HYDROLOGICAL MODELLING OF FLOOD EVENTS AROUND THE MAWDDACH ESTUARY, NORTH WALES

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Abstract: River and tidal flood mechanisms around the Mawddach estuary are investigated in a project combining field observations with computer modelling. Flood events are generally associated with intense frontal storms over the surrounding mountains, often accompanied by exceptionally high tides driven into the estuary by onshore gales. Modelling has been carried out using RMA2 and River2D finite element programs. The RMA2 model proved to be unstable for transient modelling of the estuary when simulating the wetting and drying of elements. River2D gave a stable model for tidal cycles with wetting and drying of salt marsh, reed beds and riparian woodland. River2D does not provide facilities for modelling flood wall overtopping, but this limitation is being addressed by the development of a new finite volume model. A range of modelling scenarios is being examined in which the estuary ecosystem is modified by land reclamation, or bathymetry is modified by accumulation of fluvial sediment.

Keywords: Mawddach, Estuary modelling, Flooding, Salt marsh , Finite element, Finite volume

1. INTRODUCTION

Flooding regularly occurs around the head of the Mawddach estuary in North Wales, disrupting communications and farming activities, and threatening low-lying buildings in the town of Dolgellau (Barton, 2002). The mechanisms of flood events are being investigated in a project combining field observations with computer modelling.

The estuary developed as a glaciated fjord inlet and is now largely infilled by glacial till, periglacial deposits and marine sands. The estuary is constricted at the mouth by the Ro Wen shingle spit (Fig.1).

Fig.1: Mouth of the Mawddach estuary, showing the Ro Wen shingle spit. A tidal gauge is positioned below the main span of the railway bridge at the estuary mouth.

The estuary can be divided into lower, middle and upper basins (Fig.2) separated by narrowing between outcrops of resistant rock. Flooding around the estuary is generally associated with intense frontal storms over the surrounding mountains, often accompanied by exceptionally high tides driven into the estuary by onshore gales. Flooding within the upper basin occurs largely by river processes, whilst tidal flooding predominates in the middle and lower basins.

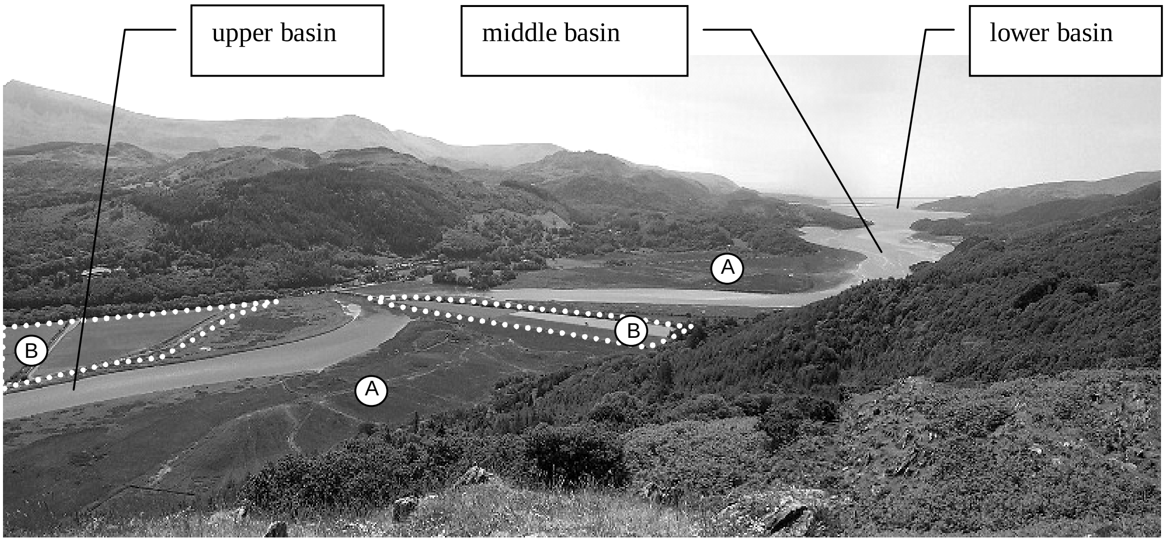

Fig. 2: Mawddach estuary. A: natural flood lands B: reclaimed agricultural land, enclosed by flood walls.

2. NATURAL VEGETATION AND LAND USE

The Mawddach estuary has ecologically important reed bed, salt marsh, water meadow and wet woodland habitats (Figs 3-5).

