Coupling of MODFLOW with the MM5 mesoscale meteorological model for real-time input of high resolution rainfall patterns in a mountainous area

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ABSTRACT

Use of the MM5 meteorological modelling system is discussed as a means of providing high resolution rainfall input to a hydrological model of a mountain area of North Wales. The model provides rainfall data on a 1km grid and 1 hour time resolution to an accuracy of better than 10% agreement with gauge readings for frontal events, and around 20% accuracy for convective events. MM5 is used in conjunction with a 50m grid distributed hillslope model, which in turn provides groundwater output to MODFLOW and surface runoff/throughflow output to the GSTARS river routing package.

INTRODUCTION

A flood prediction system is being developed for the mountainous Mawddach catchment in North Wales, where a flash flood event in July 2001 caused extensive damage to bridges, roads and buildings (Barton, 2002. Mason, 2002).

Headwaters of the river system flow from peat blanket bogs where field monitoring has identified significant water table variation during the year. The middle courses of the main tributaries flow through steep gorges, with river bed temperatures indicating resurgence of groundwater during flood events (fig.3). For these reasons it has been necessary to incorporate groundwater modelling into the flood prediction scheme.

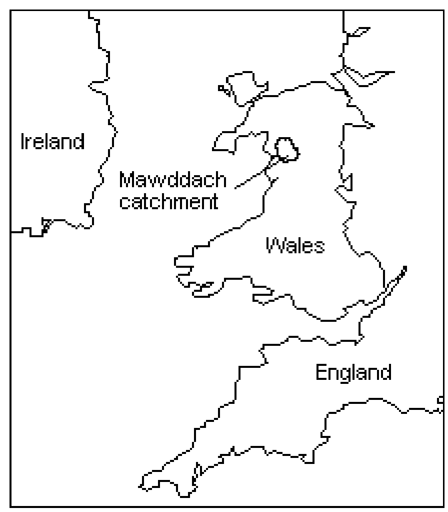


Figure 1. Location of the Mawddach catchment.

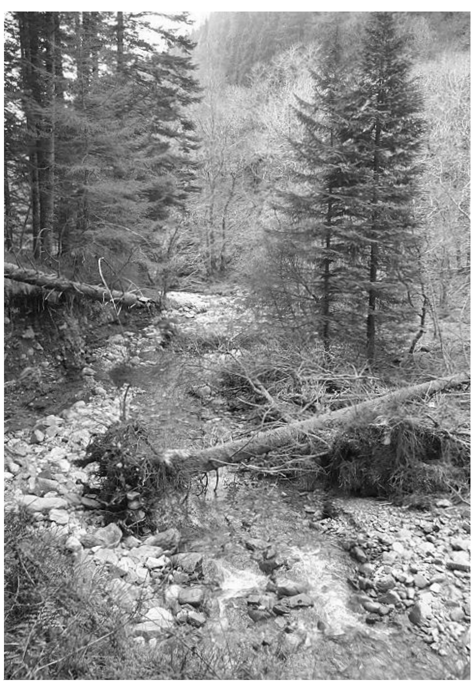


Figure 2. Valley of the Afon Wen, a tributary of the Mawddach, showing thick glacial till forming a river cliff.

Continuous data from 30 raingauges across the area indicate wide variations in rainfall on a microclimate scale between adjacent valleys during the passage of frontal systems or the development of convective storms (Figure 4). Sensitivity analysis suggests that accurate spatial and temporal input of recharge volumes to the MODFLOW model of the catchment is crucial to the realistic prediction of groundwater movement and flooding.

A majority of flood events within the Mawddach catchment result from prolonged rainfall accompanying the slow passage of frontal systems. Progressive saturation of thick glacial and periglacial sediments leads to a condition of extensive shallow sub-surface runoff, enhanced by river resurgence. Less frequent but more destructive summer convective storms occur in association with squall lines. These can produce flooding by a mechanism of rainfall intensity exceeding soil infiltration rates (Hall and Cratchley R., 2005b).

