3.3 Sediment movement

Sediment accumulation around Dolgellau

The problem of sediment accumulation on the lower reaches of the Afon Wnion around the town of Dolgellau was introduced in section 1.1 (cf. figs 1.21-1.23). Gravel banks along the 2km stretch of the Wnion between Dolgellau and the estuary tidal limit have increased significantly in height and aerial extent over the period of this research project. Aggradation is reducing the effective height of flood defence walls protecting the centre of the town (figs 3.75-3.76).

Historical flood plain deposits are exposed in the banks of the Afon Wnion at times of low river flow. The photograph in fig.3.77, at a site near Coleg Meirion-Dwyfor in Dolgellau, exhibits a band of river gravel beneath flood plain sand and silt beds. The gravel has a mean grain size of 6 cm. This is significantly smaller than the gravel and cobbles accumulating nearby at the present day (fig.3.78) which may exceed 30cm in mean dimension. This suggests that there has been a significant increase in recent decades in either the supply or transport of coarse sediment in the Afon Wnion, or both of these factors.

Increases in coarse sediment deposition are also observed in the lower reaches of the Afon Mawddach, particularly around the tidal limit at Llanelltyd bridge (fig.3.79). The confluence of the Mawddach with the Wnion at the head of the estuary is marked by a large area of unstable gravel banks (fig.3.80), with the rivers changing their courses significantly in historical times. Large amounts of sediment deposition at the estuary head is likely to raise river base levels, reduce river gradients in the already gently graded lower reaches of the Mawddach and Wnion, and further promote gravel deposition upstream.

Sediment supply into the Mawddach and Wnion river systems is largely from the erosion of glacial and periglacial valley infill deposits of the types discussed in section 1.2 (cf. fig.1.50). This supply is significantly augmented in the Coed y Brenin area by the erosion of river bank spoil tips from metal mines (cf figs1.91-1.92). Mine tip erosion accounts for the popularity of gold panning amongst the sand and gravel deposits of rocky pools in the Mawddach and Afon Wen.

Figure 3.75: Recent sediment accumulation downstream from Bont Fawr, Dolgellau

Figure 3.76: Sediment accumulation alongside the Marian Mawr playing fields, Dolgellau, at Lower Wnion site 3

Figure 3.77: Historic river bed gravels exposed at low water level, Afon Wnion near Coleg Meirion-Dwyfor, Dolgellau

Figure 3.78: Present day gravel and cobble deposits in the Afon Wnion close to the site shown in figure 3.77 above.

Figure 3.79: Gravel deposits around the tidal limit of the Afon Mawddach, Llanelltyd site 7

Figure 3.80: Area of unstable gravel deposits at the confluence of the rivers Mawddach and Wnion, Llanelltyd site 9

The Mawddach and Wnion are gravel-dominated streams for their entire courses from their headwaters to the tidal limits at the head of the estuary. Under low flow conditions, normally no gravel movement is observed. It is believed that almost all transport of gravel, cobbles and boulders occurs under flood conditions. Only sand and silt grade materials are in continuous movement within the river system throughout the year.

Effects of sediment movement are easily observed during and after flood events in the Mawddach and Wnion sub-catchments. Examples of severe erosion on the Afon Mawddach in Coed y Brenin are given in figs 1.16 and 1.17. Large amounts of sediment movement are likely to alter channel cross sections, affect channel base levels and modify river gradients. These effects, in turn, are likely to influence the locations and extent of flooding throughout the river system. It was therefore considered important to obtain some estimate of the extent of sediment movement and channel modification in response to individual flood events.

Approaches to sediment transport modelling

Two sediment transport models were examined for use in the Mawddach study: the CAESAR cellular automaton model (Coultard,1999), and the GSTARS stream tube model (Yang and Simões, 2000). These models have different starting points within the hydrological cycle, use different geometrical approaches, and employ different sedimentological formulae for erosion, transport and deposition processes.

CAESAR cellular automaton model

The CAESAR model uses a digital elevation model to create a representation of the catchment topography and river channel system. The model incorporates both hillslope runoff and river routing components, with sediment transport processes handled in addition to water flows (fig. 3.81):

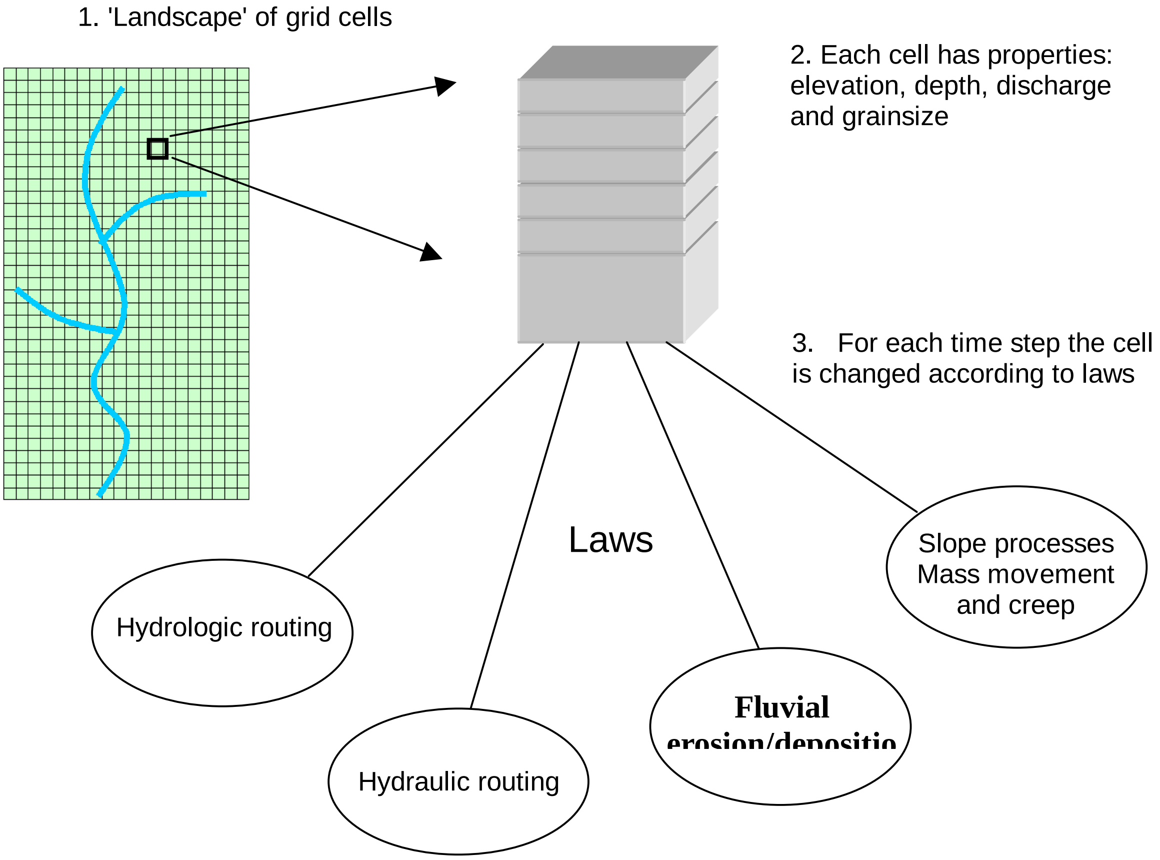


Figure 3.81: Schematic diagram of the key processes operating in the CAESAR cellular automaton model (after Coulthard, 1999)

Within each time step of the model, a sequence of operations are carried out:

- Soil saturation within each cell is calculated, based on rainfall input and infiltration,
- Hillslope surface runoff and subsurface water flows to downslope cells are calculated,
- Water flows are routed through surface channels,
- Sediment erosion within channels is calculated, depending on available sediment grain size and the available transporting capacity of the stream.
- Sediment deposition is calculated, as the excess of transported sediment over carrying capacity.
- Soil creep is determined according to slope angle.
- Mass movement is modelled whenever the slope value for a cell exceeds a critical angle. Material moves downslope until the stable angle of rest is restored.
- Vegetation growth can be modelled, and will stabilise slopes.

The CAESAR model has interesting features, particularly the ability to model sediment movement on hillslopes in addition to sediment transport in river channels. Mass movement is relatively common within the Mawddach catchment when soils and (peri)glacial deposits become saturated during storm events (fig.3.82). However, a detailed study of slope stability and erosion processes is beyond the scope of this project.

Figure 3.82: Mass movement at Oernant in the upper valley of the Afon Gain following the July 2001 storm event.

A drawback of the CAESAR model is the very large amount of parameter data needed to initialise hillslope cells for a mesoscale catchment on the scale of the Mawddach. It may be possible to run the overall simulation as a series of sub-catchment models on separate computers, but it is uncertain how sediment routing between sub-catchments would be handled. The CAESAR model seems more suited to detailed geomorphological studies of small catchments up to 10km^2 with a single trunk stream.

GSTARS sediment transport model

The GSTARS model is essentially a river routing model (cf. section 3.1, fig.3.11) to which sediment erosion, transport and deposition functions have been added. The input to the model consists of hydrograph data for channel inflows, plus sedimentological data for the river channel and banks. Slope erosion and mass movement are only modelled within the flood plain.

A decision was taken to use GSTARS for sediment modelling within the Mawddach river system. It was apparent from initial experimentation with GSTARS models that measurable sediment erosion, transport and deposition processes were restricted to the period of flood events and the few days following these events. Two significant storms were chosen for analysis:

- the convective storm of 3 July 2001, which generated the highest river discharge values of any event recorded during this research project, although the event was of only a few hours duration. This magnitude of storm was estimated to have a return period of 200 years.
- the sequence of storms of 3-4 February 2004, which generated the longest period of continuous flooding around the head of the Mawddach estuary recorded during the project, although maximum river discharge values for any one hour period were significantly less than during the July 2001 extreme event. Storms of this magnitude are estimated to have a return period of 4 years.

In this way, it was hoped to compare the amounts of sediment erosion, transport and deposition generated by rare but extremely severe flash flooding, in comparison to the less severe flood events of longer duration which occur on an almost annual basis.

Mathematical basis of the GSTARS model

To carry out a sediment transport simulation, the river is divided into a series of reaches. The twelve reaches of the Mawddach sub-catchment and the eight reaches of the Wnion sub-catchment defined in section 3.2 are again used for this model.

Within each reach, the geometry of the river must be defined. Cross sections are surveyed at a series of points, and the elevation of each cross section above a datum is recorded. Channel roughness is specified for one or more zones across each section. The downstream channel distance between cross-sections is measured.

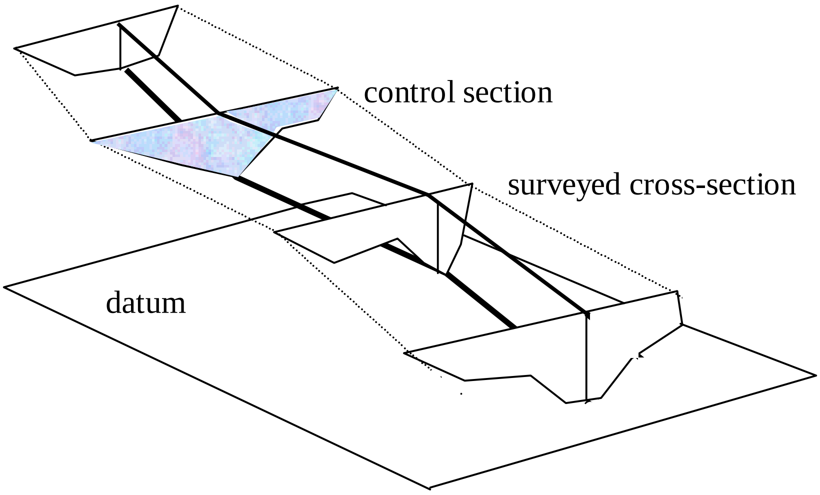


Figure 3.83: River reach data for input to the GSTARS model

One of the cross sections is chosen as a point at which river stage height and discharge will be specified for a sequence of time intervals during the flood event. The combination of channel geometrical and roughness characteristics, plus water flows at the control section, provide sufficient data to calculate water velocities and depths at the remaining points within the channel reach. This data will, in turn, be used in the calculation of sediment erosion rates, transport and deposition.

