3.6 The Mawddach Estuary

The rivers Mawddach and Wnion have their confluence at the head of the Mawddach estuary. The lower reach of each river is tidal for a distance of approximately 0.5km upstream from the confluence. Flooding of agricultural land, roads and the railway alongside the estuary have been regular problems. It is important in flood modelling to investigate the extent to which tides and river flows interact in the estuary and upstream towards the town of Dolgellau.

Physical background

The Mawddach estuary originated as a glaciated valley which was flooded by the sea after ice retreat to form a fjord (Howe and Thomas, 1968). Subsequently the Ro Wen shingle spit has grown by longshore drift of beach sediment northwards along the coast (fig.3.215). Silting is taking place in sheltered water behind the spit, and sandbanks are developing within the estuary as sand is carried in by rivers and tides.

Figure 3.215: Aerial view of the mouth of the Mawddach estuary, showing the Ro Wen shingle spit extending across the mouth of the estuary.
Photograph: Royal Commission on the Ancient and Historical Monuments of Wales

The Australian Natural Resources Atlas (Australian Government, 2008) presents a useful classification scheme for coastal inlets based on a process model. The geomorphological features which are developed depend on the relative energies of river flow, wave action and tidal flows operating at a particular location. Six classes of coastal inlet are identified (fig.3.216):

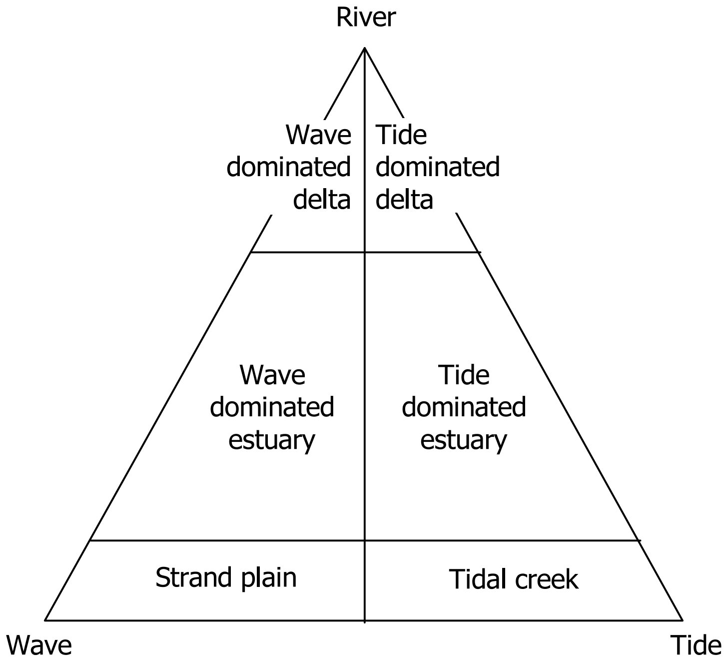


Figure 3.216: Classification of coastal inlets according to the Australian Natural Resources Atlas process model.

The Mawddach estuary fits within the ***Wave dominated estuary*** category, with kinetic wave energy dominating over tidal energy at the exposed estuary mouth which is susceptible to south westerly gales. Towards the head of the estuary, river flow can reach high kinetic energy levels during flood periods (fig.3.217):

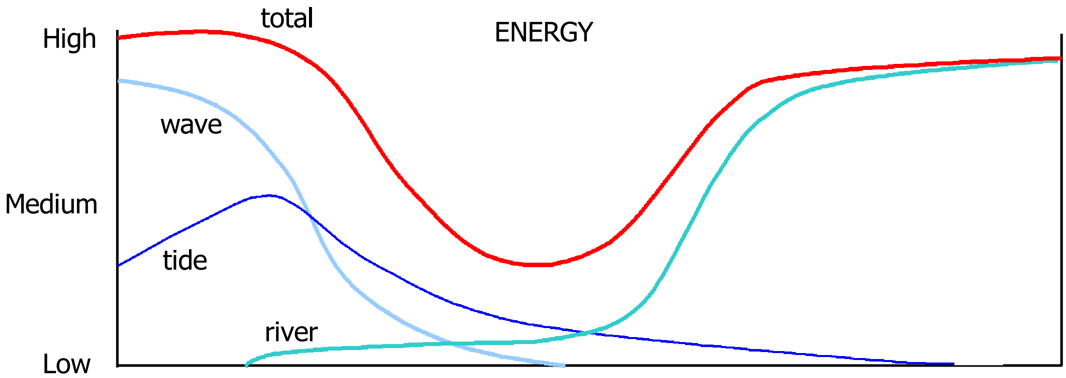


Figure 3.217: Time-integrated kinetic energy diagram for a wave dominated estuary (after Australian Government, 2008)

An idealised morphological model for a wave-dominated estuary is presented in the Australian Natural Resources Atlas (fig.3.218):

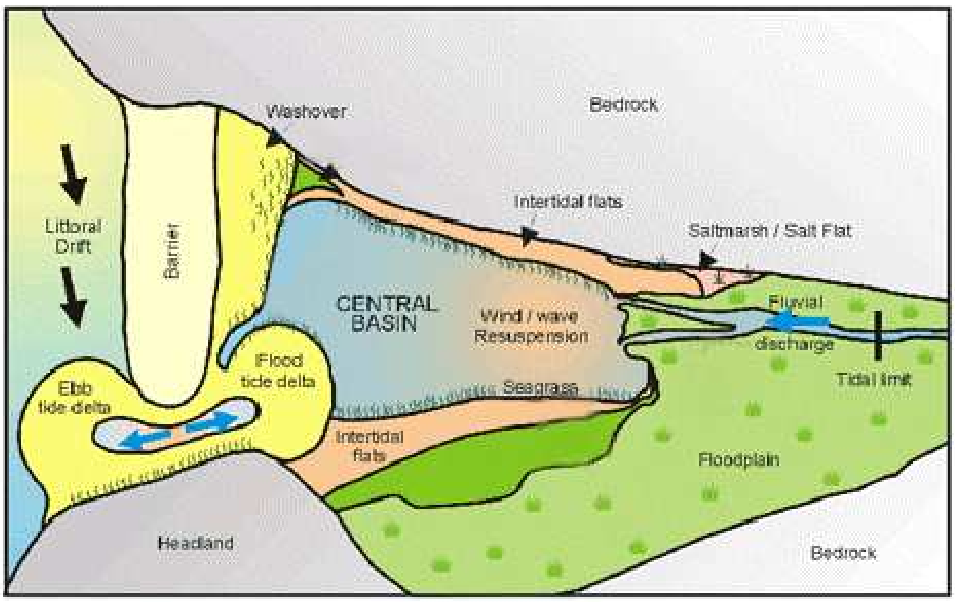


Figure 3.218: Idealised model for a wave-dominated estuary
(after Australian Government, 2008)

Most features of the idealised model can be identified in the Mawddach estuary. Sediment enters the estuary both from the sea, carried through the narrow estuary mouth by high velocity tidal inflows, and from the river system at the estuary head. Water turbidity is low. Waves cannot effectively penetrate the estuary due to the constricted mouth, and tidal energy is dissipated in the flood delta area inside the estuary mouth. Energy levels for sediment transport are low in the middle regions of the estuary and sediment trapping efficiency is high. Fine sediment is deposited along the estuary margins to form sandflats and muddy saltmarshes. There is a high risk of habitat modification or loss due to dynamic and unstable sedimentation processes.

Sobehrad (1997) identifes three mixing modes of fresh and salt water in estuaries:

- Salt wedge estuaries, where river flows are high and tidal flows are weak, leading to a highly stratifed estuary with fresh water overlying salt water.
- Partially-mixed estuaries, where river flow and tidal flow are balanced. The boundary of fresh and salt water is less clearly defined, but waters generally becomes more saline with depth and downstream towards the estuary mouth.

The saltwater/freshwater boundary may be displaced upstream or downstream in response to individual tidal or river flood events.

- Well-mixed estuaries, where tide effects dominate. These tend to be shallow estuaries with a high tidal range.

From its depth and lateral extent, and with strong river inflows, the Mawddach is likely to fall into the category of *partially-mixed estuaries*.

Studies in various regions of the world have examined water circulation patterns in estuaries:

Schramkowski and De Swart (2002) discuss the influence of the Coriolis effect in deflecting inflowing tides to the right and outflowing tides to the left when viewed into an estuary in the Northern Hemisphere. They model the Scheldt estuary and show that channels are assymetic in cross section due to lateral deflection of sediment under the Coriolis effect.

Montero et al. (1999) identify a similar Coriolis effect in water circulation of the Ria de Vigo, North Portugal. They show that water enters the estuary along its southern shore and leaves along the northern shore.

Zheng and Weisberg (2004) study the Charlotte Harbour estuary of West Florida and again identify a Coriolis-induced flow pattern, with tidal inflow along the south eastern shore and outflow along the north-western shore.

Valle-Levinson, Reyes and Sanay (2003) discuss factors affecting the location of maximum tidal flows within a large estuary. Density differences exist between inflowing salt water and outflowing fresh water. Where bed frictional effects are strong, dense inflows tend to be concentrated in channels, producing a persistent salt water wedge which deflects outflows to the shoals near the estuary coasts. Under lower bed friction effects, net inflow is still restricted to channels but outflow now occupies the entire near-surface (fig.3.219). The effect of the Earth's rotation, the Coriolis force, is to produce a core of maximum flow on the right of the channel during inflow (looking into the estuary in the Northern Hemisphere).

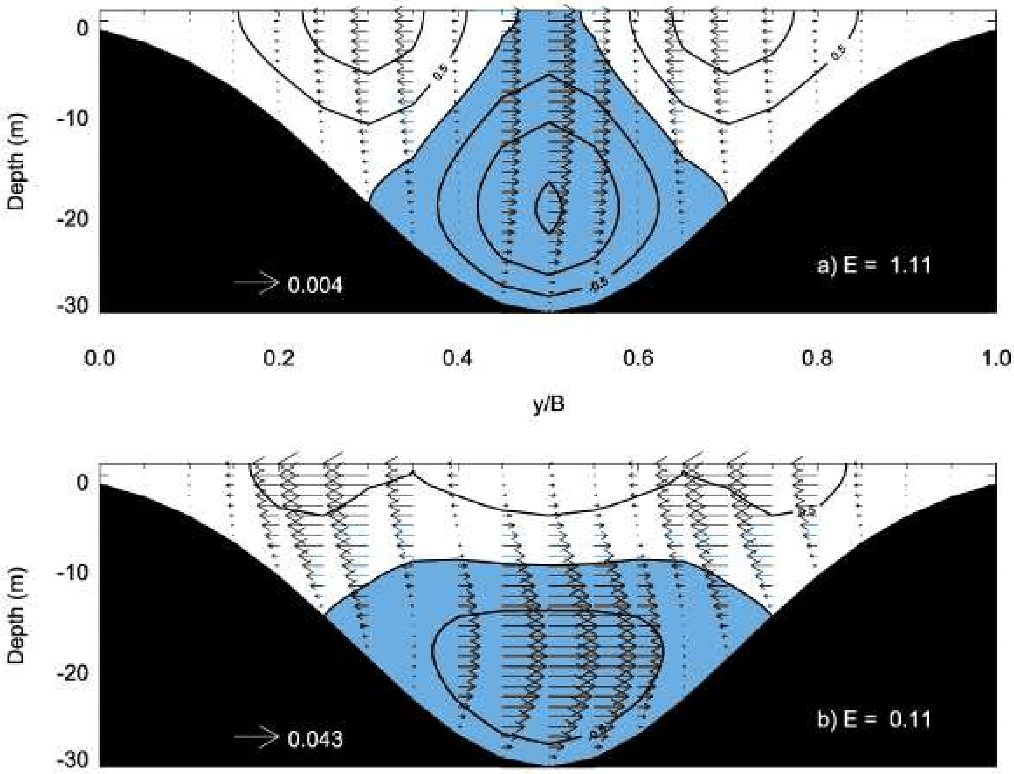


Figure 3.219 (after Valle-Levinson, Reyes and Sanay, 2003). Water flow cross sections, looking into an estuary in the Northern hemisphere. Blue shading represents zones where inflows exceed outflows. Vector arrows represent the transverse component of flow, which is to the right for inflows and to the left for outflows. The upper diagram is a model for high bed friction, as shown by the Ekman number E = 1.11. The lower diagram shows the case for low bed friction of E = 0.11.

The Mawddach estuary appears to be of sufficient depth and lateral extent for the Coriolis effect to influence water circulation and sediment movement. It is likely that some degree of salinity stratification is present, particularly in the lower estuary basin. Together, these effects would be expected to produce a relatively deep and narrow inflow channel directed towards the southern shore, with a shallower and broader outflow channel along the northern shore. This pattern is, indeed, observed in the bathymetric survey of the lower estuary (fig.3.232a) where the deep water channel sweeps towards the southern shore at Farchynys after entering around the Ro Wen spit at the estuary mouth.

The estuary may be divided into three open basins, separated by zones in which the tidal flows are constricted between rocky headlands at Farchynys and Penmaenpool. Areas of tidal marsh have developed along the north and south shores and towards the estuary head.

Lower basin

The lower basin extends from the estuary mouth to the headland at Farchynys, exhibiting a wide expanse of intertidal sediment uncolonised by vegetation. Sandbanks with large scale ripples are present across much of the central area of the basin where high energy tidal outflows would be expected . The largest ripple structures, reaching several metres in amplitude and termed megaripples, border the deep water channel where tidal inflow velocities would reach a maximum.

Figure 3.220: Sand deposits showing large scale ripples, Farchynys.

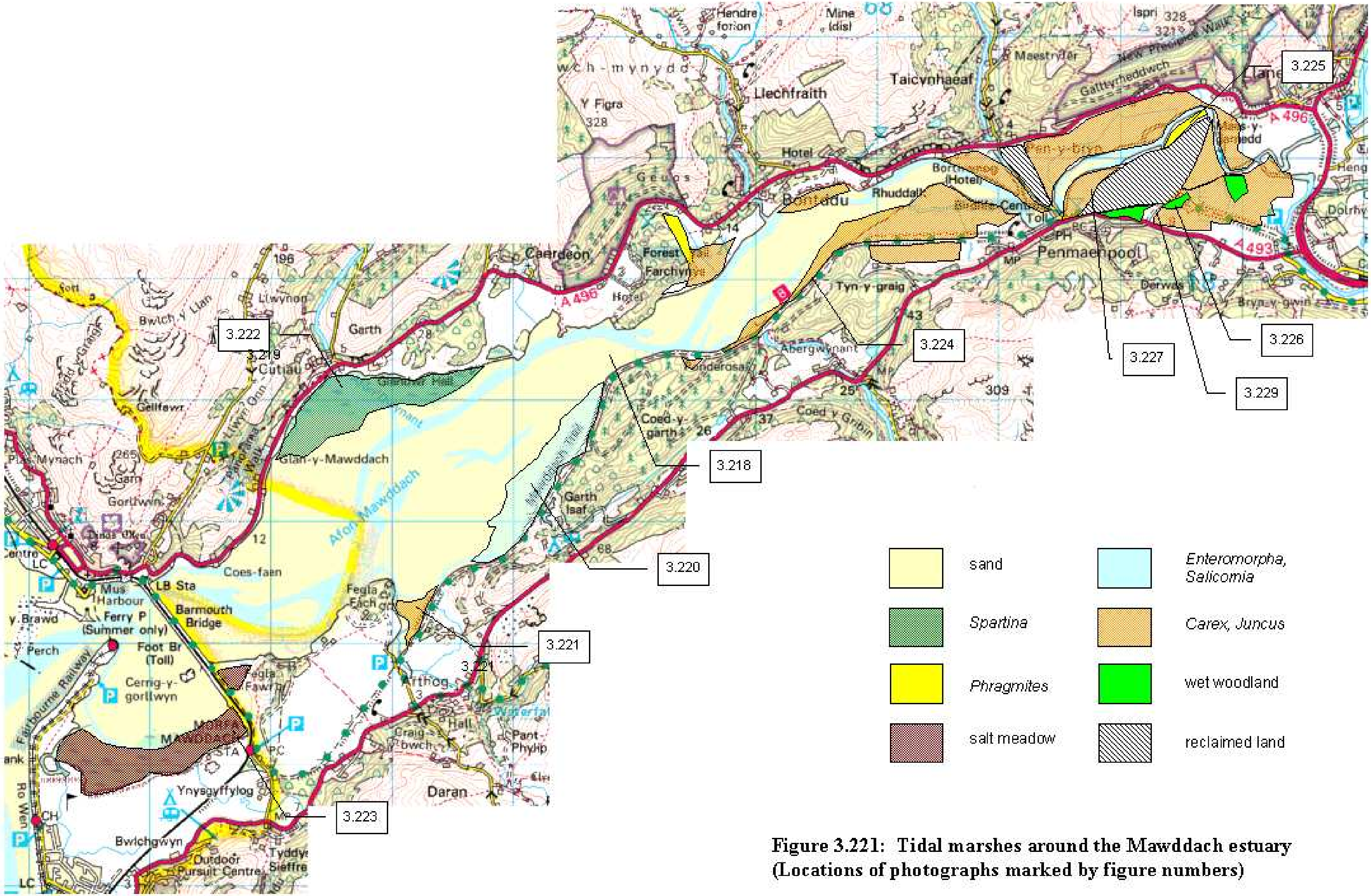


Figure 3.221: Tidal marshes around the Mawddach estuary (Locations of photographs marked by figure numbers)

Water channels are frequently developed along the estuary margins. These marginal channels may either be active, produced where meandering of the main channel impinges on the shore line, or may be inactive relics of former positions of the main channel – analogous to ox-bow lakes on a flood plain (fig.3.222).