Fig. 3: (left) *Spartina alterniflora* salt marsh in the lower basin.

Fig. 4: (below). *Phragmites australis* reed bed community in the upper basin.

Fig. 5: (above left) Species-rich water meadow in the upper basin, dominated by Rush, Sedge, the grasses *Agrostis* and *Deschampsia*, and a variety of flowering plants including: Clover, Marsh Thistle, Sharp Dock, Buttercup and Burnet Saxifrage. Wet woodland in the middle distance includes: Willow, Alder, Birch, Rowan.

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 very high tides, and have been progressively strengthened (Fig. 6). Extension of the reclaimed areas is actively continuing at the present day, with land used for sheep and cattle grazing and growing silage.

Fig. 6. Flood wall at Penmaenpool, separating salt marsh on the right from improved grassland on the left of the picture.

Fig. 7. Overtopping of flood walls in the upper basin during a river flood event, February 2004.

3. HYDROGRAPHS

Two rivers enter the head of the estuary, the Mawddach and the Wnion. Continuous water depth recordings have been made over a two year period from 2003-4 near the tidal limits on each river. Tidal graphs are available for the same period from a recorder at the mouth of the estuary (Proudman Oceanographic Laboratory, 2006). Example hydrographs for the River Wnion are given in Figs 8-9. Significant flooding is known to occur when river depth exceeds 190cm at the recording point. Fig. 8 illustrates a storm hydrograph peak on 1 April 2003 with a superimposed spring tidal spike of exceptional height due to onshore winds accompanying the storm. Fig. 9 illustrates a similar storm hydrograph peak on 11 February 2003, but at a time of neap tides when no tidal spikes are observed.

A typical correlation of tidal maximum heights at the estuary mouth and at the river tidal limits is shown in Fig.10 for the period 15-24 February 2003. A loss of hydraulic head of approximately 40cm occurs over the 12km distance that the tidal peak travels up the estuary.

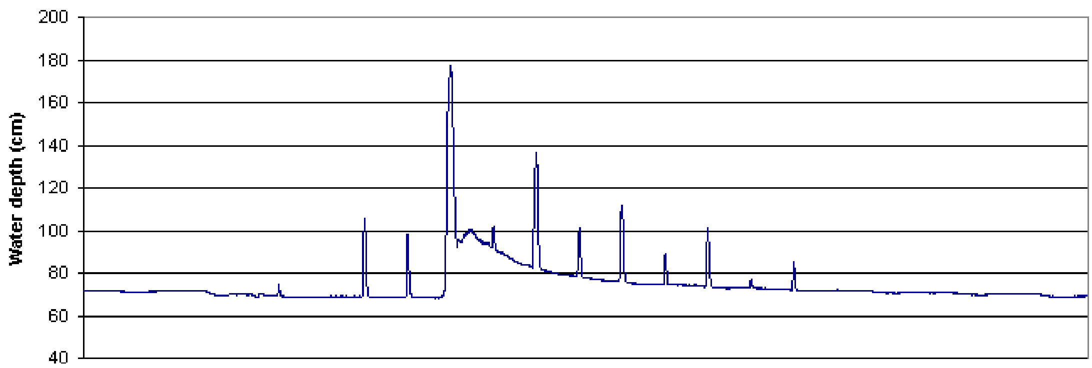

Fig. 8. River Wnion: hydrograph near the tidal limit for the period 28 March – 8 April 2003

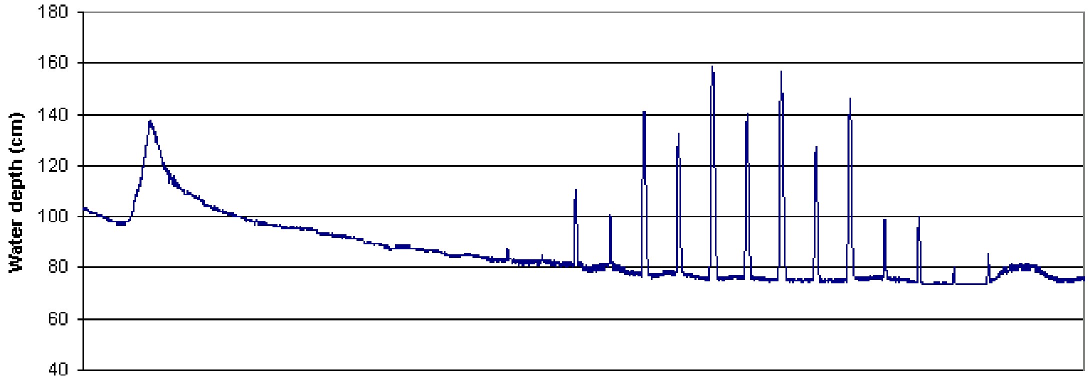

Fig. 9. River Wnion: hydrograph near the tidal limit for the period 10-24 February 2003

