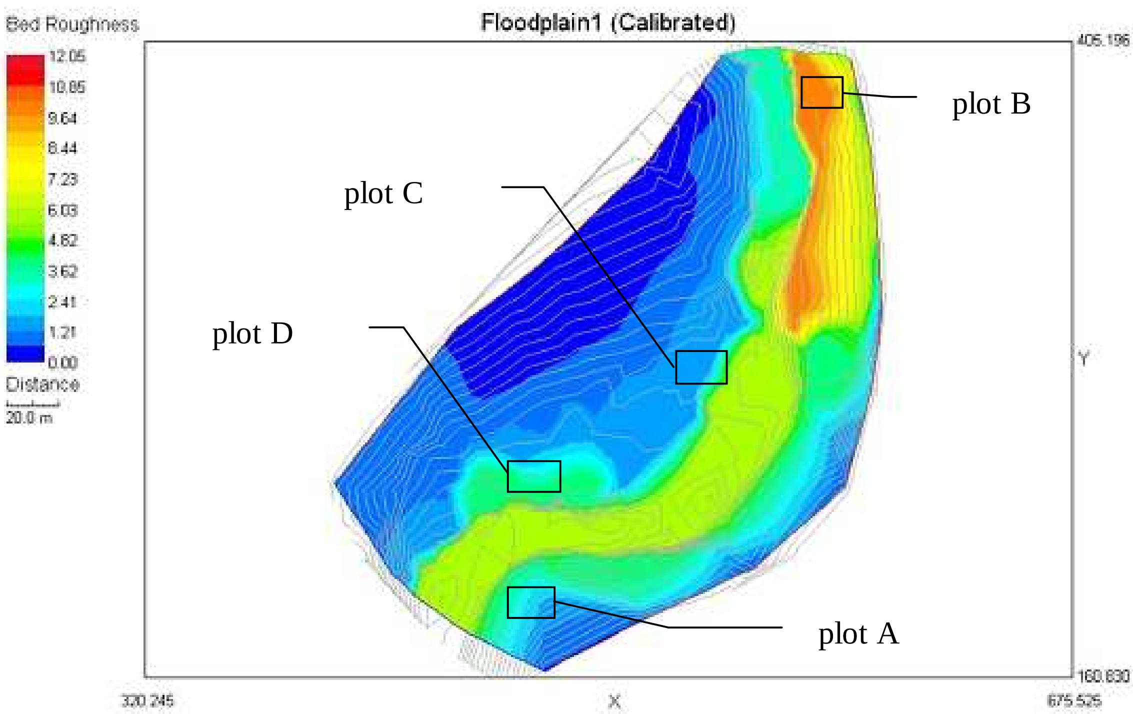


Figure 3.145: Roughness height calibration for the Tyddyn Gwladys floodplain (after O'Connell, 2004)

The eddy viscosity coefficient is made up of three components

$$v_t = \varepsilon_1 + \varepsilon_2 \frac{H\sqrt{U^2+V^2}}{C_s} + \varepsilon_3^2 H^2 \sqrt{2\frac{\partial U}{\partial x} + \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right)^2 + 2\frac{\partial V}{\partial y}}$$

where	H	flow depth
	C_s	Chezy coefficient related to roughness height and depth of flow

The ε_1 term is a constant, and the ε_2 term represents a bed shear. The default value for ε_1 is 0, and for ε_2 is 0.5. The key variable is the ε_3 term, representing transverse shear which will be high for water flows through dense, tall vegetation but low for unimpeded flows across grassland.

The eddy viscosity coefficient ε_3 was systematically adjusted to obtain a best fit between the peak water levels recorded in the field and the water boundaries of the models. Results of low flow and peak flows for the July 2001 event are shown in figs 3.146 – 3.147.

Best fit values obtained for ε_3 were:

Tyddyn Gwladys floodplain	1.20
Cefn Deuddwr floodplain	1.35

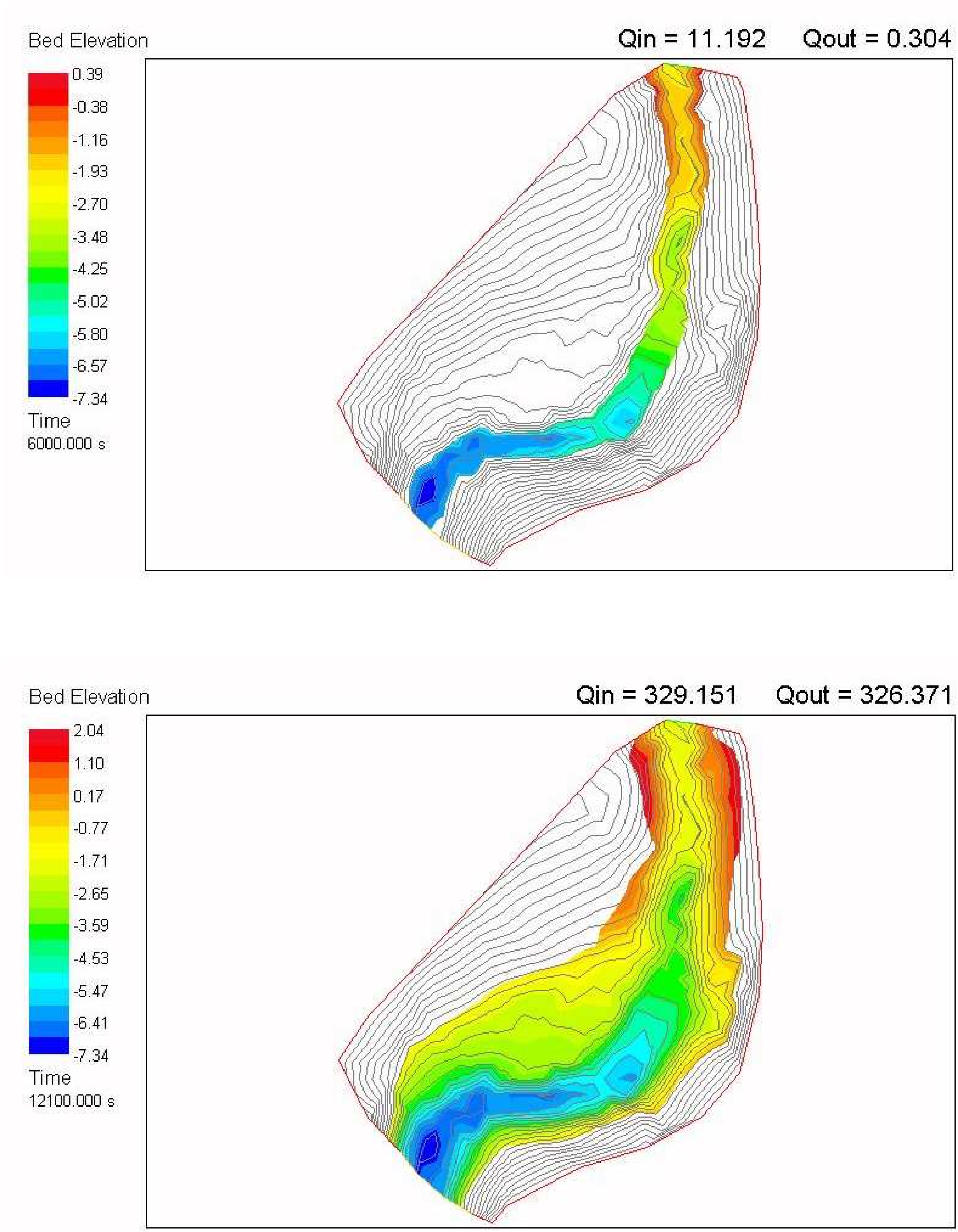
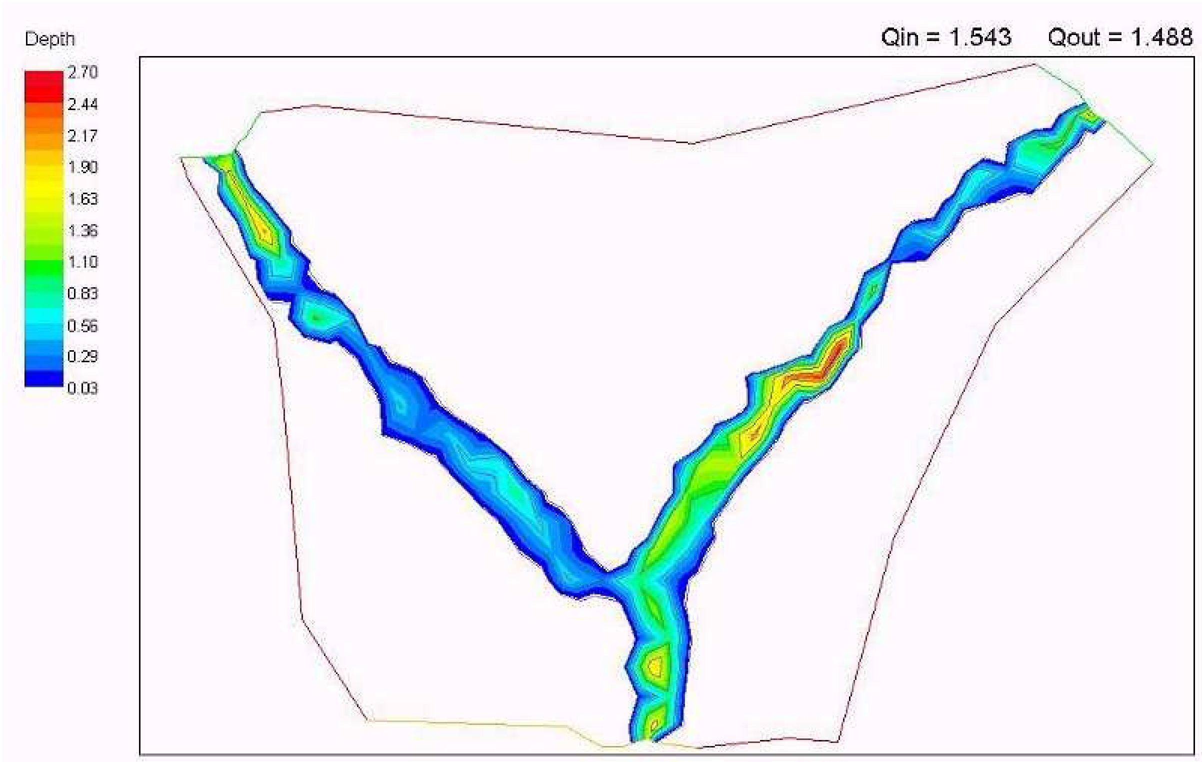


Figure 3.146: River2D models for the Tyddyn Gwladys forestry site.

(above) low flow conditions

(below) best fit to field evidence of the maximum extent of the 3 July 2001 flood



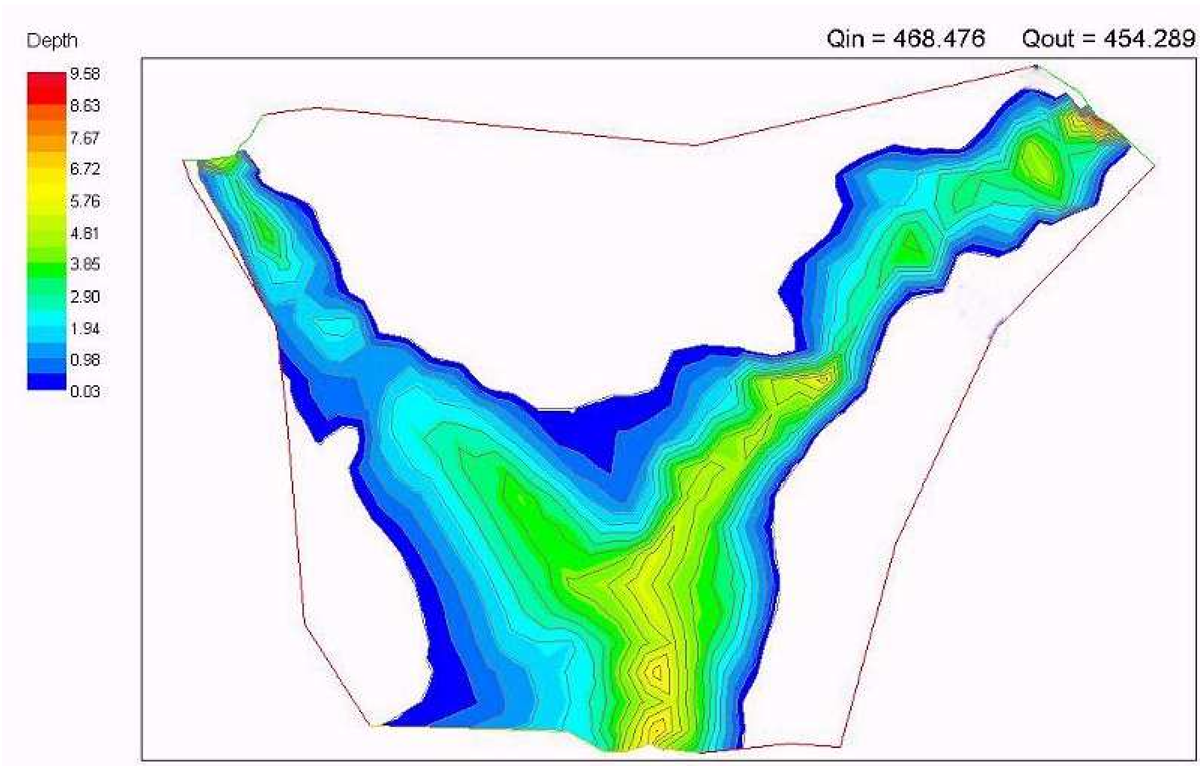


Figure 3.147: River2D models for the Cefn Deuddwr forestry site.

(above) low flow conditions

(below) best fit to field evidence of the maximum extent of the 3 July 2001 flood

Simulation of floodplain forestry schemes for the Wnion valley

Flooding of Dolgellau can occur due to peak flows on the Afon Wnion overtopping or circumventing the flood defence walls and embankments on the northern edges of the town. Reduction in flood risk could be achieved by various possible strategies:

- increasing the effectiveness of the flood defences by engineering works such as construction of walls and embankments,
- increase in channel capacity by a combination of sediment deposition control and gravel removal,
- measures to limit the peak flood levels on the river by management of the catchment upstream.

Hard engineering works have the disadvantages of being costly and environmentally intrusive within a historic town. Sediment control has been discussed in section 3.3. The current section focuses on options for limiting flood peak flows by catchment management upstream, using a combination of flood interception basins and floodplain forestry schemes in the lower Wnion valley.

Computer modelling has been used in various studies to evaluate the hydrological effects of changing land management within floodplains. An interesting example is the study of Lower Deer Creek, California by MacWilliams, Street and Kitanidis (2004). The floodplain modelled is geographically similar to the Wnion valley between Bontnewydd and Dolgellau and the river is of a similar size. The Deer Creek model examined a proposed scheme to breach river embankments and allow natural flood channels to develop across the flood plain, whilst allowing wet woodland to regenerate. Definite advantages were identified, in terms of flood control, nature conservation and fish habitat improvement. MacWilliams et al. used a flood modelling program similar to River2D in their work.

The lower Wnion valley can be separated into upper and lower floodplain basins, divided by a gentle step in the valley floor with increased river gradient in the vicinity of the confluence of the Afon Clyweddog and the Afon Wnion. The upper and lower floodplain basins are indicated on the Environment Agency flood map of the Wnion valley (fig.3.148).

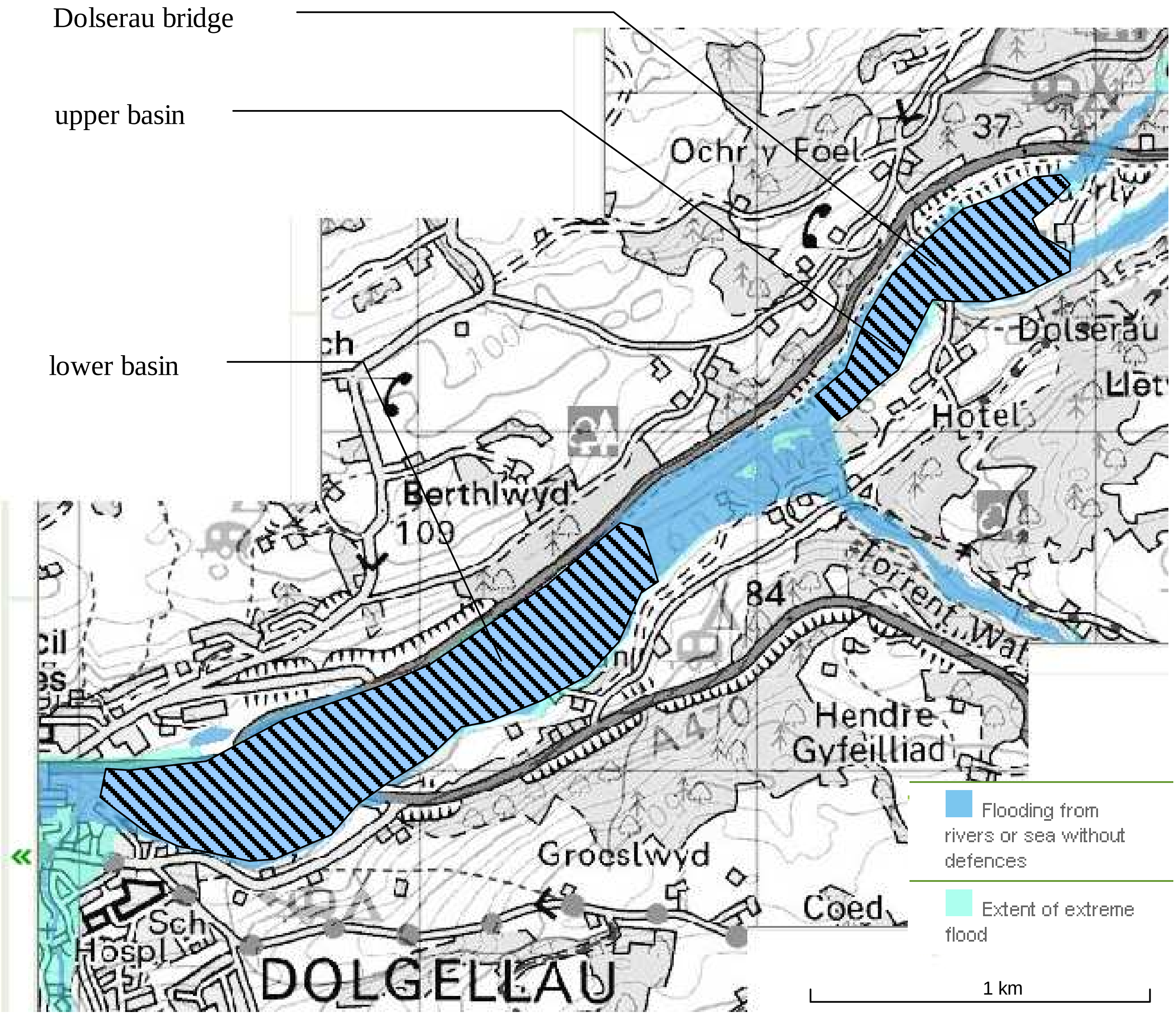


Figure 3.148: Environment Agency flood map for the lower Wnion valley between Bontnewydd and Dolgellau

This section will examine options for flood interception within either the upper or lower basins of the floodplain. In each case, two scenarios will be modelled using the River2D program:

1. Flood water interception under current channel configuration,
2. Flood water interception by increasing the extent of overbank discharge through the construction of weirs to raise the channel base level at the basin outlet, with the addition of flood plain forestry to enhance temporary water storage within the floodplain basin.

Modelling of flooding for the town of Dolgellau assumed a steady river flow. In the current case, a large potential rate of interception of floodwater onto the flood plain must be taken into account when determining the downstream flow leaving the lower Wnion reaches on route to Dolgellau. A lag time is anticipated between flood peaks entering and leaving the section. A transient model will be used, with a storm hydrograph determining the input time sequence for the Afon Wnion. The flash flood event of 3 July 2001 is used as a test case.