Figure 3.222: Surveying in the area of Garth Isaf to determine the relative elevations of estuary sediment and vegetation zones.
(above) Channel along the shoreline, with offshore mudbanks stabilised by *Carex-Juncus* association,
(below) Pioneer colonisation of mudflats by *Enteromorpha* and *Salicornia*.

Mud is present in lower energy zones away from the active inflow channel and the broader area of outflow shoals. Nearshore mudbanks show a sequence of stabilisation and colonisation to form salt marsh. The process begins with growth of *Enteromorpha* algal mats, within which *Salicornia* (glasswort) can take root (fig.3.222). *Carex* (sedge) and *Juncus* (rush) species further stabilise and trap sediment, building mats of vegetation up to 1m above the surrounding open mudflats. Species diversity increases, with the introduction of flowering plants such as *Limonium* (sea violet) and Spergularia (sea spury). This progression is seen in the salt marshes bordering the muddy outflow channel of the Afon Arthog at Fegla Fawr (fig.3.223).

Where inflows of muddy sediment from rivers are not present, bays may become filled with sand. In this situation, stabilisation by deep rooted *Spartina* grass is the likely method of salt marsh colonisation. The highly salt tolerant species *S. alterniflora* is the early pioneer species, being replaced in the high intertidal areas by *S. patens* (fig.3.224). As in the case of *Carex-Juncus* saltmarsh, the *Spartina* marsh traps sediment and can grow to a height of 1m above bordering areas of open sediment.

In the shelter of the Ro Wen shingle spit, stable *Spartina-Carex* salt meadows have been long established, and are used for sheep grazing (fig.3.225).

Figure 3.223:
Stabilised mudflats around Fegla Fach:
(top) Mouth of the Afon Arthog,
(middle) Carex-Juncus salt marsh association with tidal channel along the shoreline,
(bottom) Upper salt marsh with Sea Violet.

Figure 3.224: Development of salt marsh at Glandwr: (above) Early colonisation of sand by *Spartina alterniflora* (below) High intertidal area of *Spartina patens* with *Spergularia* (sea spury).

Figure 3.225: Morfa Mawddach. Sheep grazed salt meadow with extensive *Spartina alterniflora* growth in natural drainage channel.

Middle basin

The middle basin extends from Farchynys to Penmaenpool. Within this section of the estuary are substantial areas of older saltmarsh stabilised by vegetation.

Upstream from Farchynys, the main tidal channel is migrating towards the southern shore at the present day. This meander development is consistent with tidal inflow deflection to the right after passing through the estuary constriction at the Farchynys headland. Active erosion of upper saltmarsh is occurring around the mouth of the Afon Gwynant where it enters the middle estuary basin (fig.3.226).

Figure 3.226: Erosion of saltmarsh alongside the main tidal channel, Abergwynant.

On the northern shore, reed beds of *Phragmites australis* are well developed at Farchynys with plants growing to a height of over 2m. Close by, an area of salt marsh has been reclaimed as agricultural land by the construction of embankments as defence against tidal flooding .

Upper basin

The upper basin extends upstream from Penmaenpool to the tidal limits on the rivers Mawddach and Wnion. The basin is dominated by salt marsh vegetation, with some extensive areas of reclaimed farmland.

Reed beds are well developed alongside the tidal channel (fig.3.227), and show an ecological progression to wet woodland (fig.3.228).

Figure 3.227: (above).
***Phragmites australis* reed bed community alongside the tidal channel of the upper basin.**

Figure 3.228: (right)
Wet woodland of willow, alder and birch above *Phragmites* reed bed near Penmaenpool

Sections of the estuary flood lands began to be reclaimed for agriculture in the middle of the 19th century by the construction of flood walls and by carrying soil onto the land by horse and cart. The walls have been periodically breached by high tides, and have been progressively strengthened (fig.3.229). Extension of the reclaimed areas is actively continuing at the present day near Penmaenpool, with building waste being tipped into reed beds to raise the land surface above maximum tidal level (fig.3.231).

Figure 3.229: Flood wall at Penmaenpool, separating salt marsh on the right from improved grassland on the left of the picture. Tree debris from the 2001 flood in the foreground.

Figure 3.230: Overtopping of flood embankment in the upper basin during the flood event of 3 February 2004.

Figure 3.231: Area of land reclamation by tipping of building waste into reed beds, Penmaenpool

Bathymetry of the estuary

A bathymetric model has been produced as a basis for hydrological modelling of tidal flows and river interaction:

- Within the limits of normal tides in the estuary, data has been provided by a bathymetric survey carried out for the Central Electricity Generating Board (Binnie and Partners, 1985). The CEGB bathymetric survey on paper was traced into the Mapmaker software application, and mean altitude values were allocated to the polygons created between contours. Field survey data points were added, contours created, and mean elevation polygons were added to complete the mapping area (fig.3.232).

- The CEGB bathymetric survey focuses on the navigable waters, so additional surveying was needed to establish the relative elevations of areas of salt marsh, mud and sand around the estuary margins. Data was transferred in vector shapefile format from Mapmaker to the SAGA Geographical Information System program. The data was interpolated to a 25m grid and smoothing applied. A three-dimensional point data set was created.

- The Ordnance Survey 50m DEM model provided gridded elevation data above the high water mark of ordinary spring tides. Ordnance Survey 50m DEM points were added to the point data file. This file provides input to the River2D_Bed program in preparation for waterflow modelling.

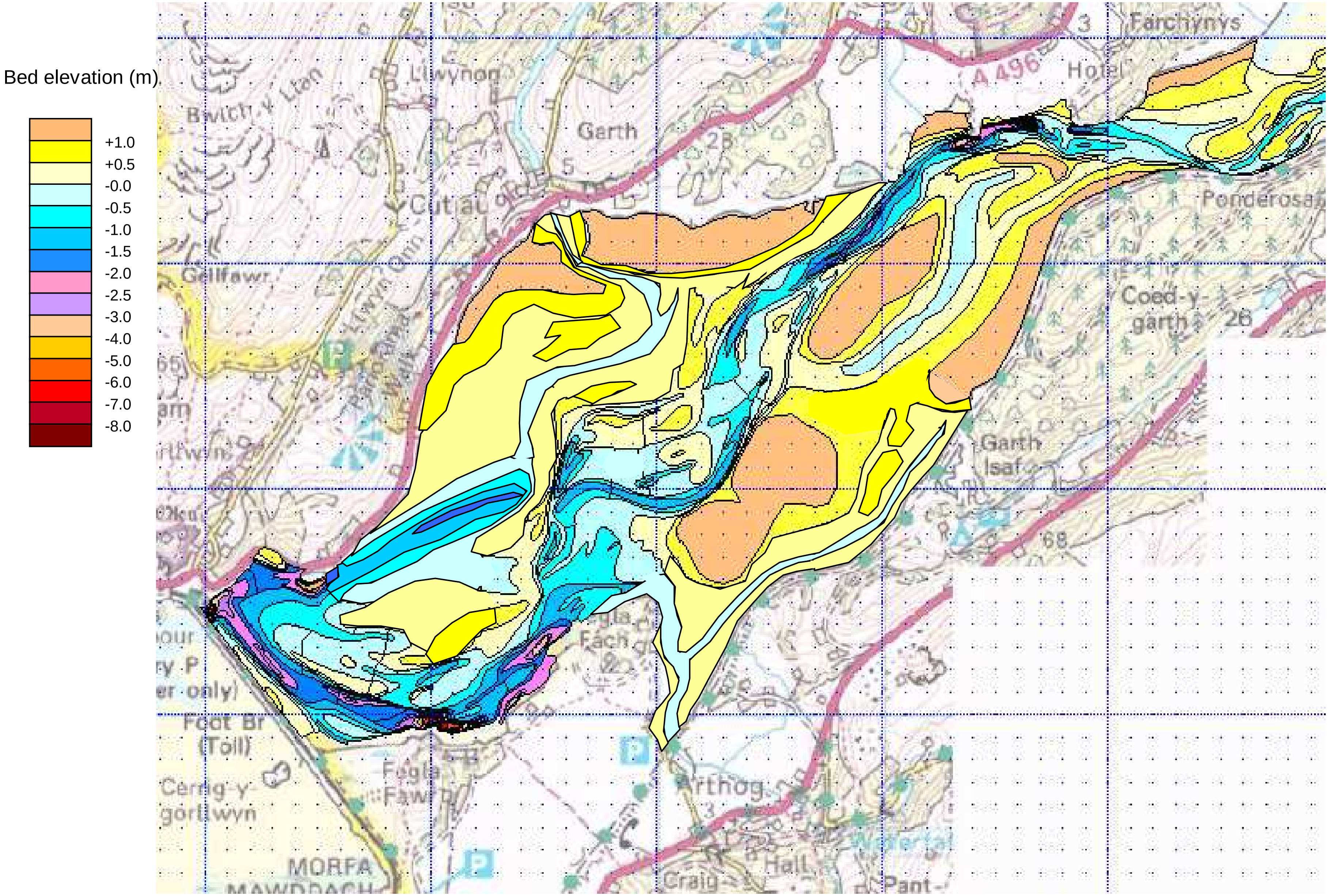


Figure 3.232a. Bathymetry of the Mawddach estuary – lower basin

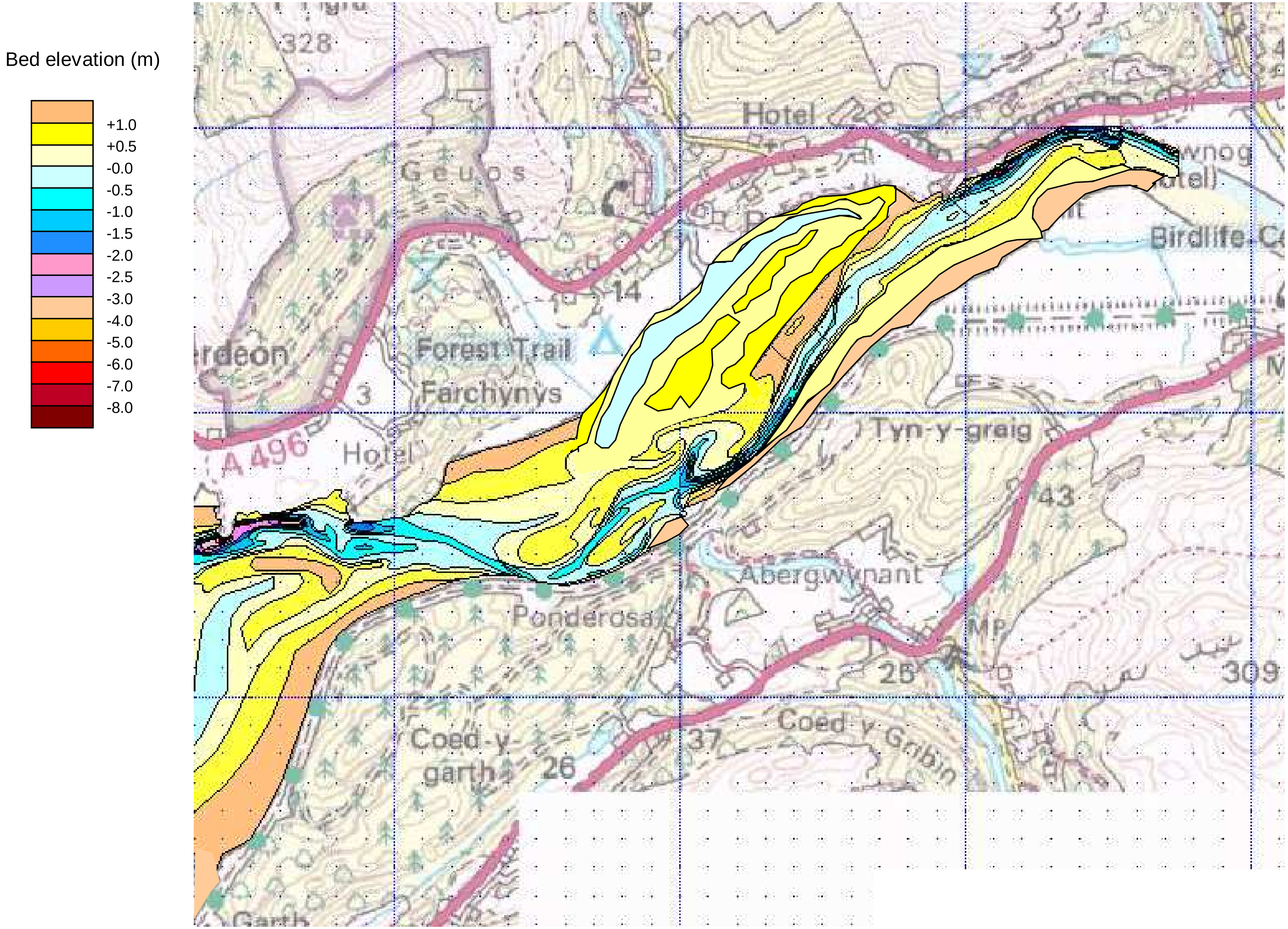


Figure 3.232b. Bathymetry of the Mawddach estuary – middle basin

Tidal flows in the estuary

Investigations of tidal flows within the Mawddach estuary have been carried out by means of hydrograph recordings. Data has been available from:

- Barmouth tidal gauge
- a water depth gauge operated at Penmaenpool bridge
- water depth recorders operated on the Wnion and Mawddach close to the tidal limits.

Barmouth tidal gauge

The Barmouth tidal gauge forms part of the national network of tidal gauges operated by the Proudman Oceanographic Institute (Proudman Oceanographic Laboratory, 2006). The gauge is located below the Barmouth railway bridge within the deep water channel close to the north shore (fig.3.233).

Figure 3.233:
Location of the Barmouth tidal gauge below Barmouth railway bridge.
photograph: Proudman Oceanographic Institute

Figure 3.234 shows a typical month's data from the Barmouth tidal gauge. Spring tidal ranges of 4.5m and neap tidal ranges of 1.5m are typical.

Barton (2002), in a study of historical tidal flood events on the Mawddach estuary, investigated two major floods in the town of Barmouth. In both cases, 2 January 1976 and 11 November 1977, the tidal height reached several metres above the predicted level as a result of an onshore storm surge.

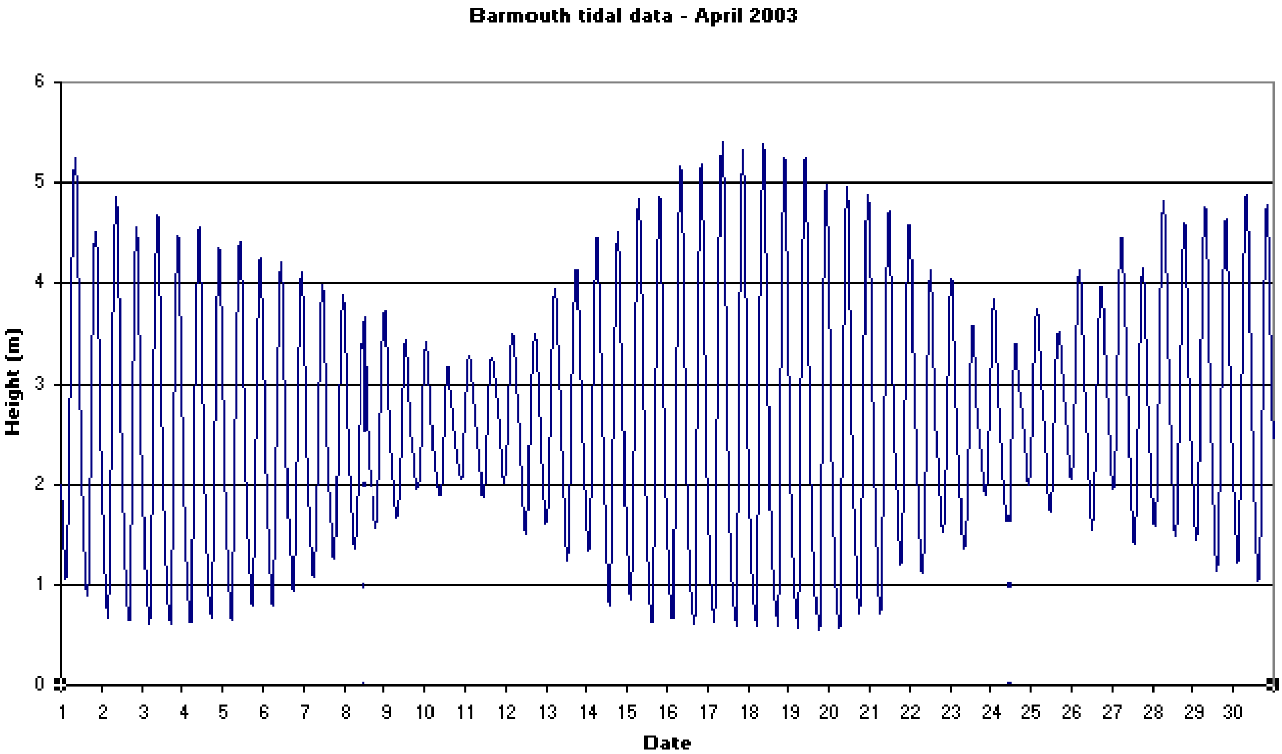


Figure 3.234: Tidal height data for the month of April 2003, Barmouth bridge

Penmaenpool tidal recorder

During January and February 2003, a barometric water depth recorder was operated at Penmaenpool bridge in order to investigate the heights and relative timings of tidal peaks in comparison to Barmouth. A typical hydrograph, covering four tides between 15 and 17 January, is given in fig.3.235.