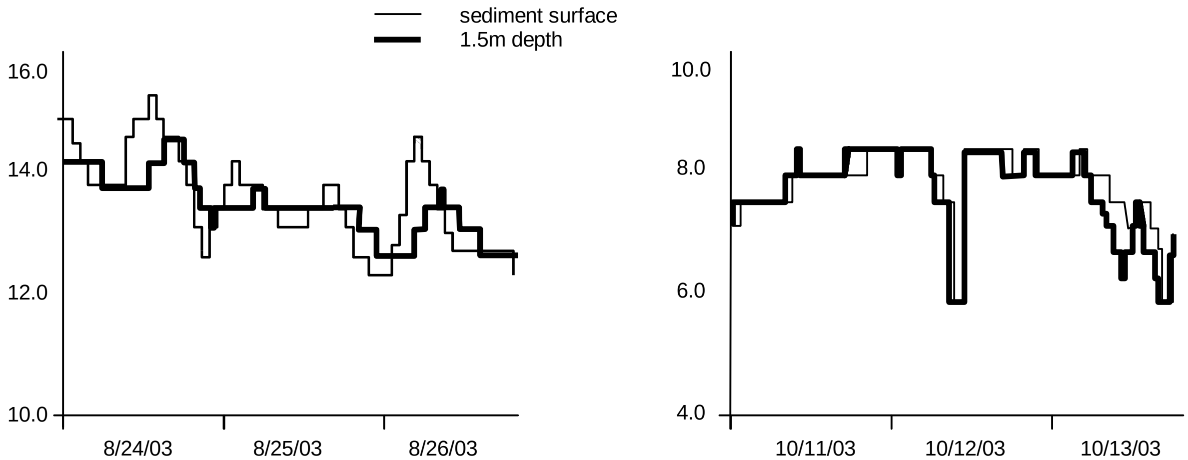
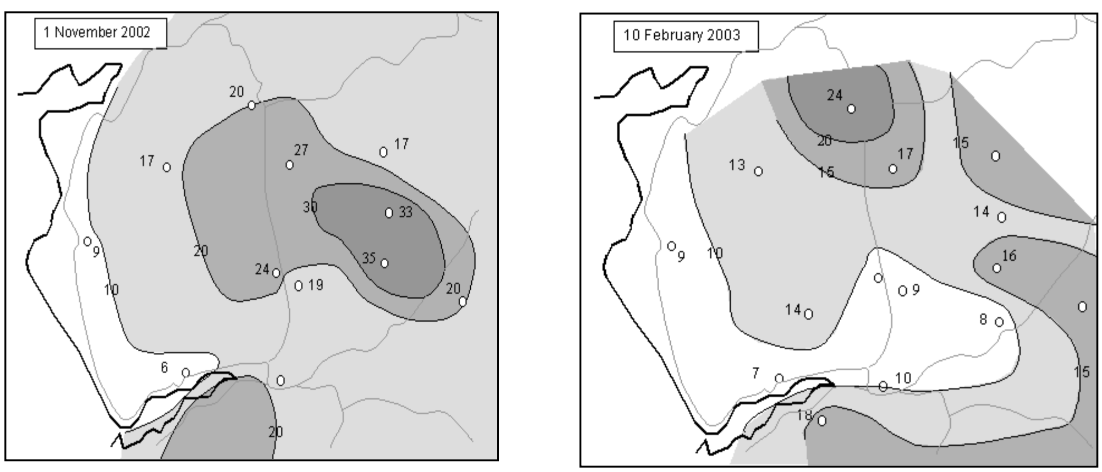


Figure 3. Riverbed temperatures in the Afon Wen, close to the location shown in Figure 2. The shallow thermometer is located at the sediment surface, and the deep thermometer at a depth of 1.5m in river gravels. Under low flow conditions, river water seeps downwards to groundwater store, showing a deep temperature response some 6 hours after surface temperature changes. In flood conditions, the flow is reversed, with changes in deep sediment temperature reflected in surface temperature changes around 2 hours later.