The method used by GSTARS to determine water depths and velocities through the river reach is based on the energy equation:

$$z_1 + y_1 + \alpha_1 \frac{V_1^2}{2g} = z_2 + y_2 + \alpha_2 \frac{V_2^2}{2g} + h_l$$

where: z is channel bed elevation, y is water depth, V is mean water velocity, and α is a correction factor (close to 1) which allows the approximation of discharge as the product of mean water velocity and channel cross sectional area. Subscripts 1 and 2 refer to locations at locations at each end of a river reach. The significance of the equation is shown in fig.3.84.

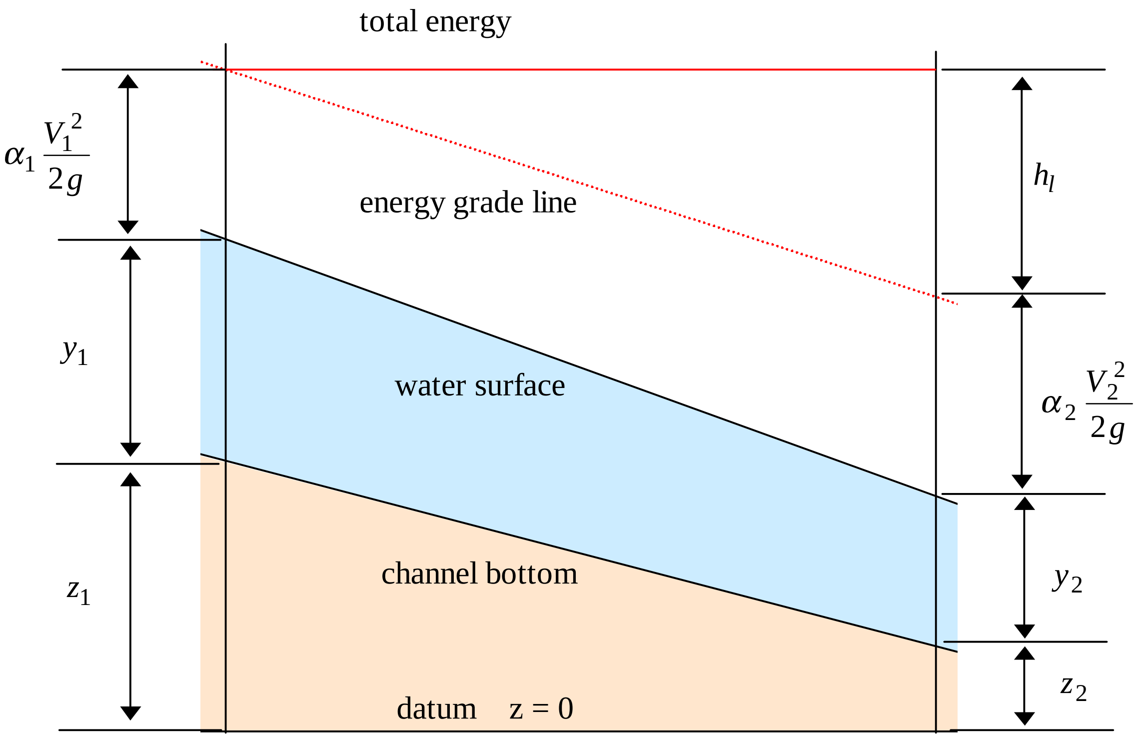


Figure 3.84: Calculation of total stream energy

The total energy of the stream flow at any point will be the sum of the potential energy and kinetic energy of the water.

- Potential energy at the water surface is determined by the surface elevation, which is in turn the total of the river bed elevation and the water depth.
- Kinetic energy of the water flow per unit area can be determined from the water velocity, allowing a correction α for channel shape.

The quantity h_l represents graphically the energy loss which occurs over the length of the river reach as a result of processes such as turbulence.

It is apparent from fig.3.84 that a stream could possess equal total energy under different flow conditions:

- shallow fast flow, where kinetic energy was increased but potential energy reduced,
- deep, slow flow, where potential energy was increased but kinetic energy reduced.

These two situations can indeed exist in nature, and are illustrated as points on a plot of kinetic energy E against water depth h under conditions of constant discharge (fig.3.85). The energy minimum occurs at a water depth known as *critical depth*. A shallow fast flow, such as point A, is said to be *super-critical*, whilst a deep, slow flow, as at point B, is said to be *sub-critical*. For example, it is common for a stream to change abruptly from super-critical to sub-critical flow where the river gradient is suddenly reduced, as at the base of a weir. This process is known as a *hydraulic jump*.

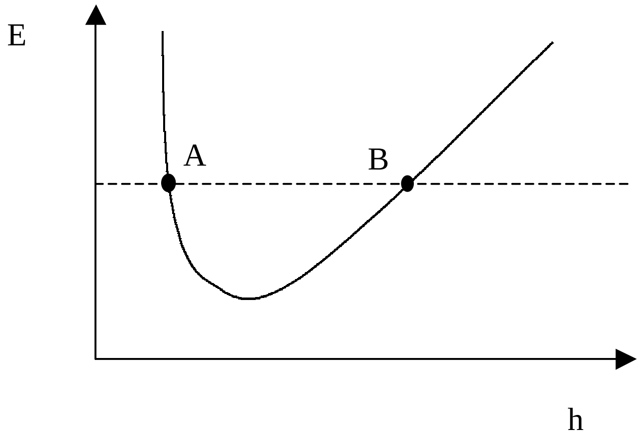


Figure 3.85: Kinetic energy – water depth curve for constant discharge

The GSTARS program is able to determine a continuous water surface profile where a change in flow regime occurs between two measured cross sections.

The determination of water depths is carried out by an iterative process using the relationship:

$$Z_{new} = Z_{old} - \frac{H_{old} - H_{new}}{1 - F_{old}^{2}\left(1 \mp 0.5C_{L}\right) \mp \left(\frac{3}{2}\right)\left(\frac{h_{f}}{R}\right)}$$

This equation involves six parameters:

Z	water surface elevation
H	total energy line
F	Froude number
R	hydraulic radius of the channel
C_L	energy loss coefficient
h_f	friction loss

The process begins by estimating values for Z and H at the channel cross-section, then progressively determining new values for Z and H until the difference between H_{old} and H_{new} falls below a specified tolerence. From the initial value of Z, an initial value for H can b determined using the relationship:

$$H = \frac{\alpha V^{2}}{2g} + y + z$$

where:	z	bed elevation
	y	water depth
	V	flow velocity
	α	velocity distribution coefficient
	H	elevation of the energy line above the datum.

Water velocity V can be determined by assuming that river discharge for the current time interval is equal to the discharge at the control section.

Hydraulic radius of the channel is the the ratio of its cross-sectional area to its wetted perimeter, and can be determined from the surveyed cross-section and specified water depth.

Froude number is the ratio of the inertial and gravitational forces operating within the stream, and is a measure of the resistance to water flow induced by the channel.

Froude number is computed by the equation:

$$F = \frac{Q}{A\left(\frac{g y_d \cos\theta}{\alpha}\right)^{1/2}}$$

where:		
	Q	water discharge
	A	cross sectional area
	y_d	hydraulic depth = area/top width
	θ	angle of inclination of channel bed
	α	velocity distribution coefficient, approximately 1

The energy loss coefficient C_L depends on channel geometry. This is set to 0.1 for a contraction in the channel cross-section, and 0.3 for an expansion.

The friction loss h_f is computed from the values of the friction slope S_f at adjacent sections using the formula:

$$h_f = \frac{1}{2}\left(S_{f1} + S_{f2}\right)\Delta x$$

where Δx is the downstream separation of the sections. The friction slope can in turn be calculated by a choice of methods in the GSTARS program: Manning's formula, Chézy's formula or the Darcy-Weisbach formula. Manning's formula is:

$$Q = \left(\frac{1.49}{n} A R^{3/2}\right) S_f^{1/2}$$

where:		
	A	cross sectional area
	R	hydraulic radius
	n	Manning roughness coefficient

A suitable value for Manning's roughness *n* can be selected by comparison with photographs of specimen river channels of known roughness (Arcement and Schneider, 2003; Barnes, 1967).

In order to determine suitable water surface profiles between channel cross-sections, it is necessary to identify situations where changes take place between *sub-critical, critical* or *super-critical* flows. To assist with this task, two quantities are calculated – the *critical depth* and the *normal depth* of the channel at each cross section.

For gentle or moderate downstream gradients, the *normal depth* is greater than the *critical depth*. If the water depth is greater than the *normal depth* at both ends of the section, then no change in flow regime occurs (fig.3.86, profile M1). If the water depth is less than the *normal depth*, the water surface will follow a parabolic path as it adjusts towards a *critical depth* downstream. The surface curve will follow M2 or M3, depending on whether the initial depth is above or below the *critical depth*.

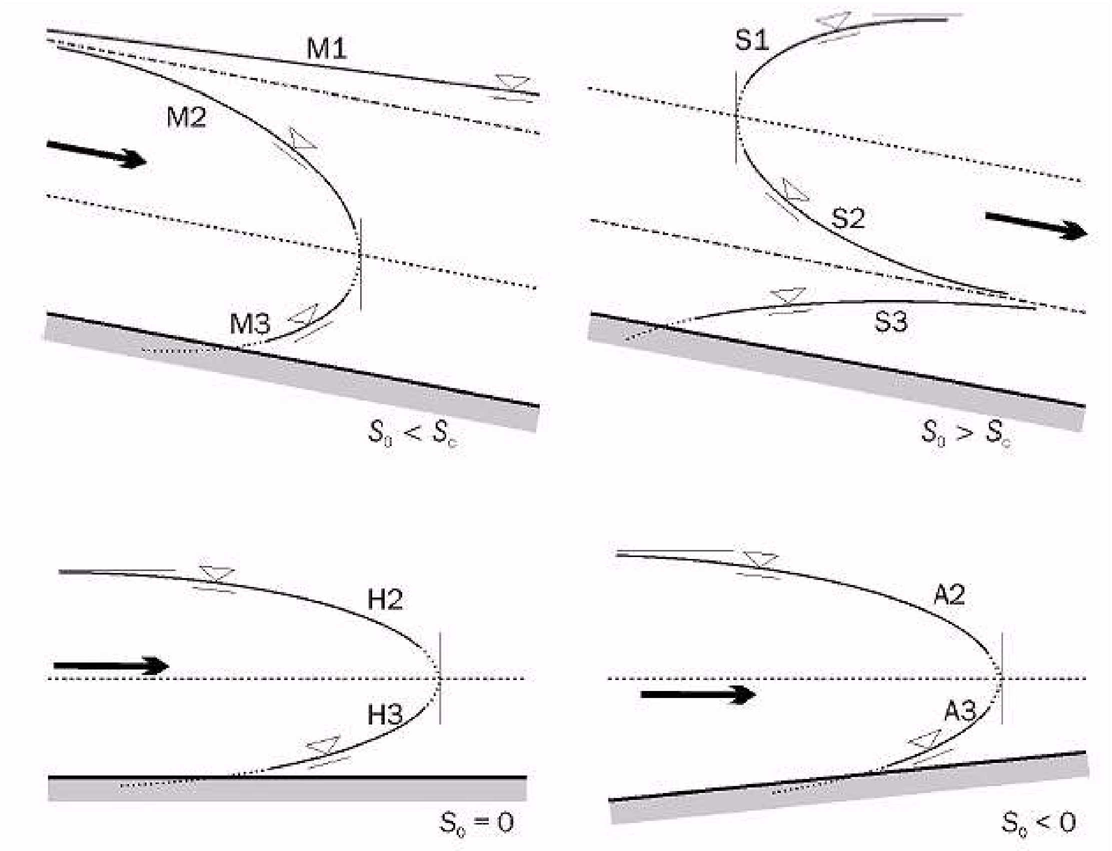


Figure 3.86: Water surface profiles in gradually varied flow (after Yang and Simões, 2000)

Normal depth may be less than *critical depth* for steep downstream slopes. If the initial water depth is above the *critical depth*, it will remain so (profile S1). If the initial water depth is below the *critical depth*, then it will trend towards the *normal depth* following parabolic profile S2 or S3.

In cases where the river channel is horizontal or slopes upwards in the downstream direction, the water profile will always trend towards the *critical depth*, following one of the paths H2,H3, A2 or A3.