The upper basin

The upper basin extends downstream for a distance of 0.5km from the weir at Dolserau bridge and includes low lying land upstream of the bridge. The Afon Wnion is incised into the alluvial floodplain to a depth of approximately 2m. Evidence of flood debris accumulated against the bridge after the February 2004 event provides an approximate maximum July 2001 flood height for use in validating the model.

Figure 3.149: Upper floodplain basin, Afon Wnion, south-west of Dolserau bridge.
(above) improved grassland land on the floodplain
(below) the river incised into the floodplain to a

(left) Figure 3.150(a)

Low lying fields within the Wnion floodplain upstream from Dolserau bridge

(right) Figure 3.150(b) Shallow stream draining the floodplain shown above. This stream has its confluence with the Afon Wnion at Dolserau bridge

(left) Figure 3.151(a) Afon Wnion at Dolserau bridge. View downstream, showing flood debris from the *3-4 February 2004 storm accumulated against the bridge pier and girders*

(right) Figure 3.151(b) *View upstream, showing the weir below the bridge.*

The lower floodplain basin

The lower floodplain is larger in extent than the upper floodplain, extending for a distance of 1.5km downstream from the confluence of the Wnion with the Afon Clyweddog, and reaching the outskirts of the town of Dolgellau. The floodplain is utilised for animal grazing and silage production. The river is incised into the floodplain to a depth of approximately 2.5m (fig.3.152).

Floodplain modelling

Lower basin

A River2D model was run using the current topography of the lower basin, with a transient inflow sequence corresponding to the hydrograph recorded on the Afon Wnion in Dolgellau for the flood event of 3 July 2001.

> Low flow conditions prior to the flood event are shown in fig.3.153.
>
> The maximum extent of flooding within the lower basin is shown in fig.3.154. The river is confined within the incised channel over most of the reach, with limited overbank flooding onto low lying fields between the Wnion viaduct and Bont Fawr, Dolgellau.
>
> River depth and flow velocity are shown in fig.3.155 at a stage on the rising limb of the inflow hydrograph close to maximum river flow.

Figure 3.152: Lower floodplain basin, Afon Wnion. (above) view north-east from the A470 viaduct across improved grassland *(left) the river incised into the floodplain to a depth of approximately 2.5m, (below) continuation of the lower floodplain basin to the*

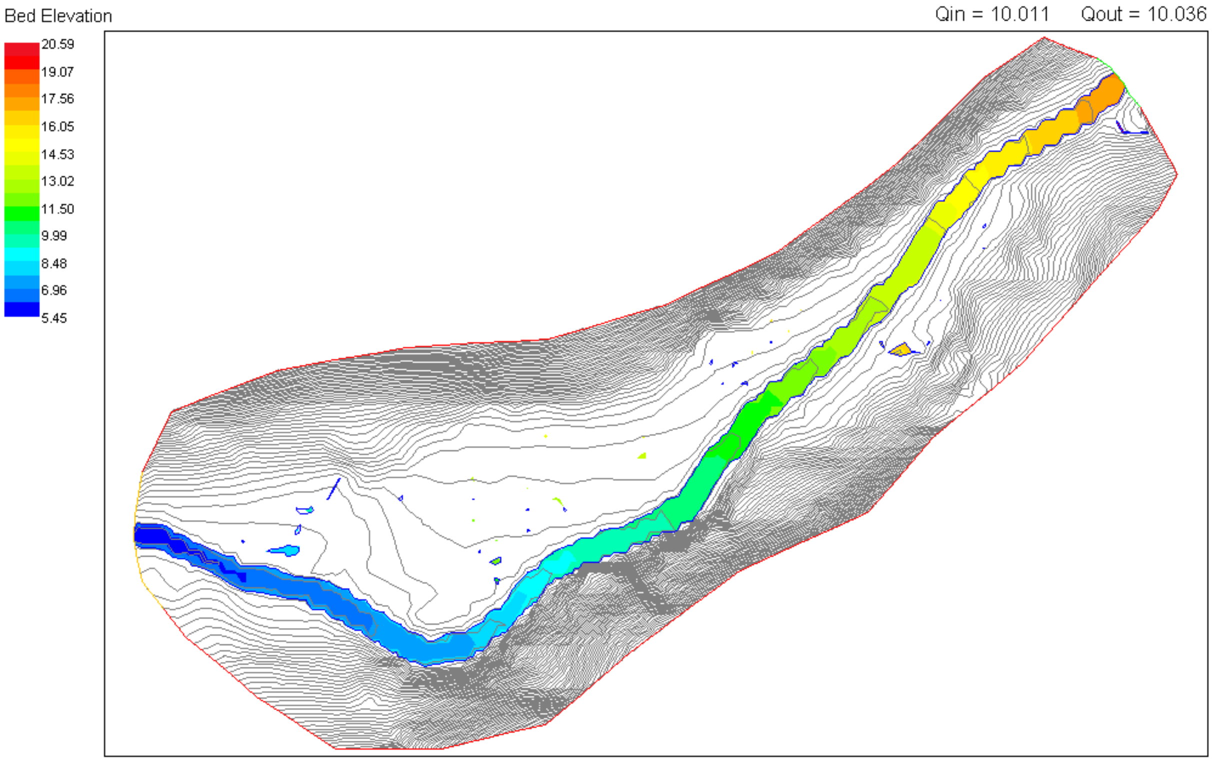


Figure 3.153: Low flow conditions for the Afon Wnion lower basin

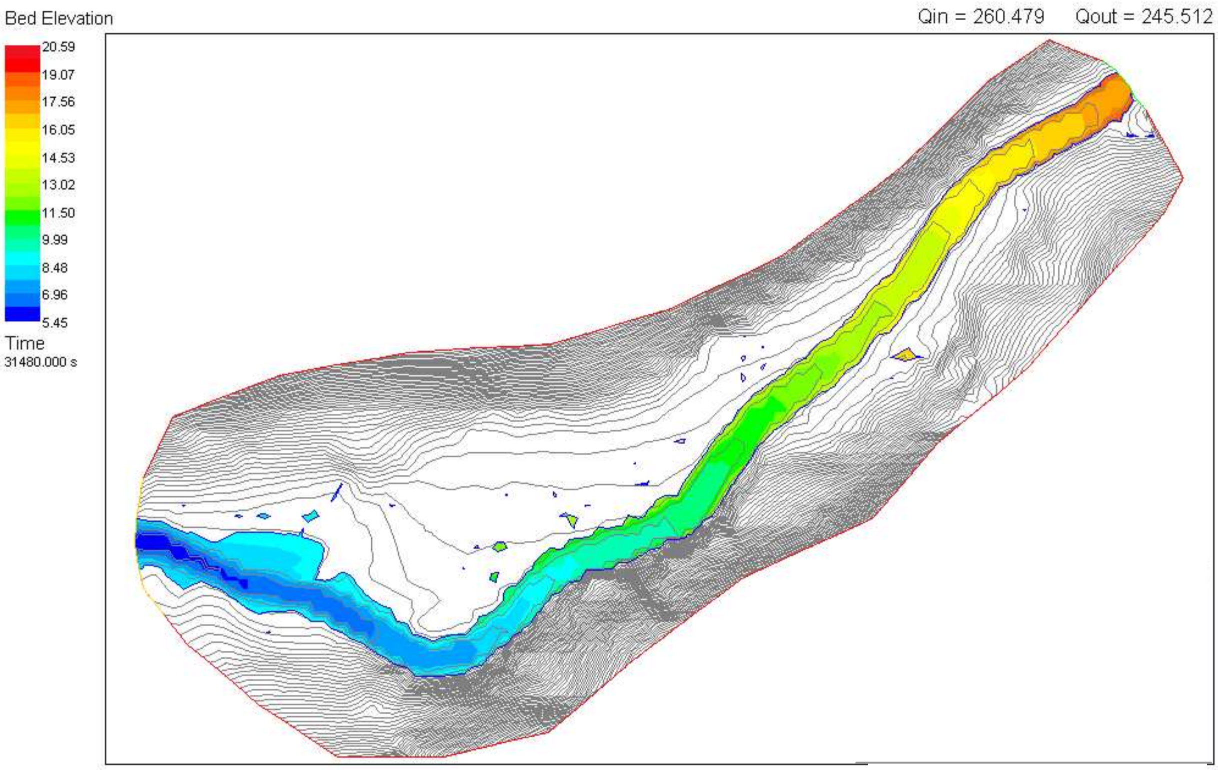


Figure 3.154: Maximum extent of flooding in the Afon Wnion lower basin during the 3 July 2001 storm event

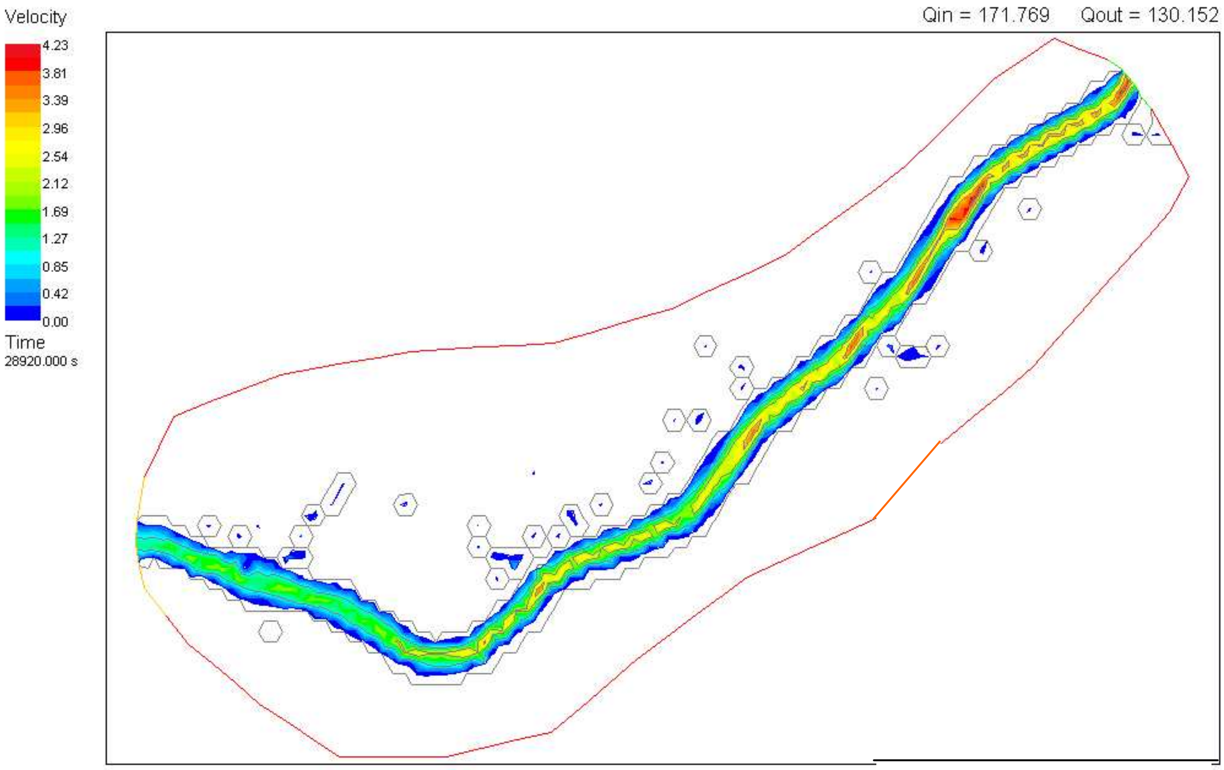


Figure 3.155(a). Afon Wnion: water velocity (m/s), close to maximum flow during the rising stage of the 3 July 2001 storm event

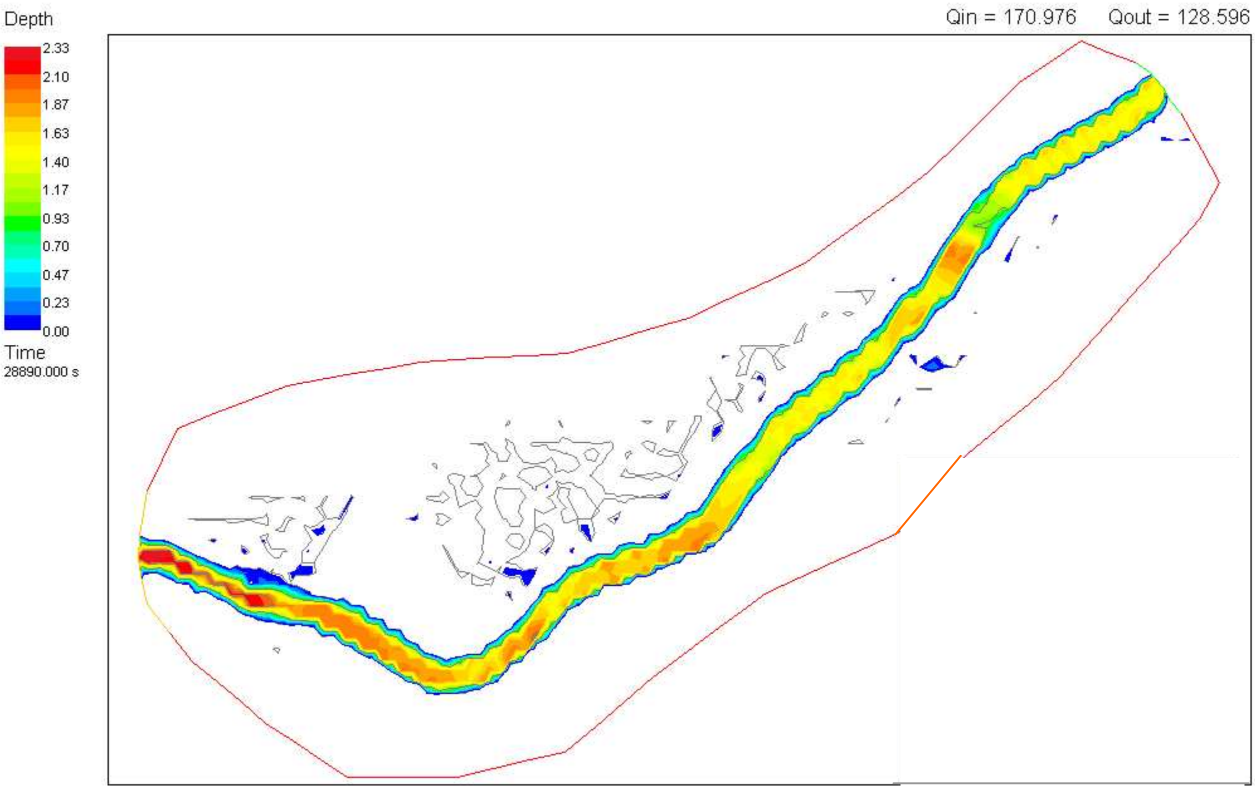
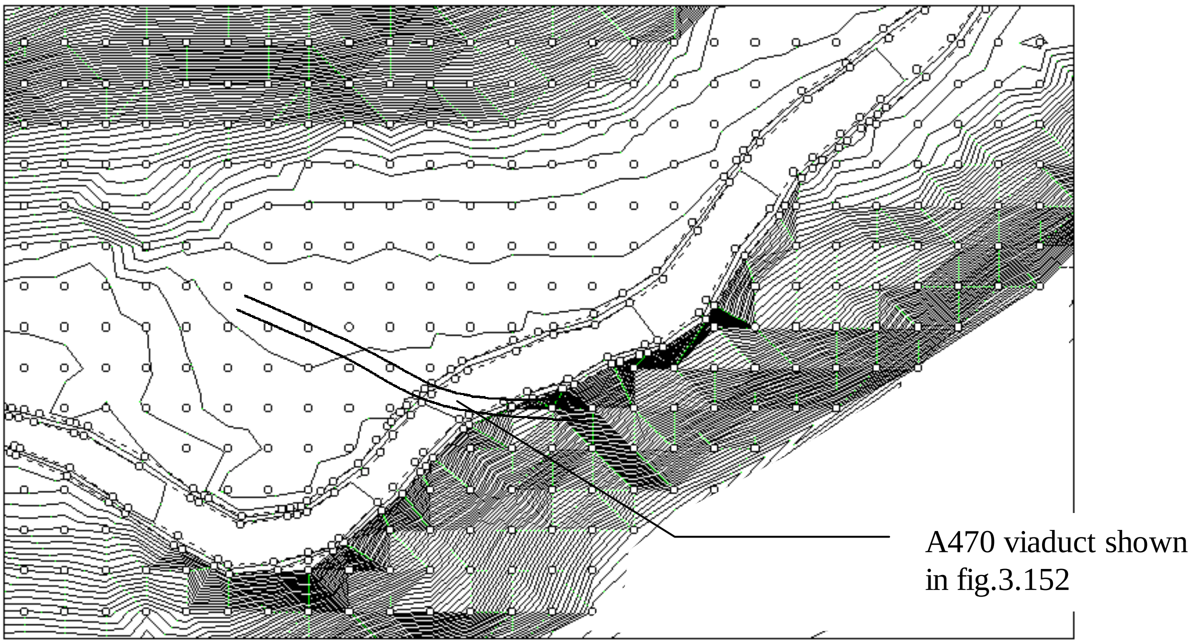


Figure 3.155(b). Afon Wnion: water depth (m), close to maximum flow during the rising stage of the 3 July 2001 storm event

In the next model, a weir has been introduced close to the Wnion viaduct (fig. 3.156). This structure raises the upstream channel bed elevation by 2m. The bank elevations have also been raised by 1m to maintain an incised channel whilst reducing the elevation difference with the main area of the valley floor. The floodplain is modelled as wet woodland, with roughness height and eddy viscosity adjusted accordingly.



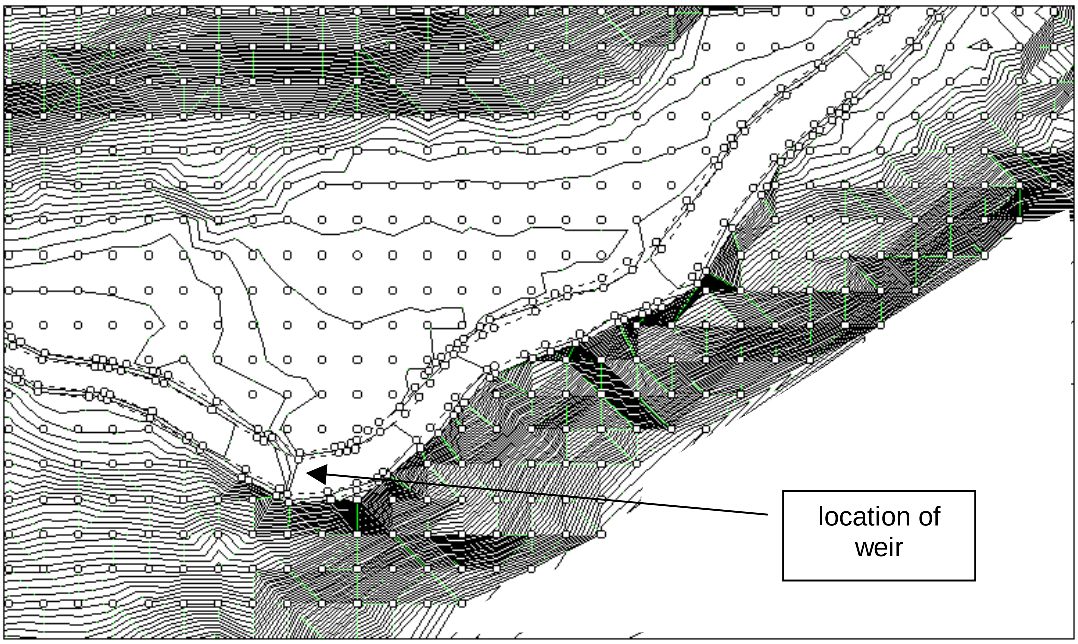


Figure 3.156 (above) Topographic model for the Wnion lower floodplain basin under current channel conditions, (below) after introduction of a 2m weir close to the Wnion viaduct.