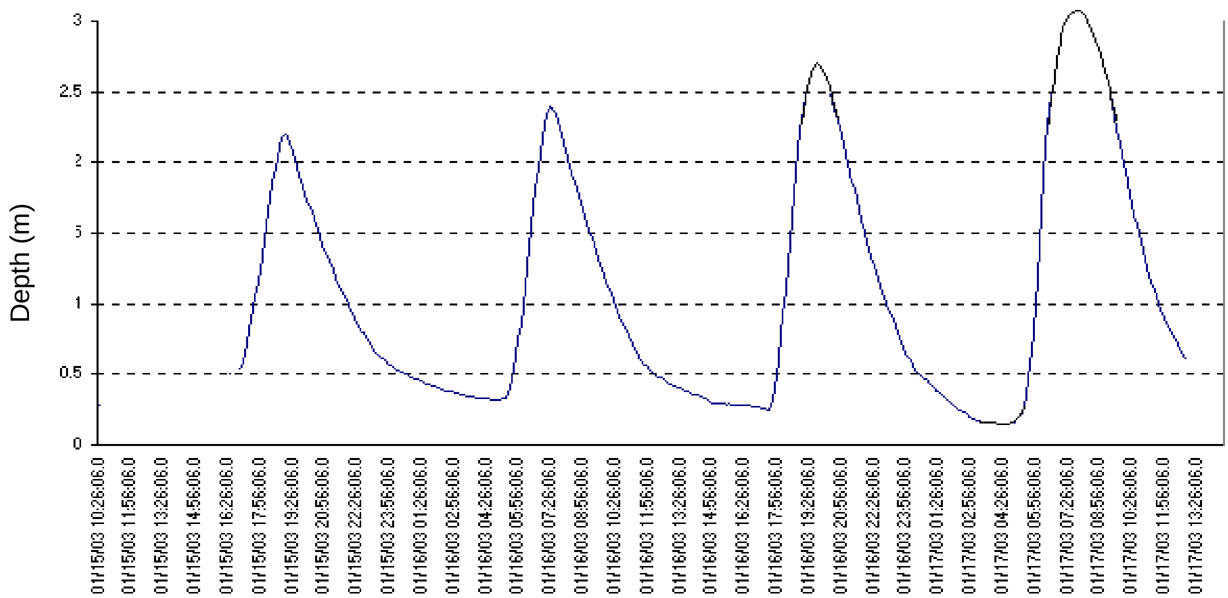
Tidal hydrographs are asymmetric, showing a rapid rise with the incoming tide but a more gentle decline towards low tidal level, which at Penmaenpool is determined largely by river flow. The exponential shape of the falling limb suggests slow release of water from temporary storage in tidal marshes alongside the main channel within the upper estuary basin.

Figure 3.235:
Tidal recording at Penmaenpool bridge.

(top) Location of the tidal gauge,

(middle) Data logger for the tidal gauge,

(bottom) Example tidal graph for the period 15-17 January 2003.



Tidal monitoring on the rivers Mawddach and Wnion

Hydrograph recorders were operated from June to September 2003 near the tidal limits on the rivers Mawddach and Wnion, approximately 0.5km upstream from their confluence at the head of the estuary The hydrographs obtained are shown in figures 3.237 and 3.238.

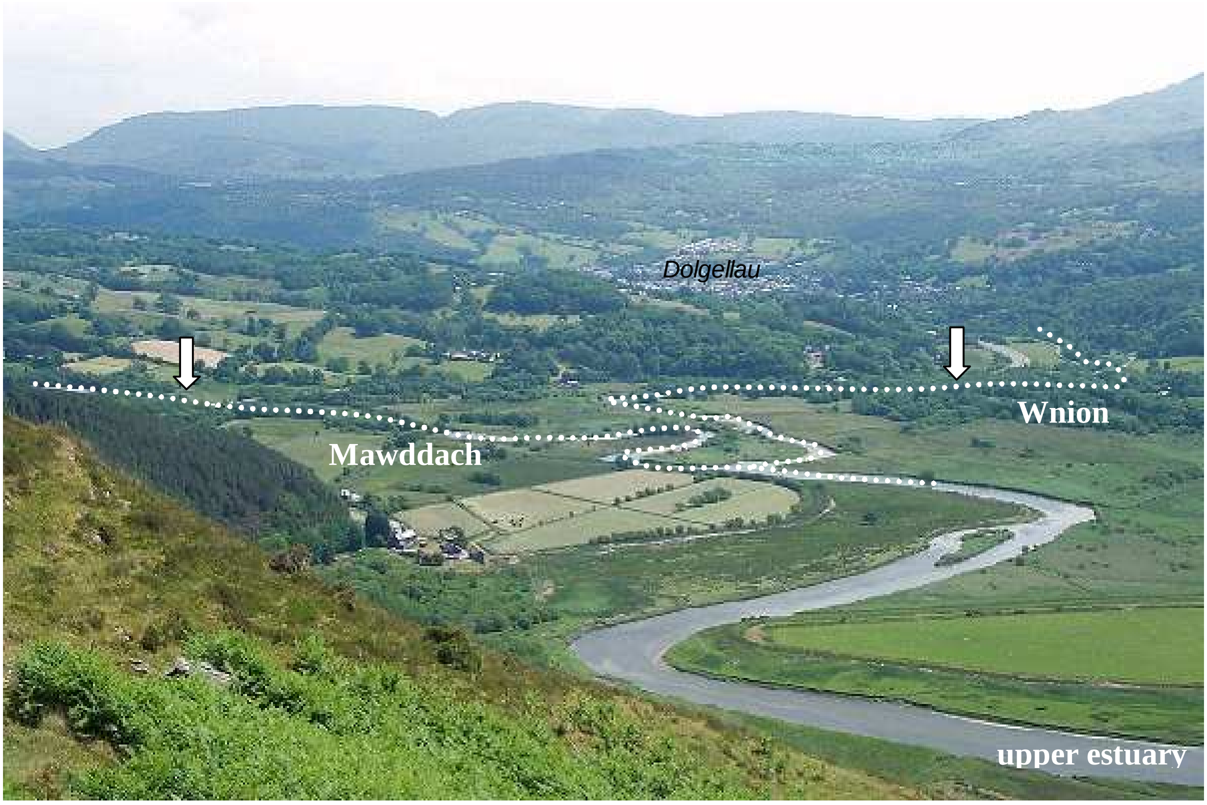


Figure 3.236: Location of hydrograph recorders on tidal reaches of the rivers Mawddach and Wnion

Tidal spikes are evident on both rivers at times of spring tides, adding up to 90cm to the river level at low flow. The diurnal inequality, the difference in height between two daily tides, is evident.

During the period of recording, a flood event occurred on 26 July when water depths on both rivers exceeded the normal tidal peaks.

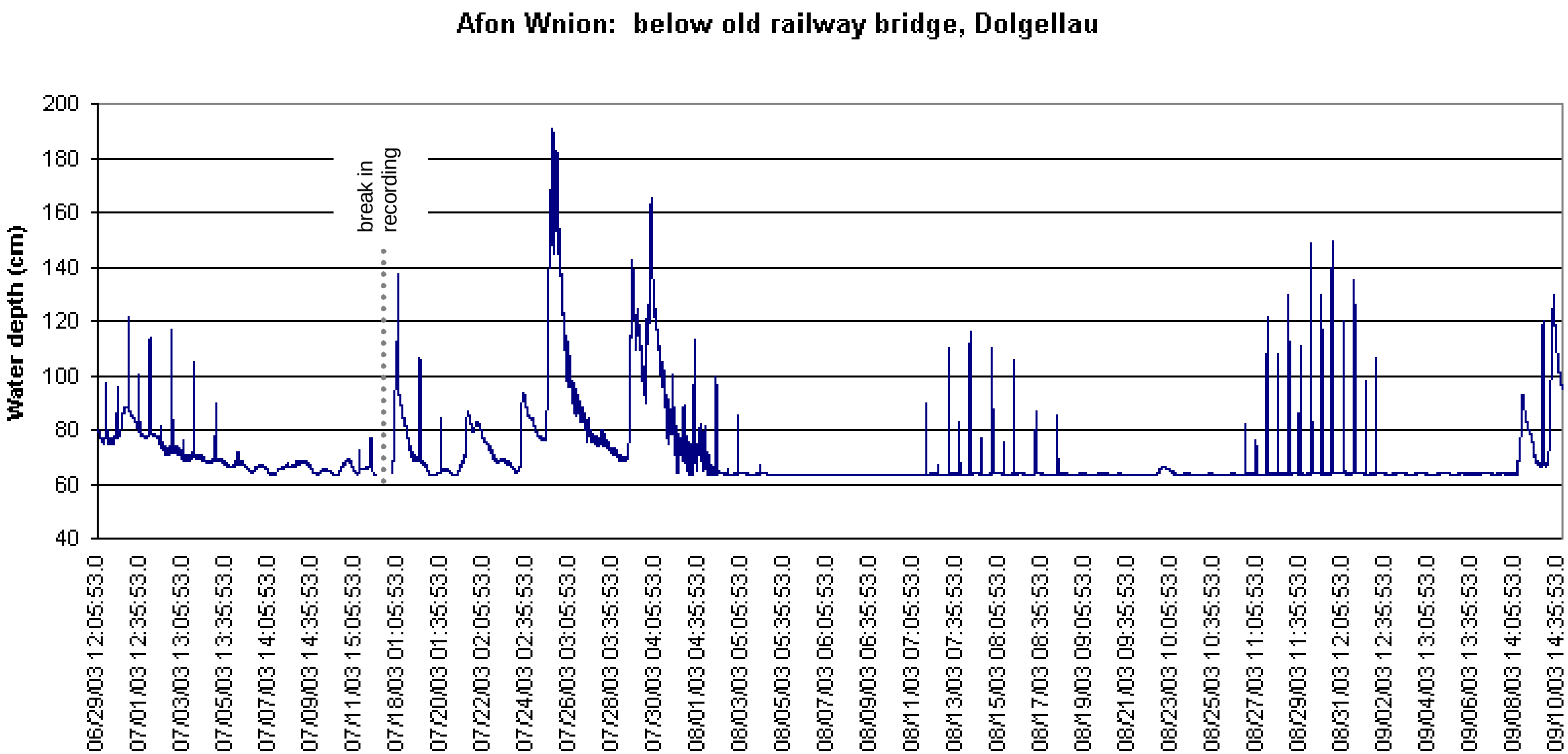


Figure 3.237: Hydrograph for the Afon Mawddach near the tidal limit at Llanelltyd, June – September 2003

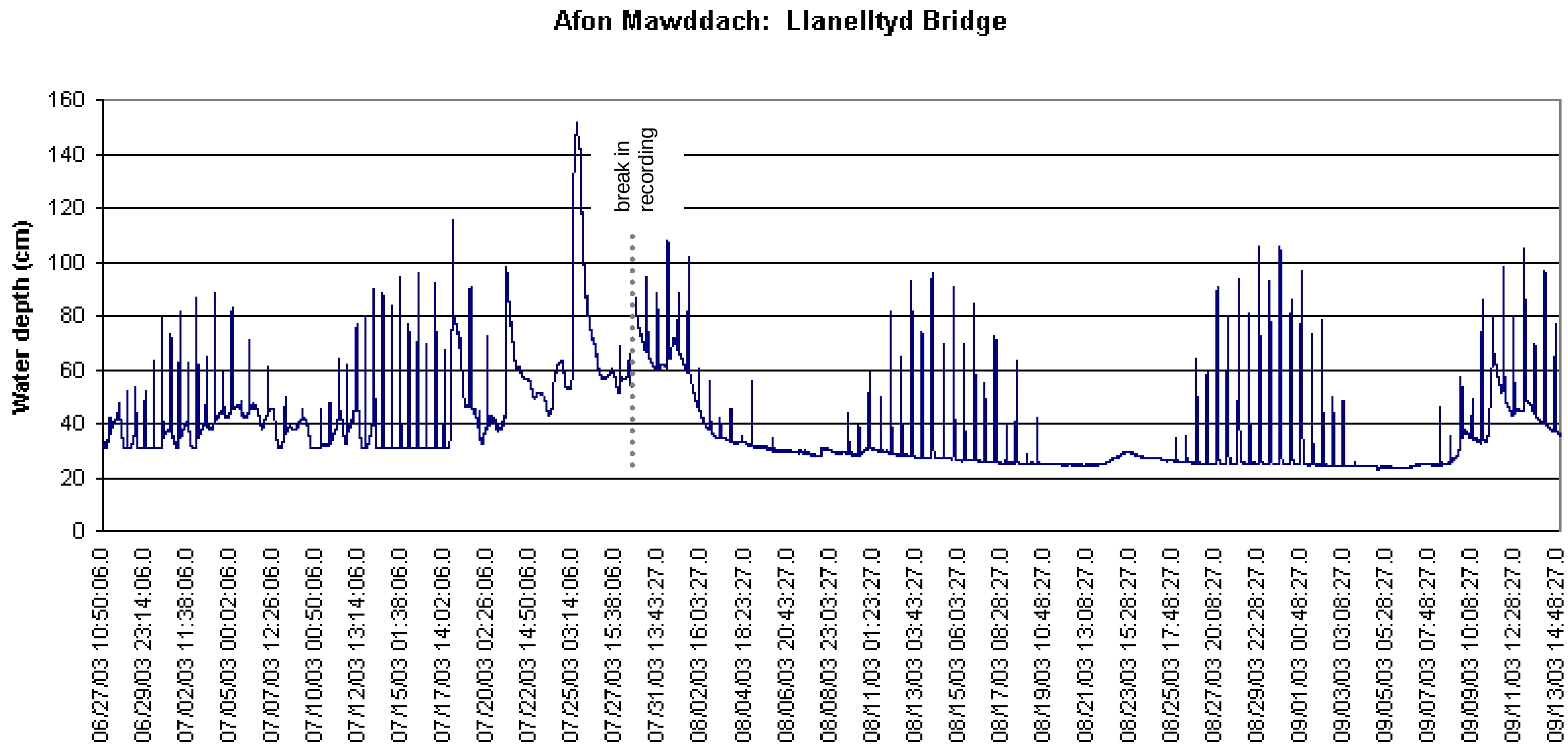


Figure 3.238: Hydrograph for the Afon Wnion near the tidal limit at Tal yr Afon, west of Dolgellau, June – September 2003

Results of tidal observations

Comparison of tidal peaks at the hydrograph recording points indicates that the travel time along the length of the estuary is 35 minutes. This represents an approximate water advection velocity of 20km/hour into the estuary in response to the tide-induced hydraulic head at the estuary mouth.

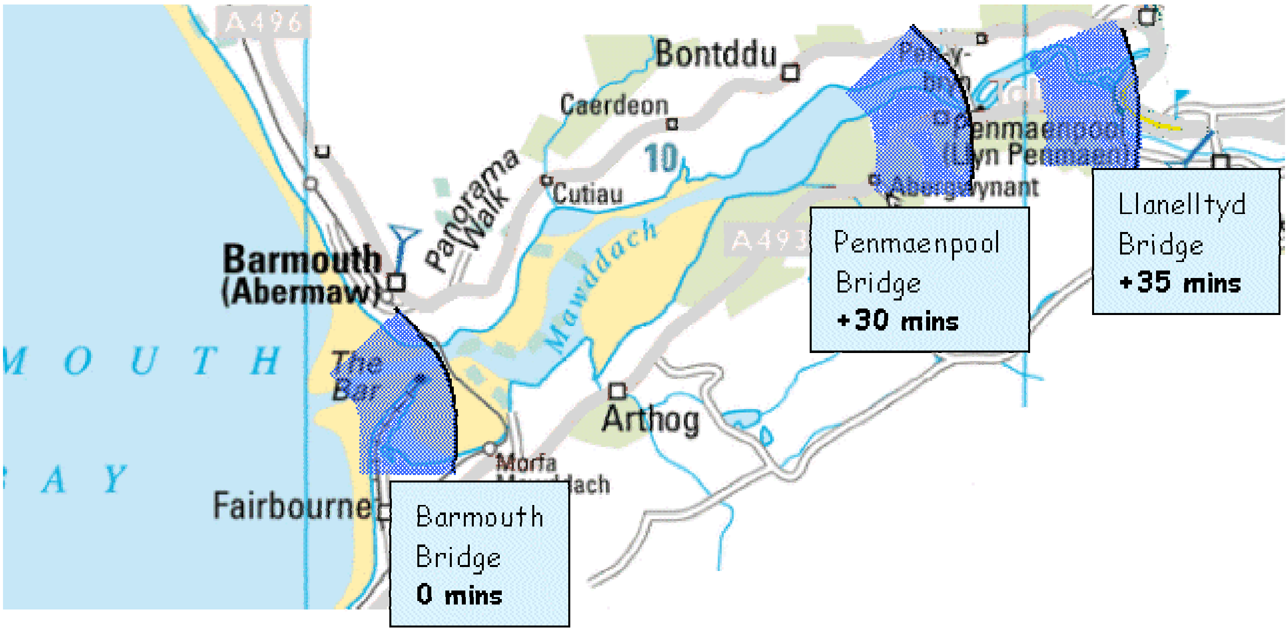


Figure 3.239: Arrival times for tidal peaks along the Mawddach estuary

It is commonly the case with long estuaries that tidal peaks are amplified as they travel upstream. This effect is most pronounced for estuaries which are wide at the mouth, but become narrower towards the head. A familiar British example is the Severn estuary, producing a bore wave on the River Severn as the tidal peak reaches the estuary head. Examinations of the tidal hydrographs were carried out to determine whether this phenomenon occurs in the Mawddach estuary.