The determination of Normal Depth *g(d)* is carried calculated by:

$$g(d) = Q - K(d)\sqrt{S_0} = 0$$

where:		
	K(d)	conveyance
	S_0	bottom slope

Conveyance is related to friction slope S_f:

$$Q = KS_f^{1/2}$$

Critical depth is determined by setting the value of the Froude number to 1:

$$F = \frac{Q}{A\left(\frac{gy_{critical}\cos\theta}{\alpha}\right)^{1/2}} = 1$$

Sediment modelling

After determining water depths and flow velocities for a time interval of the simulation, the next stage is to determine the amounts of sediment erosion, transport and deposition for each section of the reach. Conservation laws are applied, as illustrated in fig. 3.87.

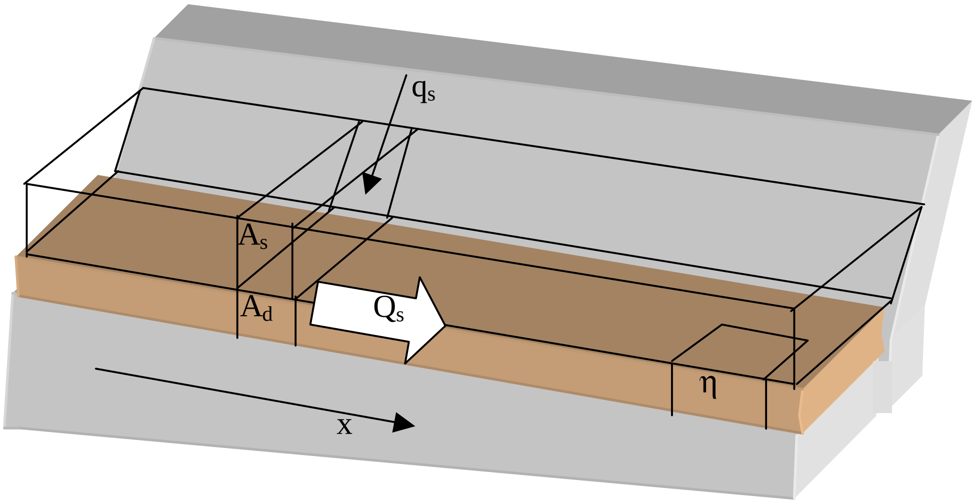


Figure 3.87: Components of the model for conservation of sediment mass

Conservation of sediment mass is determined by:

$$\frac{\partial Q_s}{\partial x}+\eta\frac{\partial A_d}{\partial t}+\frac{\partial A_s}{\partial t}-q_s=0$$

where

η	volume of sediment in a unit bed layer volume
A_d	volume of bed sediment per unit length
A_s	volume of sediment in suspension at the cross section per unit length
Q_s	volumetric sediment discharge
q_s	lateral sediment inflow

Essentially this equation is stating that any change in the amount of sediment being transported at successive monitoring points downstream must be balanced by erosion of the river bed adding sediment to the transport stream, or deposition removing sediment from transport.

The expression may be simplified by making an assumption that the change in suspended sediment concentration in a cross section is much smaller than the change of the river bed during any time interval, ie.

$$\frac{\partial A_s}{\partial t}<<\eta\frac{\partial A_d}{\partial t}$$

Assuming that the sediment transport function for a cross section remains constant during a time interval, then

$$\eta\frac{\partial A_d}{\partial t}+\frac{dQ_s}{dx}=q_s$$

The program routes sediment in stream tubes whose walls are defined by streamlines. Flow does not cross streamlines, so sediment remains within each stream tube as it is carried downstream. The number of streamtubes to be used by the model can be defined by the user. Sediment processes within each stream tube are modelled separately. Thus it is possible for GSTARS to model both erosion and deposition simultaneously on different sections of a channel cross section during a particular time interval.

Sediment transport is computed by size fraction. Particles of different size are transported at different rates. Depending on water velocity, some size fractions may be eroded whilst others are deposited. The model uses an *active layer*, which represents all the sediment which is available for transport during a time interval. Active layer thickness can be defined by the user. The program is able to model a situation known as *armouring* where all fine material is eroded from the surface of the active layer, leaving stable coarser sediment exposed. Deposited sediment during any time step is initially added to the active layer, but may be transferred to an inactive deposition layer when the thickness of the active layer is reset at the start of the next time interval (fig.3.88).

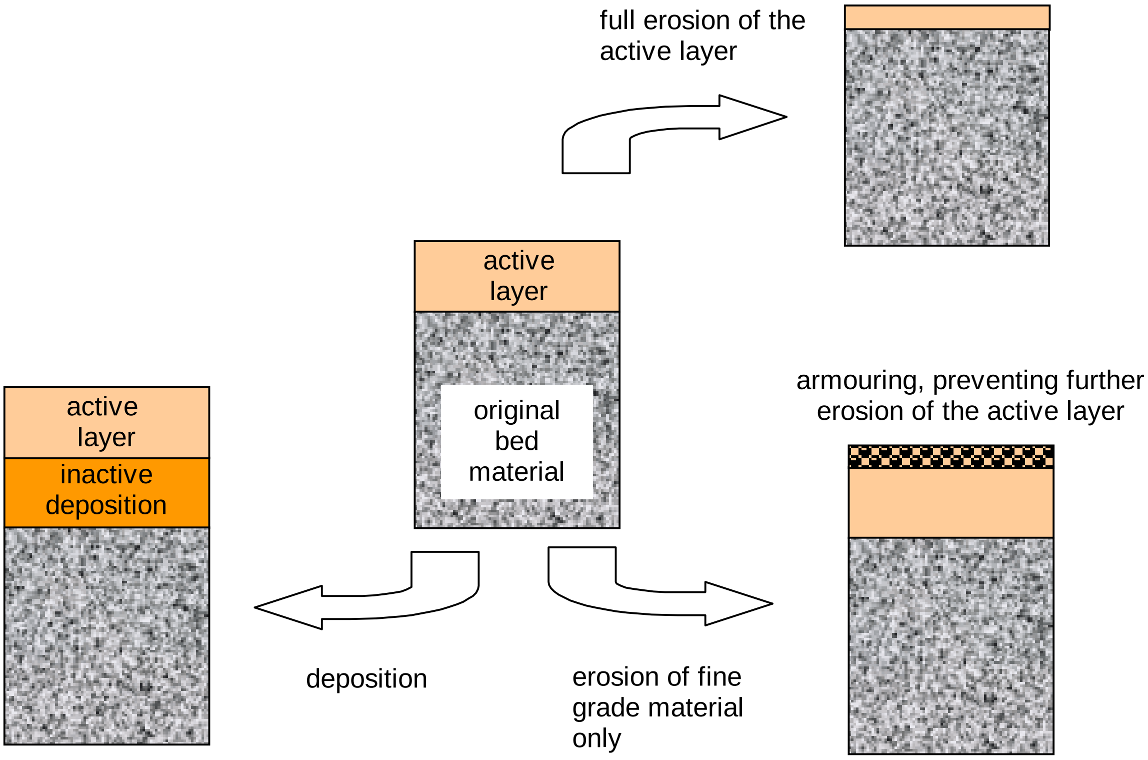


Figure 3.88: Sediment processes modelled by GSTARS

Initial sediment size distributions at each cross section must be specified when setting up a simulation.

For any time step, erosion may occur if the transport capacity of the stream at a cross section is greater than the incoming load from upstream. Various sediment transport functions are available within GSTARS. The method chosen for the Mawddach model is Yang's Sand (1973) and Gravel (1984) Transport Formulas, which is valid for the range of sediment sizes common within the river system:

Unit stream power formula for sand transport:

$$\log C_{ts} = 5.435 - 0.286 \log \frac{\omega d}{v} - 0.457 \log \frac{U^*}{\omega} + \left(1.799 - 0.409 \log \frac{\omega d}{v} - 0.314 \log \frac{U^*}{\omega} \right) \log \left(\frac{VS}{\omega} - \frac{V_{cr} S}{\omega} \right)$$

Unit stream power formula for gravel transport:

$$\log C_{tg} = 6.681 - 0.633 \log \frac{\omega d}{v} - 4.816 \log \frac{U^*}{\omega} + \left(2.784 - 0.305 \log \frac{\omega d}{v} - 0.282 \log \frac{U^*}{\omega} \right) \log \left(\frac{VS}{\omega} - \frac{V_{cr} S}{\omega} \right)$$

where:

C_{ts}	total sand concentration
C_{tg}	total gravel concentration
ω	sediment fall velocity
d	sediment particle diameter
U^*	shear velocity
VS	unit stream power
V	flow velocity
S	water surface slope
V_{cr}	critical flow velocity at incipient motion

The sand transport formula is used for grain sizes less than 2mm, whilst the gravel formula is used for grain sizes of 2mm or greater.

Channel width and depth adjustment

The GSTARS model uses minimum energy dissipation rate theory (Song and Yang, 1979) to determine the relative amounts of bed erosion in a vertical direction and bank erosion in a horizontal direction at each cross section. This theory specifies that when a closed and dissipative system reaches its state of dynamic equilibrium, its energy dissipation rate must be at its minimum value:

$$\Phi = \Phi_w + \Phi_s = \text{minimum}$$

where

Φ	total rate of energy dissipation
Φ_w	rate of energy dissipation due to water movement
Φ_s	rate of energy dissipation due to sediment movement.

The system will tend to adjust itself until the energy dissipation rate is a minimum. The program attempts to minimise the stream power:

$$\gamma QS$$

where

Q is discharge,

S is channel slope,

γ is the specific weight of water.

A consequence is that horizontal erosion is favoured where river gradient is gentle, but vertical bed erosion is favoured where channel gradient is steep.

GSTARS sediment models for the Mawddach catchment

Modelling has been carried out using twelve sub-catchments for the Afon Mawddach and eight sub-catchments of the Afon Wnion. The model treats discharge as uniform along each reach. To set up the model for a reach, the course of the river is entered on a base map. The position of cross section points are then chosen (fig.3.89).

