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Modelling Effects of Rural Land Management on Flood Risk

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ABSTRACT: Around the world, rural land use and land management are changing. Effects are often subtle, and not possible to detect from catchment-scale data analysis. There is a need for new methodologies that can represent the local scale response and the aggregated effect at catchment scale.

In the UK, recent floods have renewed speculation about the linkage between agricultural land management and flooding. Available data to quantify effects of agricultural intensification have been limited, small scale, and mainly focused on the lowlands and arable agriculture. There is a need to quantify impacts for upland areas, which are source areas for runoff generation, and to develop methods to extrapolate from small scale observations to predict catchment-scale response. With assistance from a cooperative of Welsh farmers, and support from the EPSRC Flood Risk Management Research Consortium, a multi-scale experimental programme has been established at Pontbren, in mid-Wales, an area of intensive sheep production. The data have been used to support development of a multi-scale modelling methodology to assess impacts of agricultural intensification and the potential for mitigation of flood risk through land use management.

Data are available from statistically-replicated experimental plots under different land management treatments, from instrumented field and hillslope sites, including tree shelter belts, and from first and second order catchments. Measurements include rainfall and climate variables, soil moisture, soil water pressure and soil hydraulic properties at multiple depths and locations, tree interception, overland flow and drainflow, groundwater levels, and streamflow from multiple locations. Detailed, fine resolution, physics-based models have been developed to represent soil and runoff processes, and conditioned using experimental data. The response of these detailed models is used to develop and calibrate simpler 'meta-models' to represent individual hydrological elements—in this case mainly individual fields, with their associated field drainage. These meta-model elements are then combined in a distributed catchment-scale model.

The paper presents results of detailed field-scale simulations to demonstrate the dominant runoff processes under intensive sheep production, and impacts of the use of tree shelter belts in improving soil structure and reducing peak runoff intensities. Catchment-scale simulations show the effects of improved and unimproved grassland, and the potential effects of land management interventions, including farm ponds, and tree shelter belts and buffer strips. It is concluded that the methodology developed has the potential to represent and quantify catchment-scale effects of upland management; continuing research is extending the work to a wider range of upland environments and land use types, with the aim of providing generic simulation tools that can be used to provide strategic policy guidance.

Keywords: Land Use, Land Management, Flood Risk Modelling.

INTRODUCTION

In most countries of the world, the rural environment has been subject to significant change in recent decades. In developing economies, land use change may be dramatic and widespread, for example associated with forest clearance for agricultural production, or the development of new irrigation schemes. In developed economies, changes in land use may be more subtle; cropping patterns may change in a piecemeal manner in response to agricultural policy and market forces. However, hydrological change can also occur with no change in land use, as agricultural intensification leads to changing land management practices, with associated effects on soil structure and soil properties.

Quantifying the effects of land use and land management change at catchment scale remains a major challenge for hydrologists. Effects on hydrological processes are often subtle, and there are dangers in over-generalisation. For example, it is generally accepted that evapotranspiration losses are greater for mature forests than for grassland, with an expected reduction in runoff associated with afforestation. However, in the Coalburn catchment, UK, afforestation was associated with an increase in flood peaks, due to the land drainage that was installed to establish an appropriate soil water regime for the young trees (Robinson, 1986). Another example is the role of agricultural drainage on runoff from agricultural land in the UK. The effects on runoff vary greatly, depending on soil type, so that flood runoff may decrease or increase (Robinson and Rycroft, 1999).

Hydrological effects associated with land use or land management change are difficult to detect through catchment-scale analysis. The UK Flood Studies Report (NERC, 1975) included regional analysis of flood response using unit hydrograph methods. The effects of urban development on flood runoff were clearly identified, but in that study and more recent regionalisation work (O'Connell *et al.*, 2004), effects of agricultural change were not identifiable. Part of the difficulty comes from the fact that land use in catchments is heterogeneous, and also that where land management has changed, but not land use, statistics on the nature and extent of agricultural intensification are generally not available. However, there are more fundamental problems. A recent UK study (Beven *et al.*, 2008) attempted to identify catchment-scale data sets where extensive land use change had taken place, and to use advanced methods of time-series analysis to detect change. The conclusion was that the noise in the available input-output data, together with natural climatic variability, meant that signals of land use and land management change could not be detected.