A second issue of concern is the possible additive effect of a river storm hydrograph peak with a tidal peak to generate conditions for increased depth of flooding around the head of the estuary. The tidal and river hydrographs were examined for evidence of this mechanism.

Two spring tide periods, 10-24 February 2003, and 28 March to 8 April 2003, were chosen for analysis. The February period was one of low river flows, whilst the March-April period includes a river flood event.

Spring tide period 10-24 February 2003

Hydrographs obtained for the period 10-24 February are displayed in fig.3.241. A set of short duration tidal peaks are seen to be superimposed on the hydrographs of both rivers.

The elevations and base levels of the three recording stations were determined from field measurements and the Ordnance Survey digital elevation model. The accuracy of correlation of heights is expected to be within 10cm. Elevations of successive tidal peaks measured at the estuary mouth and on the tidal rivers at the estuary head are summarised in fig.3.240.

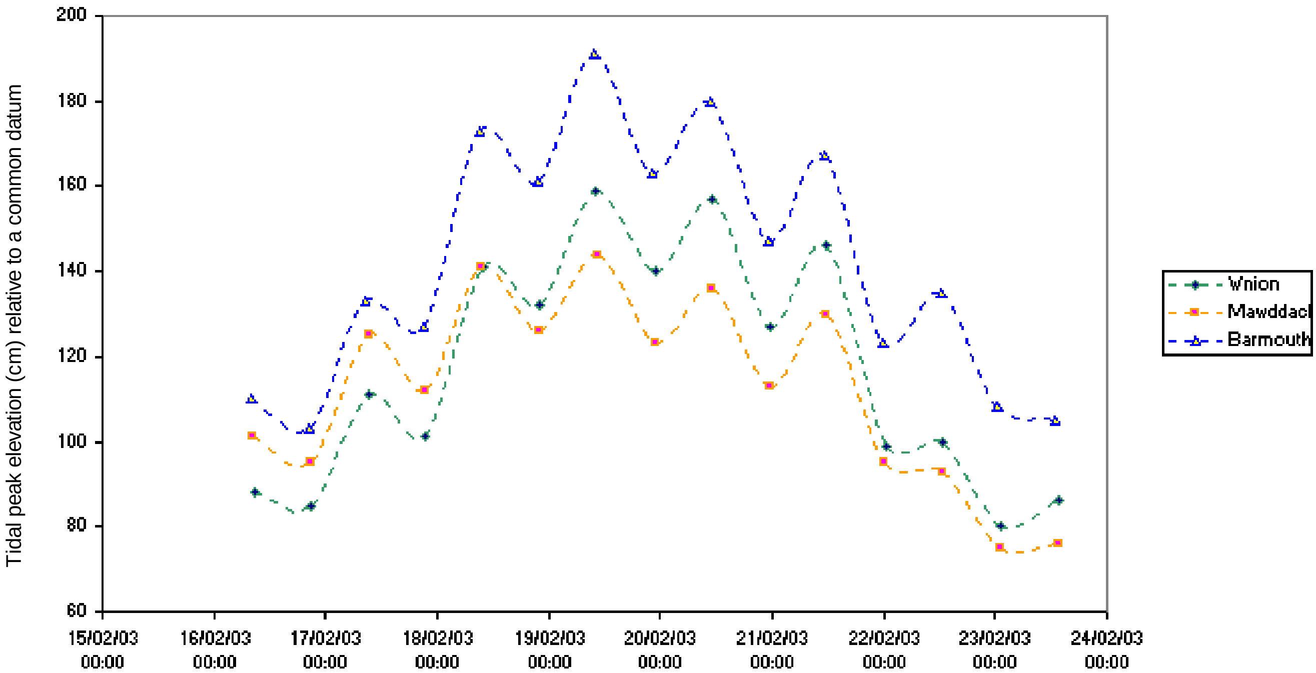


Figure 3.240: Tidal maximum heights, at the estuary mouth and on river reaches at the estuary head, for the period 16-24 February 2003

In contrast to the amplification effect observed in some estuaries, the results for the Mawddach indicate a slight reduction in peak height as the flood tide travels up the estuary. Each tidal peak on the Mawddach or Wnion rivers is 20 - 30cm lower in elevation than the corresponding tidal peak at Barmouth. This may be due to water entering temporary storage within saltmarshes. Areas of open vegetation close to low tide level may be particularly effective in absorbing tidal flows, for example: reed beds, *Spartina* marshes and wet woodland.

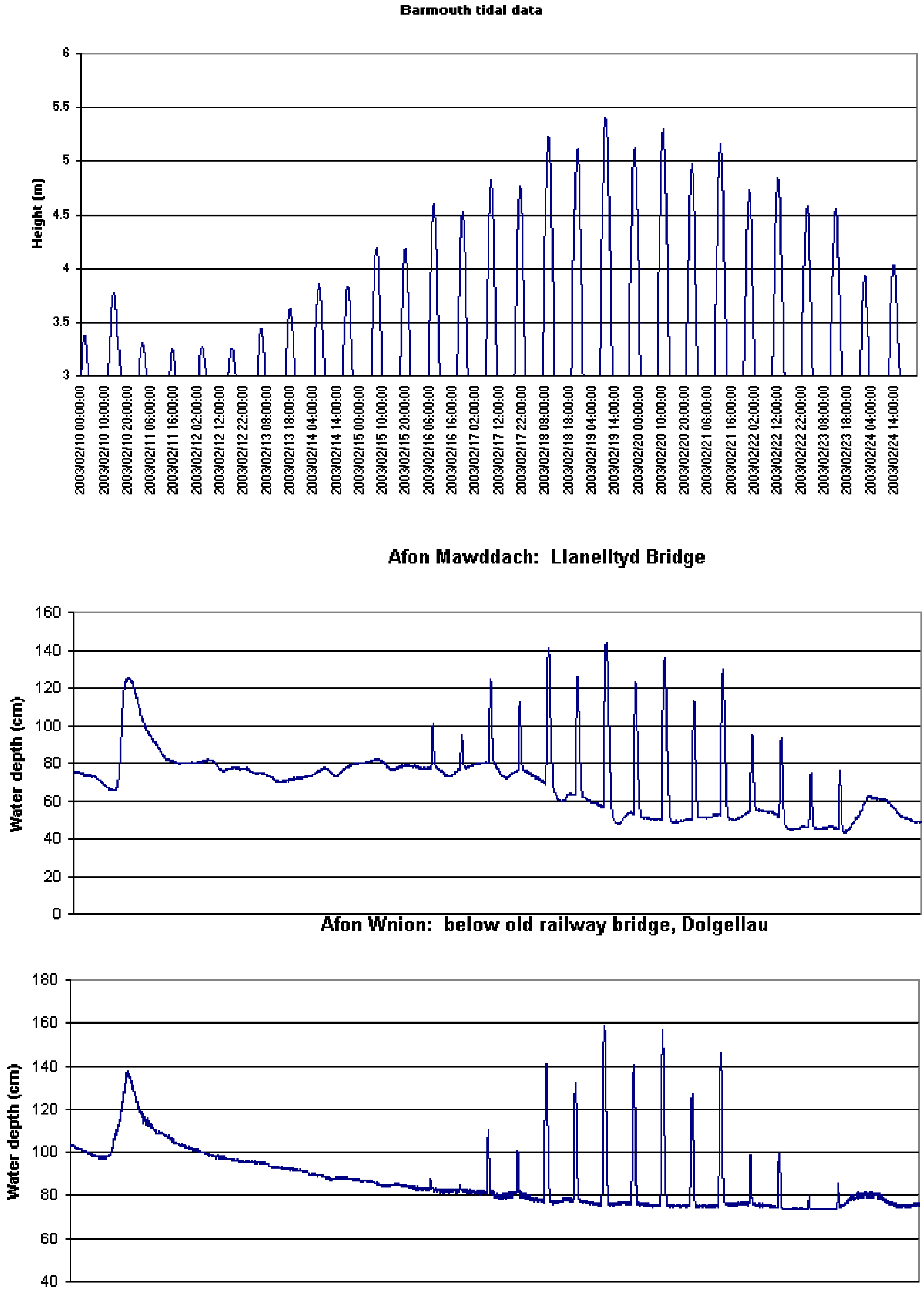


Figure 3.241: Hydrographs for recording points at the mouth and head of the Mawddach estuary, 10-24 February 2003

Spring tide period 28 March - 7 April 2003

Hydrographs obtained for the period 28 March-7 April are displayed in fig.3.243. A flood peak appears on both the river Mawddach and Wnion on 1 April, and corresponds approximately with a high spring tide at Barmouth. It should be noticed that the Barmouth tidal peak exceeds predicted height by approximately 45cm, and is likely to be due to an onshore surge associated with strong westerly winds in the Irish Sea during the storm event.

Elevations of successive tidal peaks measured at the estuary mouth and on the rivers at the estuary head are summarised in fig.3.242.

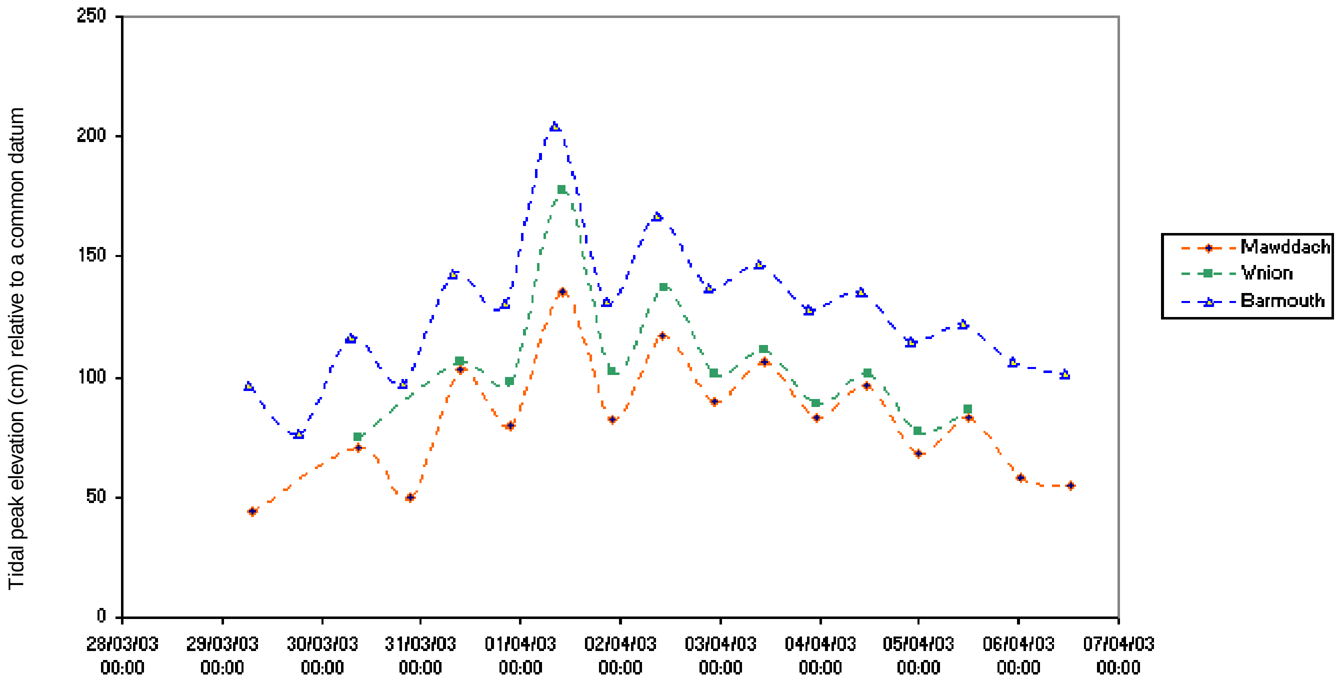


Figure 3.242: Tidal maximum heights, at the estuary mouth and on river reaches at the estuary head, for the period 29 March to 7 April 2003

When the elevations of peaks are compared, no additive effect between river and tidal levels can be found. The tidal peak passes upstream through high river flow with no apparent interaction. This, perhaps surprising, result may be due to the fast advection of the tidal peak over water surfaces of near-constant elevation within the river channels. For additive effects to occur, wave theory suggests that the tidal wave and the river flood wave should be travelling at similar velocities, whereas in practice the river hydrograph is rising and falling much more slowly.

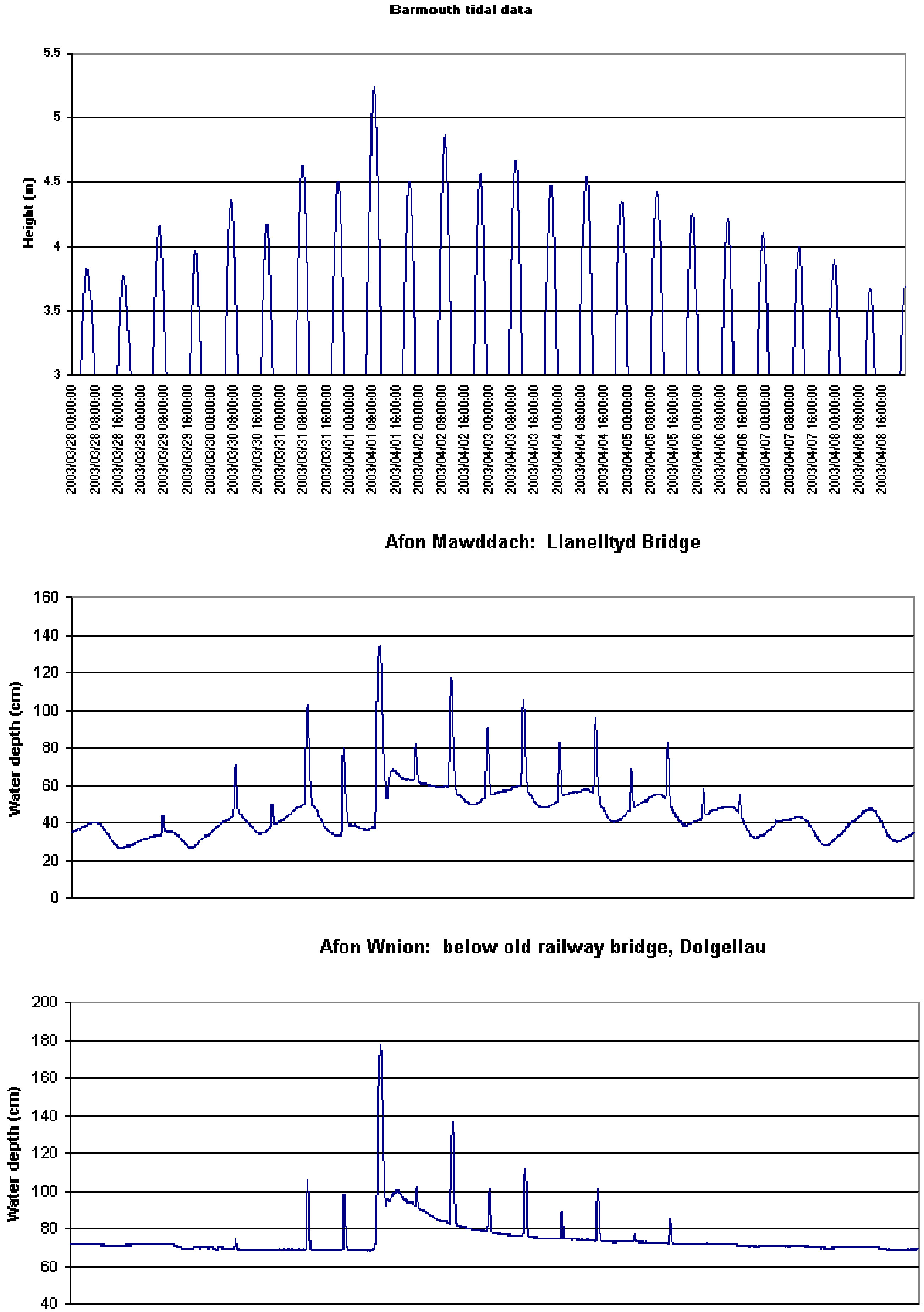


Figure 3.243: Hydrographs for recording points at the mouth and head of the Mawddach estuary, 28 March – 8 April 2003

Estuary hydrological model

Modelling has been used to investigate the extent of river-tidal interaction during river flood events in the upper basin of the Mawddach estuary. Flooding of a purely tidal nature is known to occur in the middle and lower estuary basins and has been considered by Barton (2002). Pure tidal flooding, however, is beyond the scope of the present study.

