Flood forecasting for the Mawddach catchment, North Wales

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Abstract
This paper describes a project carried out in the mountainous Mawddach river catchment of North Wales to design a high resolution flood forecasting model. The model was evaluated by field monitoring of storm events using an array of instruments across the catchment. A new hill-slope runoff model has been developed which focusses on relationships between surface runoff and shallow downhill subsurface water flows through superficial deposits based on the HOST (hydrology of soil types) scheme. The flood forecasting system combines this model with existing meteorological, river routing and floodplain models. Acceptable 3-hour flood forecasts can be computed from rain gauge data. Frontal rainfall can be modelled 6 to 9 hours ahead with errors of around 25% in total rainfall volume. Accuracy can be improved by applying neural network processing at the start of a storm event. Rainfall patterns during convective storms are more uncertain, though the Anthes-Kuo convective physics scheme within the MM5 modelling system gave good results for a major convective storm of July 2001 over the Mawddach catchment.

1. Introduction

This paper reviews a PhD project (Hall, 2008) carried out in the mountainous Mawddach river catchment of North Wales with the objective of designing a high resolution flood forecasting model. Motivation came from the extreme event of 3 July 2001, when a convective squall line storm over the Mawddach catchment led to extensive damage in the forested area of Coed y Brenin, with roads and bridges washed away and properties flooded. The main town within the catchment, Dolgellau, has a long history of serious flooding.

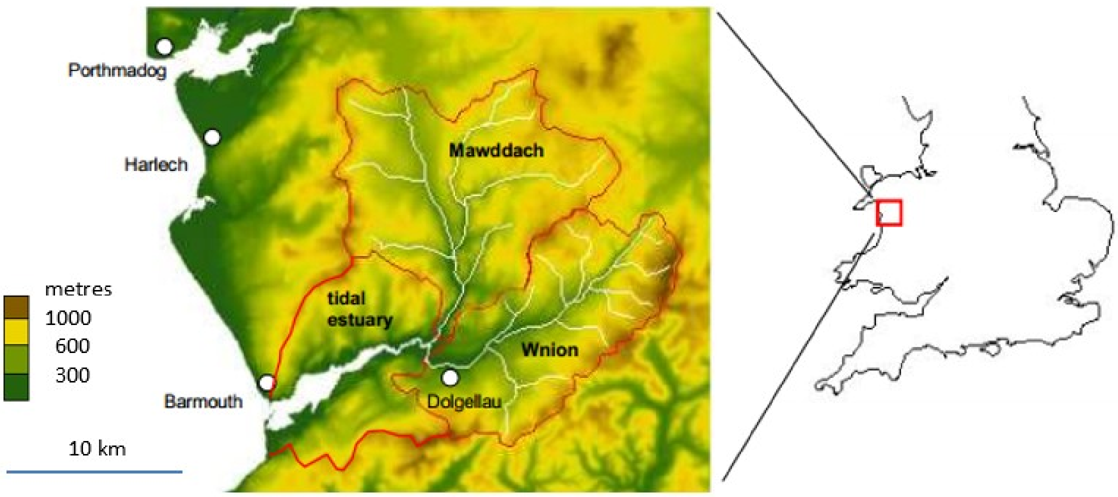

FIGURE 1. The Mawddach catchment, North Wales

The study area consists of two sub-catchments: the linear catchment of the Afon Wnion with an area of approximately 120 km^2, and the dendritic catchment of the Afon Mawddach with an area of approximately 160 km^2. Field monitoring of storm events was carried out over a period of four years using rain gauges, hill slope runoff measurement, and river depth gauges at a number of locations across both sub-catchments. Computer models of rainfall patterns, hillslope water movement and river flows were evaluated against field data.
A hill-slope runoff model has been developed which focusses on relationships between surface runoff and shallow downhill subsurface water flows. A flood forecasting system has been constructed for the Mawddach catchment by combining the hill slope model with existing meteorological, river routing and floodplain models.