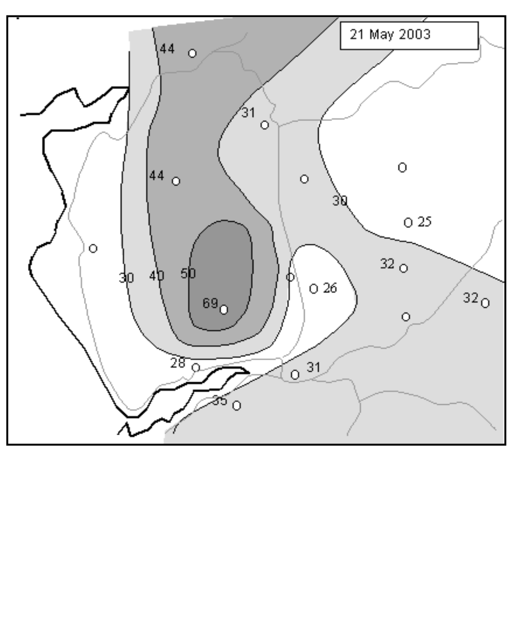


Figure 4. Examples of total storm rainfall(mm) across the Mawddach catchment for frontal systems. Variations in rainfall distribution result from different approach directions of fronts, the triggering of instability and precipitation by different mountain blocks within the path of the frontal system, and the effects of wind speeds in the middle and lower troposphere advecting falling raindrops by different distances before reaching the ground surface. These mechanisms are discussed by Browning et al. (1973), Browning et al. (1974), Browning et al. (1975).

USE OF THE MM5 METEOROLOGICAL MODEL

Analysis of six major storms during the period 2001-2004 has been carried out using the NCAR MM5 mesoscale meteorological model (Grell, Dudhia and Stauffer, 1995). It is found that rainfall can be predicted on a 1km grid and 1 hour time resolution to an accuracy of better than 10% agreement with gauge readings for frontal events, and around 20% accuracy for convective events.

An MM5 model is set up by creating a nest of domains, focussing in at increasing resolution on the study area. For the Mawddach model, four domains have been used with 60 x 60 grids of resolution 27km, 9km 3km and 1km respectively (Figure 5). In the vertical dimension, 23 atmospheric levels are used.

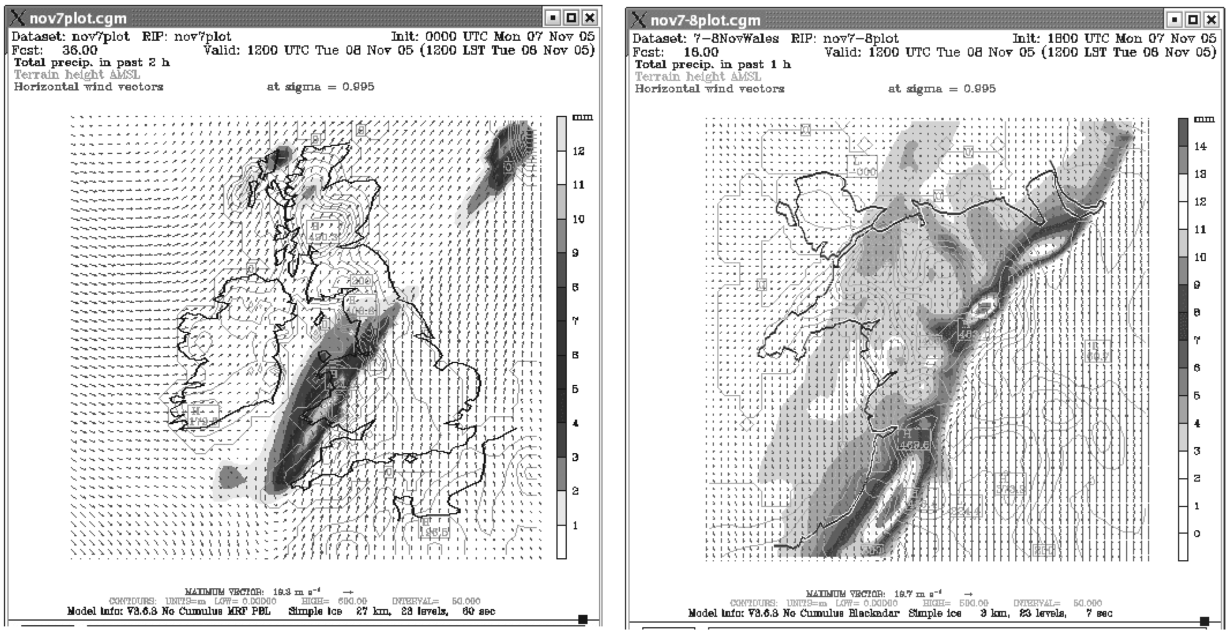


Figure 5. Frontal rainfall across Britain on 5 November 2005, showing the MM5 model on the 27km resolution British Isles domain, and the 3km resolution North Wales domain.