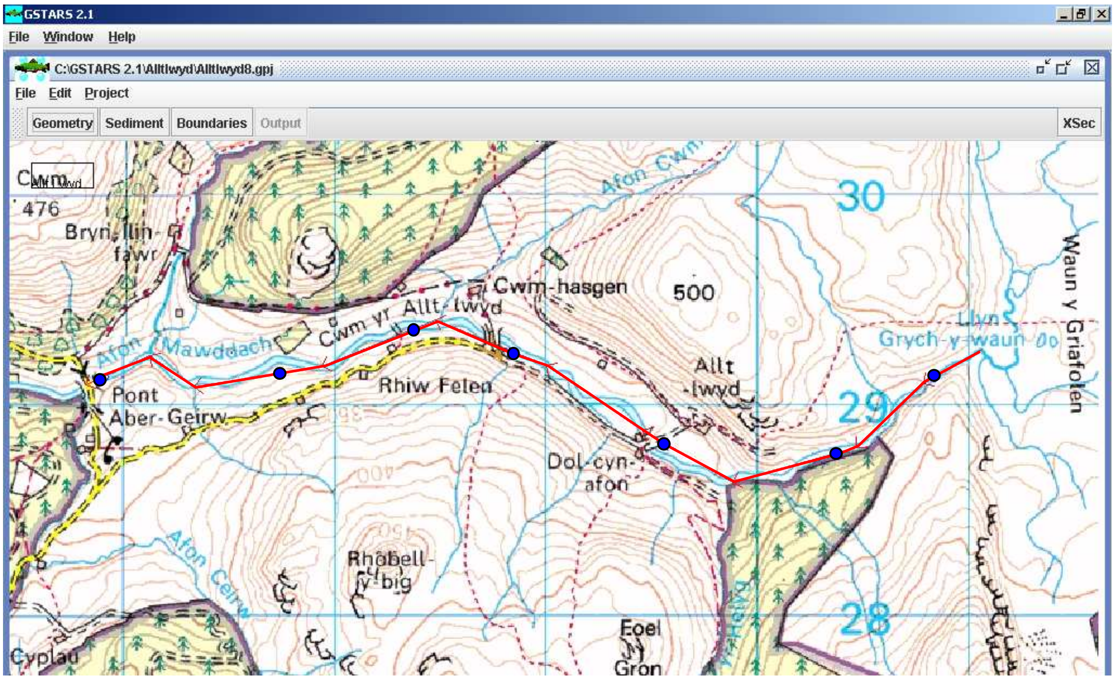
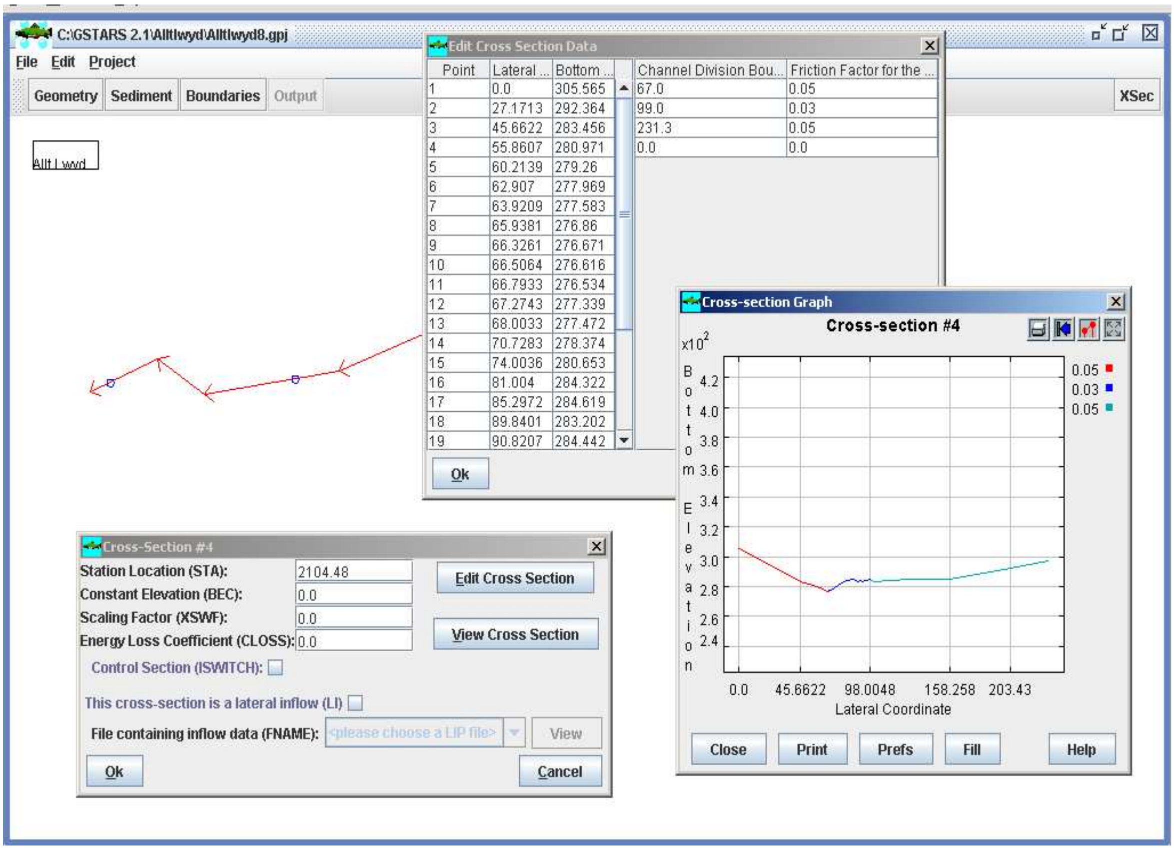


Figure 3.89: Entry of channel course and locations of surveyed cross-sections for the Alltlwyd reach, Afon Mawddach

Survey points for each cross-section are then entered, specifying distance across the section and elevation above Ordnance datum (fig.3.90). Cross-sections should extend to a level above maximum flood height on each bank of the stream. The collection of survey data for this purpose is described in chapter 3.2 above (cf fig.3.20). The GSTARS program displays the cross section, and allows Manning roughness values to be specified for different zones of the section.

Several choices of parameterisation and calculation method need to be made:

- options are available within GSTARS for the method of channel friction loss,
- the number of stream tubes should be specified for sediment transport,
- the sediment transport equation is selected,
- the depth of the active sediment layer is specified.



Point	Lateral ...	Bottom ...
1	0.0	305.565
2	27.1713	292.364
3	45.6622	283.456
4	55.8607	280.971
5	60.2139	279.26
6	62.907	277.969
7	63.9209	277.583
8	65.9381	276.86
9	66.3261	276.671
10	66.5064	276.616
11	66.7933	276.534
12	67.2743	277.339
13	68.0033	277.472
14	70.7283	278.374
15	74.0036	280.653
16	81.004	284.322
17	85.2972	284.619
18	89.8401	283.202
19	90.8207	284.442

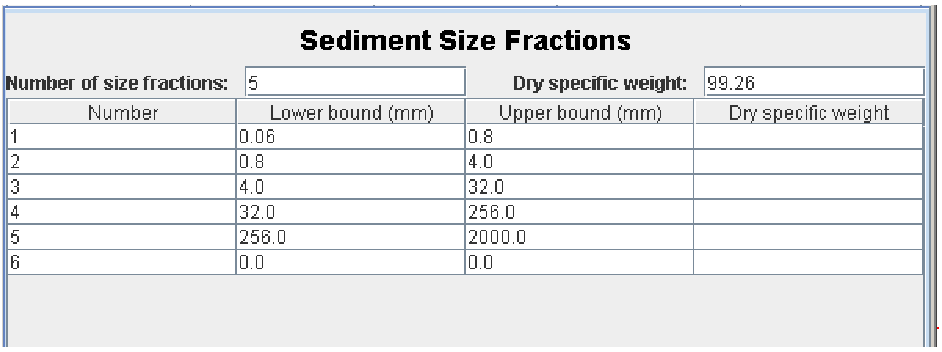
Channel Division Bou...	Friction Factor for the ...
67.0	0.05
99.0	0.03
231.3	0.05
0.0	0.0

Station Location (STA): 2104.48
Constant Elevation (BEC): 0.0
Scaling Factor (XSWF): 0.0
Energy Loss Coefficient (CLOSS): 0.0
Control Section (ISWITCH): ☐
This cross-section is a lateral inflow (LI) ☐
File containing inflow data (FNAME): <please choose a LIP file>

Figure 3.90: Input of river cross-section geometry and surface roughness

The size boundaries should be specified for each sediment class which is to be modelled separately in the transport model. For the Mawddach simulation, five size classes have been chosen to represent the range of grain sizes common within the river channels(fig.3.91):

1. silt – coarse sand
2. very coarse sand – fine gravel
3. medium gravel – coarse gravel
4. very coarse gravel – cobbles
5. boulders



Number of size fractions: 5
Dry specific weight: 99.26

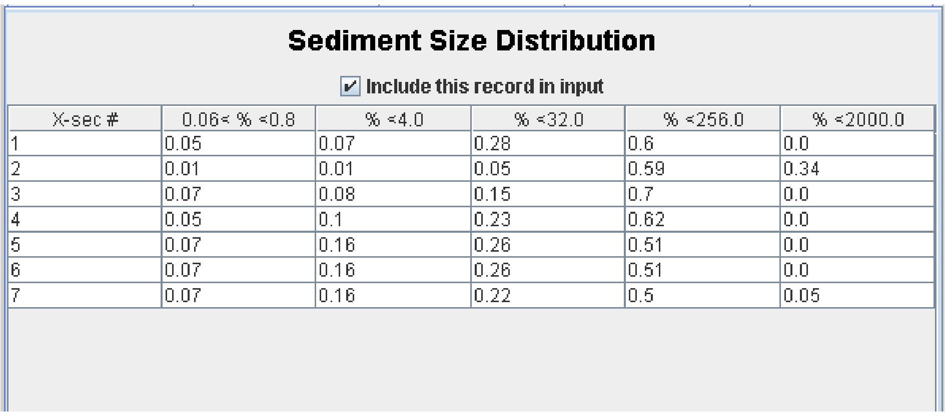
Number	Lower bound (mm)	Upper bound (mm)	Dry specific weight
1	0.06	0.8	
2	0.8	4.0	
3	4.0	32.0	
4	32.0	256.0	
5	256.0	2000.0	
6	0.0	0.0	

Figure 3.91: Specification of size fraction boundaries for the Mawddach model

For each cross-section, it is necessary to specify the fractions of each sediment class exposed within the channel bed and banks (fig.3.92). These fractions were estimated at the time that the cross-sections were surveyed in the field. The procedure involved:

- selection of a series of sampling points at intervals of 2m along the channel cross profile at bankfull level,
- estimation of the percentages of visible sediment within each of the five size grades, aided by the use of a 1m botanical quadrat frame divided with strings into 100 percentage squares.
- averageing of the results from each sample point to provide sediment size grade percentages for the overall cross section.

Fig.3.93 illustrates the typical wide variation in grain size observed within the bed and banks of upland reaches of the Mawddach and Wnion.



Sediment Size Distribution

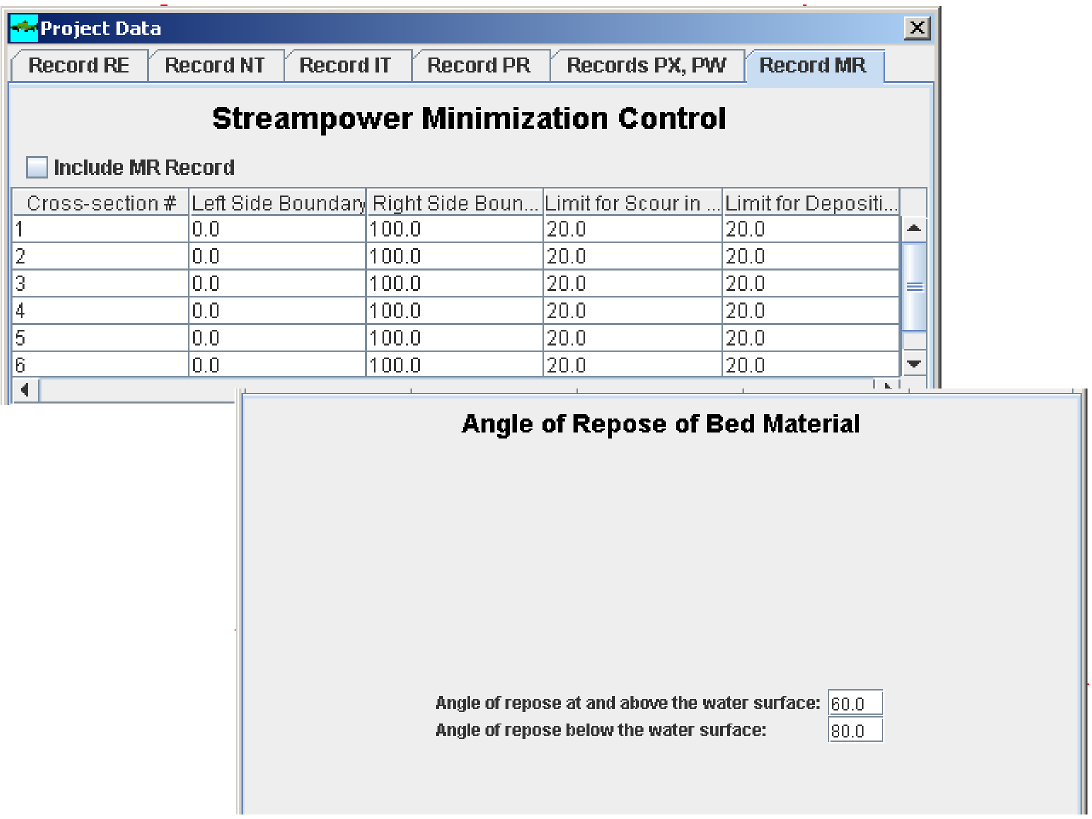
☑ Include this record in input

X-sec #	0.06< % <0.8	% <4.0	% <32.0	% <256.0	% <2000.0
1	0.05	0.07	0.28	0.6	0.0
2	0.01	0.01	0.05	0.59	0.34
3	0.07	0.08	0.15	0.7	0.0
4	0.05	0.1	0.23	0.62	0.0
5	0.07	0.16	0.26	0.51	0.0
6	0.07	0.16	0.26	0.51	0.0
7	0.07	0.16	0.22	0.5	0.05

Figure 3.92: Specification of fractions of different sediment size grade at each cross-section site within a river reach

Figure 3.93: Sediment ranging from sand to cobble grade, exposed in the bed and banks of the Afon Gain, Oernant reach.