Simulation of the 3 July 2001 storm event was carried out for the weir and flood interception basin model:

Under slightly increased flow conditions, the floodplain woodland upstream of the weir begins to receive overbank flow from the Afon Wnion (fig.3.157).

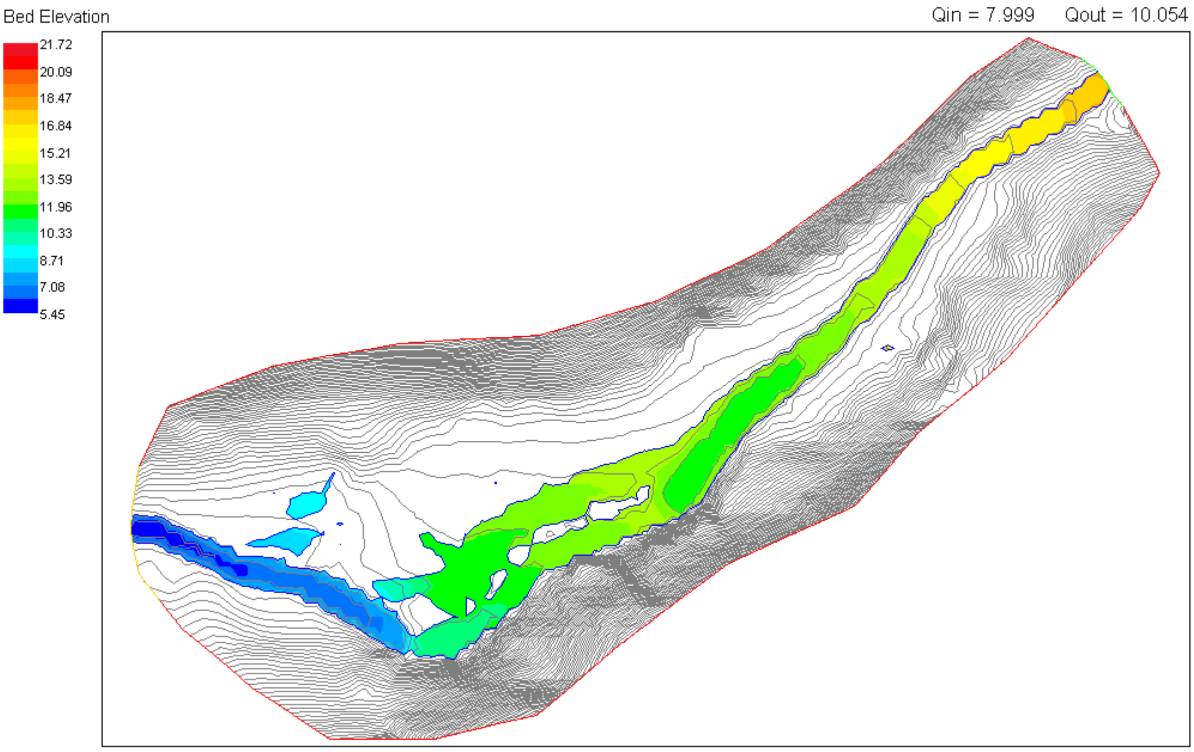


Figure 3.157: Afon Wnion lower floodplain: simulation of weir and flood interception basin under slightly increased flow conditions.

Fig.3.158 shows conditions during the rising limb of the flood hydrograph. Water is progressively diverted into the floodplain woodland, reaching depths over 1.5m, although flow velocity within the woodland remains below 1m/s. Water flow leaving the woodland returns to the main channel of the Wnion downstream of the weir.

The maximum extent of flooding is shown in fig.3.159, and may be compared with the current flow model of fig.3.154.

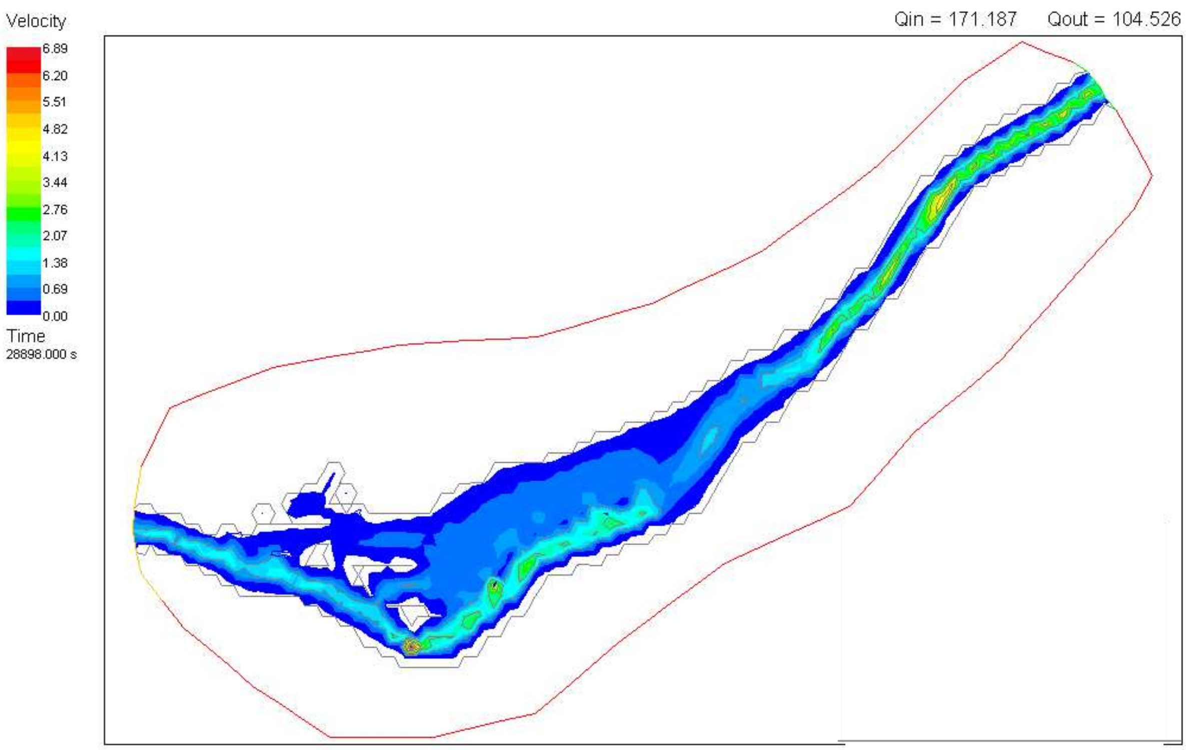


Figure 3.158(a). Afon Wnion: water velocity (m/s), close to maximum flow during the rising stage of the 3 July 2001 storm event

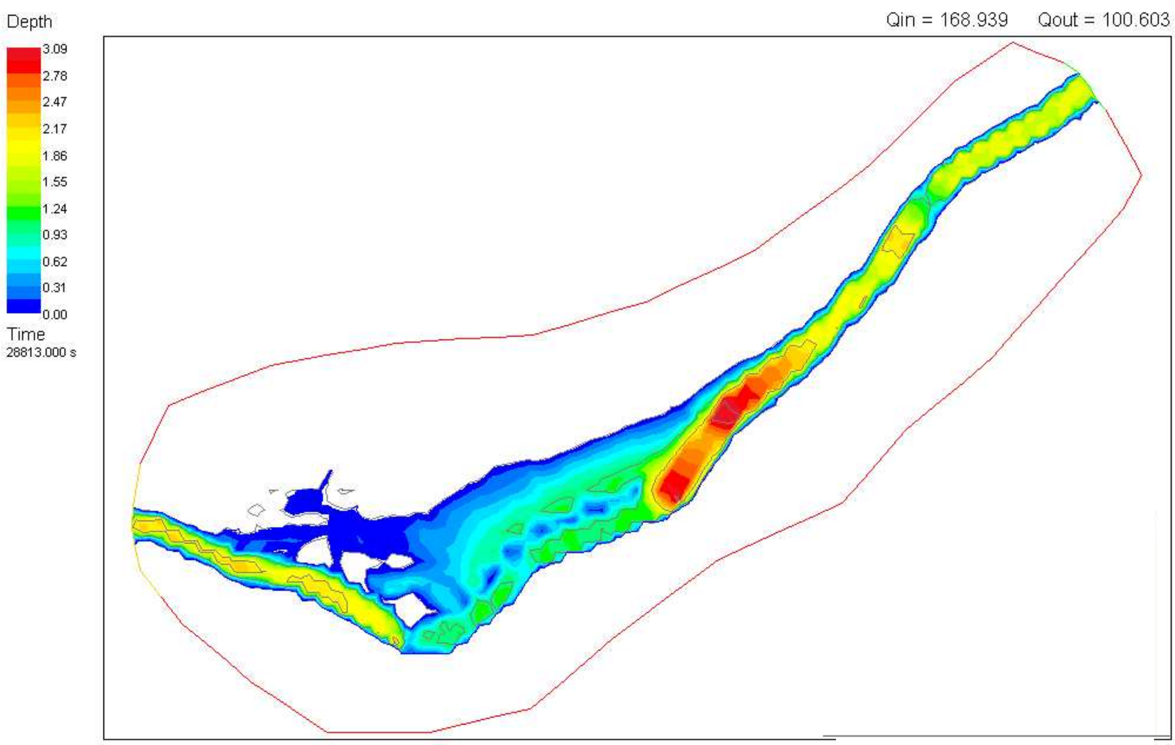


Figure 3.158(b). Afon Wnion: water depth (m), close to maximum flow during the rising stage of the 3 July 2001 storm event

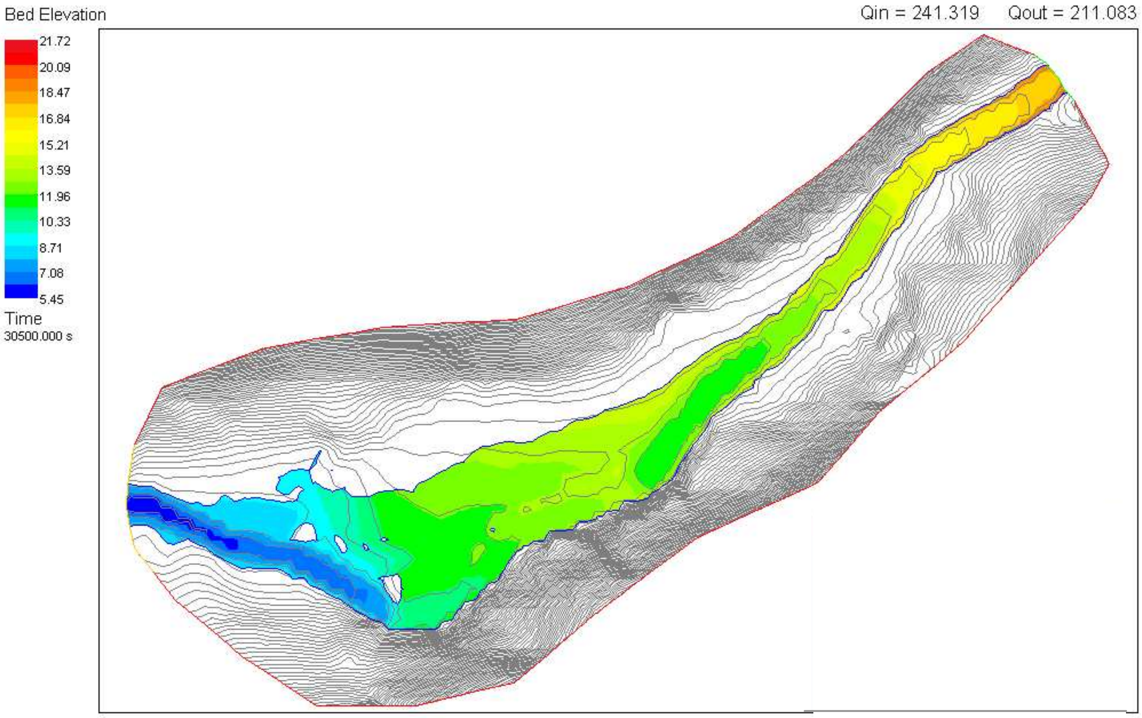


Figure 3.159: Maximum extent of flooding for the Afon Wnion lower basin with weir scheme: 3 July 2001 storm event

Upper floodplain

The River2D model was run for the upper basin with current topography, again using the inflow Dolgellau hydrograph for the flood event of 3 July 2001.

The maximum extent of flooding within the upper basin is shown in fig.3.160. The river is confined within the incised channel over most of the reach, with limited overbank flooding upstream of Dolserau bridge. Some ponding is taking place within the low lying fields to the north east of the river meander.

River depth and flow velocity are shown in fig.3.161 at a stage on the rising limb of the inflow hydrograph close to maximum river flow. Water flow velocity outside the main channel is low, and ponding on the floodplain generally has a depth of less than 0.5m.

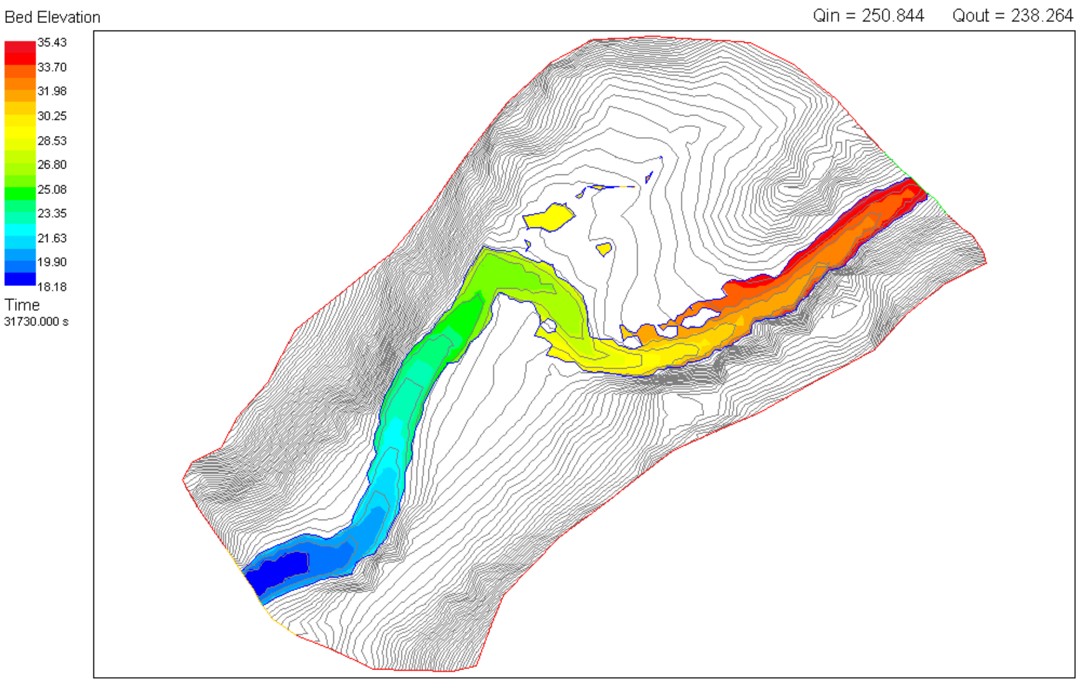


Figure 3.160: Afon Wnion upper floodplain: extent of flooding during the 3 July 2001 storm event

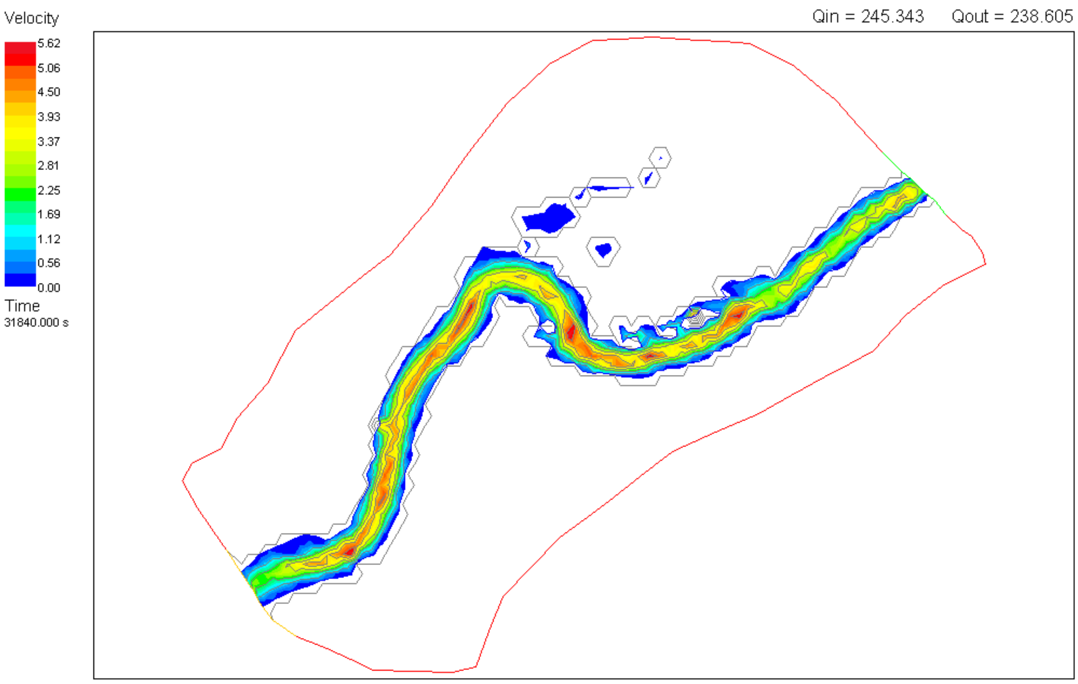


Figure 3.161(a). Afon Wnion upper basin: water velocity (m/s), close to maximum flow during the rising stage of the 3 July 2001 storm event