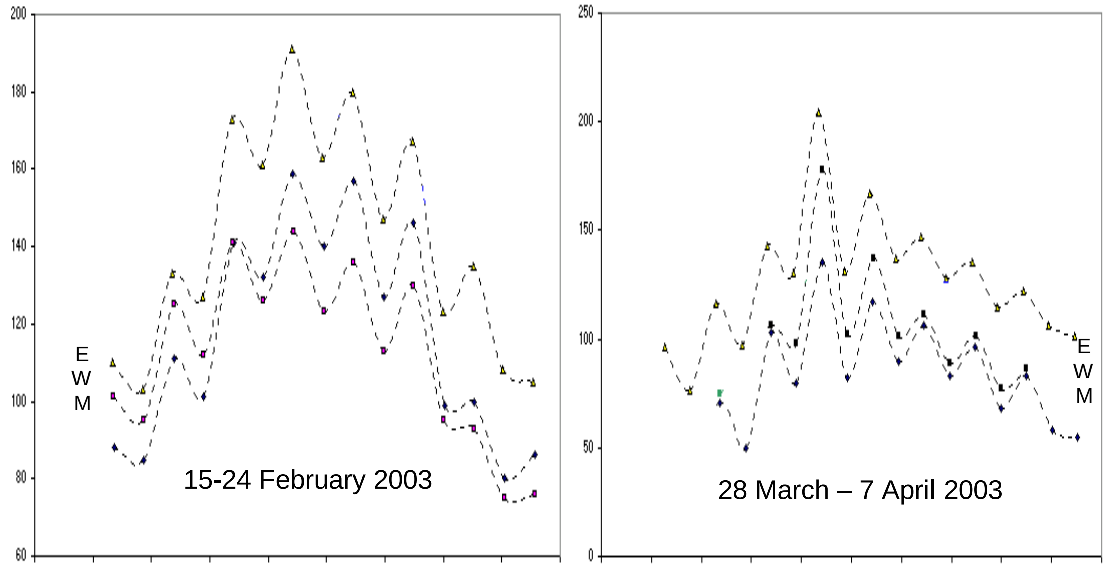

Fig. 10. Correlation of tidal maximum heights at the estuary mouth (E) and at the river tidal limits of the Mawddach (M) and Wnion (W).