Limits can be specified for the maximum vertical or horizontal erosion permissible at any cross-section site (fig.3.94). This allows erosion to be limited where solid bedrock is present in the river bed or river banks, or where walls or bridge abutments stabilise the channel. The maximum permitted deposition may also be specified.



Streampower Minimization Control

☐ Include MR Record

Cross-section #	Left Side Boundary	Right Side Boun...	Limit for Scour in ...	Limit for Depositi...
1	0.0	100.0	20.0	20.0
2	0.0	100.0	20.0	20.0
3	0.0	100.0	20.0	20.0
4	0.0	100.0	20.0	20.0
5	0.0	100.0	20.0	20.0
6	0.0	100.0	20.0	20.0

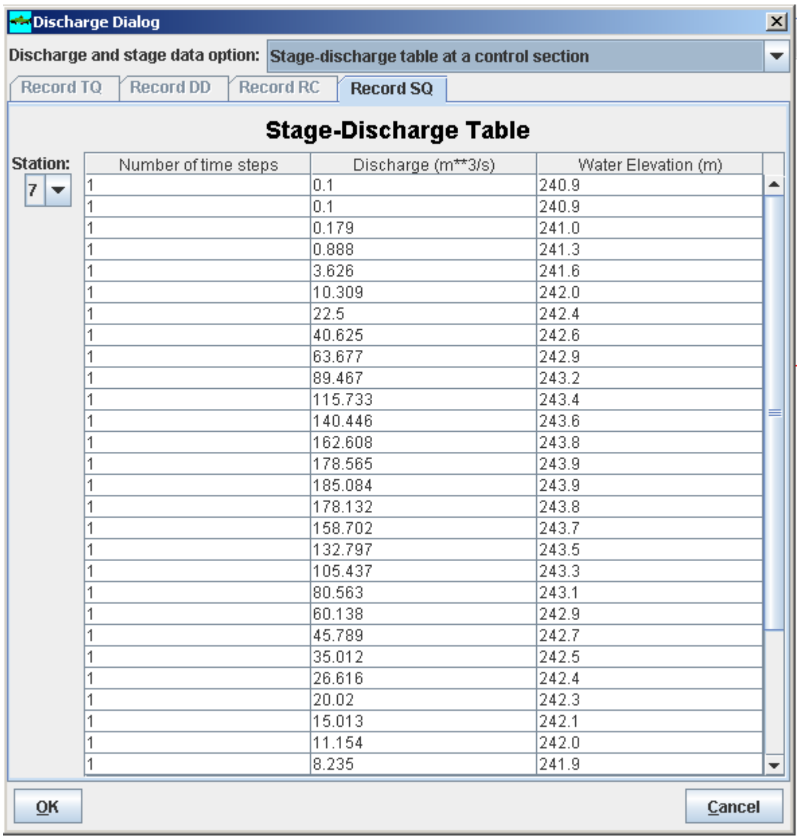
Angle of Repose of Bed Material

Angle of repose at and above the water surface: 60.0
Angle of repose below the water surface: 80.0

Figure 3.94: Specification of controls on bed and bank erosion and deposition

A further parameter required is the maximum stable slope angle allowed for the channel banks, above and below the water level. This which will depend on the cohesive properties of the exposed sediment .

Once the channel geometry and sediment characteristics have been specified, it is possible to simulate individual storm events. GSTARS requires discharge and water surface elevation data to be entered for a series of time steps during the simulation (fig.3.95). The actual length of a time step may be set by the user: 15 minute time steps have proved satisfactory for the Mawddach model.



Discharge and stage data option: Stage-discharge table at a control section

Stage-Discharge Table

Station: 7

Number of time steps	Discharge (m**3/s)	Water Elevation (m)
1	0.1	240.9
1	0.1	240.9
1	0.179	241.0
1	0.888	241.3
1	3.626	241.6
1	10.309	242.0
1	22.5	242.4
1	40.625	242.6
1	63.677	242.9
1	89.467	243.2
1	115.733	243.4
1	140.446	243.6
1	162.608	243.8
1	178.565	243.9
1	185.084	243.9
1	178.132	243.8
1	158.702	243.7
1	132.797	243.5
1	105.437	243.3
1	80.563	243.1
1	60.138	242.9
1	45.789	242.7
1	35.012	242.5
1	26.616	242.4
1	20.02	242.3
1	15.013	242.1
1	11.154	242.0
1	8.235	241.9

Figure 3.95: Entry of discharge and water elevation data during a storm event on a reach of the Afon Mawddach.

Discharge data for storm events in July 2001 and February 2004 were determined by the HEC-1 hydrograph model within the Watershed Modelling System. Water depths were calculated from the discharge values and river cross-section calibrations described previously in section 3.2.

The final stage in setting up a GSTARS simulation is to specify the quantity and frequency of output data during the run of the model. Output may include water depth and velocity values for each cross-section, sediment volumes transported within each size class, the extent of bed and bank erosion or deposition, and data for plotting changes to channel cross-sections.

Sediment transport modelling has been carried out for two flood events over the Mawddach–Wnion catchment, the convective storm of 3 July 2001 and the sequence of frontal storms of 3-4 February 2004:

Flood event of July 3, 2001

The flash flooding caused by the squall line thunderstorms of 3 July 2001 has been described in chapter 1.1. A vast amount of erosion of valley-infill periglacial and glacial sediments occurred during the flood. Particularly significant changes to valley form have occurred within the gorge sections of the Mawddach and its tributaries in the Coed y Brenin forest (Mason, 2002).

A hydrological model was produced using HEC-1 software for the 12 sub-catchments of the Mawddach and 8 sub-catchments of the Wnion. The synthetic hydrographs generated (figs 3.59-3.60) provide river discharge data for input to the GSTARS sediment model.

The results of the run of the GSTARS model for the Mawddach sub-catchments are summarised in Appendix D Table 1, which illustrates the methodology for carrying out the simulation. Sediment movement is calculated over a 9 hour period following the commencement of storm rainfall:

- Calculations begin with the headwater streams of the Mawddach and Gain in the Alltlwyd and Oernant reaches respectively.
- Sediment quantities within each size category are passed downstream to the next reaches; the Gwynfynydd reach on the Mawddach and the Pistyll Cain reach on the Gain.
- Sediment from these converging headwaters is combined as input to the Ganllwyd reach.
- Sediment from the Eden and Gamlan is combined the output from the Ganllwyd reach of the Mawddach main stream, as input to the Gelligemlyn reach.
- Sediment from the Afon Wen is finally added to provide input to the Llanelltyd reach.

- Output from the Llanelltyd reach enters the tidal head of the Mawddach estuary.

Data from Appendix D Table 1 is summarised in the chart of fig.3.97. It is seen that both erosion and deposition occurred at different points within the Mawddach river system during the flood event. This is related to the polycyclic relief of the Mawddach catchment, producing a series of steep rejuvenated river reaches interspersed by reaches of gentle gradient (fig.3.96).

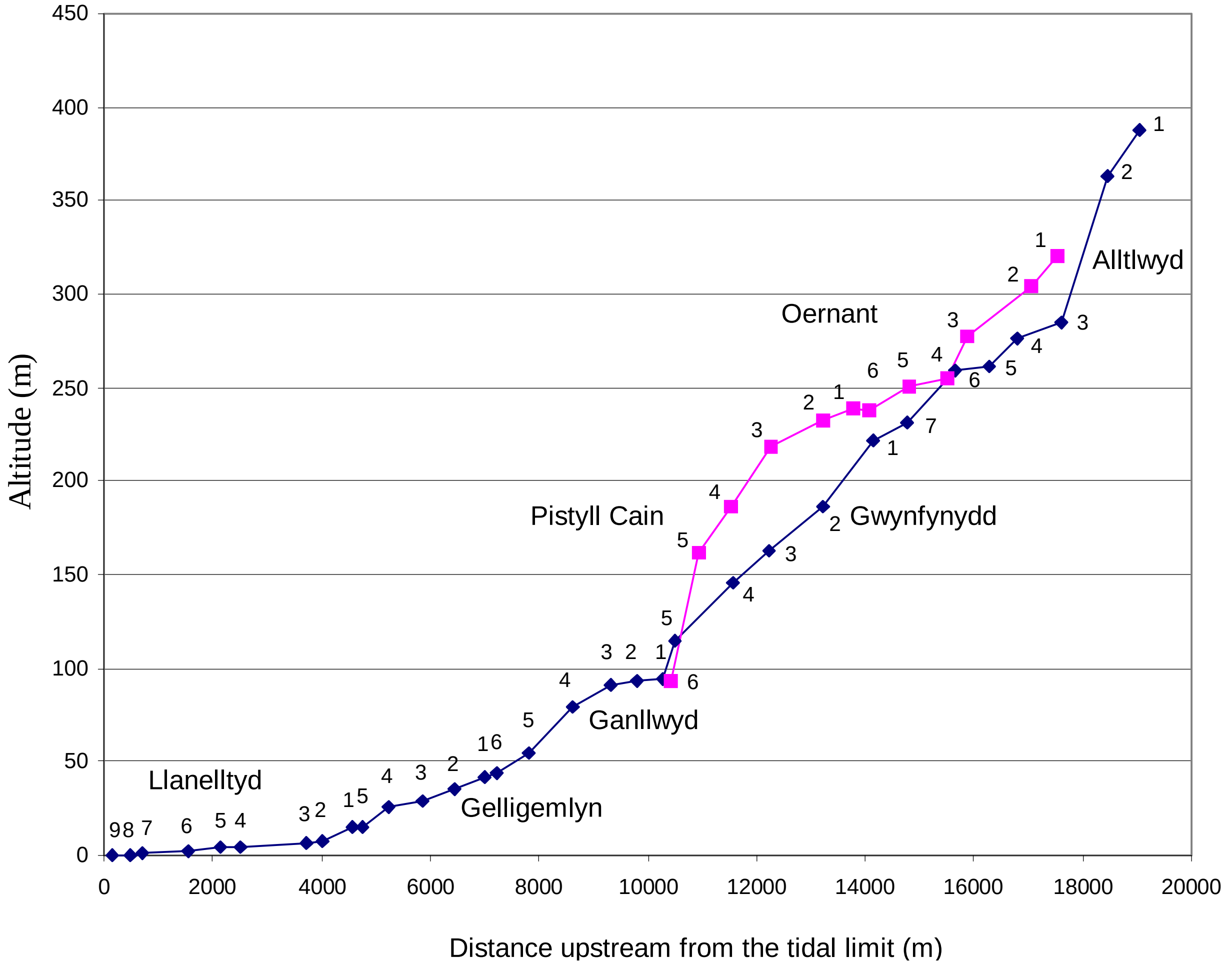


Figure 3.96: Reaches of the Mawddach sub-catchment.
Reach reference numbers refer to figs 3-97 and 3-100.