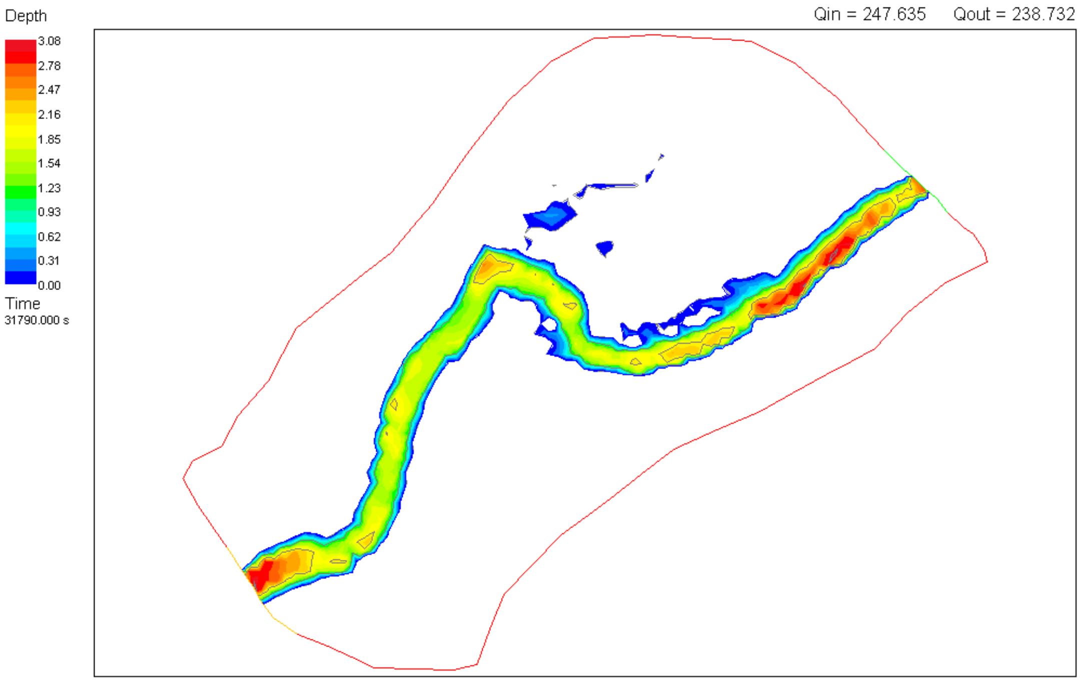
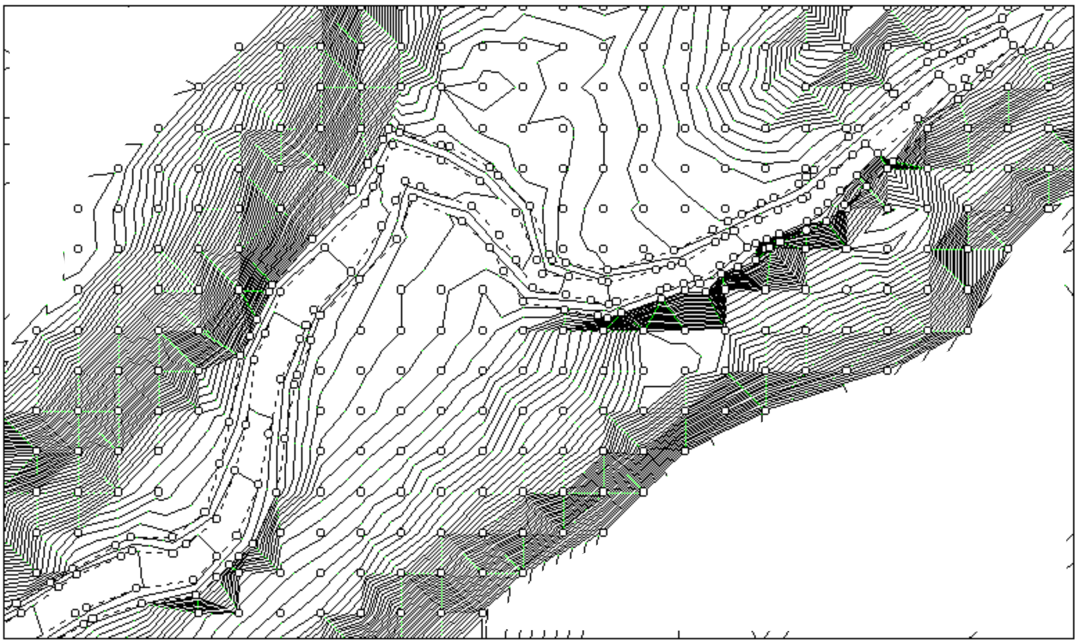


Figure 3.161(b). Afon Wnion upper basin: water depth (m), close to maximum flow during the rising stage of the 3 July 2001 storm event

The model was then run with a weir introduced at the downstream closure of the floodplain (fig.3.162). As for the Wnion lower basin model, this structure raises the channel bed elevation by 2m. Bank elevations have also been raised by 1m to maintain an incised channel. The floodplains to the south and north of the river meander are both modelled as wet woodland, with roughness height and eddy viscosity adjusted accordingly.

The maximum extent of flooding during the flood event of 3 July 2001 is shown in fig.3.163. Extensive overbank discharge has occurred both to the south and to the north of the river meander.

River depth and flow velocity are shown in fig.3.164 at a stage on the rising limb of the inflow hydrograph close to maximum river flow. Deep ponding has occurred to the north of the river, with little water movement evident. To the south of the river there is a significant water flow through the woodland to rejoin the Afon Wnion downstream of the meander.



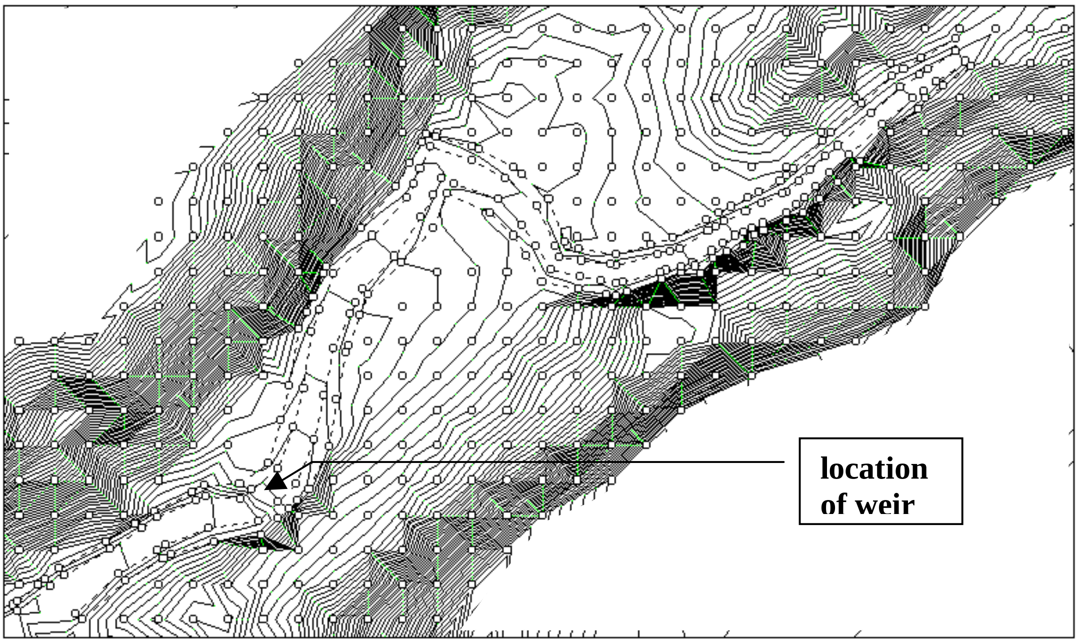


Figure 3.162(above) Topographic model for the Wnion upper floodplain basin under current channel conditions, (below) after introduction of a 2m weir at the downstream closure of the floodplain basin.

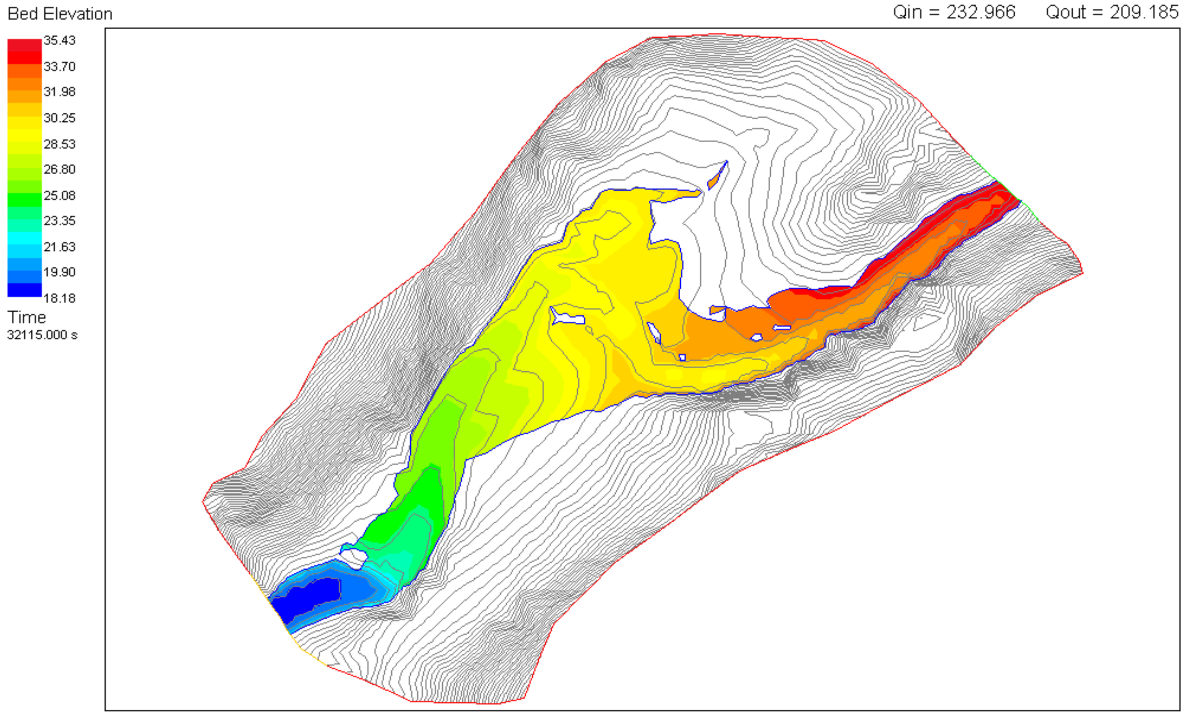


Figure 3.163: Maximum extent of flooding for the Afon Wnion upper basin with weir scheme: 3 July 2001 storm event

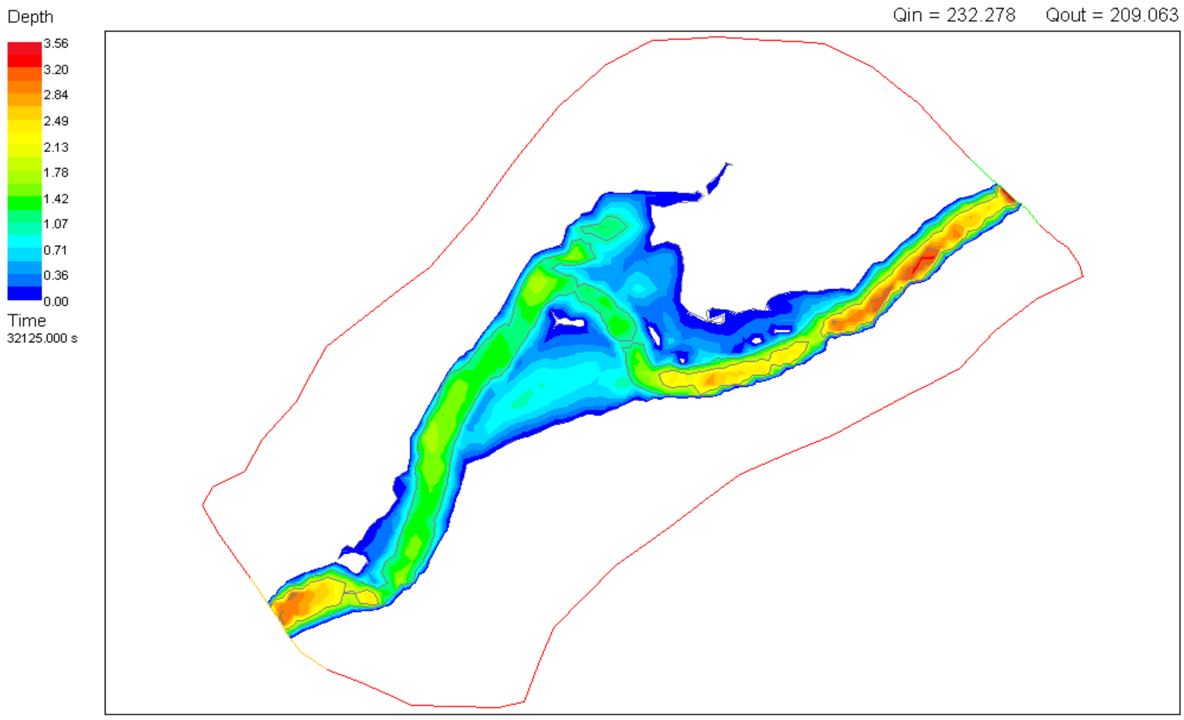


Figure 3.164(a). Afon Wnion: water depth (m), close to maximum flow during the rising stage of the 3 July 2001 storm event

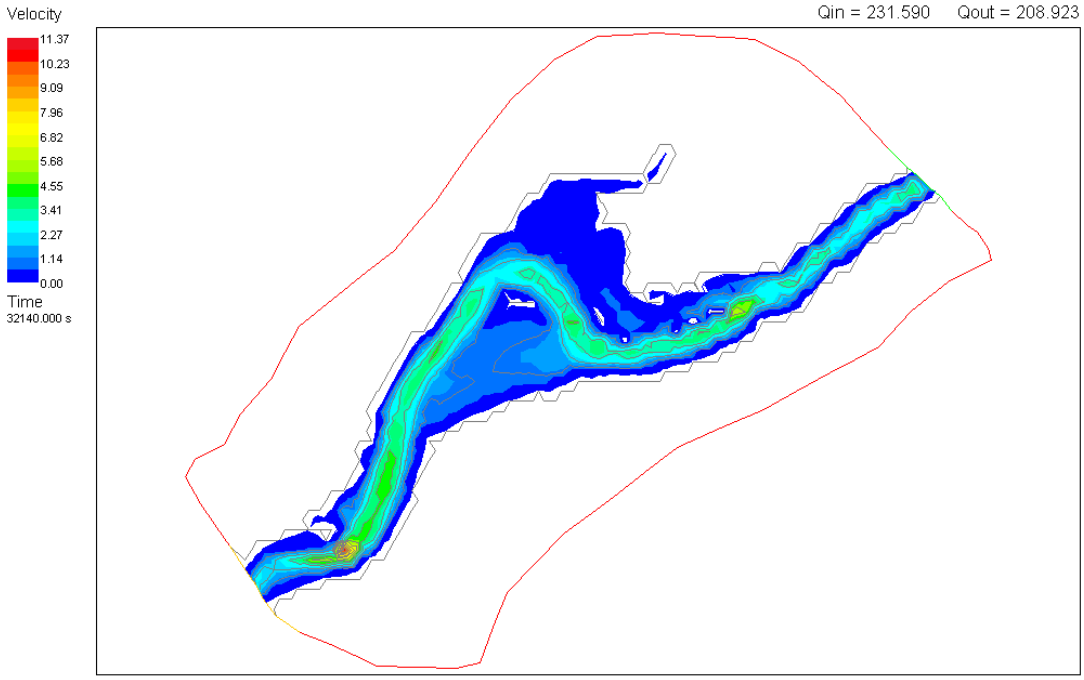


Figure 3.164(b). Afon Wnion: water velocity (m/s), close to maximum flow during the rising stage of the 3 July 2001 storm event

Flow data for the Wnion flood basin models

Input and output hydrographs for the lower basin models are given in fig.3.165, and for the upper basin models in fig.3.166.

Lower basin

Under current channel conditions, the hydrograph peak is delayed by approximately 11 minutes by passage through the reach. A slight reduction in peak flow from 260.9 m^3/s to 257.8 m^3/s is produced, probably as a result of temporary storage of flood water on low lying land to the east of the town.

The effect of the weir and flood interception scheme is to delay the arrival of the flood peak by an additional 6 minutes, but only a very slight further reduction in flood peak flow of 0.8 m^3/s is observed. This rather surprising result may be due to the initial filling of all available storage within the floodplain forestry area, so that the peak flow is directed mainly through the main channel. Any additional flow into the woodland appears to displace an equivalent amount of water back into the Wnion downstream.

Upper basin

The upper basin has a significant effect in delaying and reducing the flood peak under current channel conditions. This appears to be due to temporary storage of flood water in the low lying fields to the north of the main channel. Water diverted into this basin is held until the river level falls, before returning to the main channel. An alternative outflow route is only available for the section of the basin downstream of Dolserau bridge.

Flood peak reduction can be considerably enhanced by raising the channel level through construction of a weir, and by the planting of floodplain woodland within the interception basin. Hydrological effects will be dominantly due to the weir construction, but floodplain woodland will play a significant role in enhancing temporary water storage capacity in the flood interception basin during storm events.

The conclusion of the modelling is that development of a weir and floodplain forestry scheme for the Wnion upper floodplain basin around Dolserau bridge would have considerable benefits in reducing flash-flood peaks downstream in the town of Dolgellau. It appears that a similar scheme for the lower floodplain would have negligible benefits for flood control, and would not be worth undertaking.

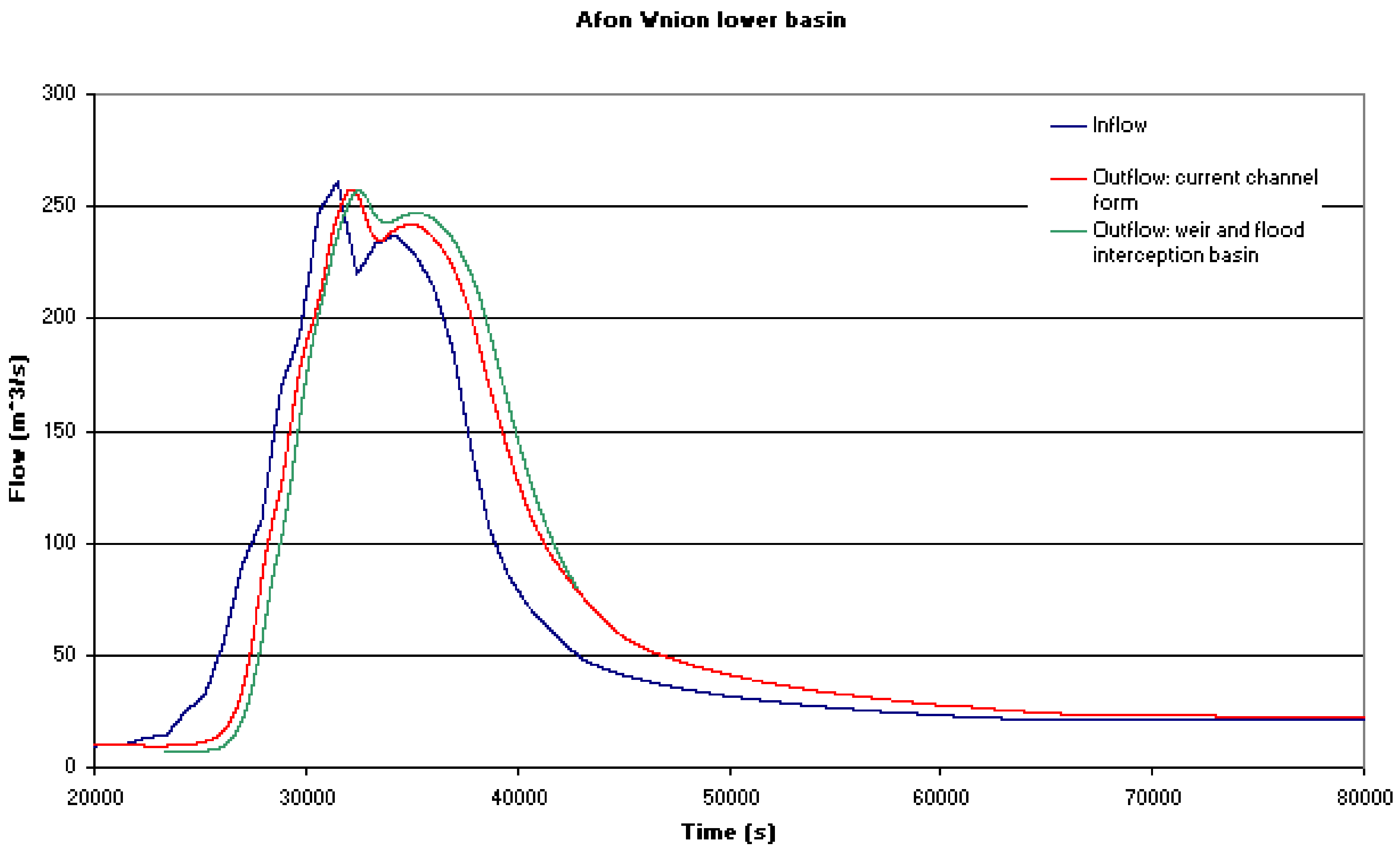


Figure 3.165: Inflow and outflow hydrographs for the Afon Wnion lower floodplain models, 3 July 2001 storm event