If catchment-scale analysis is not feasible, we must turn to a synthesis approach to represent change. However, this requires that the scale problem is confronted. Experiments to detect hydrological effects of land use and land management change can be conducted at the scale of experimental plots (at a scale of say 100 m^2). How can these results be extrapolated to catchment scale? Catchment-scale synthesis requires that the spatial heterogeneity of response is represented, both at the scale of the hillslope, or equivalent hydrological response unit (HRU), and at the catchment scale, at which the response of HRUs is aggregated and channel routing effects represented,

In this paper we report results from a major UK study, conceived to identify effects of upland agricultural land management on flooding. Our methodological solution is to develop a multi-scale modelling methodology, whereby very detailed, physics-based modelling is used to simulate effects of land use and land management change at the scale of individual fields and hillslopes. We then use 'meta-models', i.e. parsimonious hydrological models with an appropriate conceptual structure, which are trained to represent the input-output response of the detailed model for alibrary of HRUS and land use/management interventions. Finallt, these meta-models are run as elements of a semi-distributed catchment scale model.

THE UK CONTEXT

Over the last 50 years there have been significant changes in the rural landscape of the UK as a result of agricultural intensification. Obvious landscape features include the removal of hedgerows, increased field size and changing cropping patterns. In the lowlands, arable agriculture has changed, with a move to autumn-sown crops, and hence bare soil conditions over autumn/winter, and use of larger contract machinery, operating with less opportunity to consider appropriate weather conditions for field operations. In the uplands, pasture has been 'improved', by installation of agricultural drainage, ploughing, re-seeding and fertilization, and grazing densities have increased dramatically, also leading to pressures to use less suitable land under unsuitable soil conditions. There is widespread anecdotal evidence in the UK that current pressures on agriculture have led to degradation of soil structure, through a combination of surface capping of arable soils, poaching of grassland soils and topsoil compaction in both (Wheater, 2002, Holman *et al.*, 2002, O'Connell *et al.*, 2004, 2007). There are consequent concerns that runoff processes have changed, with a potential increase in flood risk.

Hard scientific evidence on local impacts is limited and mainly focussed on arable agriculture in England. However, there is information on the extent of soil degradation. For example, a survey during the Autumn 2000 floods (Holman *et al.*, 2002) concluded that 30% of soil in the Severn catchment was degraded and 55% of areas with late harvested crops showed severe soil degradation. Such data reinforce concerns for localised flooding (so-called muddy floods) and that such changes, if of sufficient spatial extent within a catchment, may significantly alter the hydrology of major rivers.

There is an urgent need to quantify these effects, and clearly the potential for reversal is also important, as well as the scope for changes in land management policy to mitigate flood risk.

As discussed above, our approach is to use models that represent local-scale effects, and aggregate the response to simulate the catchment-scale impacts.

There are two basic issues that arise. The first is the availability of appropriate data and models to characterise local scale effects, and the second, the development of an appropriate modelling strategy to address the generic problem of up-scaling from local to catchment-scale. In this paper we report the development and application of such a methodology, based on multi-scale experimental data from Pontbren, a tributary of the Severn, in mid-Wales.

THE PONTBREN EXPERIMENT

Pontbren, situated in the headwaters of the river Severn in Wales, is a farmers' cooperative concerned with sustainable upland agriculture, involving 10 hill farms and over 1000 ha of agriculturally improved pasture and woodland (Figure 1). Elevations range from 170 to 438 m AOD, and the soils are clay-rich, mainly from the Cegin and Wilcocks series, which are common in Wales. They have low permeability subsoil, overlying glacial drift deposits, and are seasonally wet or waterlogged. Field drainage is ubiquitous where pasture has been improved. The predominant land use is grazing, mainly for sheep.

The farmers' perception is that changes to land management, and in particular changes to grazing densities and animal weights, have changed runoff response. Although land use has hardly changed since the 19th Century, between the 1970s and 1990s dramatic changes in farming intensity took place; sheep numbers increased by a factor of 6 and animal weights doubled (R. Jukes, pers.comm).