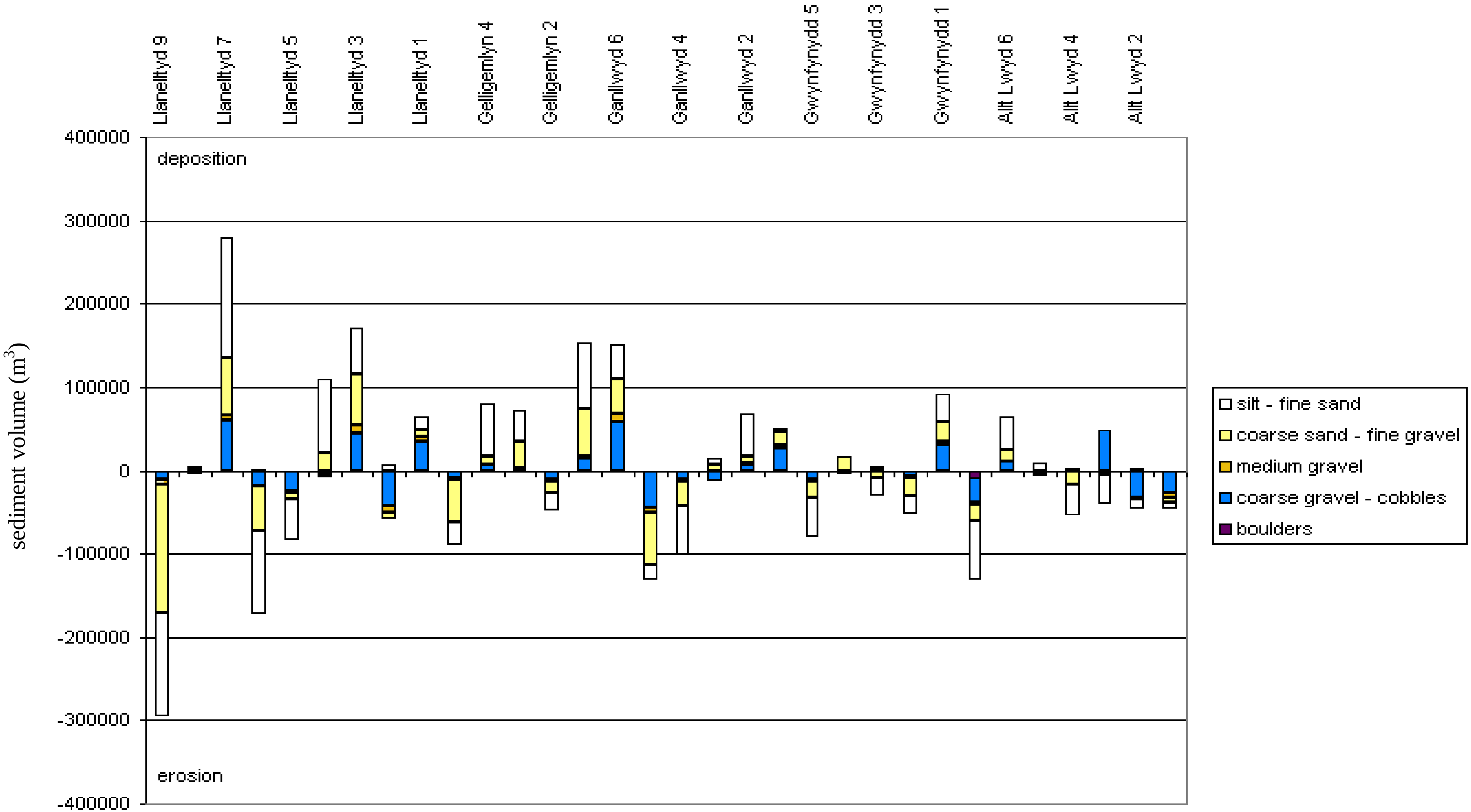


Figure 3.97: Sediment movement during the 3 July 2001 flood event: Mawddach sub-catchments

Valley cross-section plots produced by GSTARS appear consistent with profile changes which occurred during the 2001 flood event. An example is the erosion of a river cliff in glacial till at site 5 in the Oernant reach of the Afon Gain (fig. 3.99). Both vertical and lateral erosion have been simulated, along with deposition on the inner curve of a meander (fig. 3.98).

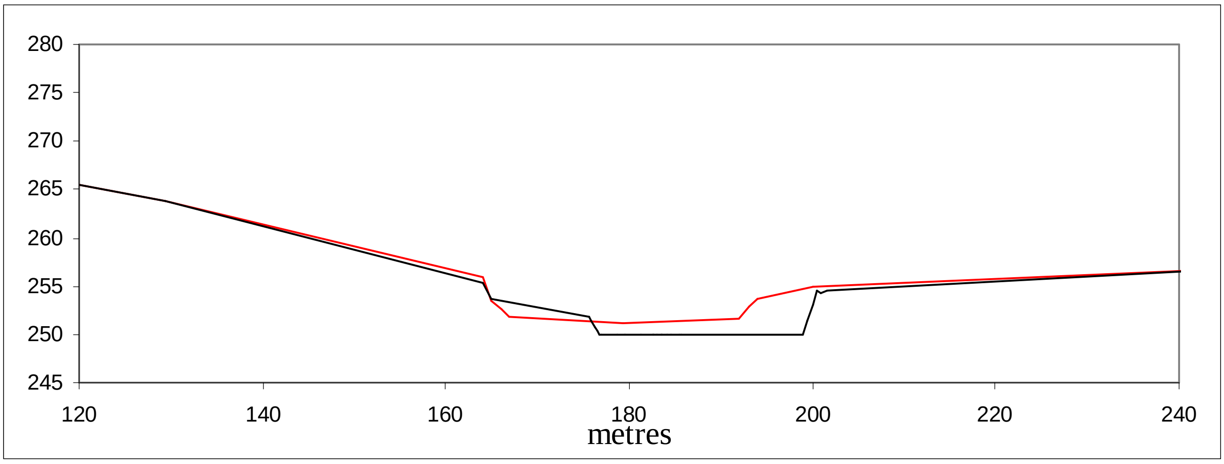


Figure 3.98: Modelling of channel profile change during the July 2001 flood event, Oernant reach of the Afon Gain. Initial pre-flood profile input to GSTARS is shown in red, with the modelled post-flood profile shown in black.

Figure 3.99: Photograph of the Oernant site depicted in the cross-profiles of fig.3.98. River cliff erosion occurred during the July 2001 flood, with gravel deposition on the meander slip-off slope opposite.

Details of sediment movement within the Oernant and Pistyll Cain reaches of the Afon Gain are given in fig.3.100.

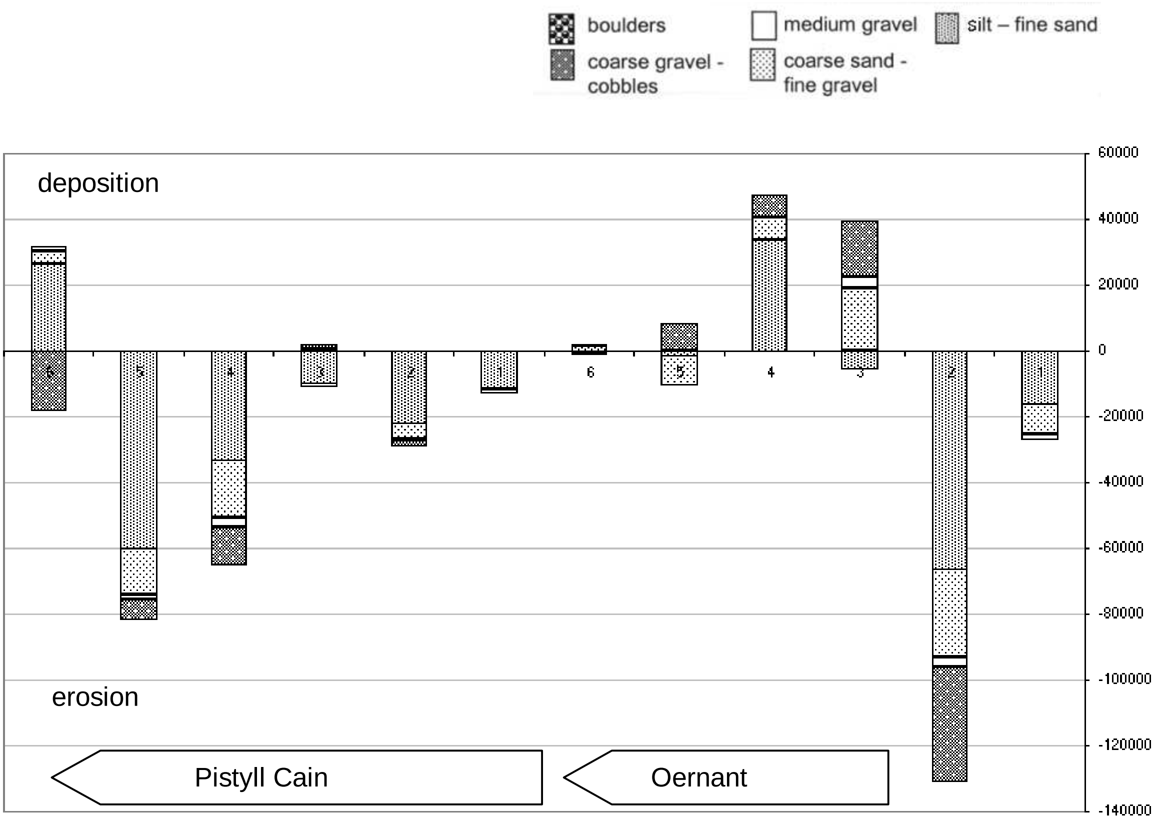


Figure 3.100: Erosion/deposition volumes (m^3) for river sections on the Afon Gain.

Sediment erosion and deposition volumes for modelled sections of the Afon Gain may be related to changes in river gradient. Erosion predominates, with a large sand fraction predicted at most erosional sites. This corresponds well with field observations of extensive erosion of glacial and periglacial valley infill, for example at Oernant sites 1–2 where the river has deeply incised a sheet of sandy glacial till (Fig. 3.101).

Sites of significant deposition, particularly of coarse grade material, may also be found within the upland reaches where valley gradients are reduced. An example is the deposition of gravel on grassland alongside the Afon Gain at Oernant sites 3–4 (Fig. 3.102).

Figure 3.101: Erosion of glacial till by the Afon Gain at Oernant sites 1–2 marked in figure 3.100

Figure 3.102: Gravel and sand deposition on grassland at Oernant site 4, along with tree debris washed down from forestry plantations bordering the river.

Movement of boulder-grade material is less common, but was predicted for the area of Pont Abergeirw on the upper Mawddach. This site (fig.1.15) has prominent boulder deposits within the channel, derived from glacial till. The simulated hydrograph for Pont Abergeirw indicates a rapid flash flood event close to the centre of the convective storm, where large water discharges from converging high-gradient streams were powerful enough to inflict considerable damage on the historic stone bridge.

The Mawddach flows through an area of disused metal mines, and considerable quantities of mine spoil were eroded from tips on the river banks (fig.1.91).
A section of forestry road along the Mawddach valley within Coed y Brenin was washed away by erosion on the outside of a meander, and has subsequently had to be rebuilt (fig.1.16). At these sites, erosion is modelled during the GSTARS simulation which is consistent with the field evidence. Large amounts of deposition and erosion are recorded for the lower Mawddach close to the tidal limit (fig.3.79), which is again consistent with field observations of the large unstabilised banks of poorly sorted sand-gravel-cobble sediment which accumulated in this area.

Fine sediment output is modelled as continuing at an exceptionally high rate for the day after the initial storm event, and was deposited on the floodplain of the lower Mawddach during overbank flow (fig.3.103). Twelve hours after the storm, the normal gravel bed of the Mawddach at Gelligemlyn was observed to be covered to a depth of several centimetres by coarse to fine sand. This sediment had been washed downstream by the following day and the clean gravel bed restored.

A feature of interest is the contrast in bed sediment grade at the confluence of the rivers Mawddach and Eden near the village of Ganllwyd (fig.3.104). Bedload of the Mawddach is predominantly of coarse gravel and cobble grade at this point, whilst the channel of the Eden is composed largely of boulders. From the sediment transport data presented in Appendix D Table 1, it is inferred that boulders within the Afon Eden are largely immobile residual deposits, left behind after the erosion of Boulder Clay valley infill. Any boulders reaching the more powerful River Mawddach may be rolled downstream as bedload and buried by large volumes of gravel during flood events.

Figure 3.103: Deposition of sand and silt on the Mawddach floodplain south of Gelligemlyn. Photograph: Chris Dixon

Figure 3.104: Confluence of the Afon Eden (approaching from the middle distance) with the Afon Mawddach (flowing towards the left in the foreground). Notice the contrast in bed sediment grade between the channels.

Modelling of sediment movement in the Afon Wnion sub-catchments during the 3 July 2001 flood event was carried out by a similar method to the Mawddach sub-catchment model.

- Sediment output is calculated separately for the Drws y Nant, Pared yr Ychain, Craig y Benglog and Rhobell Fawr reaches. These volumes are combined as input to the Craig y Ffynnon/Bontnewydd reach.
- Output from the Afon Clyweddog is combined with sediment from the Bontnewydd reach to provide input to the Lower Wnion reach.

Sediment transport data is summarised in Appendix D Table 2, and presented graphically in fig.3.105. Significant sediment erosion and deposition is restricted to the western part of the Wnion sub-catchment, particularly the Bontnewydd, Clyweddog and Lower Wnion reaches. This is constant with the raingauge data (cf fig.3.55). The maximum storm rainfall centre was located to the north over the Mawddach sub-catchment, but an additional convective cell of lesser magnitude appears to have been active over the Wnion valley between Dolgellau and Bontnewydd for part of the storm event.