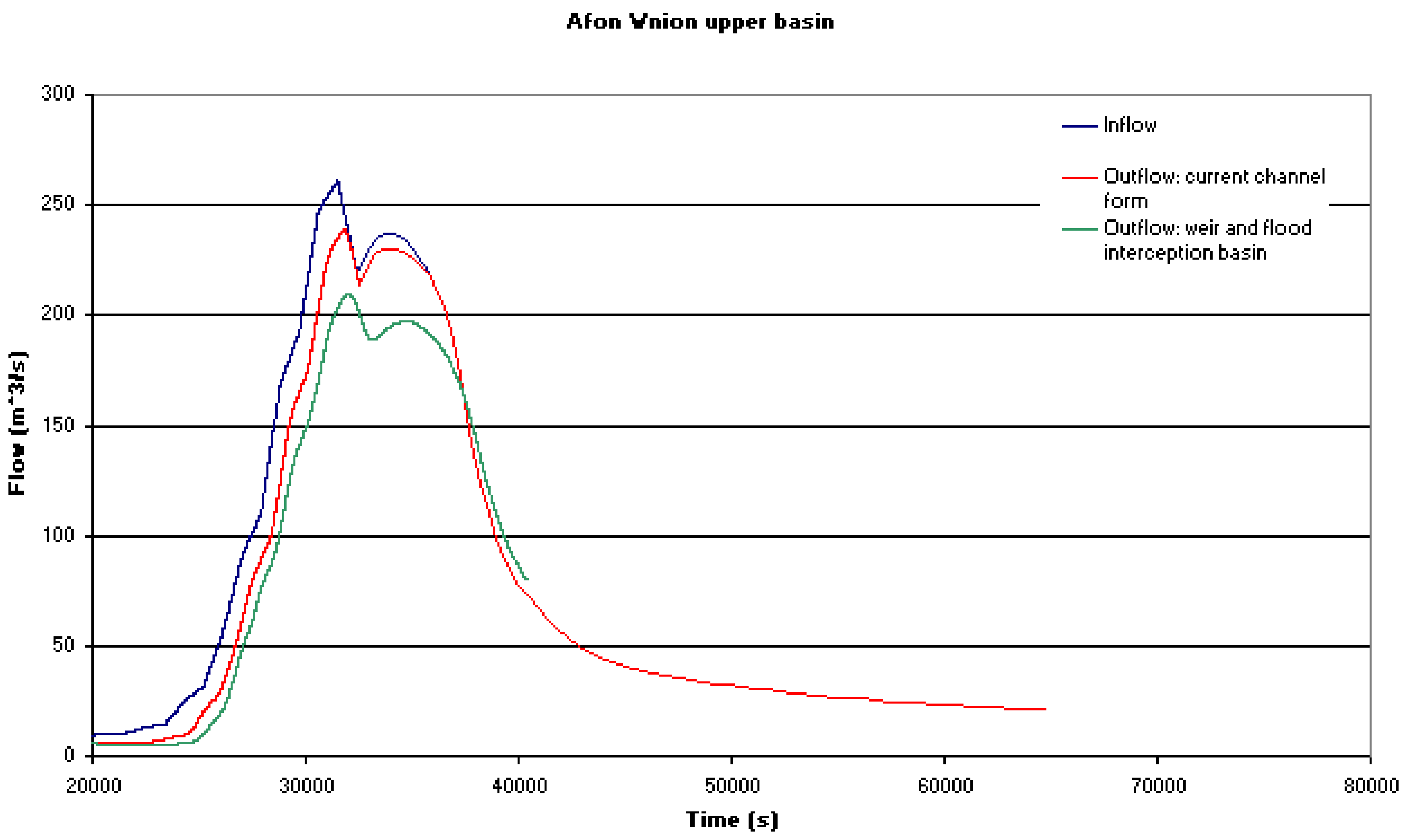


Figure 3.166: Inflow and outflow hydrographs for the Afon Wnion upper floodplain models, 3 July 2001 storm event

River-groundwater interactions

An objective of the Mawddach project is to construct a realistic computer model for hydrological processes in the catchment. The model should include those processes having a significant impact on flooding, whilst omitting processes which have a negligible effect within the time scale of a sequence of closely spaced flood events. This simplification is desirable so that the model can be run with maximum efficiency in the short time window necessary for local flood prediction.

In constructing a hydrological model for the Mawddach catchment, three hillslope process categories may be considered:

- surface runoff
- shallow throughflow in superficial deposits
- deep flow in bedrock

These processes will operate on different time scales following the initiation of storm rainfall.

A conceptual model for the steep hillslopes of the Mawddach catchment in Coed y Brenin is presented in fig.3.167. It is assumed that vertical drainage is the initial process operating within the sequence of superficial deposits, but downslope flow becomes increasingly significant under conditions of high rainfall input when the maximum infiltration rate to the underlying bedrock is exceeded.

The importance of shallow stormflow was demonstrated in previous sections. Hillslope throughflow measurements at Pared yr Ychain (fig.3.42) indicate that very substantial flow is possible through the sandy Boulder Clay derived from acid igneous rocks at that location.

In the deep river valleys of Coed y Brenin, the bedrock is overlain by thick periglacial deposits (cf. fig.1.50) dominated by sand and gravel horizons of high permeability . Results of throughflow measurements at Tir Penrhos (fig.3.44) indicate a strong correlation between high rates of shallow subsurface throughflow on hillslopes and flooding some 5km downstream in the lower Mawddach valley. Flooding generally occurs after a period of several days of heavy rainfall which saturates much of the sequence of superficial deposits. It is concluded that at times of flooding, substantial shallow throughflow into rivers is occurring, and is augmented by expanded areas of direct surface runoff from saturated superficial deposits.

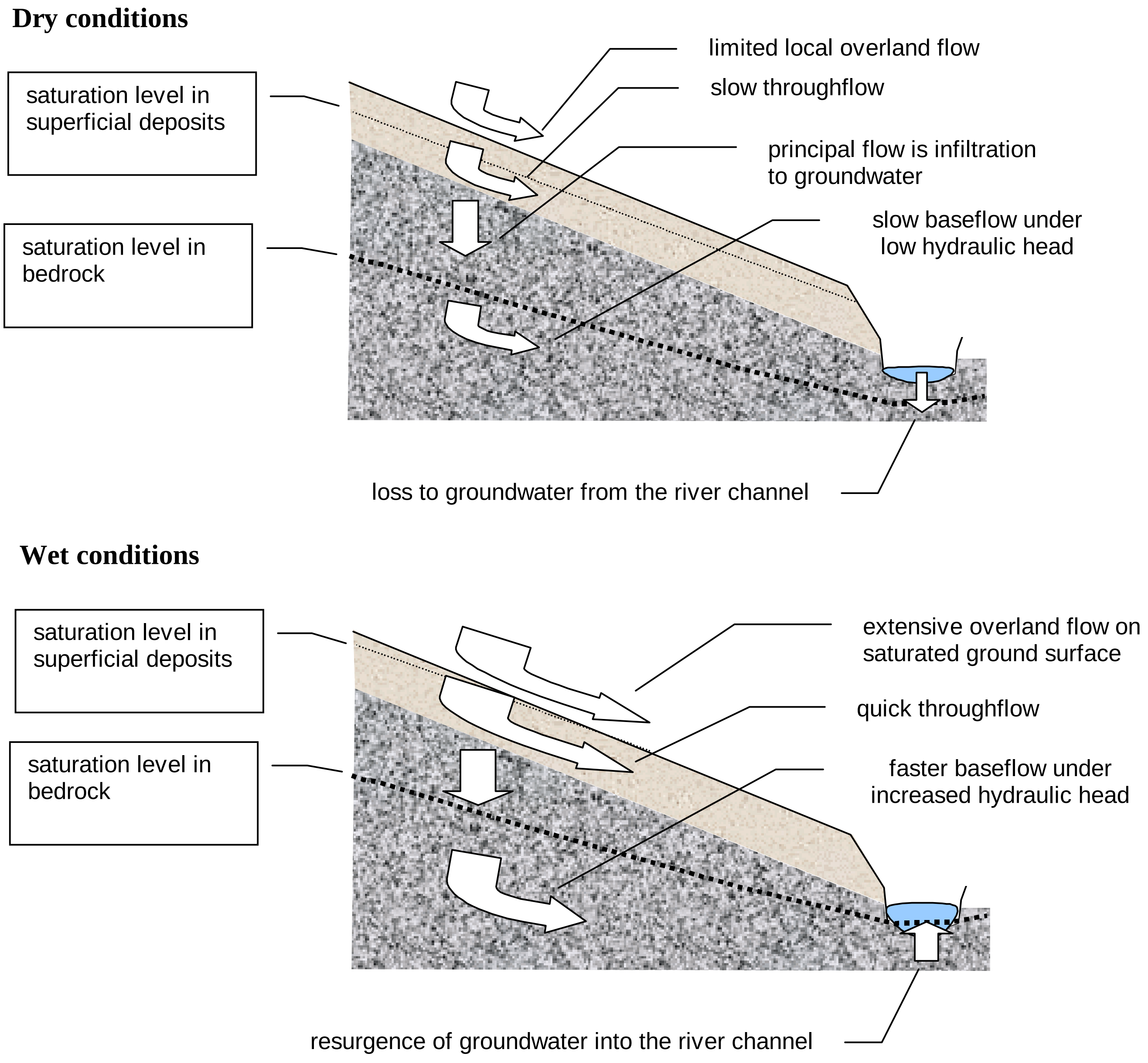


Figure 3.167: Conceptual model for responses to rainfall on steep hillslopes of Coed y Brenin

In this section, attention now turns to water flows occurring within the Palaeozoic bedrock underlying the superficial deposits. Bedrock is often exposed in the deeply incised river channels of the upland catchment, or the river has a direct connection to bedrock through a gravel bed of high hydraulic conductivity.

In section 1.2 it was shown that the geology of the central Mawddach catchment is composed of Cambrian and Ordovician silt and mud sediments which have become hard and resistant through low grade regional metamorphism, along with a variety of Ordovician volcanic ashes, lavas and sub-volcanic intrusions. It might be expected that the permeability of this old Palaeozoic bedrock sequence is low, but permeability has been increased locally by well developed cleavage fractures, joints and fault zones.

At times of dry weather, river levels may become very low within the gorge sections of the Mawddach, suggesting a loss of surface water to groundwater storage. This is observed particularly where the downstream slope of the channel is steep (fig.3.168).

Figure 3.168: Afon Wen, downstream of Hermon, during dry conditions. Water flow is very low, declining to almost zero in places. This suggests loss to groundwater - perhaps through fractures along the Afon Wen fault zone.

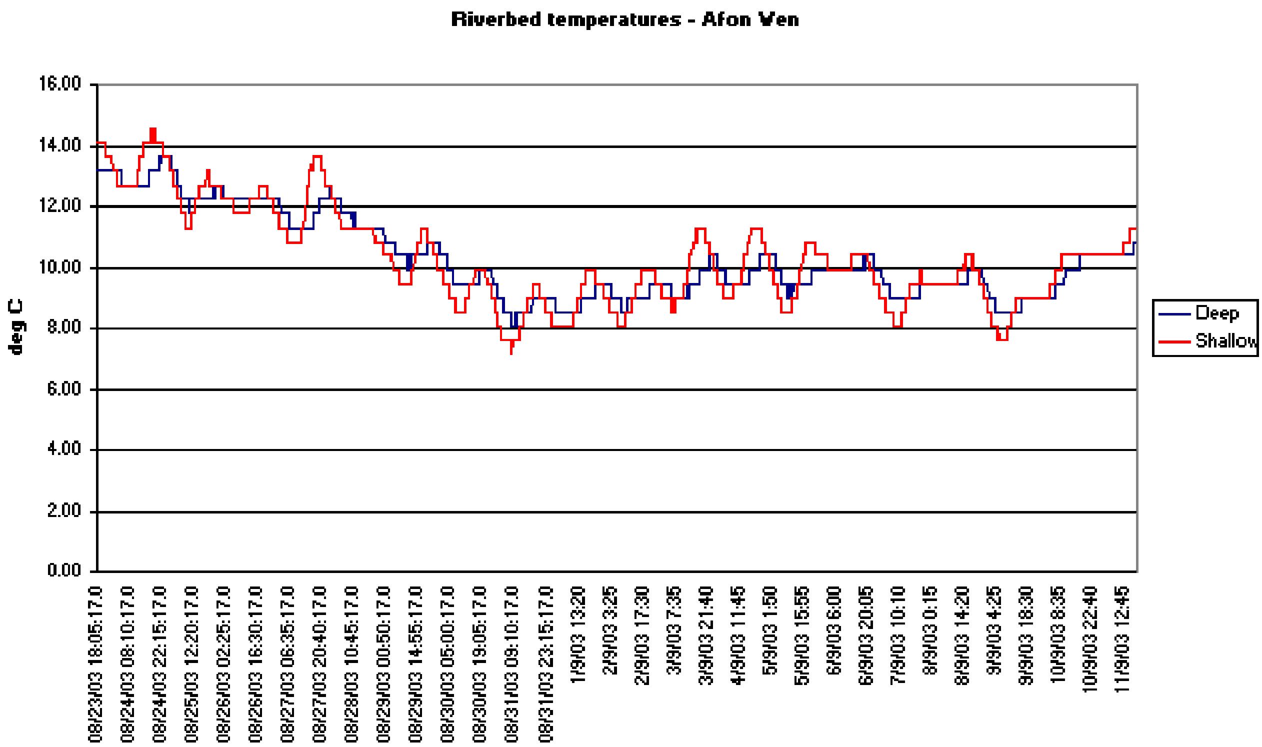
Silliman and Booth (1993) presented a technique for identification of gaining versus losing portions of Juday Creek, Indiana. This involves the recording of water temperatures at the stream bed and deep in the stream bed sediment at the bedrock interface. They were able to demonstrate the propagation of temperature changes as water moved upwards or downwards between the river and groundwater store over a period of hours.

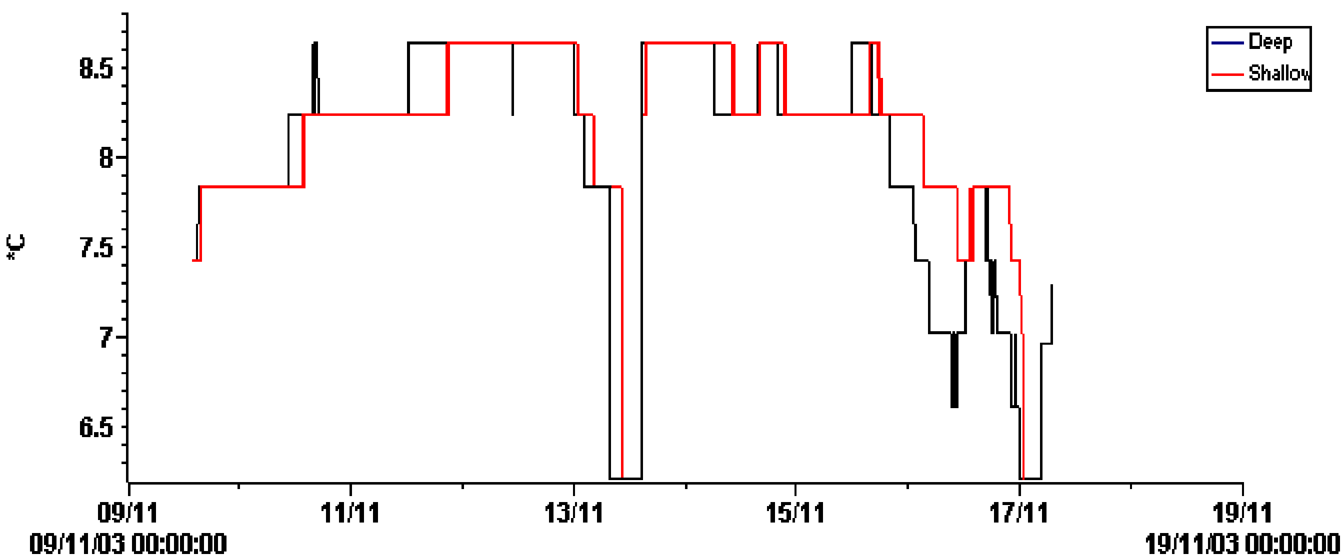
The technique of Silliman and Booth was used to investigate surface water – groundwater interactions in the Afon Wen near Hermon, at the hydrograph recording site described above in section 3.2 (fig.3.33).

Two electronic temperature probes were inserted in the river bed gravel, one close to the riverbed interface and the other at a depth of 1.6m close to the gravel-bedrock interface (fig.3.169).

Figure 3.169: Emplacement of temperature probes in river gravel. Afon Wen, Hermon.

Monitoring was carried out from August to December 2003, during which time an extended period of dry weather was succeeded by a series of storms producing flood peak flows on the Afon Wen. Example temperature data is shown in fig.3.170.





Example data from riverbed temperature monitoring, Afon Wen, Hermon.
(above) Figure 3.170a. Period of dry weather conditions, August-September 2003
(below) Figure 3.170b. Sequence of two storm events, November 2003

- Under low flow conditions, diurnal changes in river temperature is reflected some 6 hours later by an equivalent but subdued change in the deep temperature.
- In flood conditions, the response is reversed. Changes in water temperature in the deep sediment are reflected by temperature changes at the gravel surface around 2 hours later.

It is proposed that the temperature measurements are indicating transfer of water between the river channel and groundwater storage. Under low flow, water is leaking through river bed gravel into fractures within unsaturated bedrock at a rate of approximately 0.3m/hour. During floods, the bedrock hydrostatic level rises above the river bed, allowing resurgence of colder groundwater at a rate of approximately 1m/hour. Thermal conduction may occur in both cases, but is likely to be be a minor contributor to heat transfer for narrow and lengthy water pathways curling amongst pebbles of low thermal conductivity.

It is possible to make a rough estimate of the significance of resurgence from groundwater during flood events on the Afon Wen. Assuming the extent of the gorge section experiencing resurgence is 2km, and the river channel has an average width of 4m, then the contribution to river flow from groundwater resurgence may be:

$$\frac{2km \times 4m \times 1mh^{-1}}{60 \times 60} \approx 2m^3s^{-1}$$

This flow rate can be compared with a typical flood hydrograph maximum for the Afon Wen of between $15m^3s^{-1}$ and $25m^3s^{-1}$. However, the contribution to flow from groundwater resurgence appears at least 2 hours after initiation of the flood event, and probably significantly later. The resurgent flow is likely to occur within the falling limb of the flood hydrograph, so will not directly affect the severity of flooding. It would, however, help to explain the discrepancy between recorded hydrographs and the synthetic hydrographs generated by the HEC-1 model in section 3.2.

Further evidence for the extent of river – groundwater interaction can be obtained by groundwater modelling using MODFLOW software. This approach will be demonstrated in the next section.

Afon Wen groundwater model

A groundwater model for the Afon Wen sub-catchment of the Mawddach has been constructed MODFLOW 2000 software within the Groundwater Modelling System (McDonald and Harbaugh, 1988). MODFLOW is the industry standard groundwater modelling system and models for various regions of the world are described by different authors, for example: South Florida Water Management District, 2005. Use of the Groundwater Modelling System is described in a publication by Brigham Young University, 2004.

MODFLOW simulates groundwater flow by a three-dimensional array of cells:

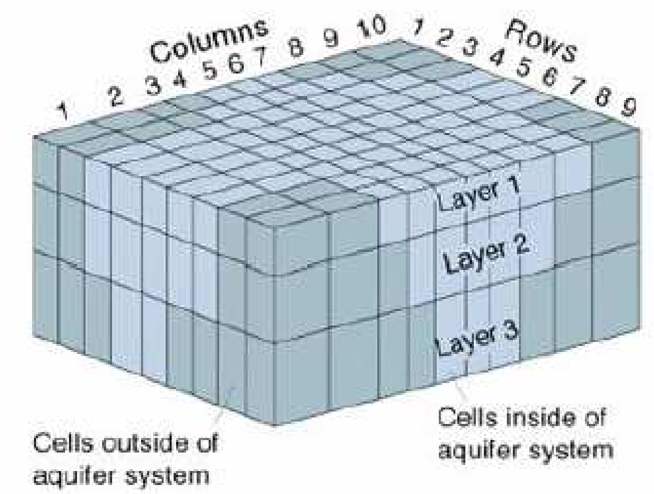


Figure 3.171: Model grid for simulating 3-dimensional groundwater flow (after South Florida Water Management District, 2005)

For each cell, the hydrological properties and dimensions must be specified, along with the top and bottom elevations. The hydraulic head within each column of cells is initialised, then updated at each time step during a simulation. Boundary conditions are applied to cells bordering the model area, and may represent a specified flow rate, a specified hydraulic head, or a no-flow condition.