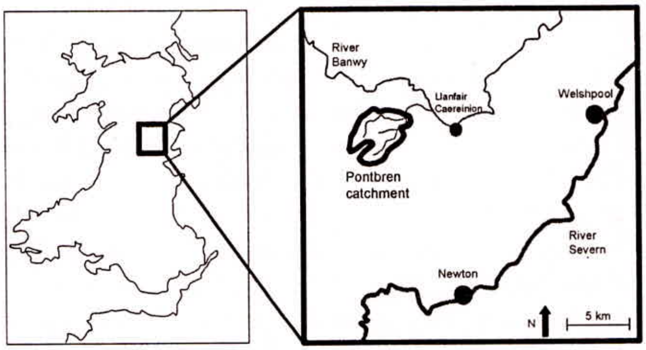
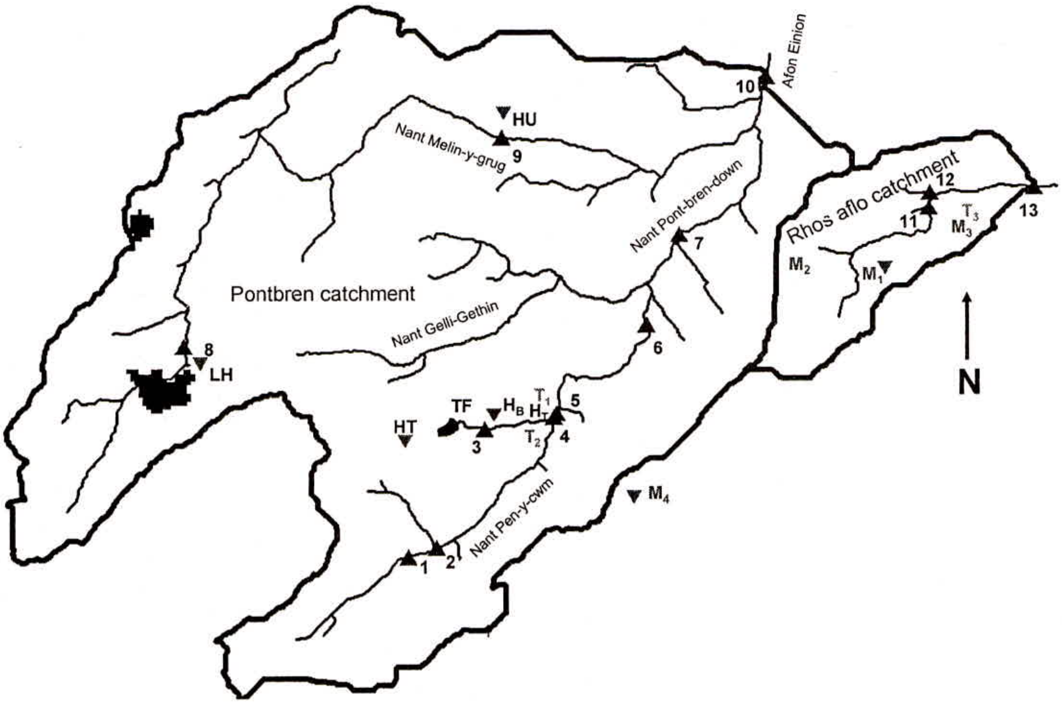


Fig. 1: Pontbren study site location

Recent work by the farmers has included the reinstatement of woodland areas and hedgerows, and preliminary research on the infiltration rates of the grazed hillslopes and woodland buffer strips by the Centre for Ecology and Hydrology, Bangor (Carroll *et al.*, 2004) demonstrated a dramatic change in soil response to rainfall. Infiltration rates on the grazed pastures were extremely low, but within a few years of tree planting, soil structure and permeability in buffer strips showed significant improvement. However, these results needed to be extended, to evaluate land use impacts in a statistically-rigorous manner and to address runoff generation at the hillslope and catchment scale. The effects must also be evaluated in the context of the complex history of land management. For example, as noted above, land drainage is extensive, with a history that is believed to go back to the Napoleonic Wars.

Multi-scale experimentation is needed to bridge the current gap between plot scale experiments and catchment scale impacts, hence a set of experiments has been designed to provide experimental support for new methodological development (Figure 2). The Pontbren project crucially provides landowner support for land access, land management manipulation experiments and for socio-economic analysis. The direct involvement of local stakeholders is also important in the promotion of policy guidance to the agricultural community. The current scales of research range from experimental plots to an 18km^2 catchment, including three first order streams.

The experiments focus on soil properties and runoff processes, based on plot and hillslope scale measurements nested within instrumented 1st and 2nd order catchments (Marshall *et al.*, 2006). At plot scale, manipulation plots have been established at four locations, representing a range of aspect and soil type. At each location three treatments are being evaluated, grazing, no grazing and newly planted woodland. Continuous monitoring includes precipitation, other climate variables, soil moisture contents, soil water potentials and overland flow. In addition, soil physical and chemical properties are characterized in annual sampling campaigns. At hillslope scale, instrumented hillslope transects include the above instrumentation, groundwater elevations and drain and ditch flows. Within the hillslope experiments, soil properties and runoff processes are being investigated under different land use treatments including woodland buffer strips. At catchment scale the monitoring is complemented by a network of stream gauges. These observations are supported by a soil survey, including estimation of soil degradation status, supplementary sampling and additional experimentation, including sprinkler and tracer experiments and woodland interception studies. The data are extensive; approximately 145,000 data items are being recorded per week.