2. Afon Wnion flood prediction

It was found that a simple mathematical transformation could be applied to river depth data from the Wnion headwaters to give an accurate 3 hour prediction of water depth downstream in the town of Dolgellau. Figure 2 illustrates depth gauge readings for the upper Wnion at Pared yr Ychain (blue) and the tidal limit of the Mawddach below Dolgellau (red), before and after an empirically determined transformation of the upper Wnion readings:

Water depth in Dolgellau = 0.05 exp (8.2 * water depth at Pared yr Ychain) – 0.15

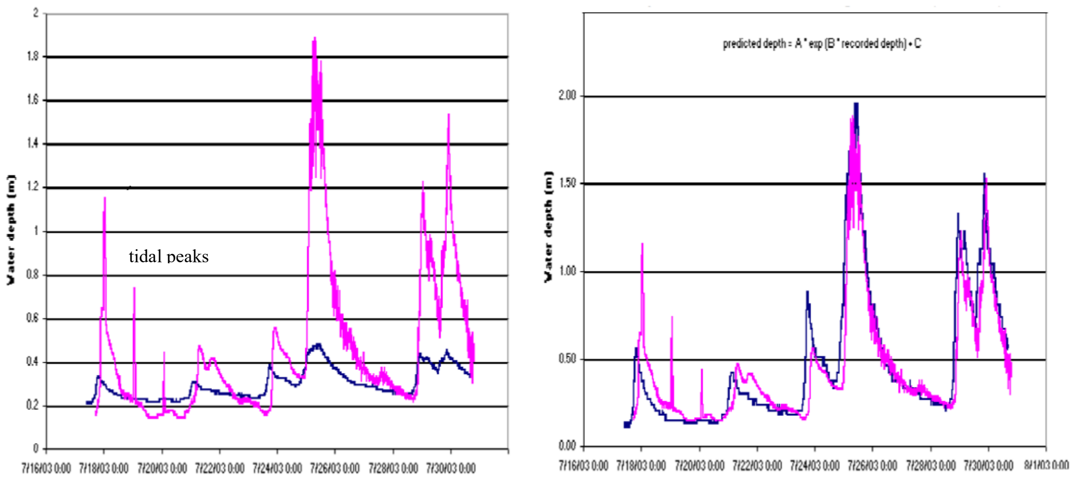

FIGURE 2. Hydrographs for the Afon Wnion

3. Mawddach hillslope hydrological model

No simple mathematical relationship was found between water depths in the headwaters of the Afon Mawddach and river flows downstream. Thick deposits of glacial and periglacial materials are locally present within this mountain region, particularly in valleys. Experiments to monitor hill slope through-flow and runoff showed that these superficial deposits play a crucial role in controlling the antecedent conditions necessary for saturation-excess flood events.
A new distributed hillslope runoff model has been developed, based on the hydrological response of different soil groups. The Hydrology of Soil Types (HOST) classification is applied, based on two parameters: wetness of the site, and variation in permeability within the soil profile. These parameters combine to generate a matrix of hydrological responses (Boorman, Hollis and Lilly, 1995).

Wetness of a particular site can be predicted by calculation of the Kirkby wetness index from a digital elevation model (Kirkby, 1978):

$$Kirkby\ wetness\ index = ln\left(\frac{a}{\tan E}\right)$$

$\text{Kirkbywetnessindex} = \ln\left(\frac{\text{a}}{\tan \text{E}}\right)$where a is contributing area of upslope drainage and E is slope angle.

Variation in permeability within the soil profile is classified within the HOST model as: *increasing downwards, uniform*, or *decreasing downwards*. This parameter is found to be closely related to the geology, with permeability increasing downwards on glacial and periglacial sands and gravels, but decreasing downwards on hard Palaeozoic sedimentary and igneous bedrock. Large variations can, however, occur as a result of vegetation type, with thick brown earths often developing beneath mature conifer plantations and natural oak woods.
From field examination of soil profiles, it has been possible to link particular combinations of geology, vegetation and site wetness to HOST classes. An initial stage in constructing the Mawddach hydrological model is to generate a predicted distribution of soil zones in each sub-catchment, based on Kirkby wetness index, bedrock and superficial deposits, and vegetation on 50m grid squares:

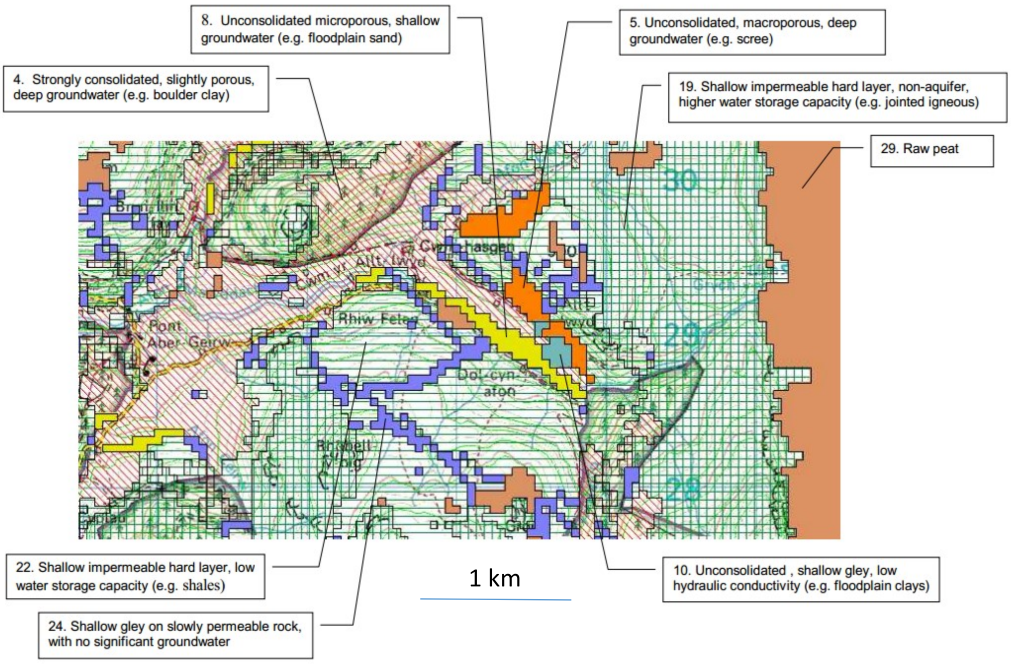

FIGURE 3. Computer generated soil distribution with HOST classes numbered, Allt Lwyd valley

Data is available which relates soil textures to water flow parameters, allowing the hydrological responses of particular HOST classes to be modelled. Hydraulic conductivity varies greatly with effective saturation, with conductivity values falling rapidly to low levels as soils become drier and pore water is retained increasing strongly by capillary forces. An equation has been proposed by van Genuchten (1980) for the calculation of soil conductivity as a function of effective saturation, depending on a parameter m related to soil texture. Typical values of m are 0.274 for coarse sandy soil, down to 0.094 for fine silty soil.

The van Genuchten equation is:

$$\frac{K(\Theta)}{K_s} = \left(\frac{\Theta - \Theta_r}{\Theta_s - \Theta_r}\right)^{1/2} \left[1 - \left(1 - \left\{\frac{\Theta - \Theta_r}{\Theta_s - \Theta_r}\right\}^{1/m}\right)^m\right]^2$$

where Θ is soil moisture content
subscript s refers to moisture content at saturation
subscript r refers to soil water retained when the soil is dry

The hillslope model employs an eight layer structure, based on 50m grid squares of a digital elevation model. Water flow between soil layers is computed, along with surface water flow, downslope throughflow, and downwards percolation into bedrock, according to the Darcy equation for porous media:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - W = S\frac{\partial h}{\partial t}$$

where h terms refer to hydraulic head, K parameters are hydraulic conductivities
W is a sink and source term, and S is water storage

Predictions of subsurface throughflow and surface runoff were obtained for time sequences during storm events over the catchment. Soil throughflow and surface monitoring sites were constructed in different geological ground conditions to evaluate the hillslope model predictions. Modelled flows were found to be in general agreement with field observations at the monitoring sites.

FIGURE 4. Field monitoring site for surface runoff and subsurface throughflow.