Models may be run as steady state simulations, or as transient sequences in which rainfall recharge is varied with time.

Grid cells may be designated as ***drains***, which are able to remove water from the model when the hydraulic head rises above the base level of the drain. A further option is to designate cells as ***rivers***, which operate in a similar way to drains but can also allow water to be added to the model at times of low hydraulic head by leakage through the river bed. For ***drain*** and ***river*** cells, the bed elevation and maximum hydraulic conductivity of the bed must be specified.

MODFLOW is able to display the volumes of water flow within sections of drains or rivers at particular time steps during the simulation. The model can also provide water budgets for particular cells or groups of cells, to show the volumes of water moving in or out of storage as a result of rainfall recharge, flow between cells, movement through the model boundaries, or transfer by drains and rivers.

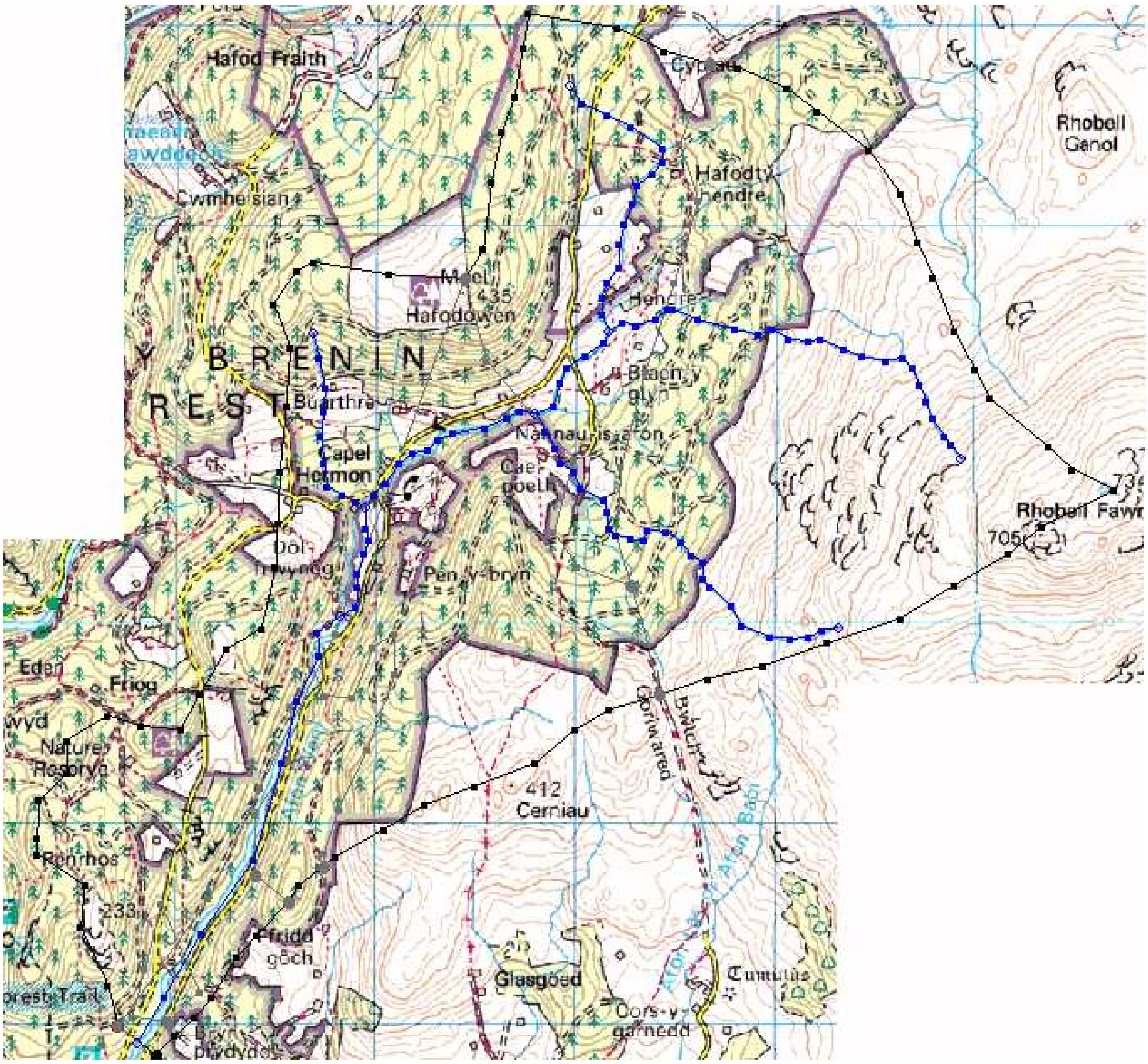


Figure 3.172: Afon Wen MODFLOW model. Base map with boundary and river system defined.

Setting up the MODFLOW model

The Watershed Modelling System allows models to be developed through a geographical information system graphical interface. Parameters are interpolated to a MODFLOW three-dimensional grid in order to run the simulation.

Construction of the Afon Wen groundwater model begins with the importing of a base map image (fig.3.172). Overlays are created to represent the model boundary and river system. A MODFLOW grid of dimension 30 cells in width by 30 cells in length was chosen, and the overlays interpolated to this model (fig.3.173). Cells lying outside the sub-catchment are excluded from computations.

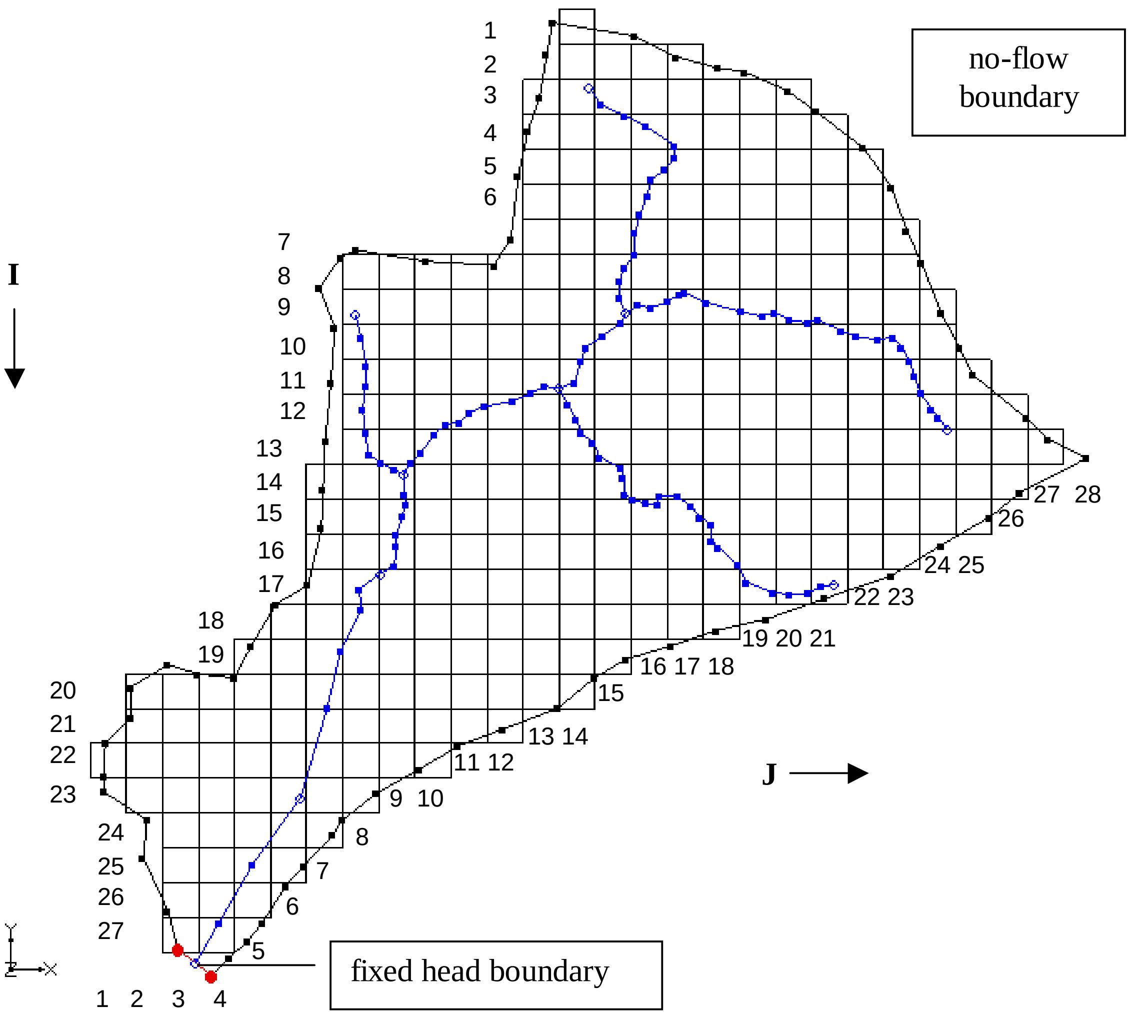


Figure 3.173: MODFLOW grid for the Afon Wen groundwater model, showing coordinate system

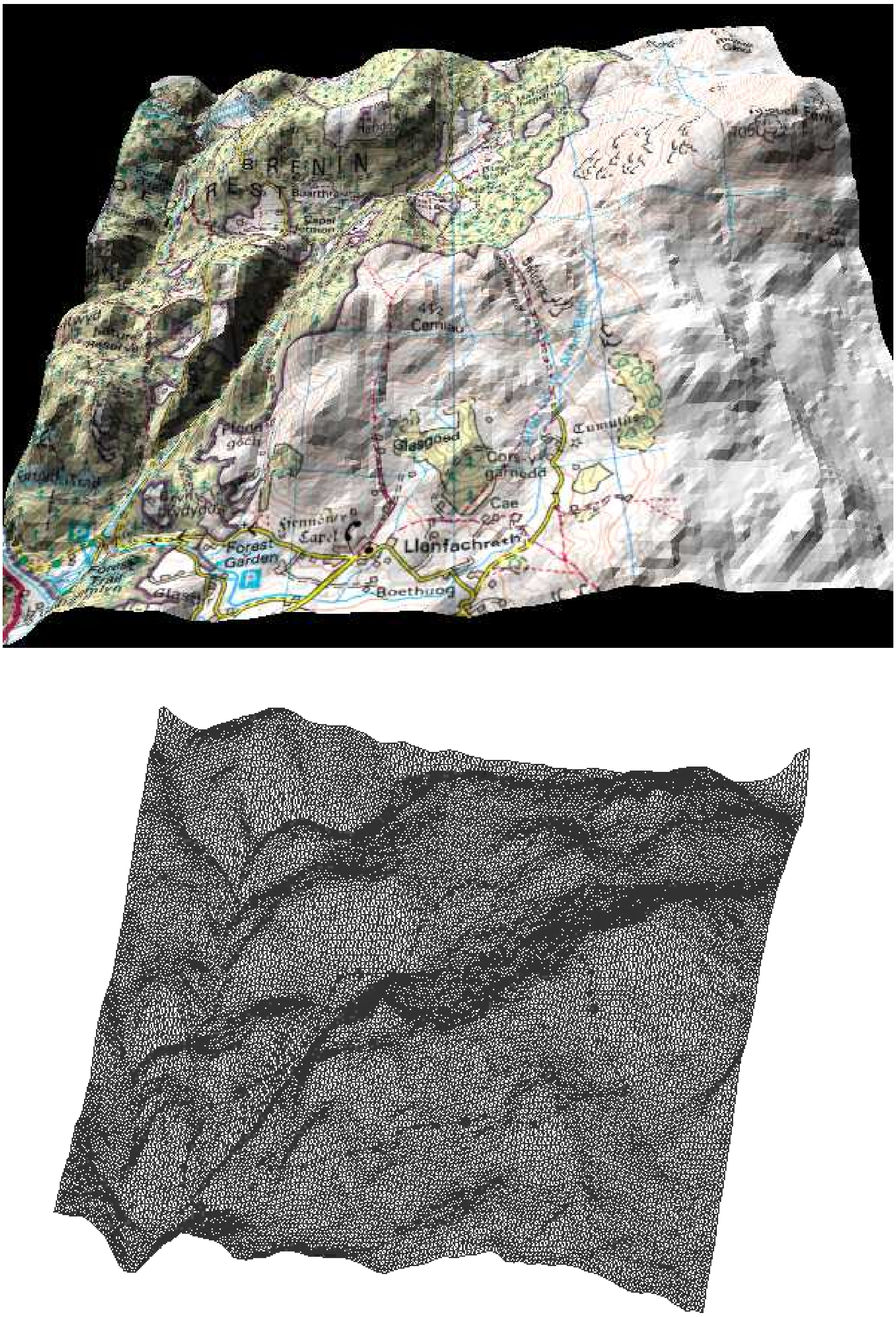


Figure 3.174: Topography of the Afon Wen subcatchment:
(above) Land surface derived from the digital elevation model
(below) DEM triangulated network used to assign cell elevations to layers of the MODFLOW model

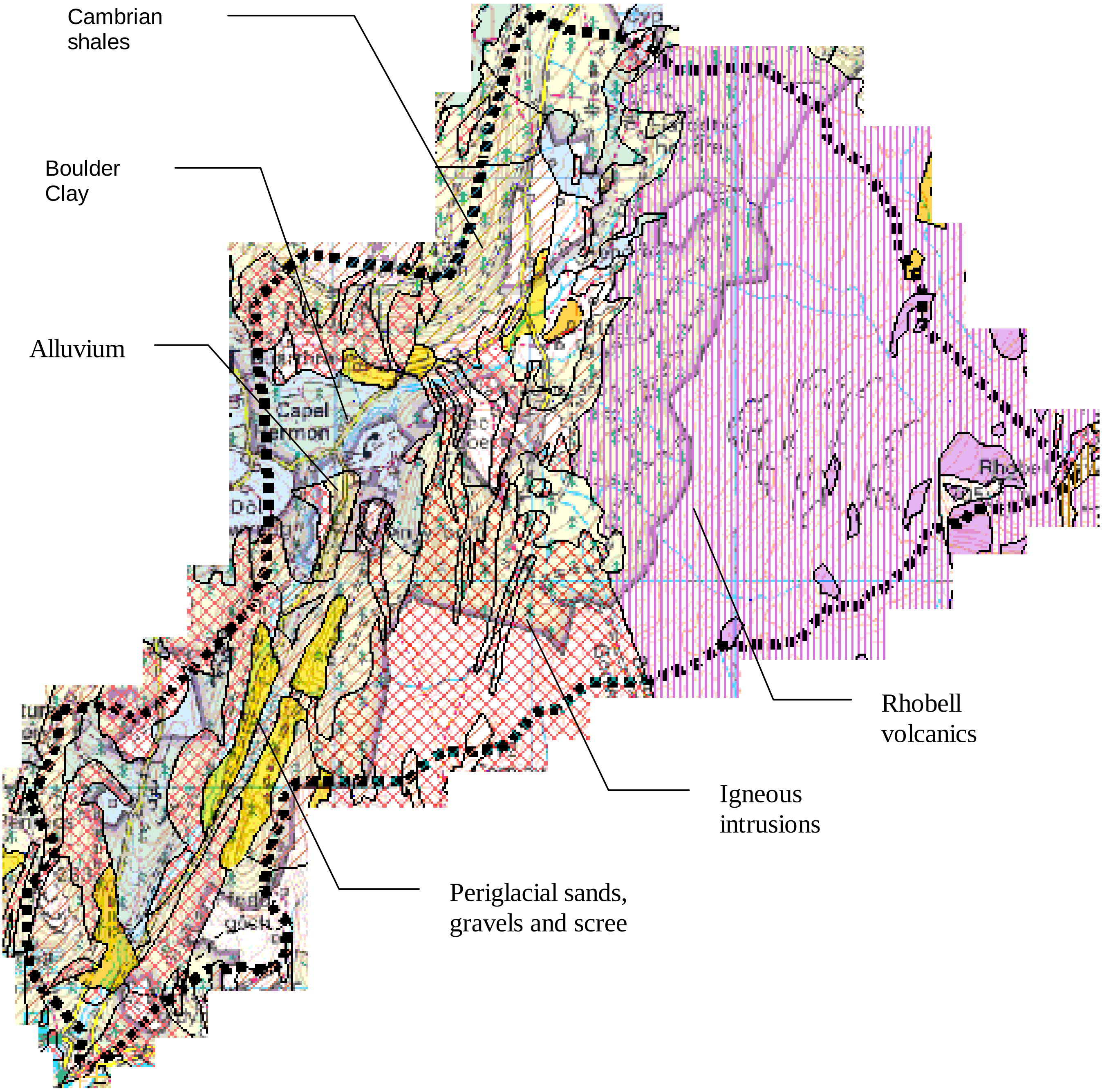


Figure 3.175: Geology of the Afon Wen subcatchment

A constant hydraulic head of 62.5m was applied to the river outflow cell, which represents average river head stage. No-flow conditions were applied to the remaining boundary cells forming the watershed around the sub-catchment. The river system has been divided into nine reaches, so that river flow values can be obtained separately for different sections of the Afon Wen between the mountain headwaters and the incised gorge downstream.

Elevation data is required for the upper and lower surfaces of each model cell. Ordnance Survey 50m gridded elevation data was imported to GMS as a point data set and converted to a triangulated network (fig.3.174). Elevations were then interpolated to the MODFLOW grid.

The next stage in developing the model is to determine hydrological characteristics for the sequence of geological formations within the model area. A geological map of the sub-catchment is given in fig.3.175. The eastern part of the catchment is underlain by volcanic lavas and a sub-volcanic intrusion complex of the Rhobell Fawr Ordovician volcanic centre. To the east appear Upper Cambrian shales. A major north-south fracture zone is present around the junction of the sediments and volcanics, with the Afon Wen fault controlling the orientation of the deeply incised valley to the south of Hermon. Substantial thicknesses of glacial and periglacial deposits are locally present, particularly within the river valleys. Blanket peat is developed on the gentler slopes of Rhobell Fawr.

Boundaries between the igneous and sedimentary rocks are close to vertical, so a single layer model was chosen for the Afon Wen. The bedrock distribution is entered as an overlay within the Groundwater Modelling System, subdivided into polygon areas with different hydrological characteristics. Initial hydraulic conductivities were assigned to each geological unit (fig.3.176).