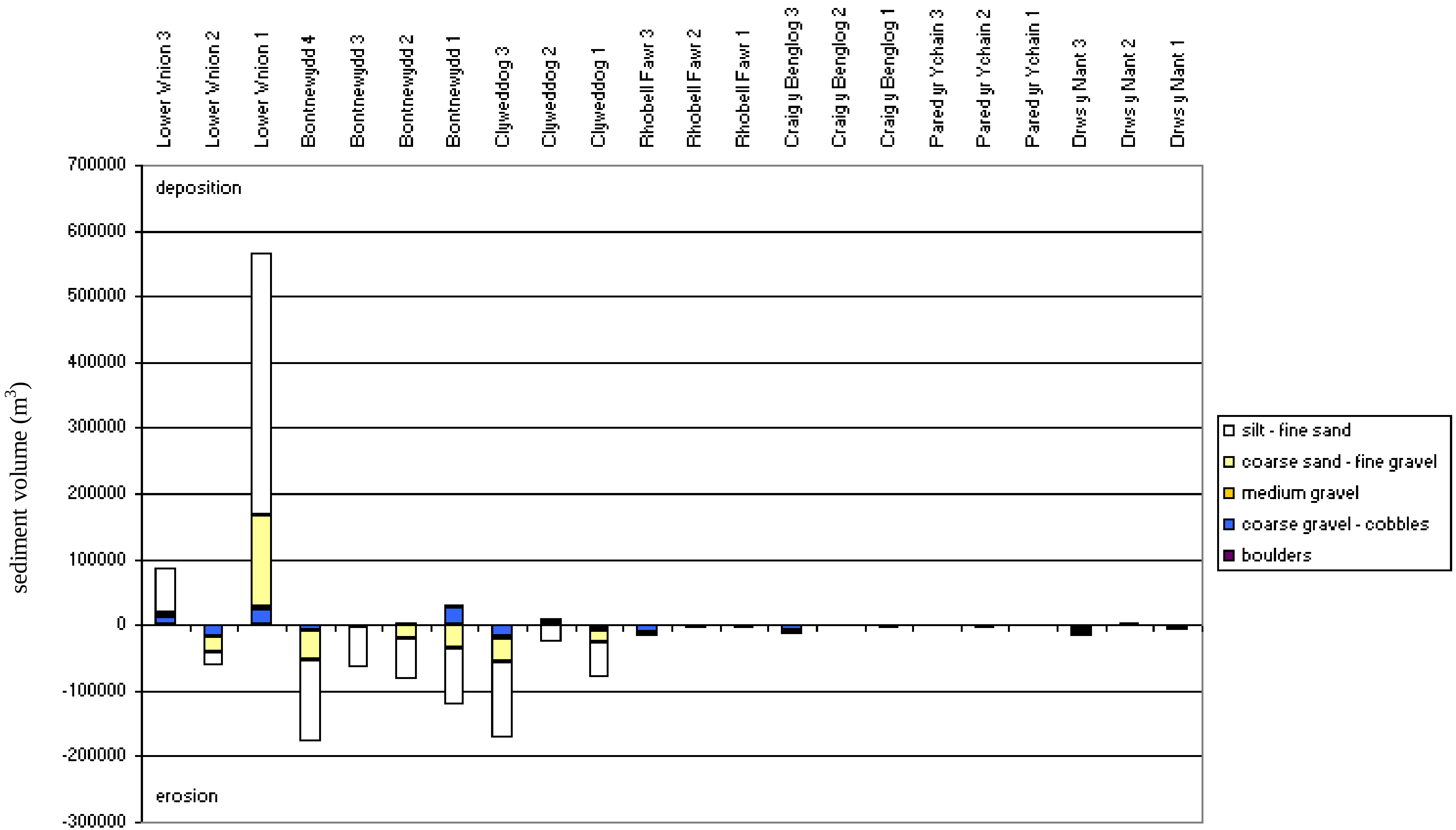


Figure 3.105: Sediment movement during the 3 July 2001 flood event: Wnion sub-catchments

Sediment ranging from coarse sand to coarse gravel grade is predicted to have been deposited around the town of Dolgellau (fig.3.105, Lower Wnion site 1). This is consistent with the large volumes of mixed sediment which accumulated at Bont Fawr (figs 3.106-3.107).

Figure 3.106 (above). Mixed sediment which accumulated close to Bont Fawr, Dolgellau, as a result of the July 2001 storm.

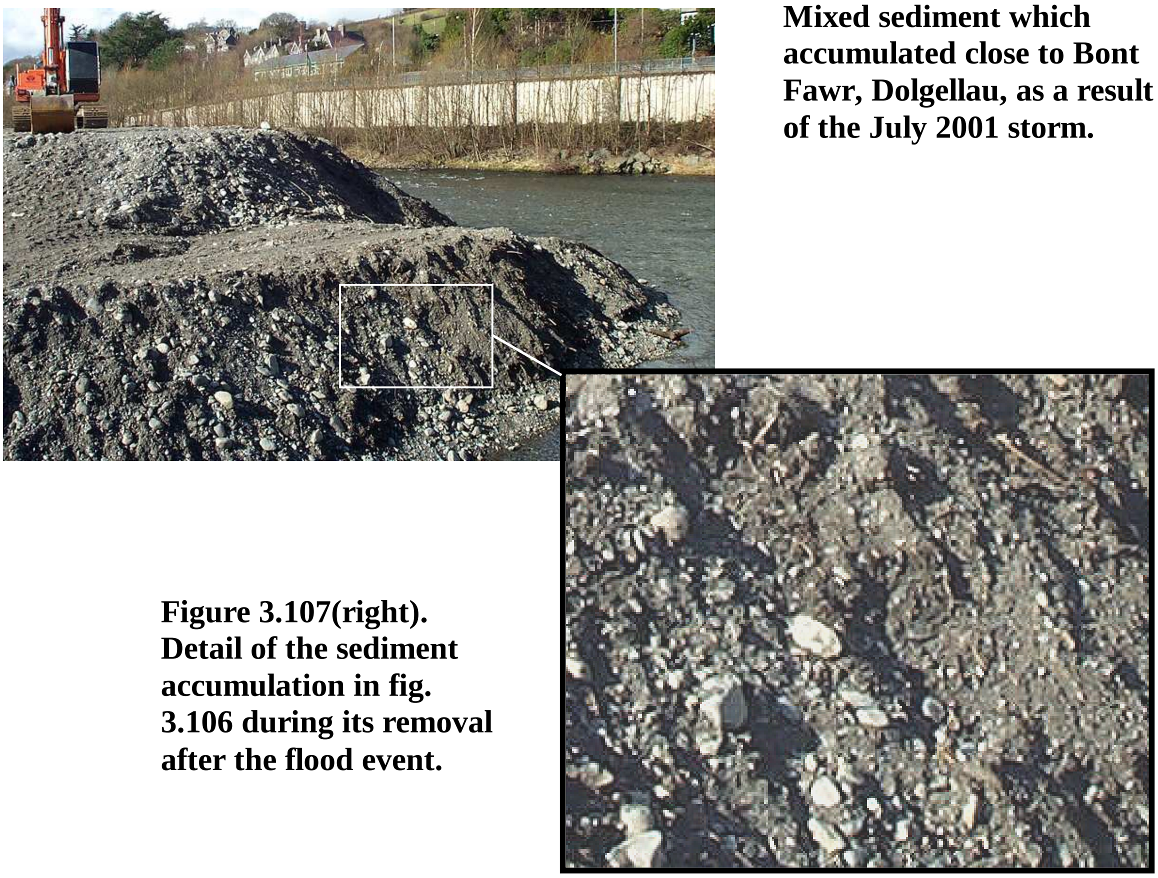


Figure 3.107(right). Detail of the sediment accumulation in fig. 3.106 during its removal after the flood event.

Output to the Mawddach estuary

Table 3.3 and figure 3.108 give GSTARS estimates of total output rates of sediment to the Mawddach estuary during each 1.5 hour time period within each sediment size grade. Sediment discharge data will be used in Section 3.4: River and Floodplain Processes, to provide input for flood scenario modelling for the Lower Wnion valley around Dolgellau.

	Sediment grade				
time (hours)	1	2	3	4	5
0	0	0	0	0	0
1.5	9476	4322	236	441	0
3	41580	39389	1447	4782	0
4.5	59634	53842	2027	5770	0
6	46960	52409	2308	4991	0
7.5	36867	32126	1859	707	0
9	26128	10676	965	0	0

Table 3.3. Sediment output rate (tonnes/hour) during each time interval of the 3 July 2001 flood event.

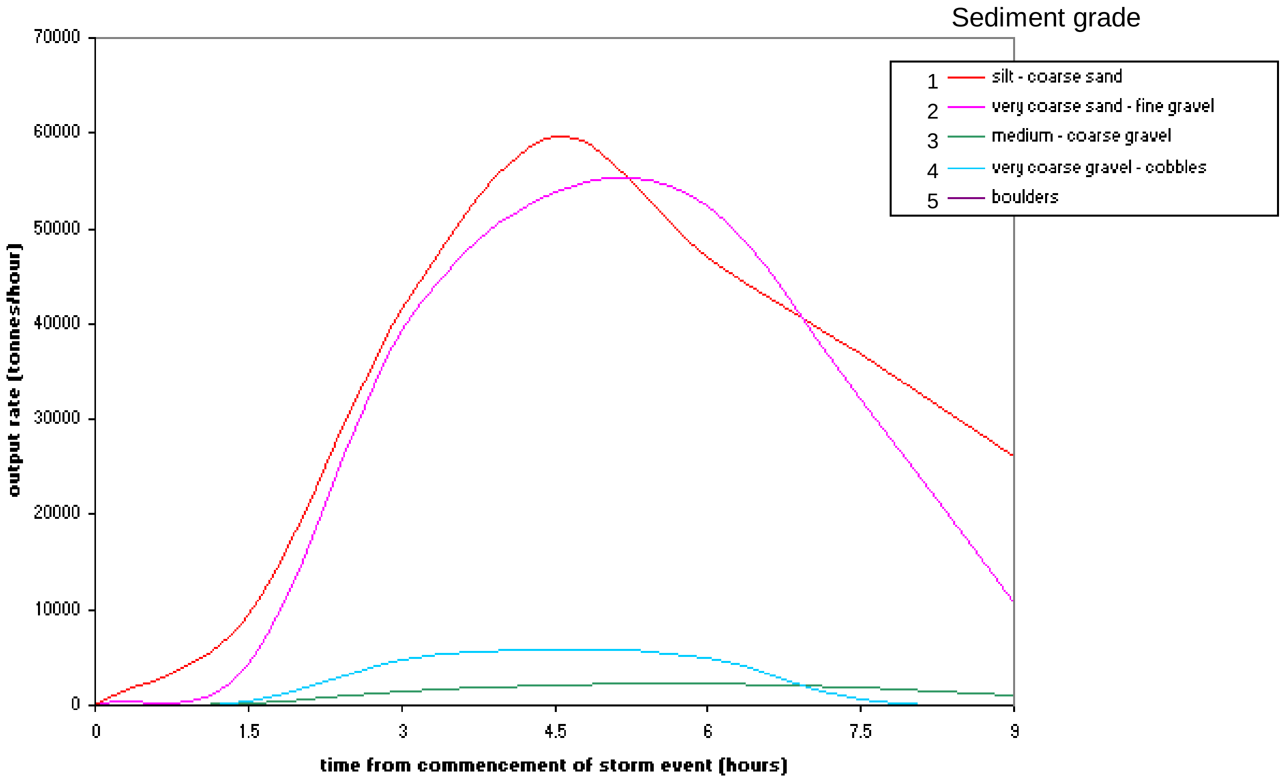


Figure 3.108: Sediment output rates for sediment size classes during each time interval of the 3 July 2001 flood event.

Flood event of 3-4 February 2004

Sediment modelling for the flood event of 3-4 February 2004 was carried out by the same methods described for the July 2001 model, with the exception that output was generated at intervals of 48 time steps of 15 minutes, i.e. each 12 hours, during the 2 day simulated period. Results for the Mawddach sub-catchments are shown in fig.3.110 and Appendix D Table 3, and results for the Wnion sub-catchments in fig.3.111 and Appendix D Table 4.