River2D software (Steffler P. and Blackburn J., 2002) proved suitable for modelling floodplain inundation in Coed y Brenin and around Dolgellau, so has again been employed for models of the Mawddach estuary. The program has effective functions for simulating the wetting and drying of saltmarshes during tidal cycles.

The hydrological simulation has been carried out in two stages:

- Stage one uses a model for the complete estuary, with the objective of establishing flow conditions corresponding to the measured tidal curves for Barmouth and Penmaenpool. It was noted that the tidal curve for Barmouth is symmetrical and sinusoidal, whilst the curve for Penmaenpool in the upper estuary basin demonstrates an asymmetric saw-tooth pattern. A control on the accuracy of the model is that it should realistically reproduce the Penmaenpool hydrograph pattern in response to sinusoidal tidal forcing at Barmouth.
- Stage two presents a high resolution model for the upper estuary basin and tidal reaches of the rivers Mawddach and Wnion. This uses hydrological parameters determined in the whole-estuary model. The model investigates both present day conditions and changes which may occur as a result of land reclamation or channel sedimentation.

A section of the finite element grid for the whole-estuary model is shown in fig.3.244. The model uses bathymetric data prepared in the manner discussed earlier in this section. Processing is carried out on a mainly uniform grid of 100m squares divided into right-angled triangles. The size and symmetry of the finite elements have been chosen to maximise processing speed and accuracy over a large modelled area, without significant loss of bathymetric resolution around channels.

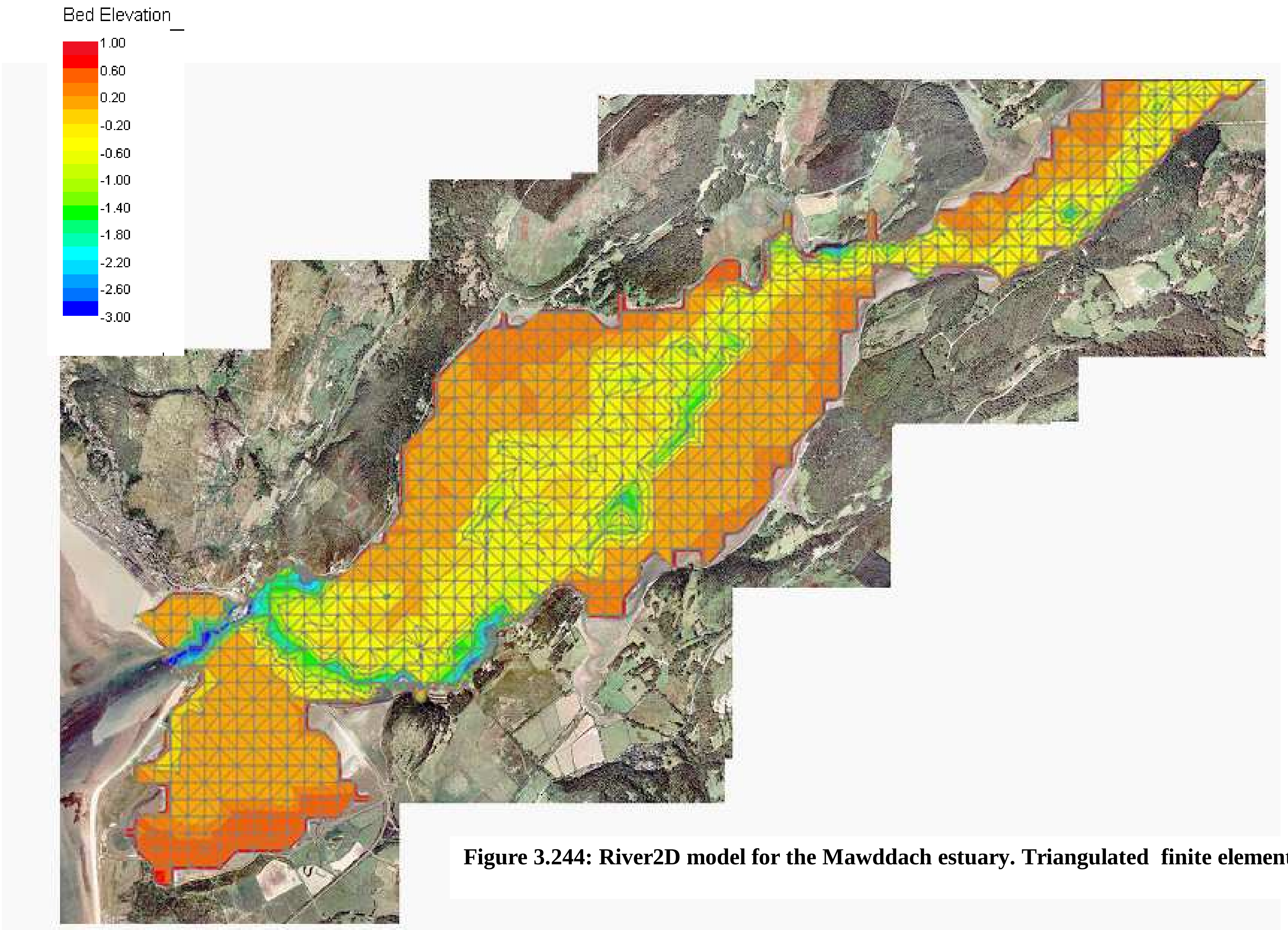


Figure 3.244: River2D model for the Mawddach estuary. Triangulated finite element grid

Bed roughness and turbulence parameters have been based on values determined from the Coed y Brenin and Wnion valley models of section 3.4, and refined to produce a best fit with observed tidal flows:

ε_2 bed shear: 0.5
ε_3 transverse shear
clean sand: 0.0
tall salt marsh vegetation: 1.2
roughness height
clean sand: 2m
tall salt marsh vegetation: 8m

The model was spun-down to a steady state low water condition to provide the starting point for a series of ebb-flow tidal simulations. Example results are shown in fig.3.245. The extent and sequence of wetting and drying of sandbanks, mudflats and salt marshes during the tidal cycle are physically realistic.

River 2D offers various options for specifying inflow and outflow boundary conditions:

- inflow rate (m^3s^{-1}), either constant or transient
- water level elevation (m), either constant or transient
- depth – unit discharge relationship

$$q=Kh^m$$

where the default values of the parameters, K=1 and m=1.666, may be redefined.

Inflows at the estuary head were specified as a constant moderate discharge of $20m^3s^{-1}$ for each of the two rivers.

In initial models, the outflow at the estuary mouth was specified by a transient water level following a sine curve for a tide of 4m amplitude. Whilst this configuration produced realistic patterns of inflow and outflow for the lower estuary basin, the time taken for the passage of a tidal peak up the estuary was an order of magnitude too slow. It was evident that the program was modelling the passive gravitational advection of an elevated water mass on the surface of a body of stationary water. The real physical situation involves the dynamic inflow of substantial water volumes at high velocities through the whole depth of the water column at the estuary mouth during a rising tide.

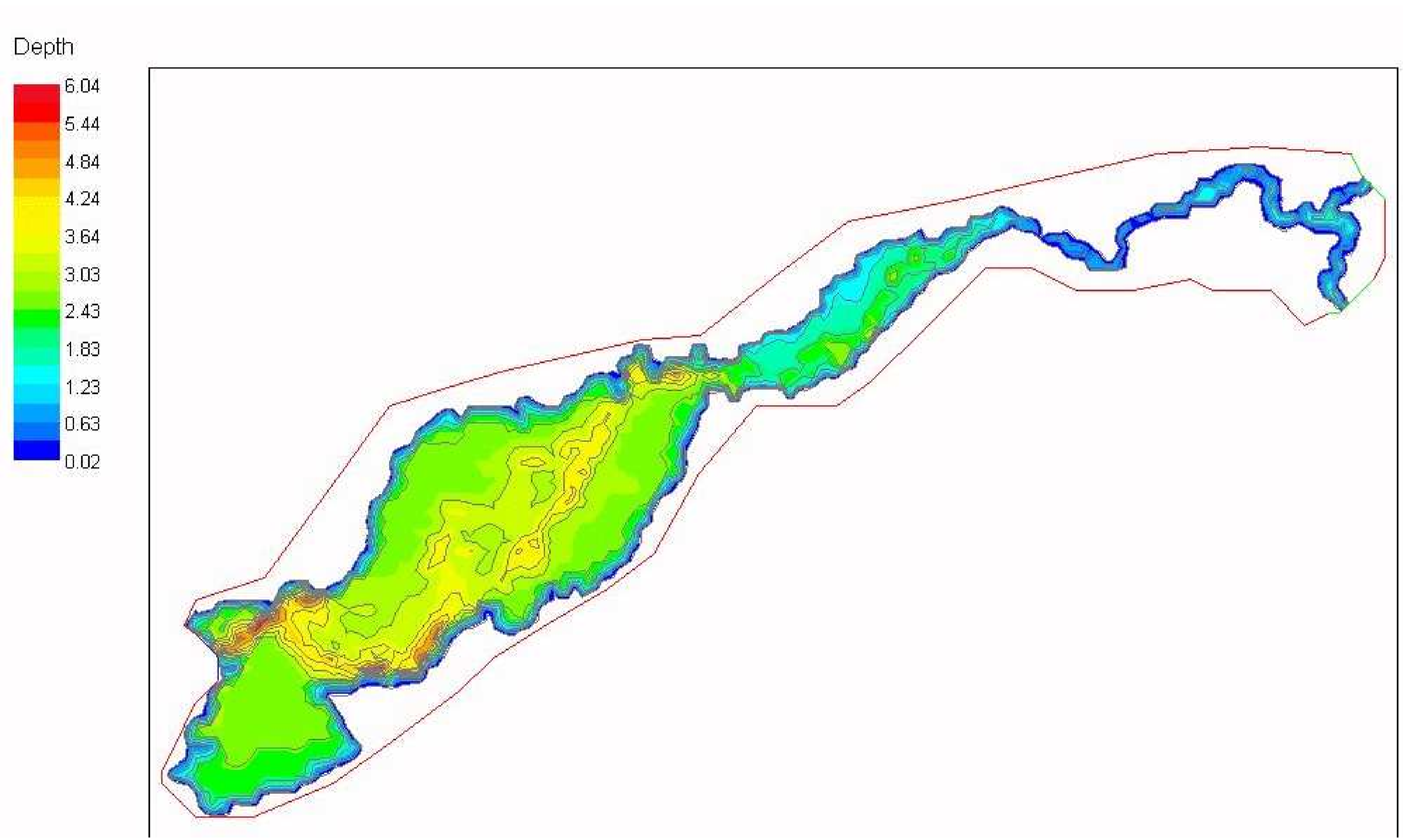


Figure 3.245a: Simulation of a 4m tide maximum water level for the Mawddach estuary.

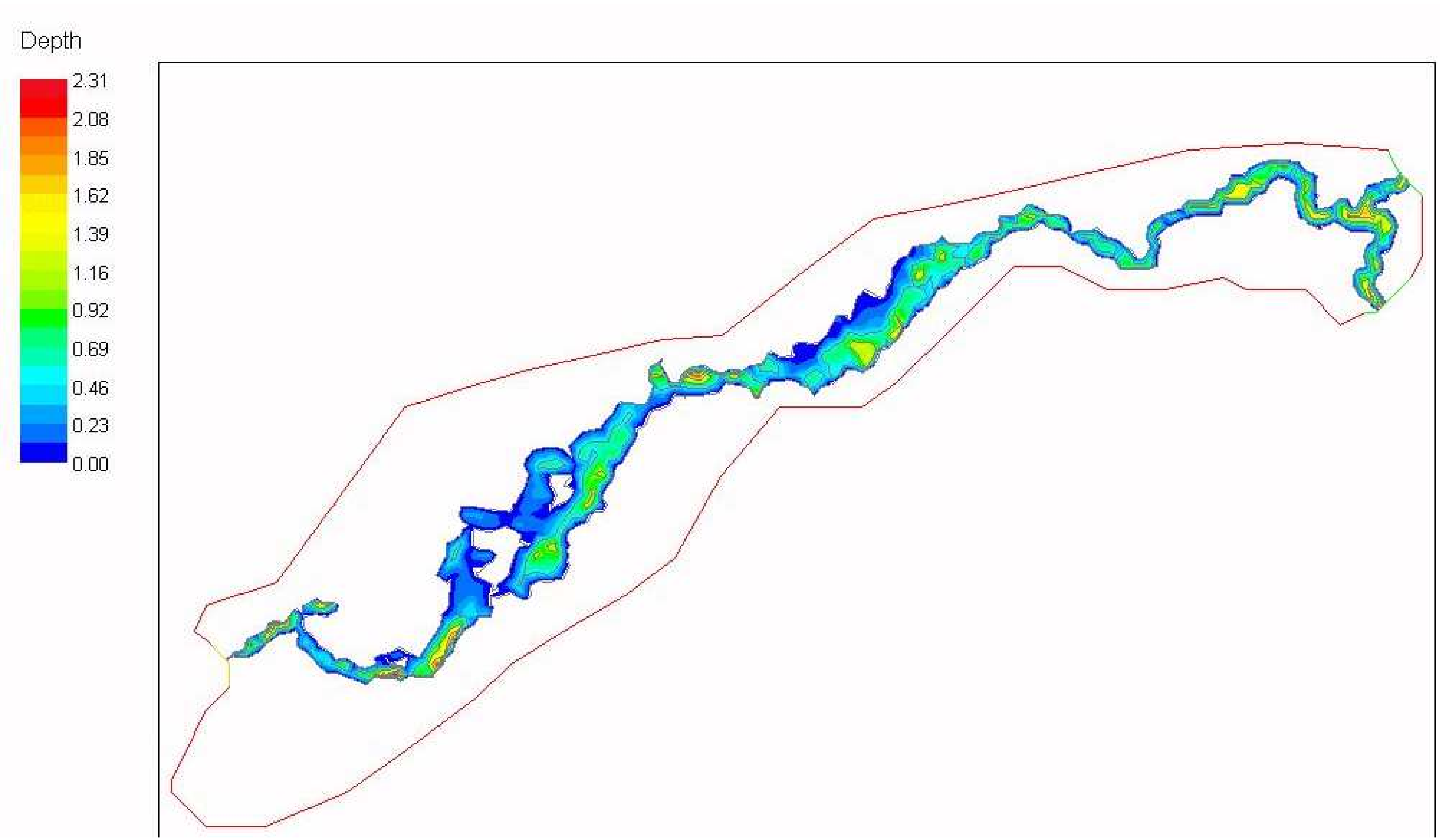


Figure 3.245b: Simulation of a 4m tide minimum water level for the Mawddach estuary.

A revision of the estuary mouth boundary condition was carried out, to model rising tides as transient inflows varying sinusoidally between 0 and 4 000m^3s^{-1}. Falling tides continued to be modelled by sinusoidally varying water level elevation at the estuary mouth. This combination of boundary conditions produced satisfactory timings for the movement of tidal peaks up the estuary.

Example flow patterns are given in figures 3.246-3.251.

The sequence begins with water inflow through the estuary mouth on a rising tide. (fig.3.246). Water flow reaches 5ms^{-1} through the estuary mouth at the time of maximum water level increase at mid-tide.

Fig.3.247 shows the tidal inflow traveling up the estuary through the channel constriction between the lower and middle basins at Farchynys, where velocities reach 3ms^{-1}.

In fig.3.248 the inflowing tide is seen to be meeting the river outflow at the channel constriction between the middle and upper basins at Penmaenpool, with the flow reversed as the incoming tide passes Penmaenpool bridge (fig.3.249).

As the tide turns and begins to fall, outflow begins at the estuary mouth (fig.3.250). Fast flow occurs within the channel system, with slower drainage from the extensive tidal flats of the lower estuary basin.

Channel water levels show a progressive decline upstream through the estuary, eventually reaching the upper basin where drainage occurs from the salt marshes and reed beds (fig.3.251).