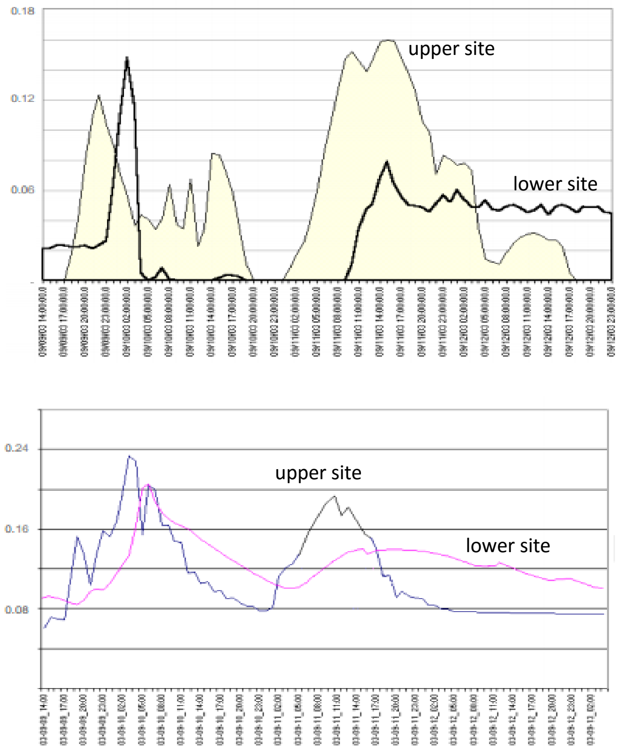

FIGURE 5. (Above) Field measurements of throughflow at sites on a valley side, Coed y Brenin. (Below) Hillslope runoff model

River routing is computed through the series of sub-catchments downstream. Hydrograph data was available from the Environment Agency gauging station at Tyddyn Gwladys, Coed y Brenin. Hydrograph recording instruments were also installed at key locations on the river system as part of the research project. Generally good agreement was obtained between recorded hydrographs and modelled hydrographs based on actual raingauge data. Antecedent soil moisture levels appear to be handled correctly by the model.

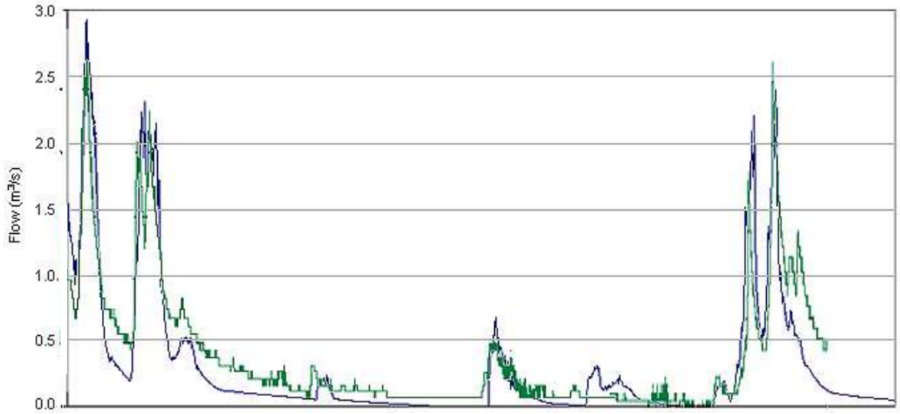

FIGURE 6. Comparison of the modelled hydrograph (green) and recorded hydrograph (black) for the Afon Ty Cerrig, Mawddach catchment for the period July - September 2003.

4. Rainfall modelling

Flooding in the Mawddach catchment can result from either saturation excess overland flow after an extended period of frontal rainfall, or infiltration excess overland flow during an intense convective storm. For forecasting further ahead than 3 hours, accurate rainfall forecasts are required. Experiments to predict rainfall on a 1km grid scale were carried out using the MM5 meteorological modelling system (Dudhia et al., 2005).

The MM5 meteorological model was able to reproduce fairly well the rainfall patterns of individual storm events, including microclimate effects of mountains and valleys. Frontal rainfall patterns were found to be strongly influenced by topography through a **seeder-feeder** rainfall generation mechanism. Rising airflows at the heads of valleys (fig.7) produce zones of enhanced rainfall. Rainfall is often substantially higher at the head of a valley than on the mountain plateau above.