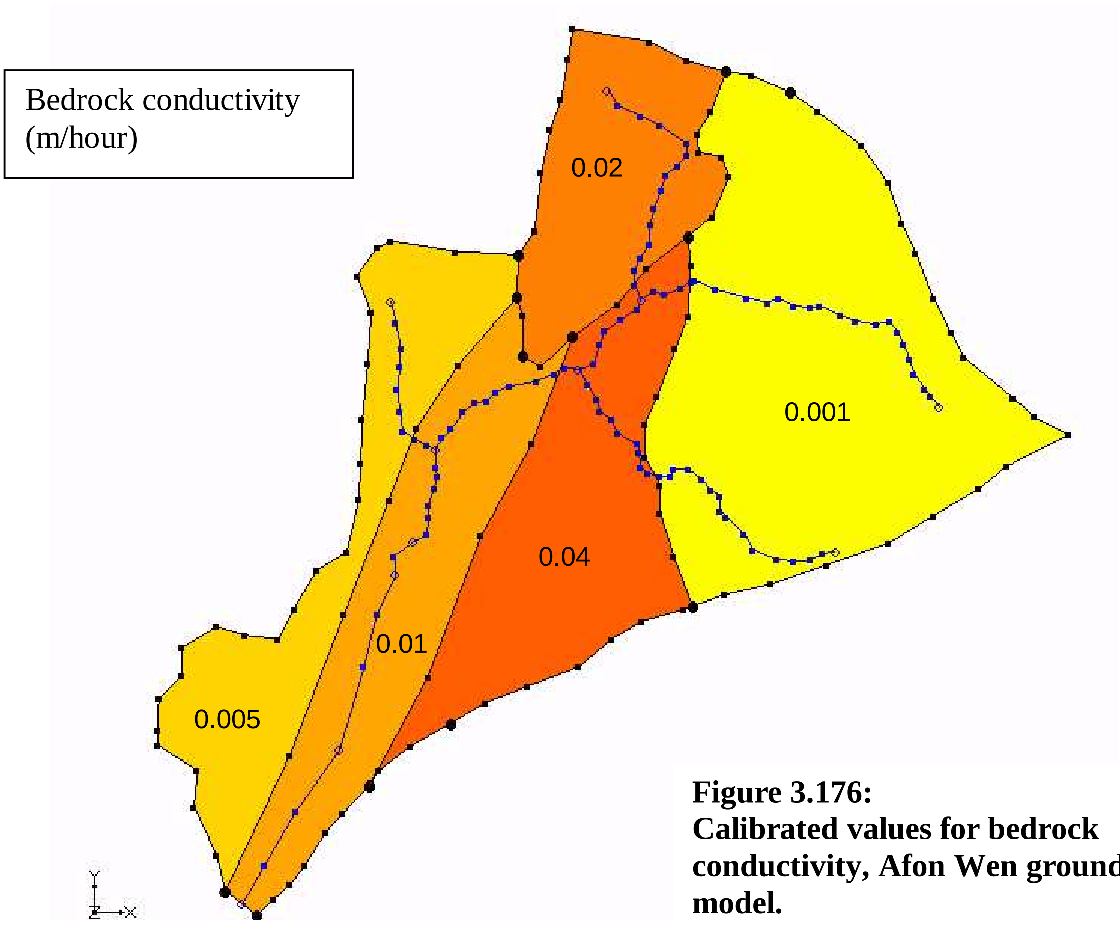


Figure 3.176: Calibrated values for bedrock conductivity, Afon Wen groundwater model.

The effect of the superficial deposits is to restrict, to varying extents, the amount of rainfall which enters the underlying bedrock to recharge the groundwater store. An overlay of superficial deposits is set up in a similar way to the solid geology overlay. Recharge values are allocated to polygon areas to represent the rate of groundwater recharge (m/hour) when one unit of rainfall (mm) reaches the ground surface during an hour period (fig.3.177). The GMS software has a function for multiplying this basic distribution to represent actual rainfall recharge over the period of a storm event. Initial values for recharge rate were assigned to each superficial deposit.

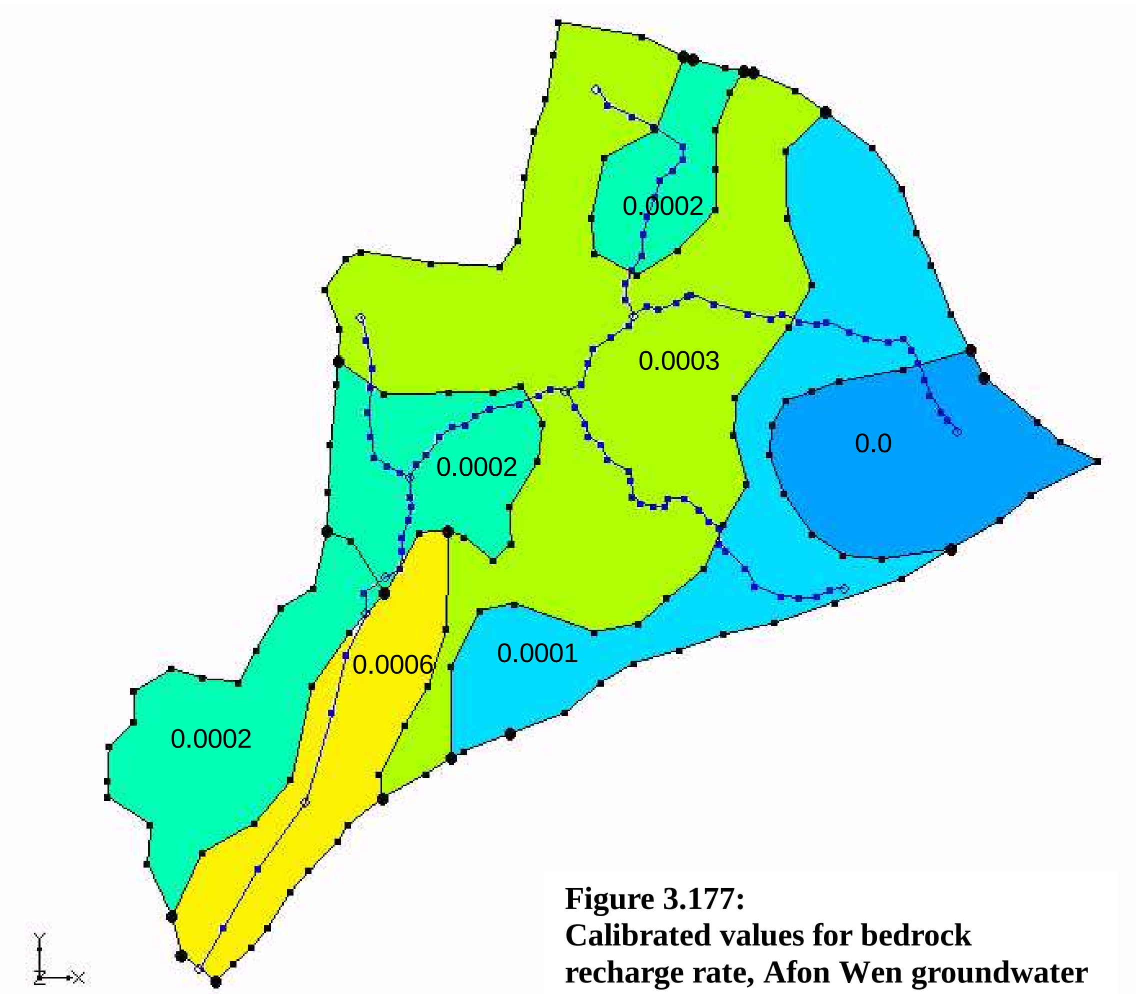


Figure 3.177:
Calibrated values for bedrock recharge rate, Afon Wen groundwater model.

A final set of parameters required are the channel bed hydraulic conductivities for sections of the river network. As before, initial values are assigned to each of the nine river reaches and then refined through calibration (fig.3.178).

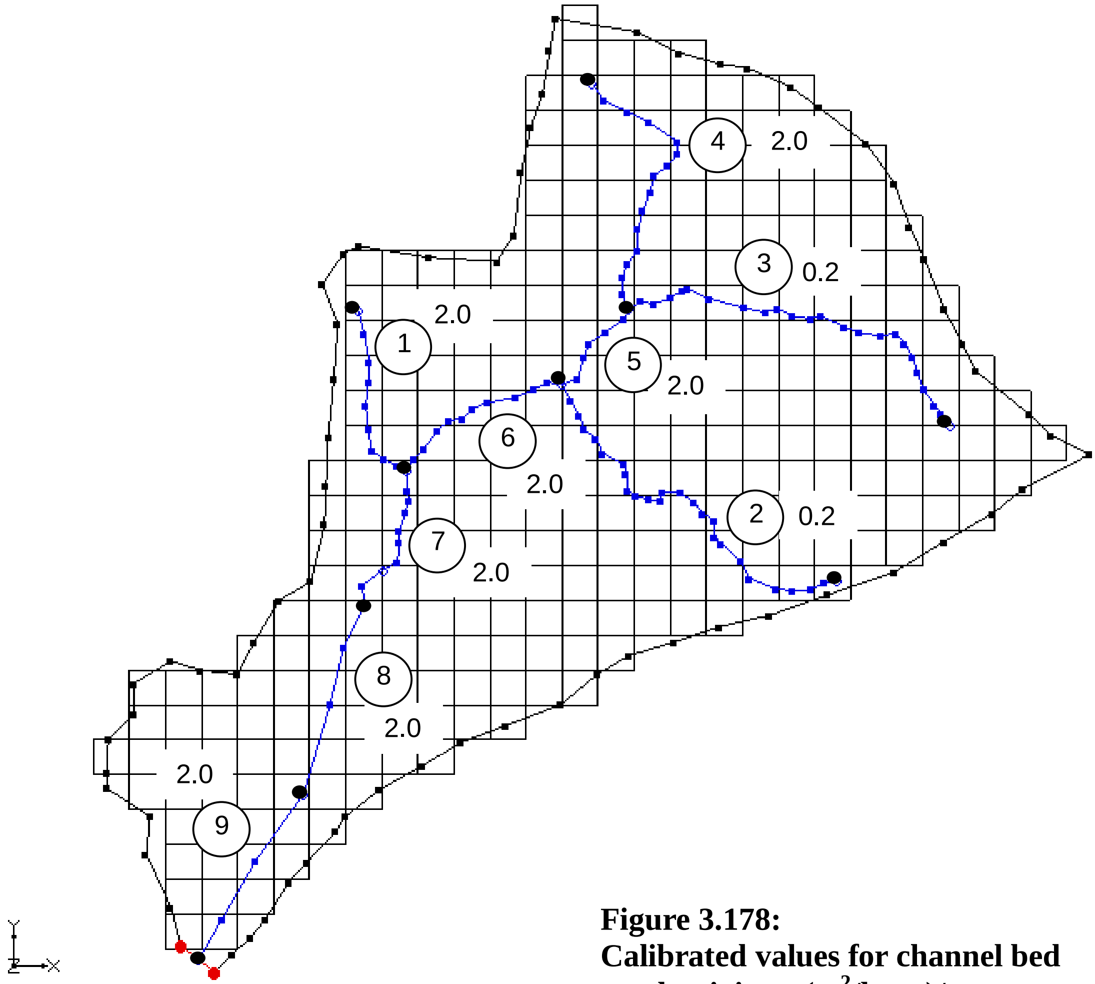


Figure 3.178:
Calibrated values for channel bed conductivity   (m^2/hour)/m

Once an initial model has been defined, the Groundwater Modelling System software provides tools for automatic refinement of the calibration of bedrock conductivity, recharge rate and channel bed conductivity. The model is run with test storm events to optimise the fit between rainfall input, the river outflow hydrograph and known water table depths at monitoring sites within the sub-catchment.

The objective of the MODFLOW modelling is to determine the groundwater response to storm events over the Afon Wen subcatchment, and in particular to characterise river reaches as gaining or losing flow through groundwater interaction at different stages during the simulation period. A storm event on 29 December 2003 was selected to provide rainfall and river hydrograph data for model input and validation (fig.3.179).

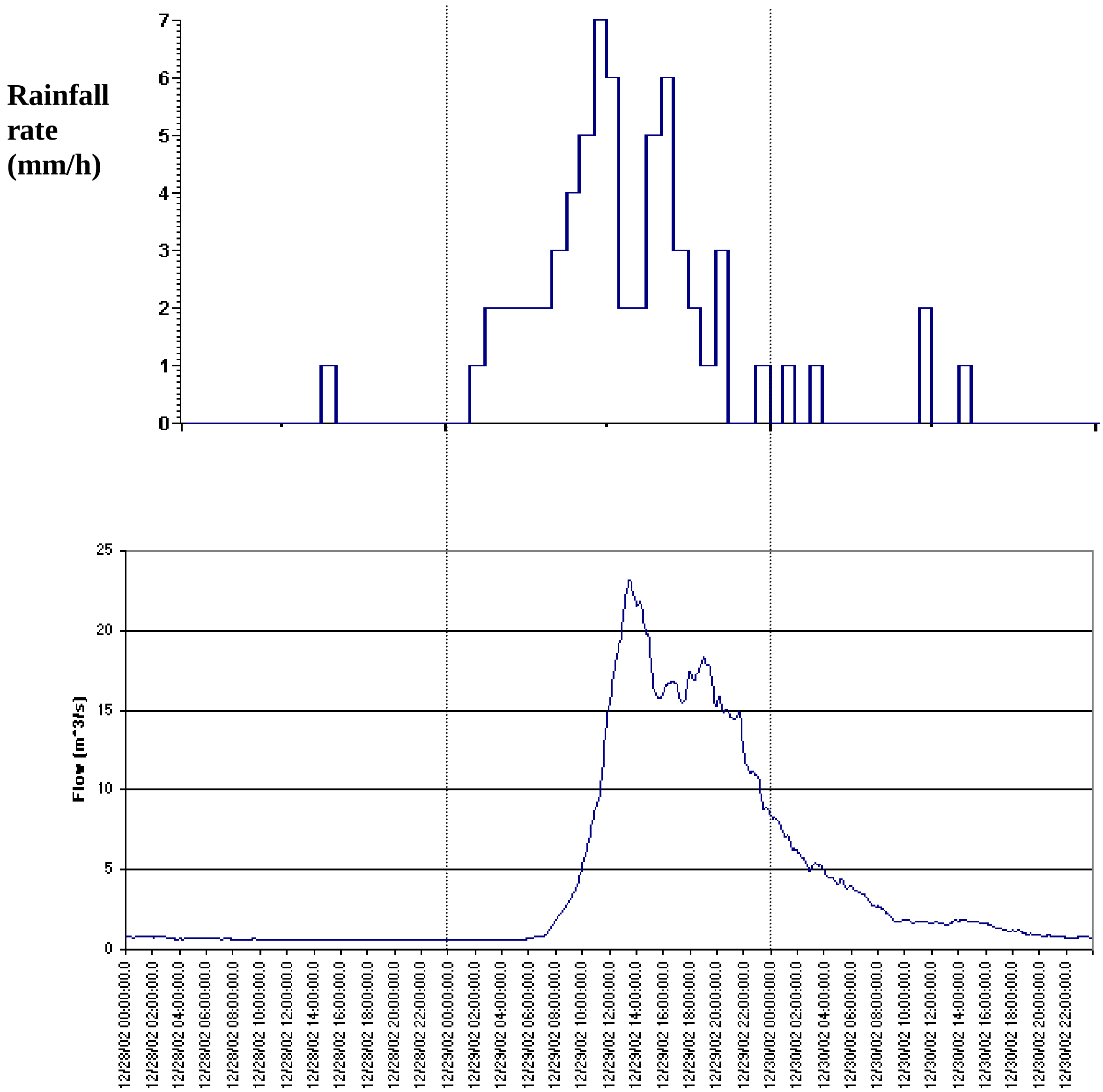


Figure 3.179: Storm event of 29 December 2003 over the Afon Wen subcatchment.
(above) Raingauge data for Hermon,
(below) Hydrograph for the Afon Wen, Hermon.

Before running the storm simulation, it is necessary to produce a steady state model in which the river baseflow is consistent with observations in the period prior to the storm event.

The model was initialised with a short period of rainfall. Runs were carried out, during which heads equalised to steady states. Progressive refinements of bedrock conductivities, recharge rates and river bed conductivities were carried out, until the model results were consistent with the steady river flow and ground conditions to be expected several days after rainfall:

- Total river discharge was assumed to be derived from the release groundwater. A typical low flow value of $0.5m^3/s$ for the Afon Wen was assumed.
- The gentle lower slopes of Rhobell Fawr are consistently wet, supporting areas of blanket peat bog (fig.3.180a). Mires with flowing water are evident where springs release groundwater. Wet conditions continue into woodland around Hermon where drainage is restricted by glacial clay (fig.3.180b). Bedrock saturation over these areas was expected for the model.
- The steep hillslopes above the Afon Wen valley are generally dry (fig.3.180c), and a deeper water table was expected.

A set of parameter values was generated which met the field criteria. These are displayed in figs 3.176-3.178:

Bedrock conductivity

> A low value of 0.001m/h is obtained for the basalt lava outcrops of Rhobell Fawr. This geological formation is massive, with little free groundwater movement possible.
> Cambrian sediments and igneous intrusions to the west of the Afon Wen valley give an intermediate conductivity value of 0.005m/h. These formations show better development of joint and fracture systems.
> A zone of higher conductivity between 0.01 and 0.02m/h follows the Afon Wen valley, and is consistent with the orientation of the Afon Wen fracture zone where faulting is evident. Highest conductivities are found for the hill

Figure 3.180a.
Lower slopes of Rhobell Fawr above Hermon, showing areas of bog and mire vegetation. Heather covered slopes in the middle distance represent drier conditions.

Figure 3.180b.
Semi-natural broadleaf woodland above the village of Hermon.

Figure 3.180c.
Dry hillslopes above the Afon Wen valley, south of Hermon.

area to the east of the Afon Wen, which at first seems a surprising result. However, this is the location of the major north-south fracture zone beneath the Ordovician volcanic centre of Rhobell Fawr, and includes the sub-volcanic intrusion complexes of Cerniau and Moel y Llan (Kokelaar, 1977). Much of the terrain is made up of heavily fractured narrow intrusions emplaced between thin sheets of Cambrian shale sediment. High hydraulic conductivity is certaily possible for such a disturbed sequence.

Recharge rates (fig.3.177)

Steep bare rock outcrops on the upper slopes of Rhobell Fawr show a very low recharge rate, treated in the model as zero.
A low value of 0.0001m/h unit recharge rate is assigned to the lower slopes of Rhobell Fawr where blanket peat is well developed.
Moderate recharge rates of 0.002m/h are assigned to the steeper slopes above the Afon Wen valley, and a higher rate of 0.003m/h to forest on gentler slopes where down-slope sub-surface flow is less well developed.
A high infiltration rate of 0.006m/h is assigned to the slopes of the Afon Wen valley where high permeability periglacial scree provides direct flow to bedrock through open cavities.

River bed conductivity (fig.3.178)

Moderate values of 2.0 (m^2/h)/h are assigned to gravel channels within the valley sections of the river, where good hydraulic connection to bedrock is maintained.
Low values of 0.2 (m^2/h)/h are assigned to the bedrock reaches of the mountain headwaters of the Afon Wen as they cross the basalt outcrop.

Results of the calibration run of the MODFLOW groundwater model are shown in figures 3.181 and 3.182. Inevitably with a highly parameterised model, it is possible that different combinations of conductivity and recharge values might have been found which similarly meet the field criteria. Further work would be necessary to investigate the range of acceptable model parameterisations and the variance in results that the models generate, but is not anticipated that alternative parameter sets would give significantly different results for the test storm of 29 December 2003.