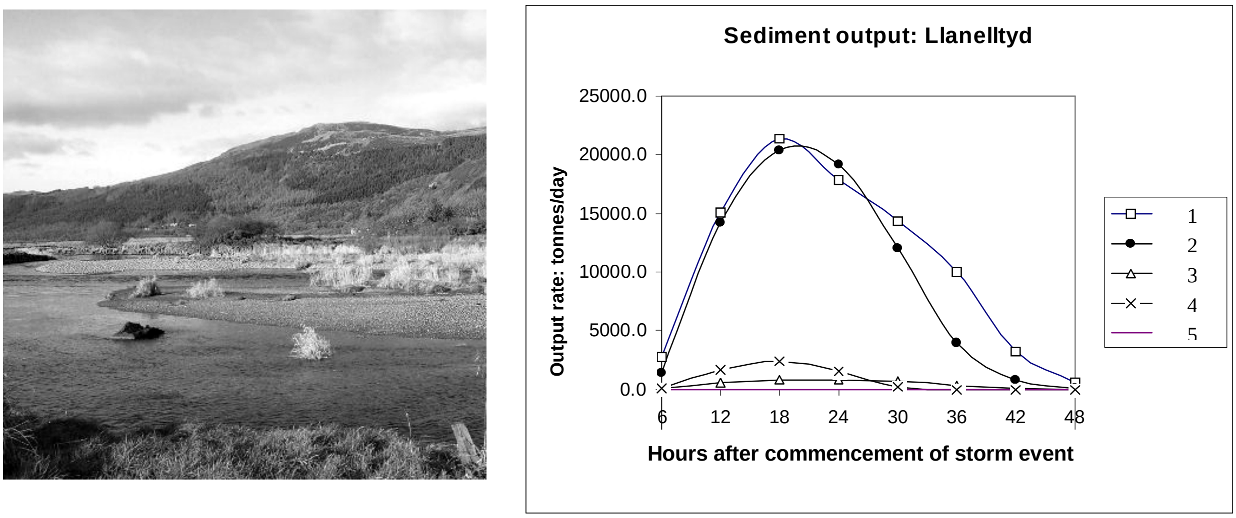

Fig. 11 (left). Area of gravel deposition at the head of the estuary. (right) Modelled output of sediment from the River Mawddach into the tidal estuary during the 3 July 2001 flood event. Legend numbers refer to sediment classes: 1, silt-coarse sand; 2, very coarse sand-fine gravel; 3, medium-coarse gravel; 4, very coarse gravel-cobbles; 5, boulders.

4. SEDIMENT MODELLING

Sediment accumulation is an issue to be considered in a management plan for the River Mawddach. 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 has been carried out using the Generalized Stream Tube Alluvial River Simulation (GSTARS) program (Yang and Simões, 2000). Results for sediment discharge into the estuary during the major flood event of 3 July 2001 are shown in Fig.11 (Hall and Cratchley, 2006). Work is currently in progress to estimate sediment deposition over future periods of 10, 20 and 50 years, using accepted forecasts for climate change. A majority of climate change models for western Britain predict an increase in winter rainfall coupled with drier and hotter summers, and a higher rainfall intensity for individual storm events (Jones et al. 2005).

5. ESTUARY MODELLING

Hydrological modelling has been carried out to investigate the effects of changing river base levels at the estuary head due to sedimentation, and increases in the extent of land reclamation for agricultural use within the estuary.

Initial work used the RMA2 program within the Surface Water Modelling System package (Donnell et al., 1997). This is a fully implicit Galerkin finite element model able to process triangular and quadrilateral surface patches (Fig.12).

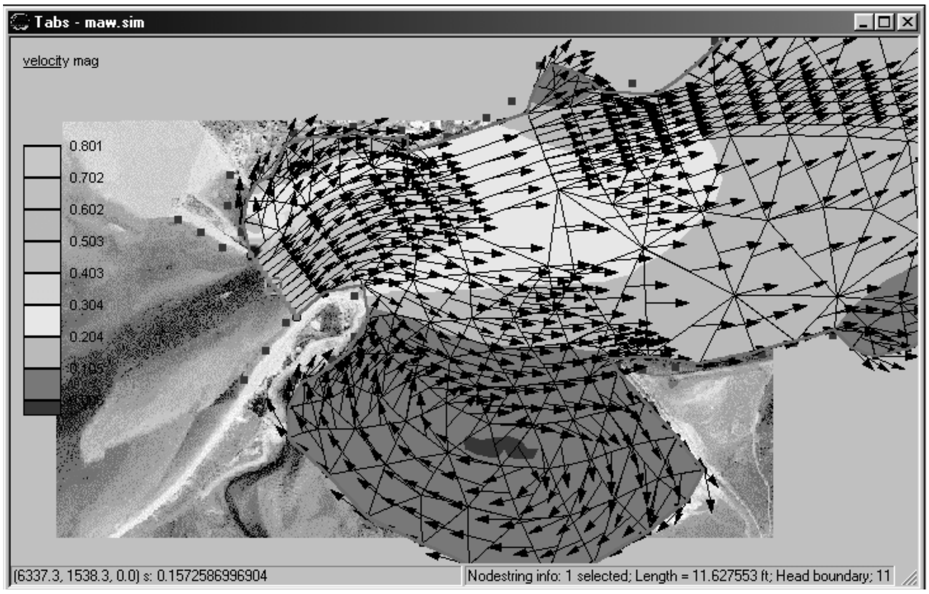

Fig. 12. RMA2 simulation of a flood tide entering the Mawddach estuary.

RMA2 has the capability to model wetting and drying of sandbanks and salt marsh by activating and deactivating elements during a simulation, in response to time-varying boundary conditions of tidal height at the estuary mouth. Our experience, however, was that mathematical instabilities can occur as elements are added or removed, leading to solution non-convergence. The program developers recommend that element edges should be positioned along bathymetric contours, to avoid the appearance of irregu1ar saw-tooth shorelines as elements are added or removed during wetting and drying. A further development has been the introduction of a marsh porosity function, to gradually reduce the storage capability of an element as it is drying, so that removal of the element causes less numerical shock. Despite application of these techniques, instability persisted with the large estuary model, and an alternative approach was sought.