The MM5 model requires a gridded land surface elevation model and gridded land use and vegetation data sets, which are available with global coverage from NCAR and the US Geological Survey (National Centre for Atmospheric Research, 2005). Individual runs of the model require initial and boundary conditions to be set using gridded meteorological data. Suitable data are available for download from the website of NCAR.

The MM5 model provides a large range of atmospheric physics options for modelling planetary boundary layer processes, radiation, cloud microphysics and cumulus convection. Multiple runs of the model have been carried out with different combinations of physics options. It is found that reliable results for the Mawddach catchment can be obtained with Blackadar PBL model, Dudhia simple ice explicit moisture model, and Anthes-Kuo cumulus parameterisation.

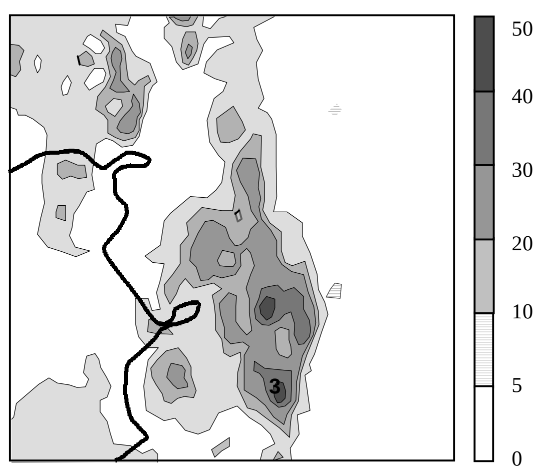


Figure 6. MM5 model for a convective storm over the Mawddach catchment in July 2001, showing 1 hour rainfall (mm). A bow echo structure and multiple convective cells within the squall line are correctly modelled.

INTEGRATED METEOROLOGICAL/HYDROLOGICAL MODELLING

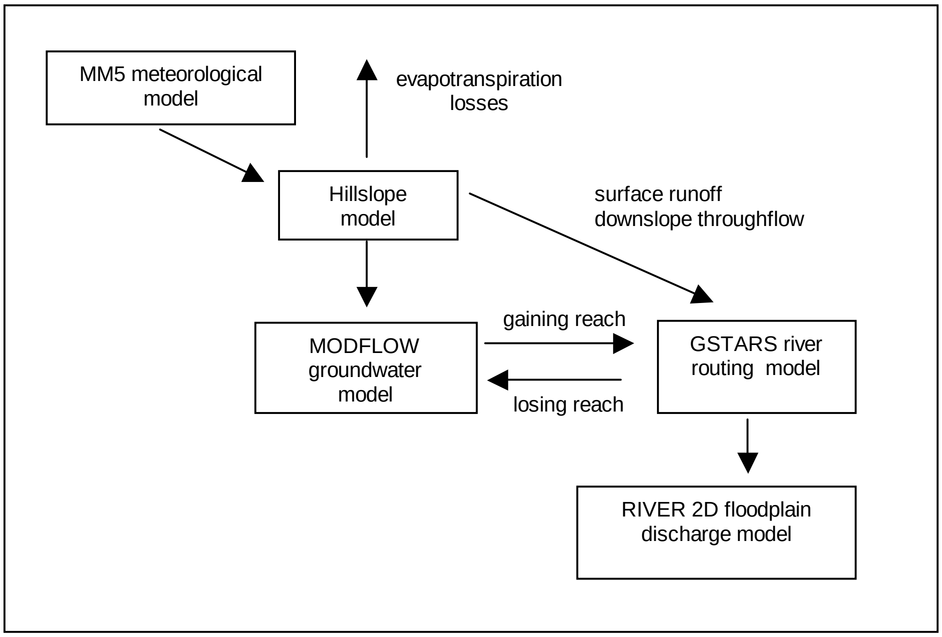


Figure 7. Integrated meteorological / hydrological model for the Mawddach catchment.

MM5 forms part of an integrated meteorological/ hydrological modelling system for the Mawddach catchment (Figure 7). The central component is a distributed hillslope runoff model developed on a 50m grid. The model uses digital elevation data to determine values of Kirkby wetness index for each surface cell (Bevan, 1997). Wetness index is combined with GIS gridded geology and vegetation data to produce a soil map using the Hydrology of Soil Types classification (Boorman et al., 1995). Soil properties across the catchment can then be estimated, and conductivity at different levels of saturation calculated by means of van Genuchten parameters (Nemes et al., 2001). Soil hydrological properties predicted by the model are being validated by field observations at 8 hillslope monitoring sites within the catchment.