Sediment output to the estuary is shown in fig.3.109 and Table 3.4. A substantial silt and sand load is modelled for the whole period of the flood event. This is consistent with observations of high suspended sediment load for the Afon Mawddach as it discharged into the head of the estuary (fig.2.49).

	Sediment grade				
time (hours)	1	2	3	4	5
0	0	0	0	0	0
12	592	275	19	99	0
24	559	262	18	54	0
36	423	161	12	28	0
48	648	319	21	77	0
60	482	174	4	16	0

Table 3.4. Sediment output rate (tonnes/hour) during each time interval of the 3-4 February 2004 flood event.

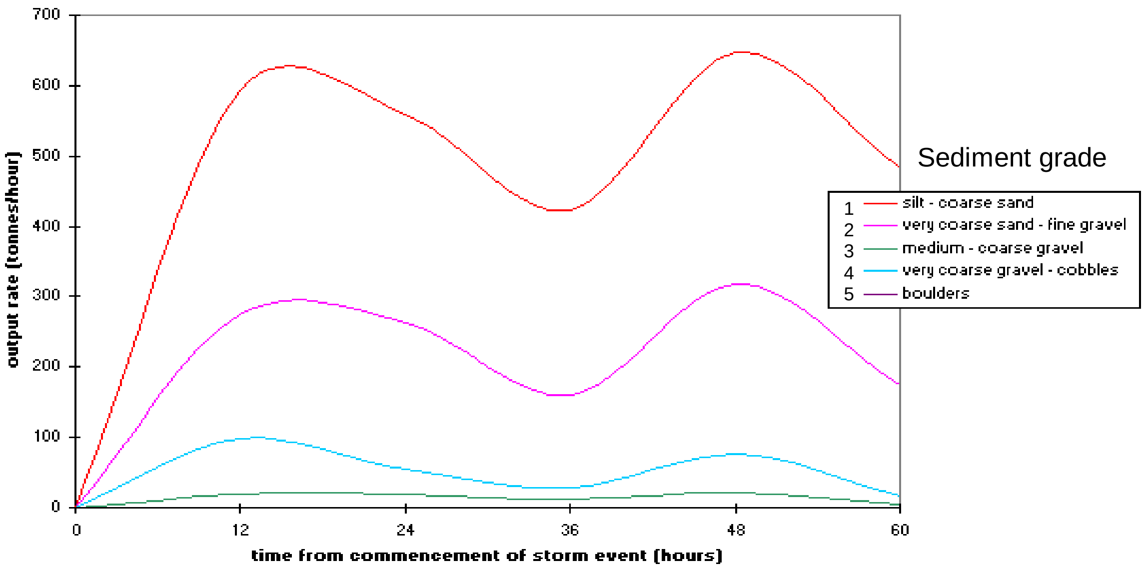


Figure 3.109: Sediment output rates for sediment size classes during each time interval of the 3-4 February 2004 flood event.

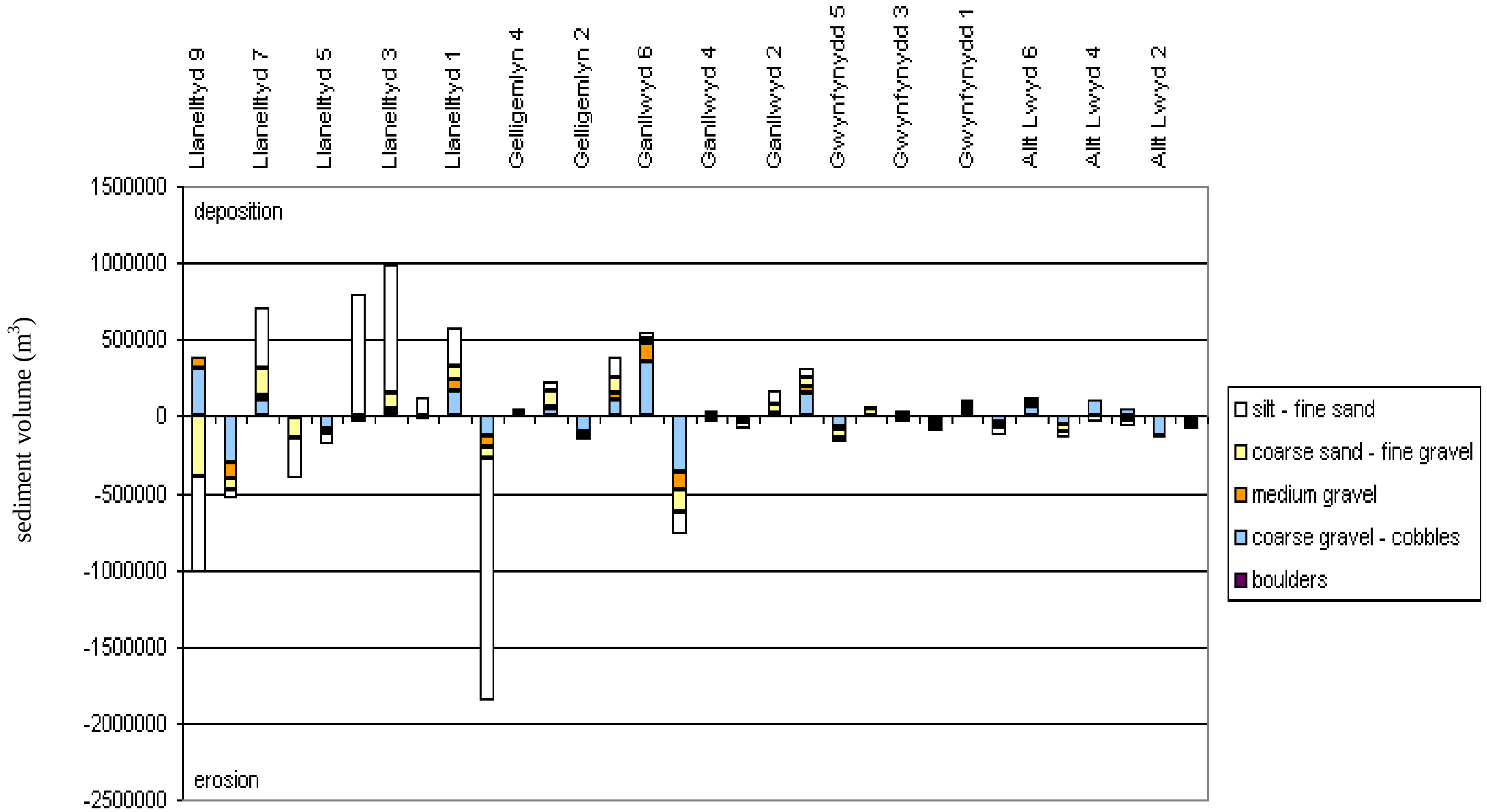


Figure 3.110: Sediment movement during the 3-4 February 2004 flood event: Mawddach sub-catchments

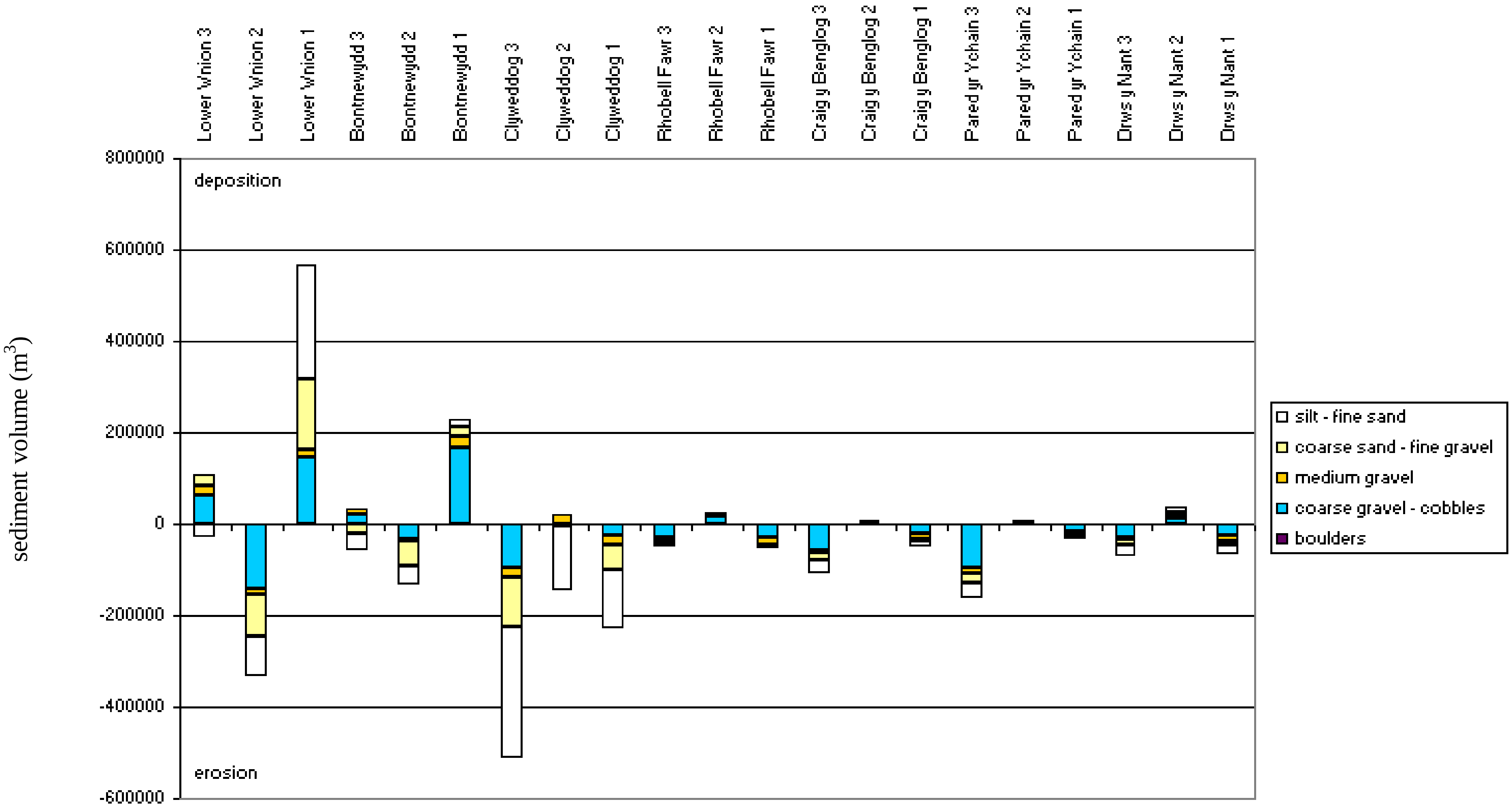


Figure 3.111: Sediment movement during the 3-4 February 2004 flood event: Wnion sub-catchments

Summary

- Modelling carried out by the GSTARS program for the July 2001 and February 2004 flood events provides results which appear consistent with field observations of erosion, sediment transport and deposition during these events. The program has been successful in predicting changes to channel cross-sections.
- Experience during the modelling activity has shown that accurate rainfall patterns and sub-catchment hydrographs are required for successful sediment modelling, with results particularly sensitive to the large localised variations which can occur within a mountain area.
- The peak rates of sediment discharge estimated by the GSTARS model for the July 2001 flood are approximately one hundred times greater then those for the February 2004 flood. This is consistent with field observations of exceptional river bank erosion to a height well above normal flood levels in the gorge section, and extensive deposition of fine sediment across agricultural land in the lower valley of the Mawddach.
- It must be taken into account that the February 2004 flood continued for approximately ten times the duration of the July 2001 flash flood, so the overall movement of sediment was considerable. Floods approaching the magnitude of the February 2004 event are an annual occurrence within the Mawddach catchment. Over a period of time, the volume of sediment redistributed by annual river processes may be equal to, or greater than, the volumes of sediment redistributed during rare extreme events.
- Estimates of coarse sediment deposition for the Lower Wnion and the head of the Mawddach estuary have been obtained for floods of different magnitude and duration, along with estimates of the volumes of coarse sediment transported downstream. This data will be used in Section 3.4: River and Floodplain Processes, to model flooding for the Lower Mawddach and Lower Wnion under different channel deposition scenarios.
- This preliminary evaluation of GSTARS has been qualitative. Further quantitative studies are needed, in which accurate field measurements of sediment erosion and deposition during flood events are compared to results generated by the sediment transport model.