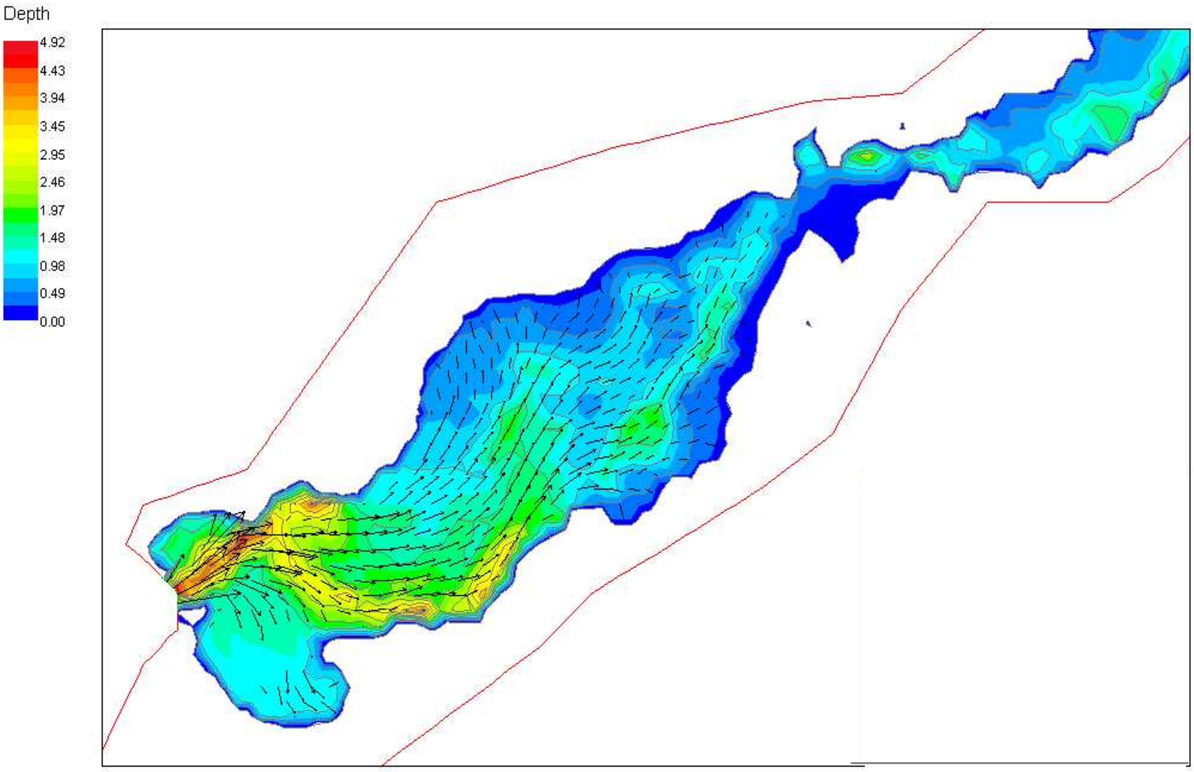


Fig.3.246: Water flows reaching 5m^{3}s^{-1} through the estuary mouth at the period of maximum inflow on a rising tide.

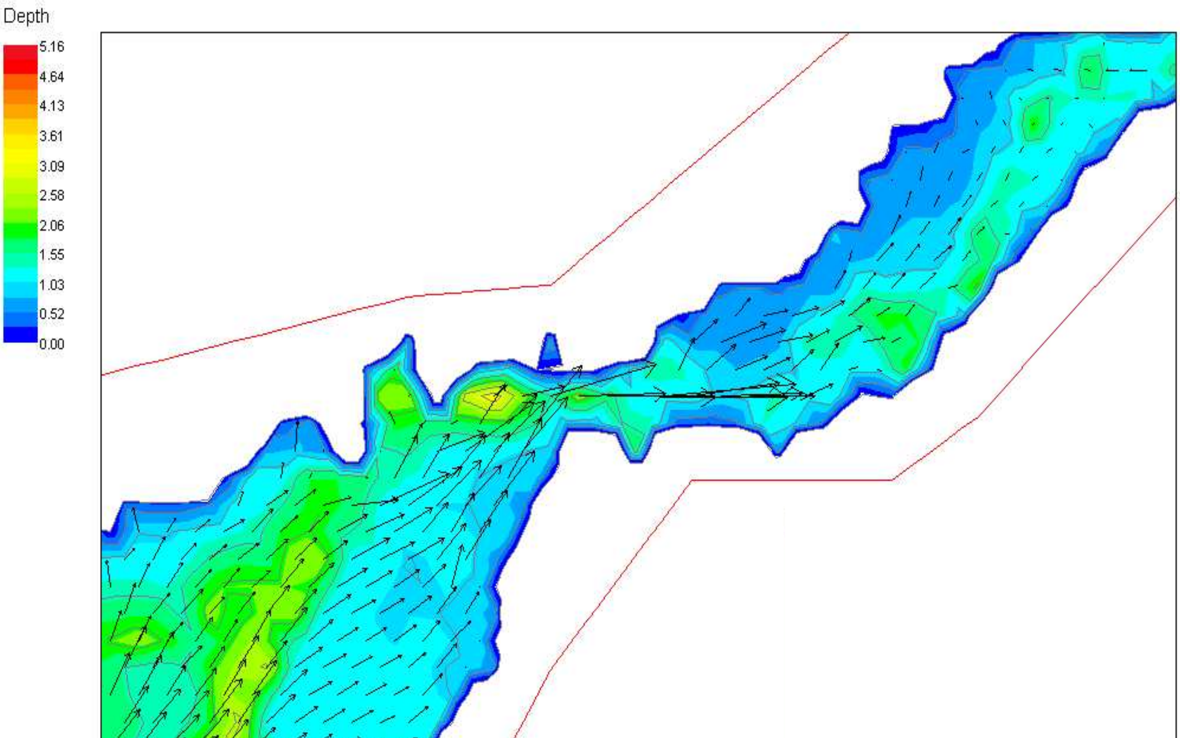


Fig.3.247: Tidal peak travelling up the estuary through the channel constriction between the lower and middle basins.

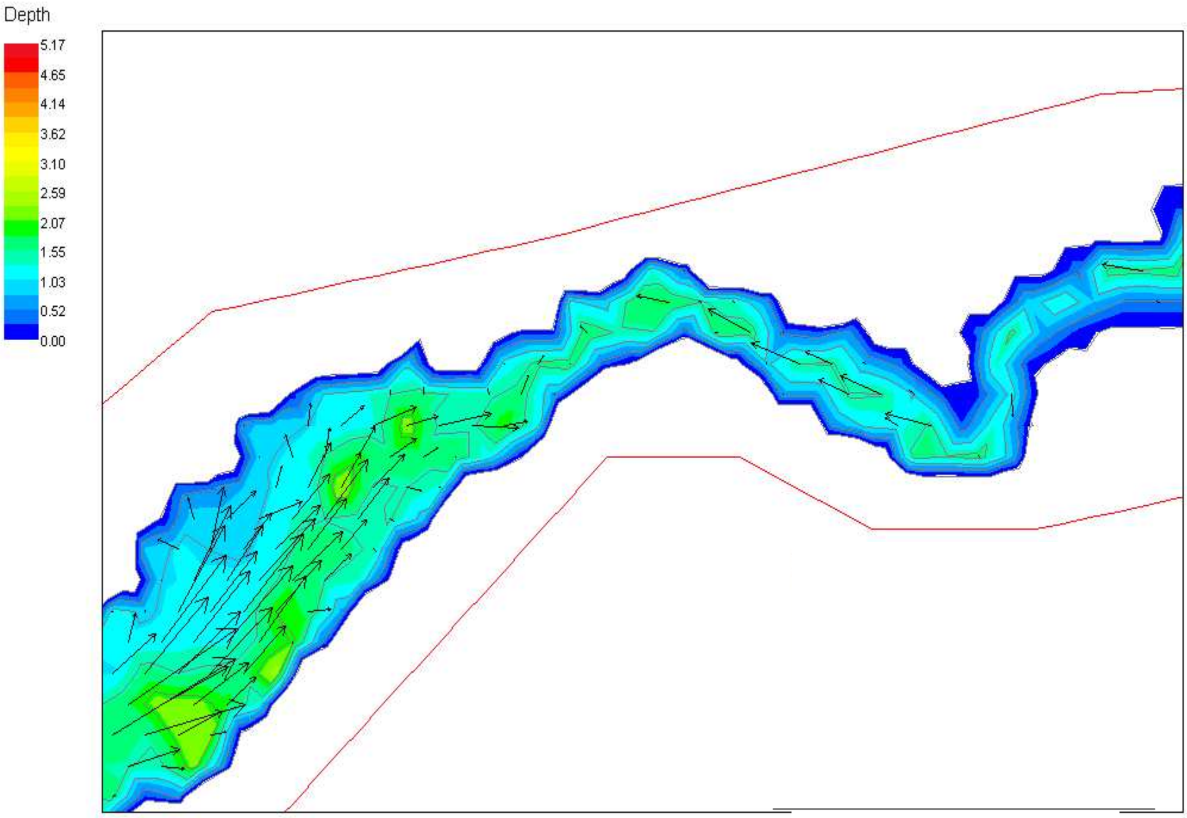


Fig.3.248: Inflowing tide meeting river outflow at the channel constriction between the middle and upper basins.

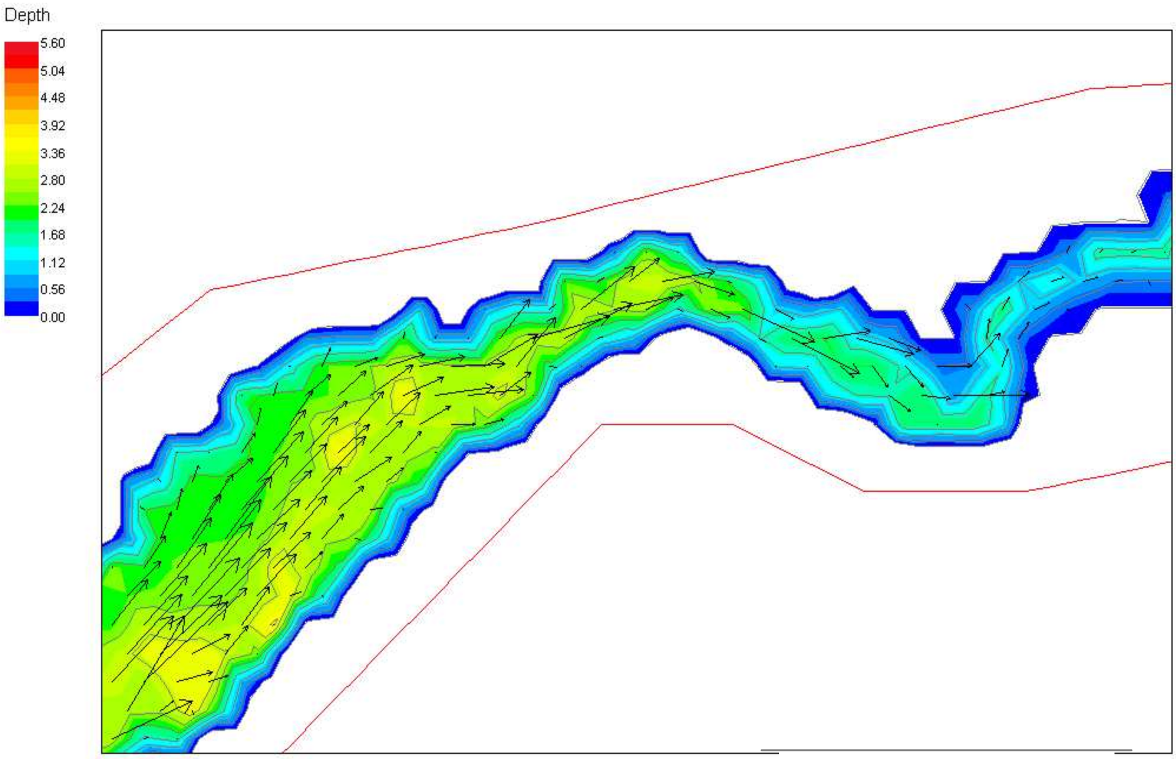


Fig.3.249: Flow reversal as an incoming tide passes Penmaenpool.

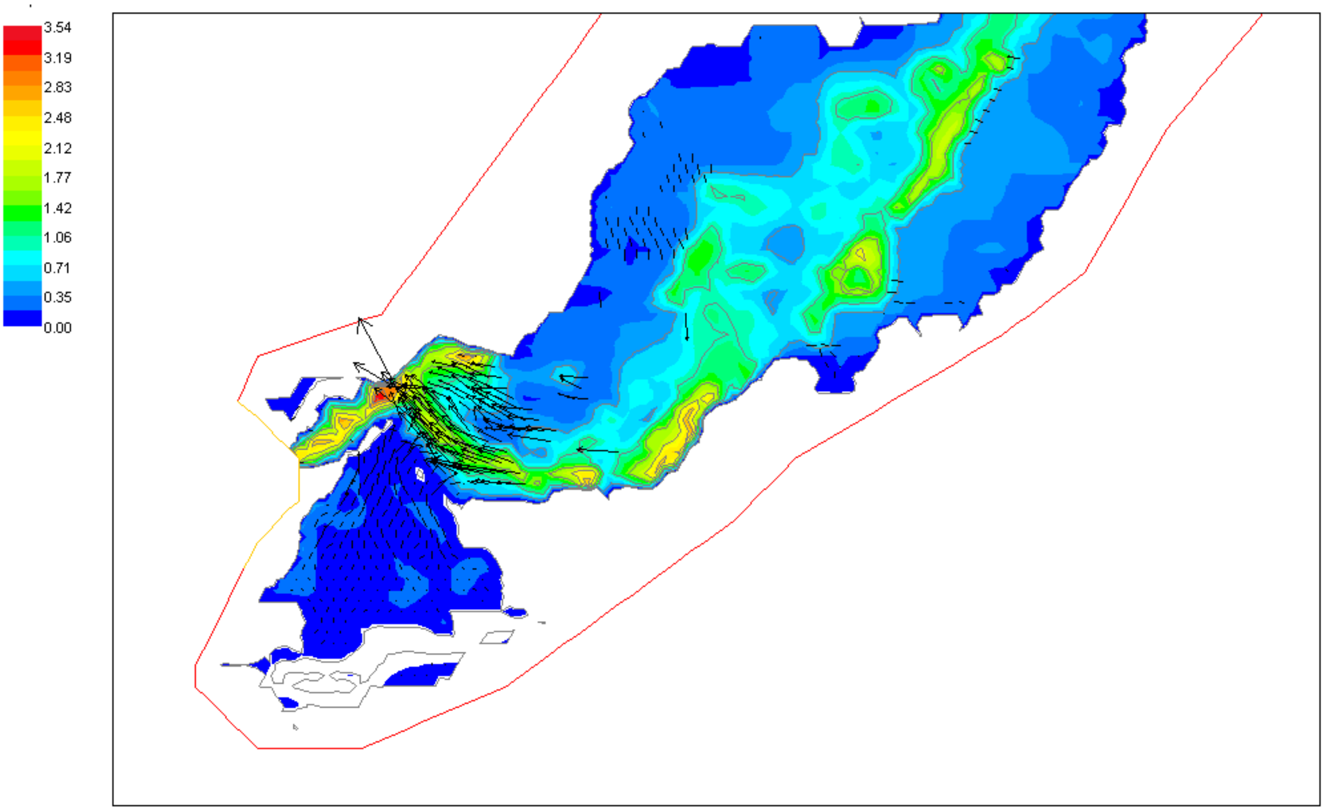


Fig.3.250: Tidal outflow begins as water level falls at the estuary mouth. Extensive drainage from tidal flats is occurring.

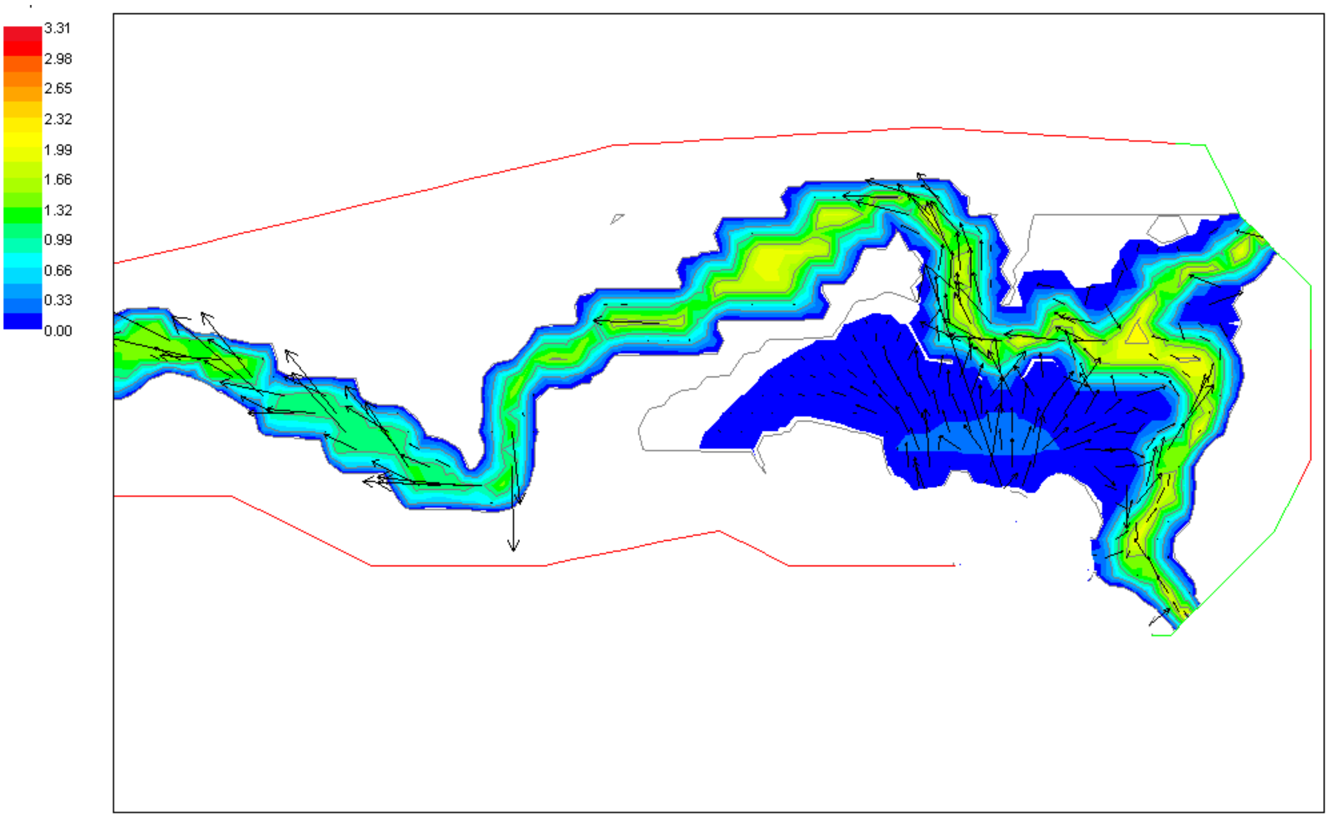


Fig.3.251: Drainage from salt marshes and reed beds in the upper estuary basin with a falling tide.