In a separate project investigating forestry for flood control (O Connell, 2004), successful floodplain wetting and drying simulation had been carried out with the River2D finite element model (Steffler P. and Blackburn J., 2002). This program is designed for use on river reaches of the order of 1km in length, but it has also proved very effective for modelling at estuary scale. The extent of water in the estuary at mean low and high tides is shown in Figs.13a-b.

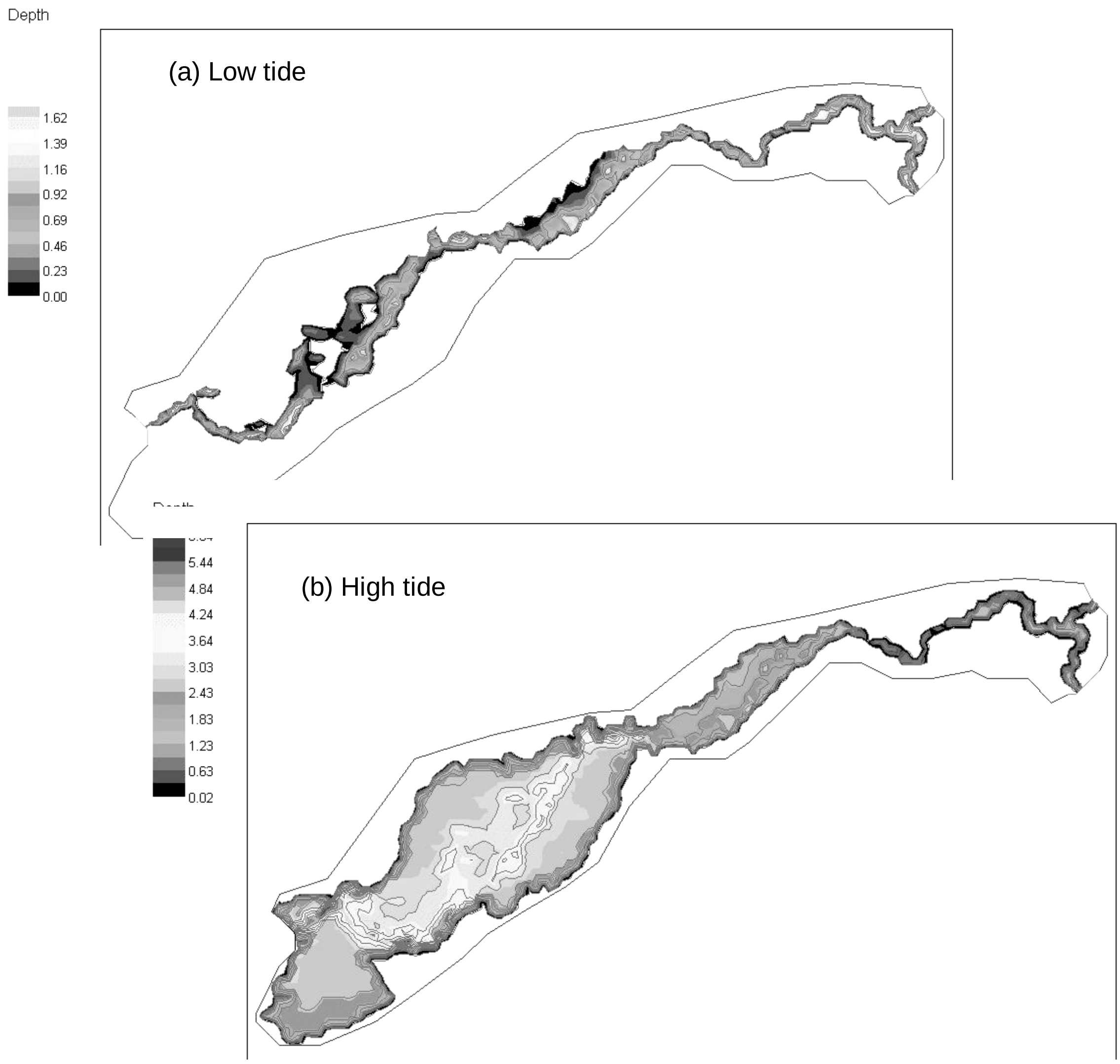

Fig. 13. Simulation of a 4m tide for the Mawddach estuary. Extent of the computation domain is outlined.