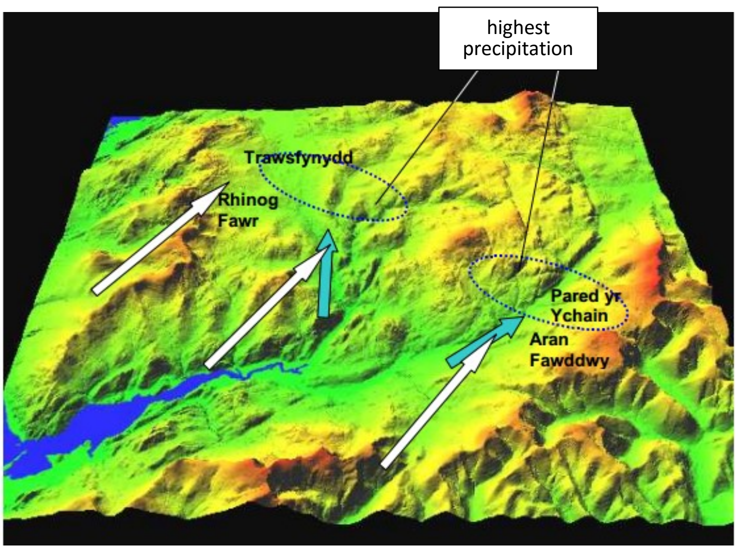

FIGURE 7. Airflow directions across the Mawddach catchment, 29 December 2002. White: middle atmospheric level, blue: valley airflows.

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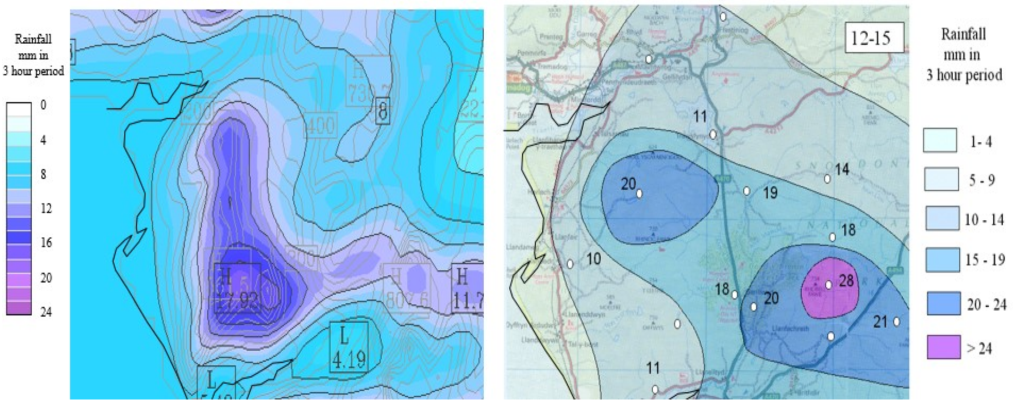

FIGURE 8. MM5 3-hour rainfall simulation (left) and 3-hour raingauge totals (right): 12:00h - 15:00h, 8 November 2002

Experiments were carried out using a neural network (Demuth and Beale, 2000) to process predictions for rainfall later in a storm event, based on iteratively improving the early rainfall predictions against actual raingauge patterns. The most successful runs of the neural network were achieved by use of log-sigmoidal elements, followed by linear elements. Neural network processing was found to improve both the absolute errors in rainfall prediction, and signed errors (where approximately the correct amount of rainfall was estimated, but in incorrect locations). The success of neural network optimisation seems linked to the large variations in rainfall pattern associated with small changes in the approach direction of a storm, and the ability of the neural network to determine correction parameters unique to that particular storm.

Greater problems are experienced in predicting convective rainfall over the catchment. The MM5 meteorological model provided a range of physics schemes for modelling convective rainfall generation. The most accurate predictions for the July 2001 squall line storm event over the Mawddach catchment were achieved using the Anthes-Kuo physics scheme. Less accuracy occurred with alternative convective physics schemes. There have been insufficient convective storms over the Mawddach catchment to determine whether the Anthes-Kuo scheme is always effective in the Mawddach area.

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