The simulated hydrograph for Penmaenpool is given in fig.3.252. In comparison with the hydrograph of fig.3.235 recorded at Penmaenpool bridge, this shows a similar asymmetric pattern with rapid water rise on the incoming tide followed by a more gradual, roughly exponential fall. Physically, this represents:

- a rapid tidal rise closely following the change in sea level at the estuary mouth, allowing a time delay of 30 minutes for upstream advection to Penmaenpool,
- a slower fall, as water flows out of temporary storage in the reed beds and salt marshes of the upper estuary basin. The falling hydrograph curve is exponential, due to decreasing flow from salt marsh storage as the hydraulic head difference declines in relation to channel base level.

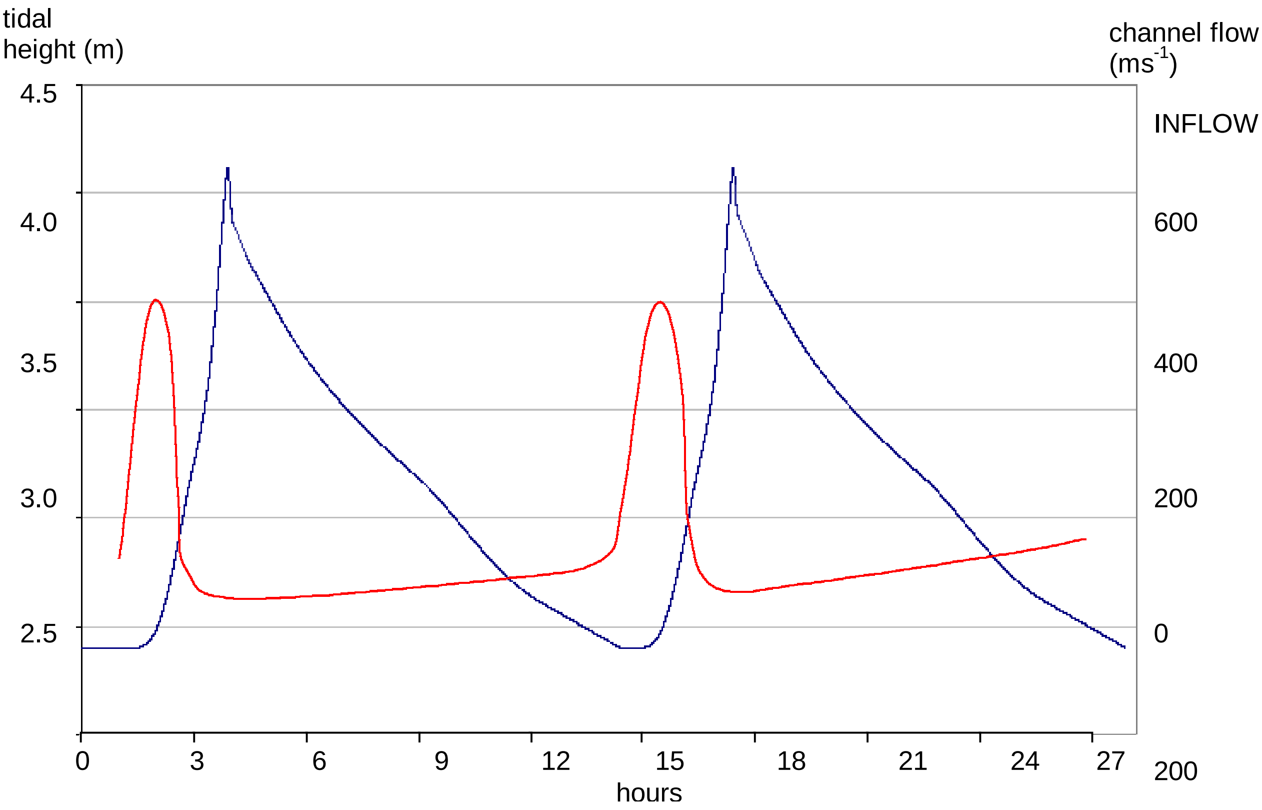


Figure 3.252: Simulated water height (blue) and channel flow (red) at Penmaenpool bridge during tidal flood-ebb cycles

The whole-estuary model is considered to give a satisfactory representation of tidal flows. The simulated water flows at Penmaenpool, shown by the red line in fig.3.252, are used as tidal inflow boundary conditions for the upper basin model described in the next section.

Upper basin model

The upper basin is modelled on an approximately 40m uniform finite element grid, modified with additional detail in the vicinity of river channels (fig.3.253). The configuration of isosceles right-angled triangles provides maximum computational efficiency whilst retaining acceptable accuracy in modelling the river channels. Topography includes the flood defence embankments around agricultural land in the lower estuary basin.

It was found that a realistic representation of tidal boundary conditions at Penmaenpool is obtained by a combination of transient inflows during the rising tidal phase, combined with a depth-unit discharge relationship:

$$q = h^{1.66}$$

during the falling tidal phase.

A series of scenarios were modelled for the upper estuary basin and tidal reaches of the rivers Mawddach and Wnion at the estuary head:

Case 1

A study was made for moderate flood conditions, using flood hydrographs reaching peaks of $200m^3s^{-1}$ for the Afon Mawddach and $150m^3s^{-1}$ for the Afon Wnion. An event of this severity would be expected to cause some flooding of low lying land around the estuary head, but overbank discharge would be minimal in the Dolgellau reach of the Afon Wnion (see section 3.4).

In a first run of the model, the flood hydrograph peak was timed to correspond with a 4m rising tide close to its peak.

In the second run of the model, the flood hydrograph peak was timed to correspond with a 4m falling tide close approaching low water in Barmouth.

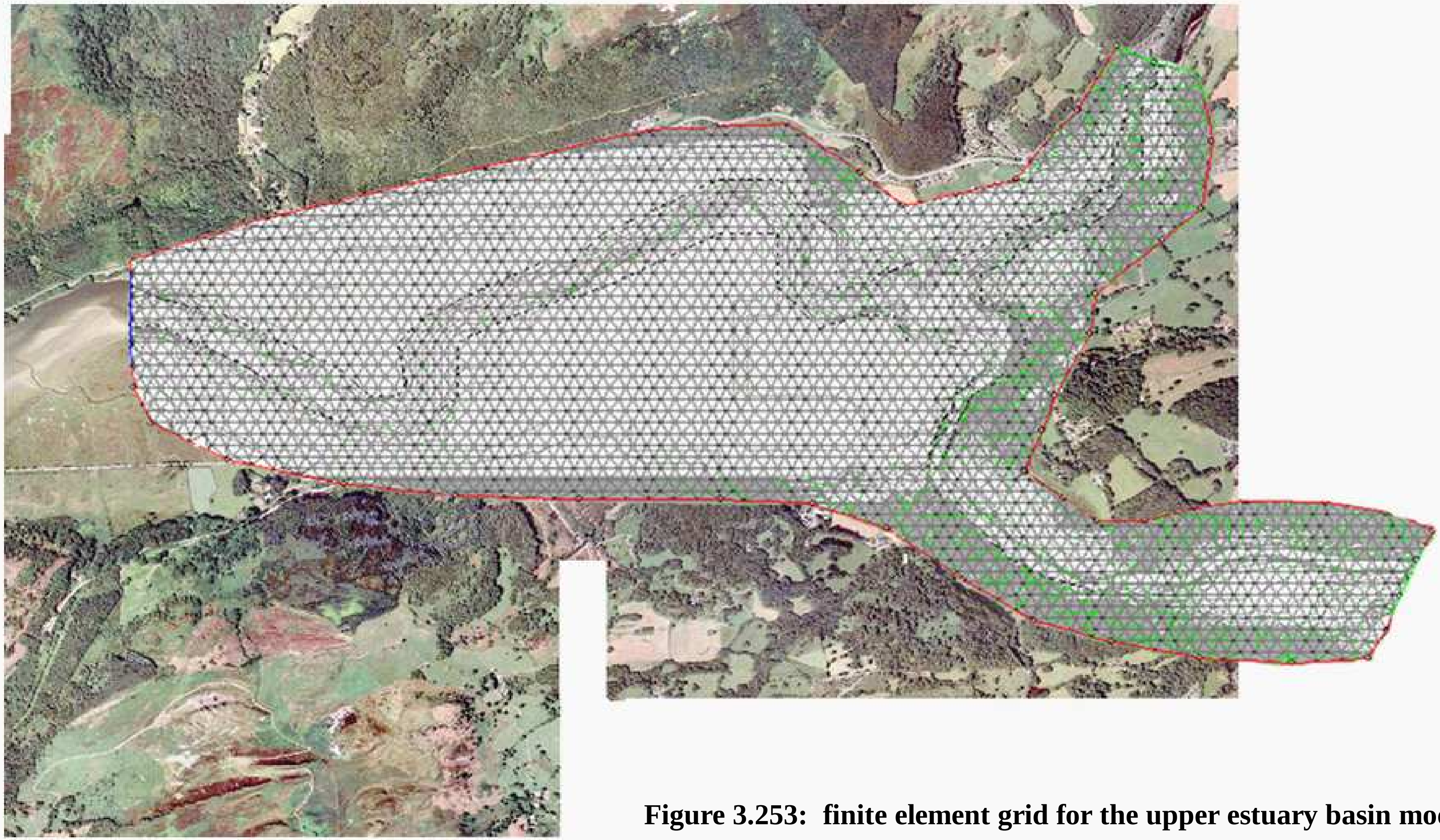


Figure 3.253: finite element grid for the upper estuary basin model

The model for tidal inflow at flood peak is shown in fig.3.254. Water accumulation within the reed beds near the Mawddach – Wnion confluence is evident, with minimal water depth across the area of reclaimed agricultural land behind the flood embankments.

At low tide, some reduction in flood depth is observed around Penmaenpool (fig.3.255), but there is little effect on flood conditions at the estuary head. This is consistent with the Australian model for river processes dominating around the head of a wave-dominated estuary.

The patterns of water flow represented in Case 1 are characteristic of more serious flooding, with even greater dominance of river flows over tidal effects in the upper basin of the estuary. During the July 2001 flood event, large amounts of forestry debris were swept downstream by the swollen Afon Mawddach and accumulated at Penmaenpool bridge (fig.3.256). Water flowed across the low lying land at the estuary head, depositing complete trees carried down from the mountain catchment (fig.3.257).

Case 2

The topography of the model was modified to simulate the reclamation of farmland across the whole of the low lying area at the head of the Mawddach estuary. This included provision for flood defence embankments around fields in a similar manner to the reclaimed areas near Penmaenpool. The model was run using the same peak flow rates of $200m^3s^{-1}$ on the Afon Mawddach and $150m^3s^{-1}$ on the Afon Wnion, and tested for situations of both rising and falling tides.

The extent of flooding of land around the estuary head was significantly less than for Case 1, and was again hardly affected by the state of the tide. A matter of concern, however, is that flooding of the lower Wnion valley upstream to Dolgellau was significantly worsened in comparison to Case 1 (fig.3.258). It appears that flood water was less able to disperse across the flat lying land at the estuary head, and a back-water effect on the river led to increased water levels upstream.

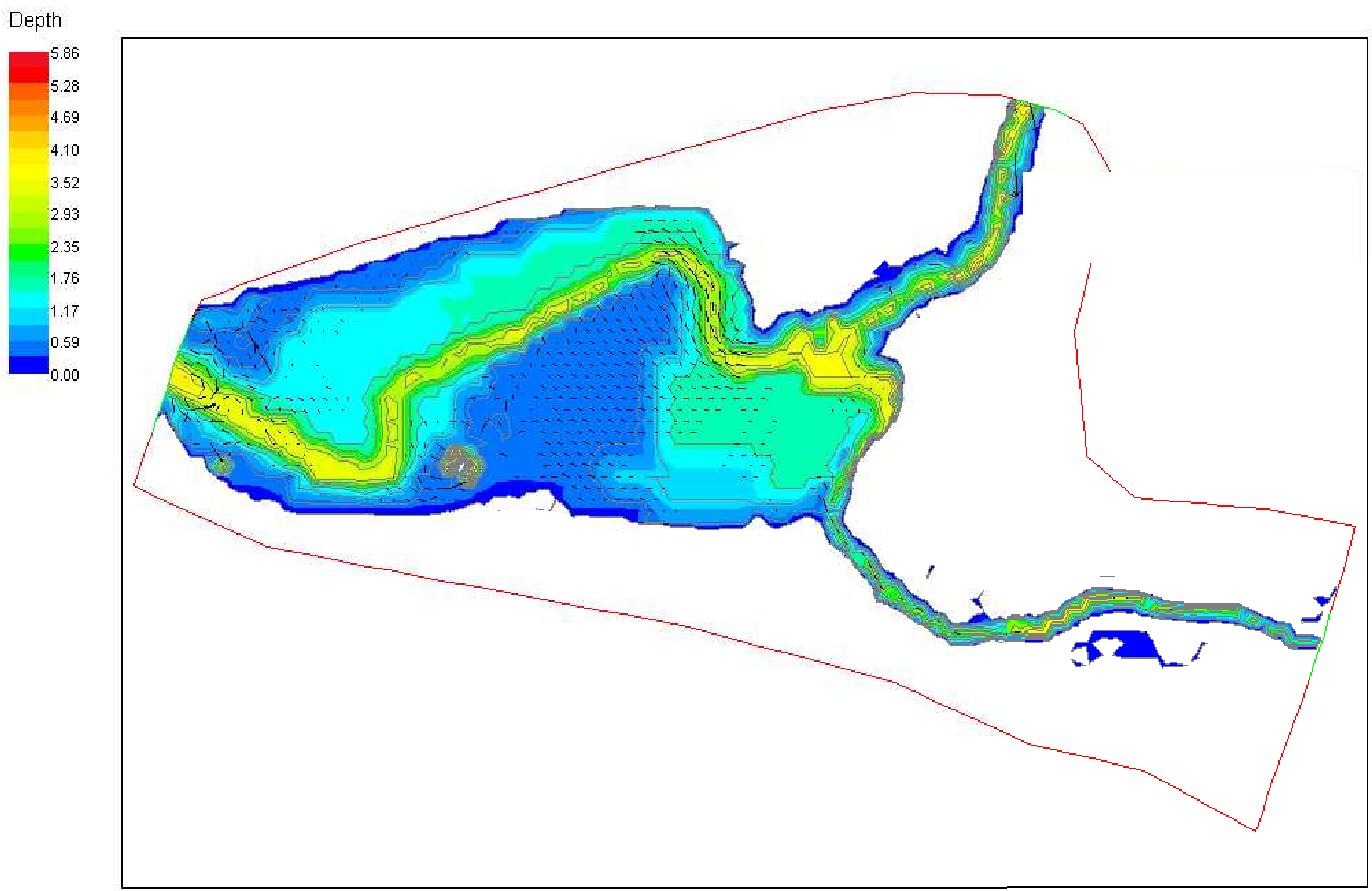


Figure 3.254: Case 1. River flood with tidal inflow under current conditions

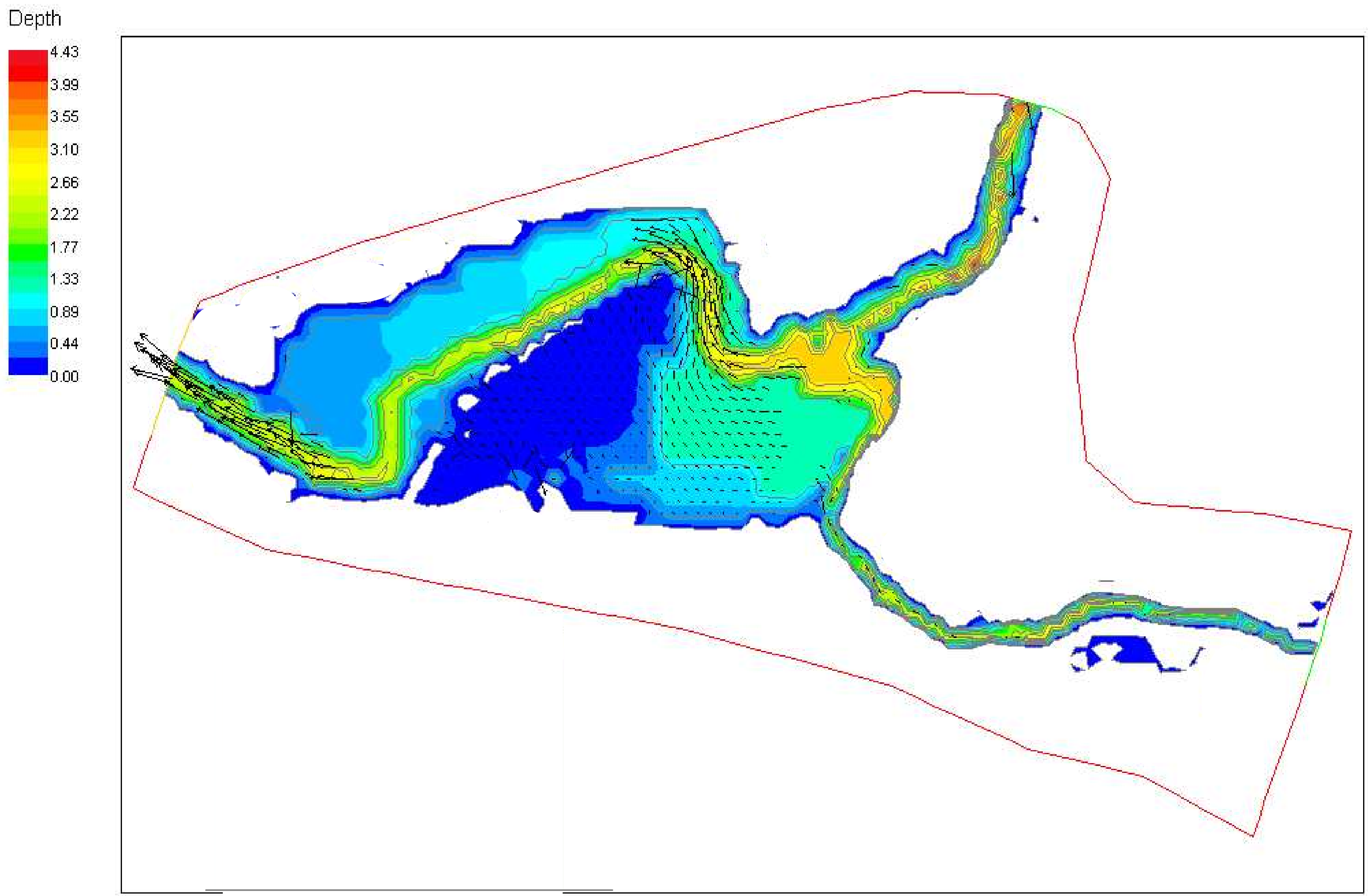


Figure 3.255: Case 1. River flood with tidal outflow under current conditions

Figure 3.256: Accumulation of forestry debris at Penmaenpool bridge from the July 2001 flood event. Photograph: Cambrian News

Figure 3.257: Tree washed downstream onto low lying land around the head of the Mawddach estuary during the July 2001 flood event.