A particular feature of the program is its ability to handle wetting and drying of elements in a very stable manner. A governing equation for the River2D program is the conservation of water mass:

$$\frac{\partial H}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \tag{1}$$

where the term in H refers to the rate of change in hydraulic head as river level changes, and the terms in q are the discharge gradients in the coordinate directions x and y.

Changes to the boundary geometry of the estuary channel are handled in the modelling code by linking water levels to the groundwater profile below adjacent floodplain. Beyond the channel margins, equation (1) is replaced by a groundwater equation

$$\frac{\partial H}{\partial t} = \frac{T}{S}\left(\frac{\partial^2}{\partial x^2}(H + z_b) + \frac{\partial^2}{\partial y^2}(H + z_b)\right) \tag{2}$$

in which T is transmissivity, a measure of the rate at which water can permeate through the sediment, S is the storativity which determines the volume of water which can be held within a unit volume of material, and z_b is the ground surface elevation.

River2D offers opportunities to investigate the effects of salt marsh, reed beds and wet woodlands in enhancing temporary water storage and reducing tidal peaks upstream. The model incorporates an eddy viscosity coefficient ν_t which is used in simulating turbulent shear stresses according to the relation

$$\tau_{xy} = \nu_t\left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right) \tag{3}$$

The eddy viscosity coefficient is made up of three components

$$\nu_t = \varepsilon_1 + \varepsilon_2 \frac{H\sqrt{U^2 + V^2}}{C_s} + \varepsilon_3^2 H^2 \sqrt{2\frac{\partial U}{\partial x} + \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right)^2 + 2\frac{\partial V}{\partial y}} \tag{4}$$

The ε_1 term is a constant, and the ε_2 term represents a bed shear. 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. Using appropriate values for ε_3, it is estimated that reed beds and riparian woodland can increase water depth on the floodplain by up to 60cm in comparison to grassland, with consequent increase in transient storage and reduction in tidal height in the upper basin.

6. DEVELOPMENT OF A FINITE VOLUME MODEL

Whilst very successful in modelling transient boundary conditions and wetting/drying, River2D is limited in its ability to model the effects of control structures – particularly flood walls and tidal drainage doors. For this reason, it was decided to develop a new mathematically stable model to incorporate features appropriate to the Mawddach case study. The model uses the weighted implicit finite volume method of Lal (1999) with a combination of triangular and quadrilateral volume elements:

Fig. 14. Finite volume discretisation for the Mawddach estuary, based on a bathymetric survey (Olding Smee Oberman Associates, 1985) and natural vegetation zones delineated from air photography.

The finite volume method uses a line integral technique for computing the water flow through the walls of volume elements, leading to a matrix solution $\mathbf{Q}^n = \mathbf{M}^n \cdot \mathbf{H}^n$ where **Q** and **H** are column matrices representing discharge and hydraulic head for the elements, and **M** is a square matrix related to the geometry of the model. Solutions to the linear system have greatest stability when carried out fully implicitly, using values at the current time step but not values at the previous time step (Press et al., 1992). The matrix **M** is sparse, with most element values zero, so special approaches are possible for fast solution. Appropriate code is available within the SciLab software package, available at the web site www.scilab.org.

7. DISCUSSION AND CONCLUSION

Various modelling techniques have been examined during the study of the Mawddach estuary. A suitable model requires to be mathematically stable during wetting/drying cycles in which the tidal boundary head condition varies sinusoidally, and river boundary inflow conditions follow storm hydrograph patterns. The model should simulate the physical processes of energy dissipation and transient water storage within different wetland vegetation communities, distinguishing between salt marsh, reed beds and riparian woodland in their responses to flooding. For the Mawddach case study, effects on bathymetry due to fluvial sediment deposition at the estuary head must be considered. A finite volume model meeting these criteria is being developed.

Preliminary results indicate that continued reclamation of flood lands for agricultural use will lead to higher water levels in the upper basin, since less reduction of hydraulic head will occur through temporary water storage. Tidal limits may move upstream, with estuary head sediment deposition moving upstream also. This can have consequences for flood frequency and intensity in low lying areas of the town of Dolgellau. It is recommended that further wetland reclamation should not take place, and that existing salt marsh, reed beds and riparian woodland be conserved for the purposes of flood control.

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