Hourly rainfall values from MM5 on a 1km grid scale are input to the hillslope model. Soil throughflow and surface overland flow are computed to produce output to the GSTARS river routing model, along with the calculation of groundwater recharge to the underlying MODFLOW bedrock model (Figure 8).

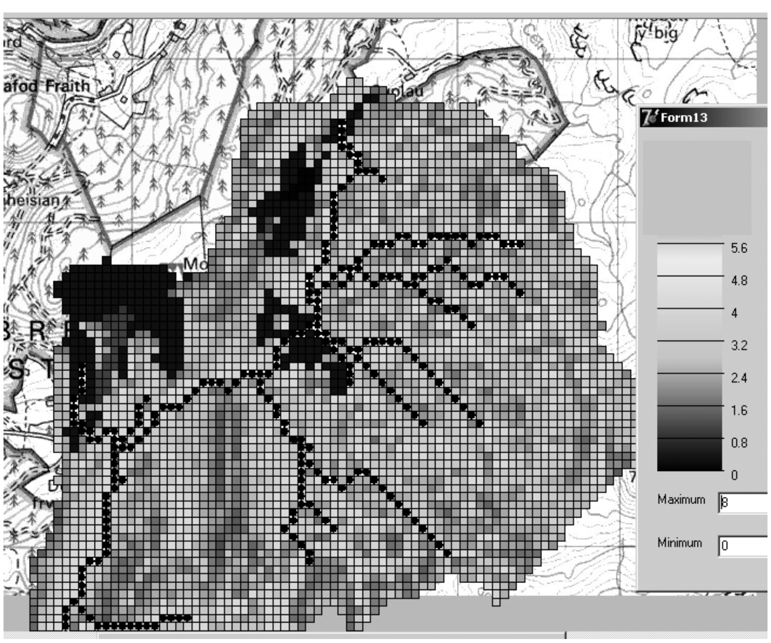


Figure 8. Graphical display of 1 hour recharge rates (m^3) to MODFLOW from grid squares of the hillslope model. November 5, 2005 storm event, Afon Wen sub-catchment.

MODFLOW is proving successful in predicting river/groundwater interaction in gaining and losing reaches of the Mawddach system during flood events (Figure 9). Water gained from groundwater storage can be added to river flows in GSTARS for prediction of hydrographs at critical flood sites downstream. Modelling of floodplain inundation is carried out by a final component of the system, RIVER2D.

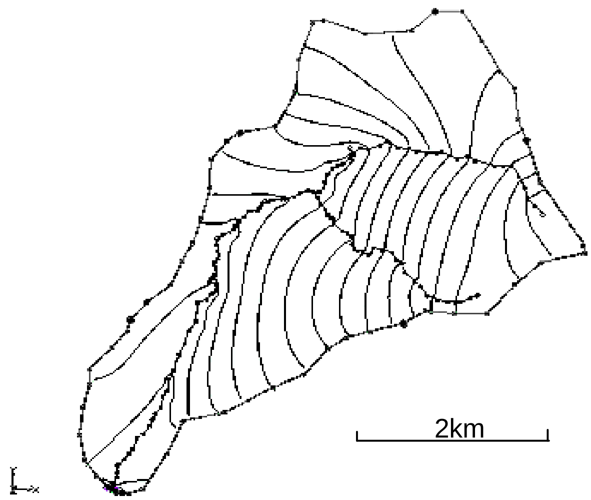


Figure 9. Use of the *River* module in MODFLOW to determine river/groundwater interactions in the Afon Wen valley, illustrated in Figure 2 above. Curvature of equipotential lines is indicative of gaining reaches in the lower valley. Flood event, 11 November 2003

CONCLUSION

The MM5 Meteorological Modelling system can provide a valuable component of an integrated hydrological model in catchments where complex rainfall patterns cannot be simply replicated by interpolation between widely distributed raingauges, or where rainfall patterns are not a simple function of altitude. It is hoped to use MM5 in real-time forecasting mode as input to a flood prediction model for the Mawddach catchment which incorporates both hillslope runoff processes and river resurgence.

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