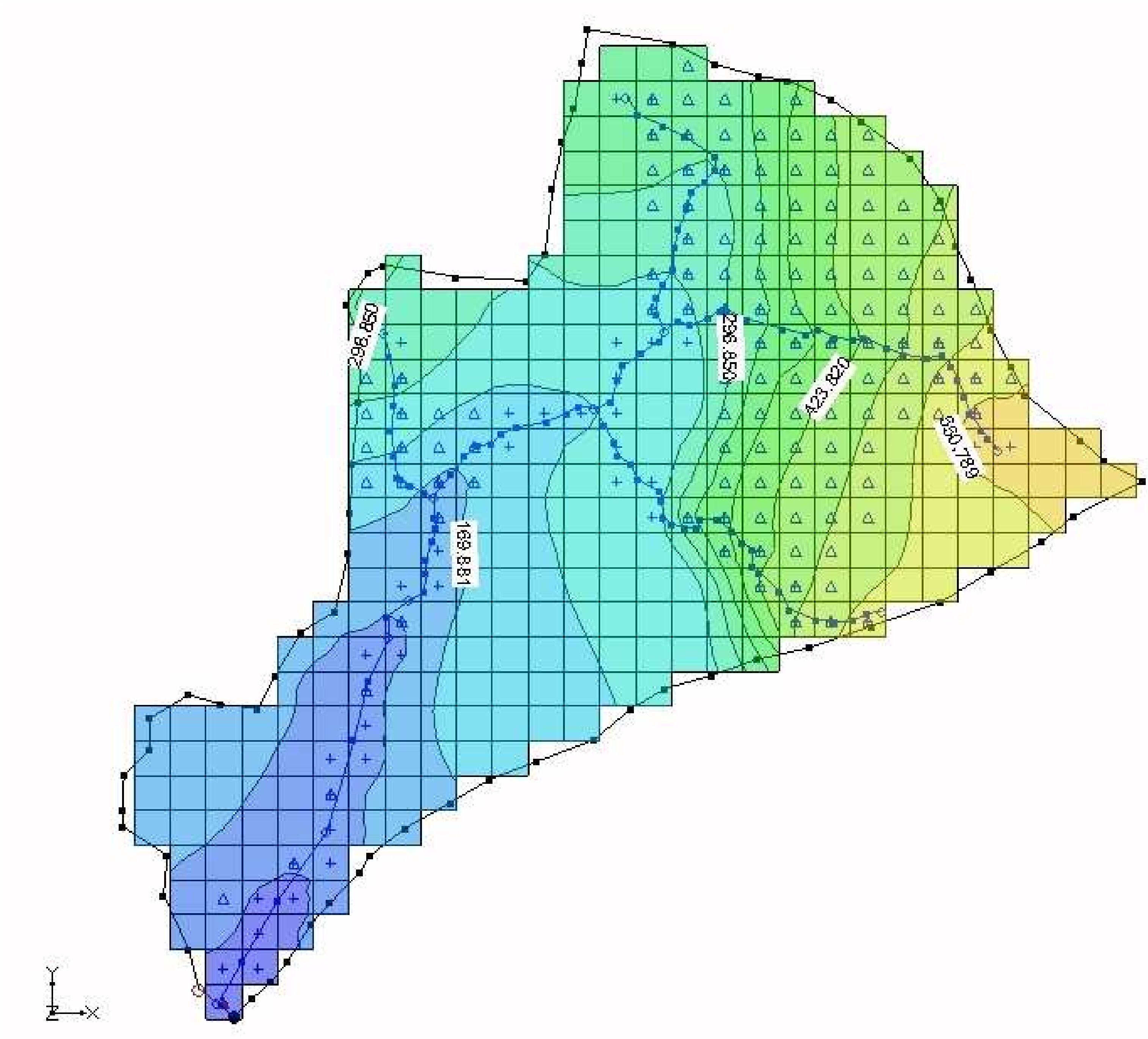


Figure 3.181: Afon Wen MODFLOW model for a steady riverflow rate of $0.5m^3/s$. Contours show hydraulic head(m). Triangle symbols indicate cells where groundwater reaches the ground surface.

Hydraulic head cross sections are given in fig.3.182 for low flow conditions. The deeply incised valley of the lower Afon Wen lies within the row range 15 to 27. Several sections within the steepest gorge section of the valley show groundwater levels well below the river bed elevation, suggesting that loss of river water by infiltration to bedrock is likely. These are interspaced between sections where the groundwater level reaches the river, and a gain of river water by groundwater resurgence is occurring.

Once a satisfactory low-flow model was obtained, the rainfall recharge sequence for the 29 December 2003 was simulated. Graphs of groundwater resurgence for the Afon Wen are given in fig.3.183:

> The total flow graph indicates that a maximum groundwater contribution of 2.5m^3/s is released into the Afon Wen seven hours after the commencement of storm rainfall. This result is roughly consistent with the field data presented earlier in this section. Decline in groundwater flow follows an exponential decay curve.

Groundwater flow curves are given for the four deeply-incised lower reaches of the Afon Wen:

> The downstream reach 9 exhibited close to zero total river/groundwater interchange at the start of the simulation period, but this figure may hide a mixture of losing and gaining sections of the river channel which are approximately in balance. The other reaches further upstream show small amounts of initial resurgence.
>
> Maximum groundwater releases into the river reaches occur at around seven hours after the commencement of the storm, as in the case of the total river groundwater flow. Maximum flows for individual reaches vary between 0.35m^3/s and 0.65m^3/s. The declines in groundwater resurgence again follow exponential curves, with flows returning to approximately the pre-flood levels after 60 hours.

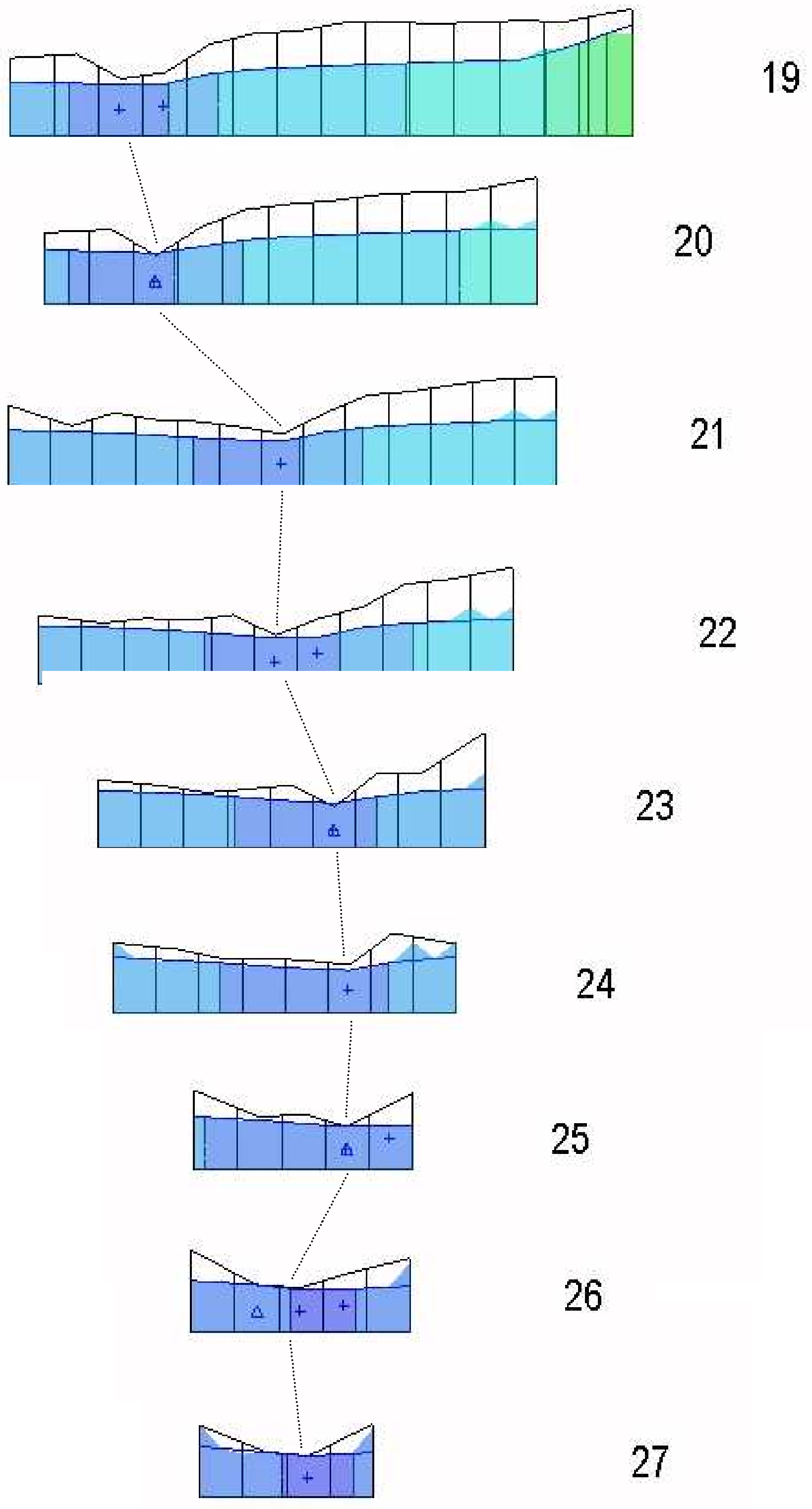


Figure 3.182(a). Hydraulic head cross-sections along west-east rows of cells of the Afon Wen MODFLOW model. Numbers relate to row index values as shown in fig.405. Dotted line indicates the location of the Afon Wen main river channel.

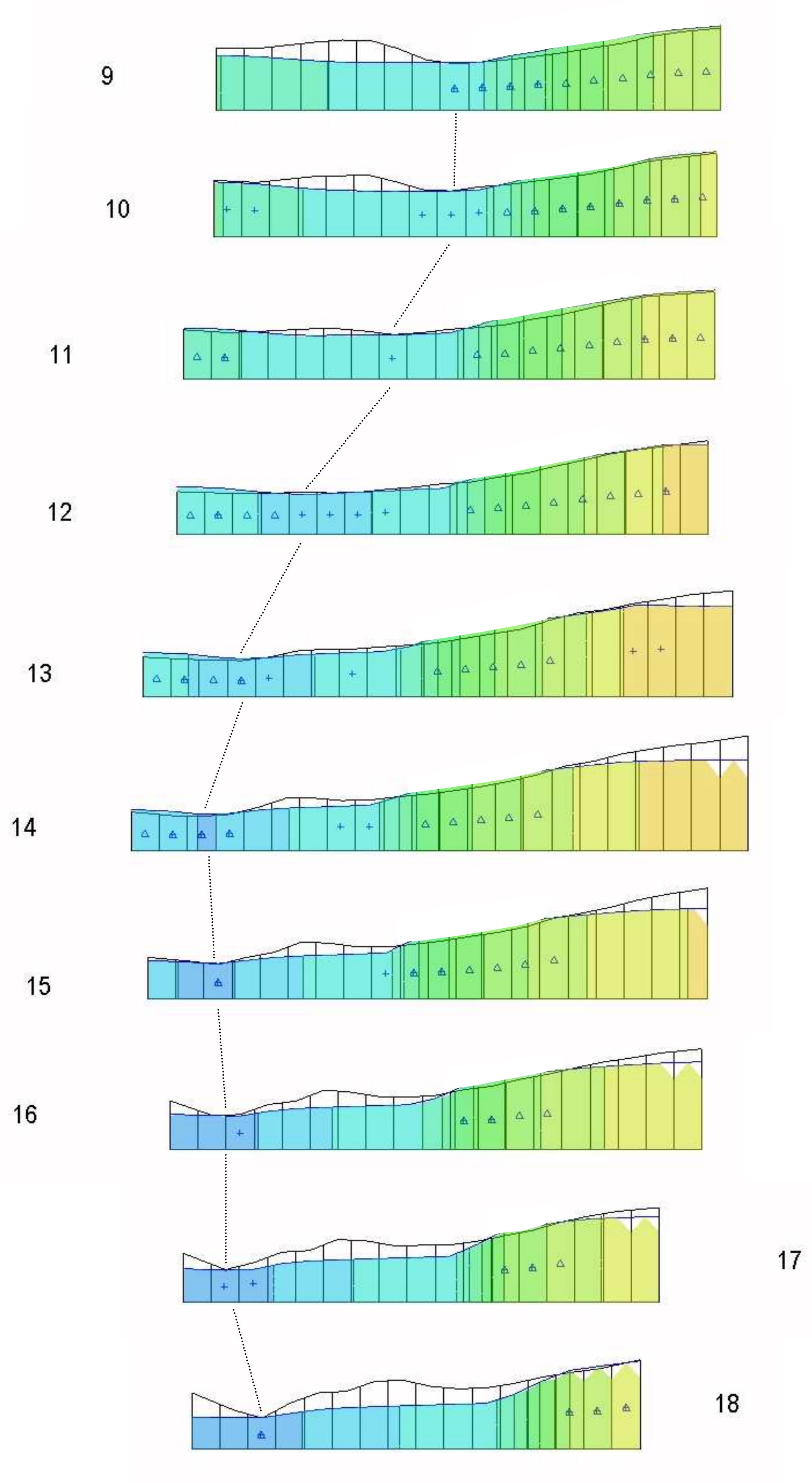
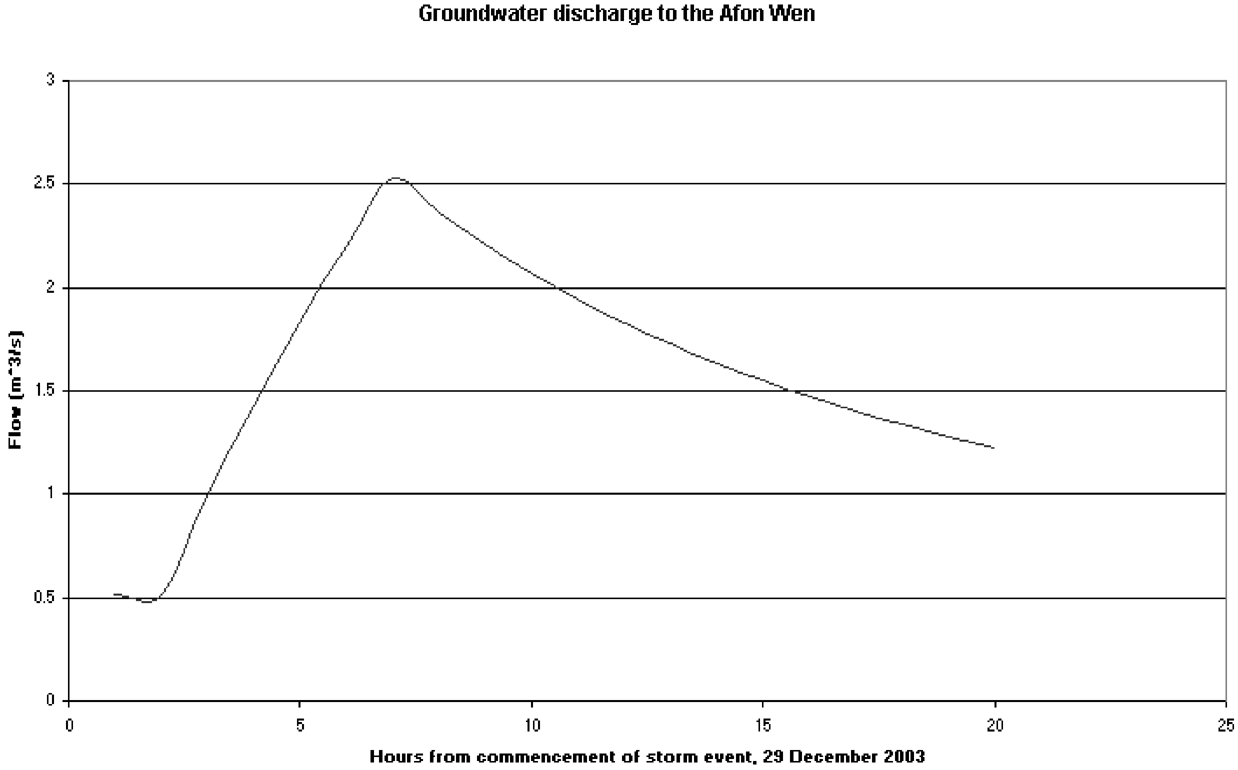


Figure 3.182(b). Hydraulic head cross-sections along west-east rows of cells of the Afon Wen MODFLOW model. Numbers relate to row index values as shown in fig.405. Dotted line indicates the location of the Afon Wen main river channel.



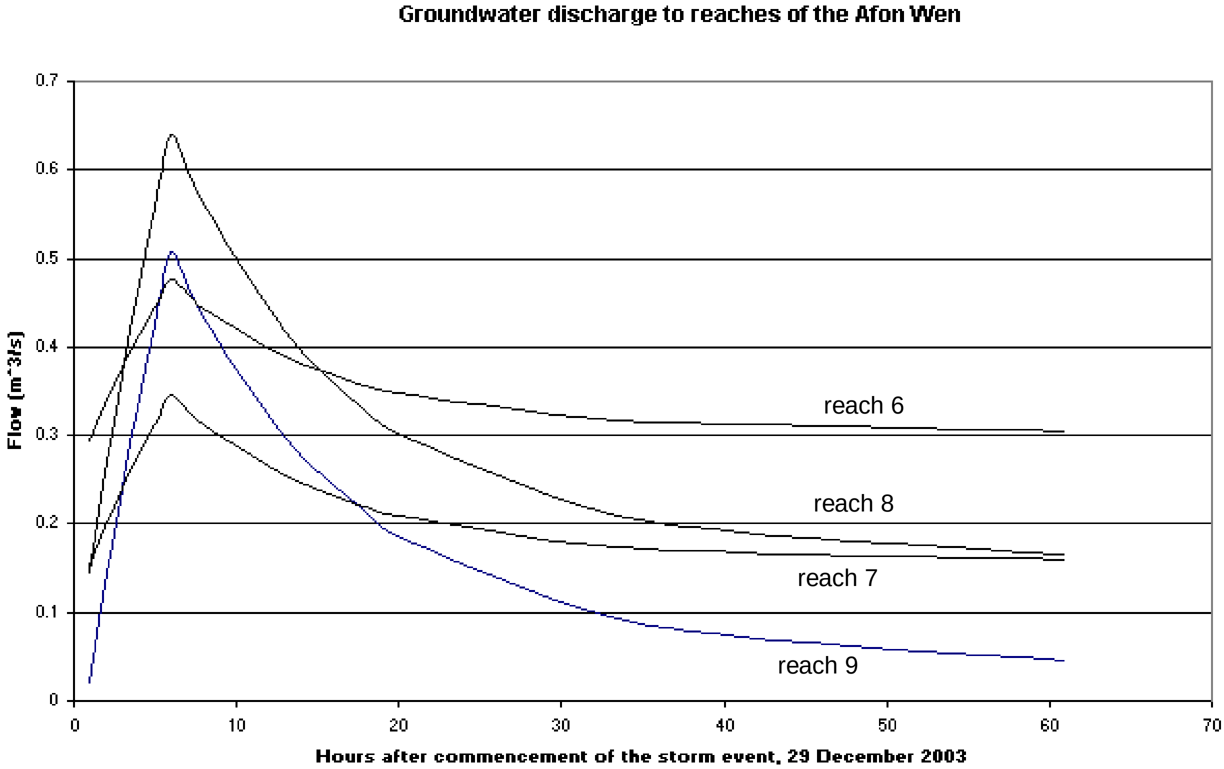


Figure 3.183: Groundwater flow graphs for MODFLOW simulation of the 29 December 2003 flood event.
(above) total release of groundwater into the river,
(below) release of groundwater to the lower reaches of the Afon Wen.

Summary

- Flood models have been produced for the town of Dolgellau at different river discharge rates. Model results are consistent with observed flooding patterns. It is possible to predict the extent of flooding in Dolgellau during a storm event if an accurate forecast of flow rate is available 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 risk from flooding is substantially less than the area marked on the Environment Agency Flood Map.
- Significant amounts of gravel and finer sediment can be deposited along the river section through Dolgellau in the course of a single storm event. The prolonged sequence of storms in February 2001 deposited over 1m of gravel in less than one week.
- Gravel deposition raises the river bed level and increases flood risk. Deposition of 1m of gravel has a similar risk effect to increasing the river flow by $50m^3s^{-1}$.
- Floodplain wet woodland can reduce peak river flows by enhancing the temporary water storage capacity of the flood plain.
- Hydrological effects of floodplain woodland were determined by calibration against known maximum flood levels at two sites in Coed y Brenin during the July 2001 flood event.
- 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 bed temperature monitoring for the Afon Wen shows groundwater being released into the river during storm events.
- Modelling suggests 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. The water release occurs over a period of 12 to 24 hours, largely after the peak storm river flow has passed.
- Flooding in the lower reaches of the Mawddach is accompanied by saturated hillslopes upstream in Coed y Brenin. Under these conditions, greatly enhanced shallow stormflow enters the rivers.