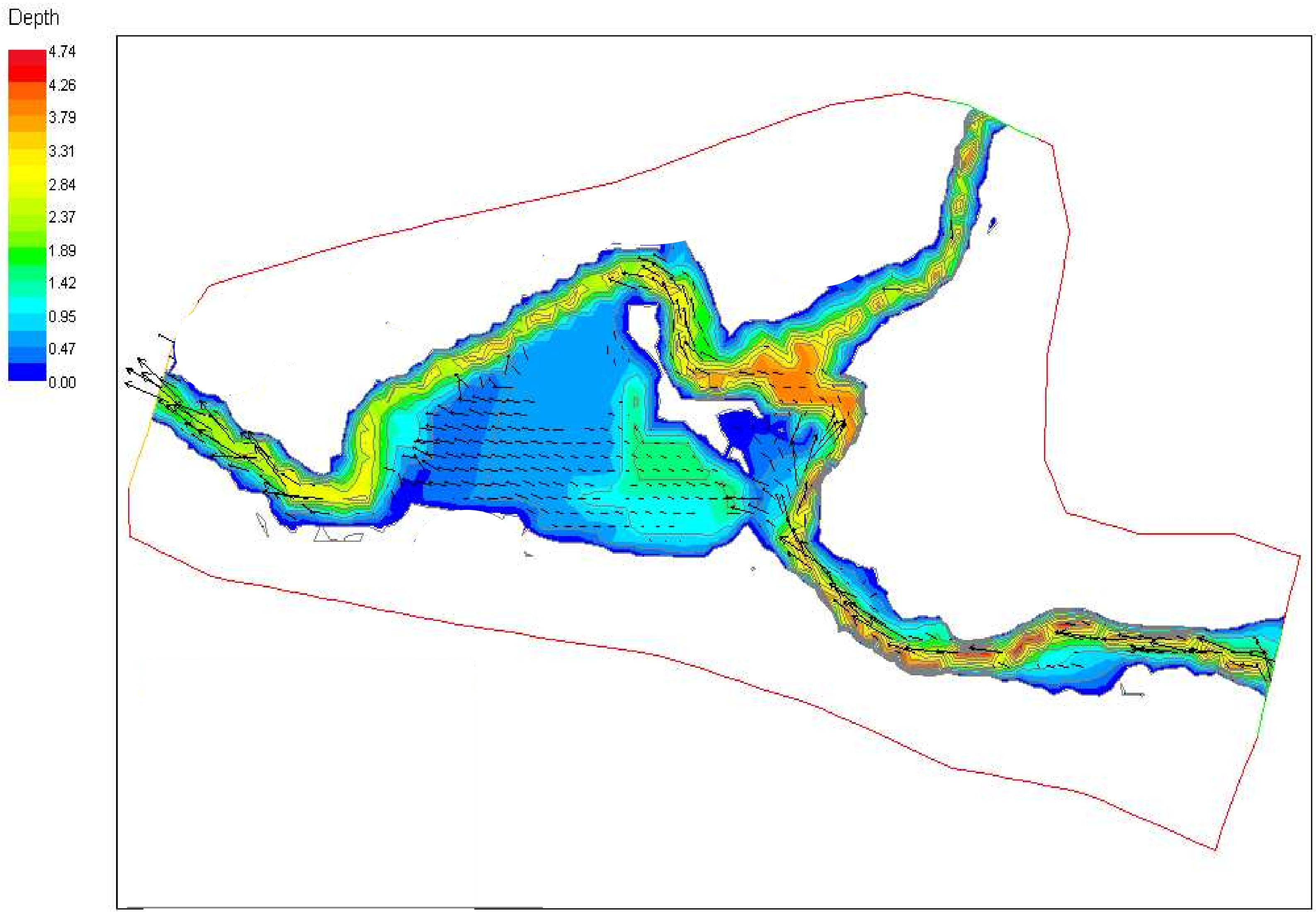


Figure 3.258: Case 2. River flood event after land reclamation and construction of flood embankments at the head of the Mawddach estuary

Sediment modelling

Sediment accumulation is an issue which should be considered when developing a management plan for the Mawddach catchment. The mountain hinterland has an extensive coverage of glacial and periglacial deposits which are readily eroded during storm events. Large volumes of sand and gravel are carried downstream and deposited in the upper estuary, leading to a progressive rise of river base level.

Modelling was carried out in section 3.3 using the GSTARS program of Yang and Simões (2000). Sediment volumes discharged into the estuary during the flood events of July 2001 and February 2004 were estimated. Field evidence indicates that gravel and cobble grade material carried downstream is unable to move much beyond the tidal limits of the rivers Mawddach and Wnion. This material accumulates as large banks of coarse sediment at the head of the estuary around the river confluence (fig.3.259).

Figure 3.259: Coarse sediment accumulation at the confluence of the rivers Mawddach and Wnion.

To investigate the effects of continuing sediment accumulation, the original model for the upper estuary basin was re-run:

Case 3

The original hydrological model for the upper estuary (case 1) was modified to simulate the accumulation of 0.5m of gravel sediment along the channel beds of the Mawddach and Wnion from the tidal limits to a point 0.5km downstream of the river confluence. This amount of sediment could accumulate as a result of approximately four floods of the magnitude of the February 2004 event.

Results of the model runs for high tide and low tide situations are given in figs 3.260-3.261. The state of the tide is seen to have little effect on the extent of flooding at the estuary head. The extent of flooding around the estuary head appears similar to Case 1. However, considerably greater overbank discharge occurs along the Dolgellau reach of the Afon Wnion. It appears that the rise in channel base level creates a backwater effect upstream.

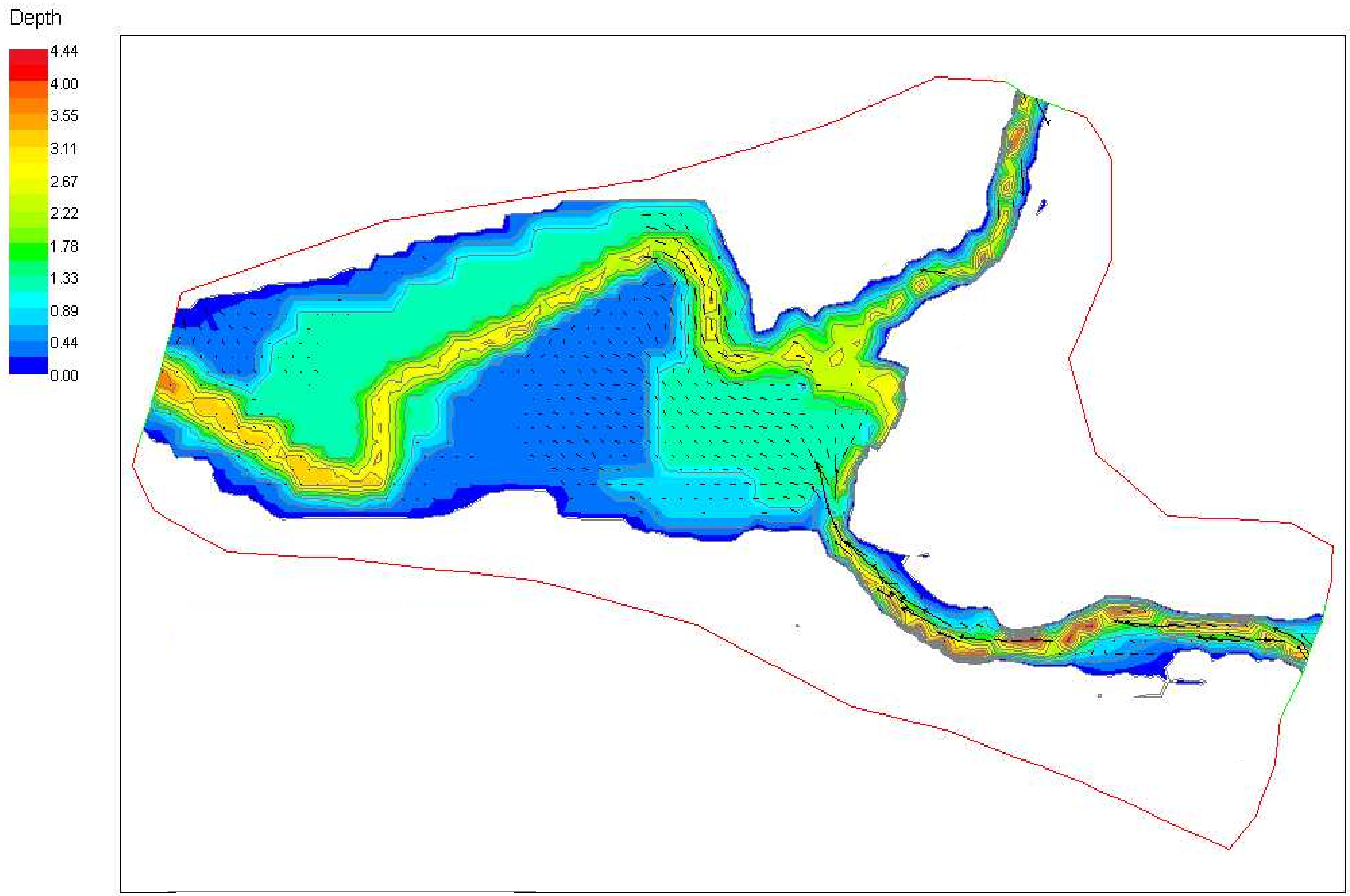


Figure 3.260: Case 3. River flood model after 0.5m gravel accumulation, rising tide

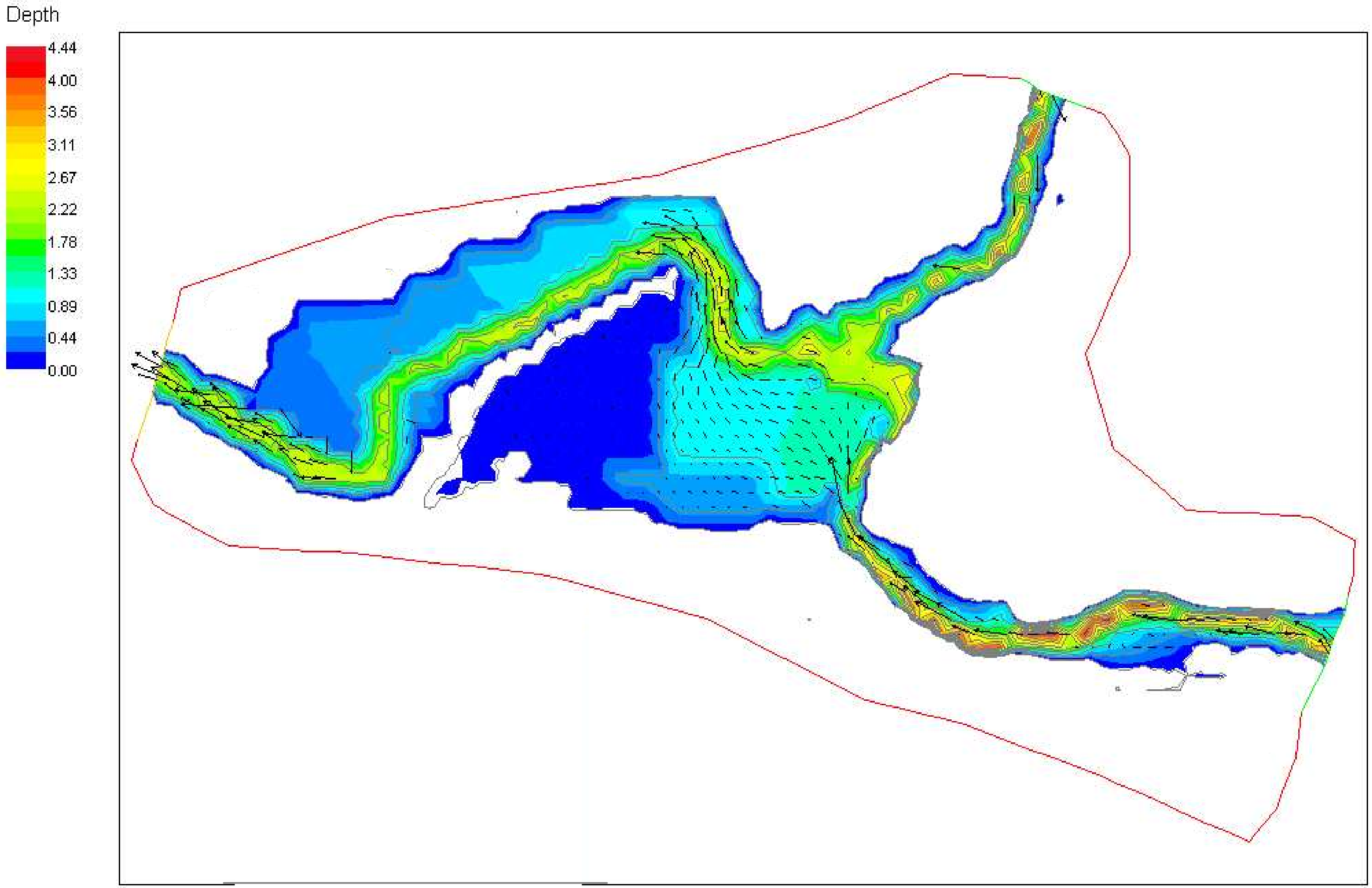


Figure 3.261: Case 3. River flood model after 0.5m gravel accumulation, falling tide

Summary

- The Mawddach estuary can be classified as a wave-dominated estuary, with high energy sand deposition near the estuary mouth and more sheltered environments inside the estuary. Near the estuary head, river flows dominate.
- A sinusoidal pattern of channels is developed for inflows and outflows through the lower and middle estuary basins as a response to Coriolis forces.
- The estuary margins consist of a variety of natural habitat zones, interspersed with areas of reclaimed agricultural land.
- The tidal peak takes 35 minutes to travel the length of the estuary from Barmouth to the tidal limits of the rivers Mawddach and Wnion near Llanelltyd. A water level displacement at the estuary mouth is advected up the estuary with a velocity of approximately 20km/hour.
- Hydrographs recorded at Penmaenpool exhibit a saw-tooth pattern, with rapid rise followed by a slower exponential fall in water level. The rise follows the water level at the estuary mouth, allowing for a 30 minute advection delay, whilst the fall is controlled by drainage from salt marshes and reed beds in the upper estuary basin.
- Tidal spikes are observed in the hydrographs of the Mawddach and Wnion near their tidal limits, and have maximum heights which can be closely correlated with the tidal heights at Barmouth, with neither a rise nor a fall in tidal height occurring during passage of a tidal peak up the estuary.
- A hydrological model for the whole estuary is able to realistically simulate the timing and heights of water flows at Penmaenpool during flood and ebb tidal cycles.
- Flooding around the head of the Mawddach estuary is dominated by river processes, with tidal flows having minimal influence on the extent of flood inundation.
- Further land reclamation accompanied by the construction of flood embankments is likely to constrict river drainage, leading to an increased flood risk upstream at Dolgellau.
- Continued gravel deposition and the raising of channel bed level is likely to produce backwater effects which increase flood risk upstream, again threatening the town of Dolgellau.