Legend: **LH** Llyn Hir; **HT** Tyn y Bryn Hilltop; **TF** Tyn y Bryn Top field; **H_B** Instrumented Hillslope – The Bowl; **H_T** Instrumented Hillslope – Tree planted hillslope; **T_n** Tree planted study site; **M_n** Manipulation plots; **HU** Hirrhos Uchaf; **▲n** Stream and drain flow monitoring site; **▼** Rain gauge.

Fig. 2: Pontbren instrumentation

MODELLING STRATEGY

The modelling strategy has three elements. At Pontbren we are concerned with representing physical changes to soil structure, vegetation and field drainage, and the associated effects on runoff processes. A key element therefore is the establishment of a detailed, physically-based model, capable of representing significant hydrological processes operating at Pontbren and similar catchments, at the scale of individual fields and hillslopes. For this we have developed further an Imperial College model based on Richards' equation for saturated/unsaturated soil water flow (Karavokyris *et al.*, 1990), now extended to represent macropore processes and overland flow, incorporating vegetation processes (such as interception), and capable of being run in 1, 2 or 3 dimensions (Jackson *et al.*, 2006). The model has been conditioned, within a Monte Carlo-based framework of uncertainty analysis, using physically-determined soil hydraulic properties and continuous measurements of climate inputs, soil water states and runoff (as overland flow and drain flow) from the Pontbren experimental sites. Due to the highly non-linear dynamics, individual fields and hillslopes are represented at fine resolution (1cm vertical and 1m horizontal resolution). The detailed model can be exercised to simulate scenarios of interest, including for example, the planting of strips of woodland within a hillslope, and the associated changes to soil structure, evaporation processes, overland flow and drainage.

The detailed model is computationally-intensive, and not suitable for direct application at catchment scale. The second element of our strategy is therefore to use a meta-modelling procedure, whereby the detailed model is used to train a simpler, conceptual model that represents the response in a parsimonious and computationally-efficient manner, using basic hydrological components of loss and routing functions. This requires classification of the landscape into hydrological units, based for example on soils, land use and existing/proposed interventions. The detailed model is run for each member of a library of hydrological units, and hence a meta-model parameterisation is obtained for each member through the model training process. Uncertainty in parameter values is carried forward to this stage via Monte Carlo analysis.

The third element of the procedure is a catchment-scale semi-distributed model, written with a modular structure, that uses the meta-model elements to represent individual hydrological elements, and routes the flows down the stream network. Using the semi-distributed model, the meta-model is further conditioned on the catchment-scale data to reduce parameter uncertainty.

RESULTS

Illustrative results are presented below; full details of the data and modelling are presented in the final report of the FRMRC Land Use Management Research Priority Area (Wheater *et al.*, 2008). Figure 3 illustrates the simulated response for a representative hillslope (100 m × 100 m) using the detailed model for a range of land management types, including grazed and ungrazed drained grassland, grassland with tree shelter belts (80 m length, 15 m width) in different locations, and full tree cover. The envelopes of response represent the range of parameter uncertainty.

The ability of the meta-model to represent detailed model response is illustrated in Figure 4 for a grazed hillslope with a woodland buffer strip at the base of the slope.

Finally we illustrate the impacts at the catchment-scale in Figure 5, for a 4 km^2 Pontbren sub-catchment. The baseline is the current day land use at Pontbren, the first scenario removes the effect of the recent Pontbren tree plantings (and hence takes the catchment back to something approximating the intensive use of the early 1990s), the second adds shelter belts to all grazed grassland sites, and the third assumes the entire catchment is woodland. The changes in flood peaks observed for the three scenarios are: removing all the trees causes up to 20% increase in flood peaks from the baseline condition, adding tree shelter belts to all grazed grassland sites causes up to 20% decrease in flood peaks from the baseline condition, and full afforestation causes up to 60% decrease in flood peaks from the baseline condition.

SUMMARY AND CONCLUSIONS

Rural land use and land management change are taking place around the world. Hydrological effects are often subtle, and dependent on the local context of soils and runoff processes. Quantification of the hydrological effects is scientifically challenging; effects are generally not amenable to catchment-scale analysis, and hence simulation methods are required. However, these must capture the detail of local response, as well as the propagation of those effects to catchment scale.

A new modelling methodology has been presented, in which detailed physics-based modelling is used to represent effects of land use and land management change on local scale soil hydrology and runoff processes. Performance of the detailed model for a library of hydrological elements is captured using simpler meta-models, and hence incorporated within a semi-distributed catchment-scale model to quantify catchment-scale effects. Applications have been based on issues of upland land management and the drained clay soils of the Pontbren catchments (at scales of up to 18 km^2) in mid-Wales, UK.

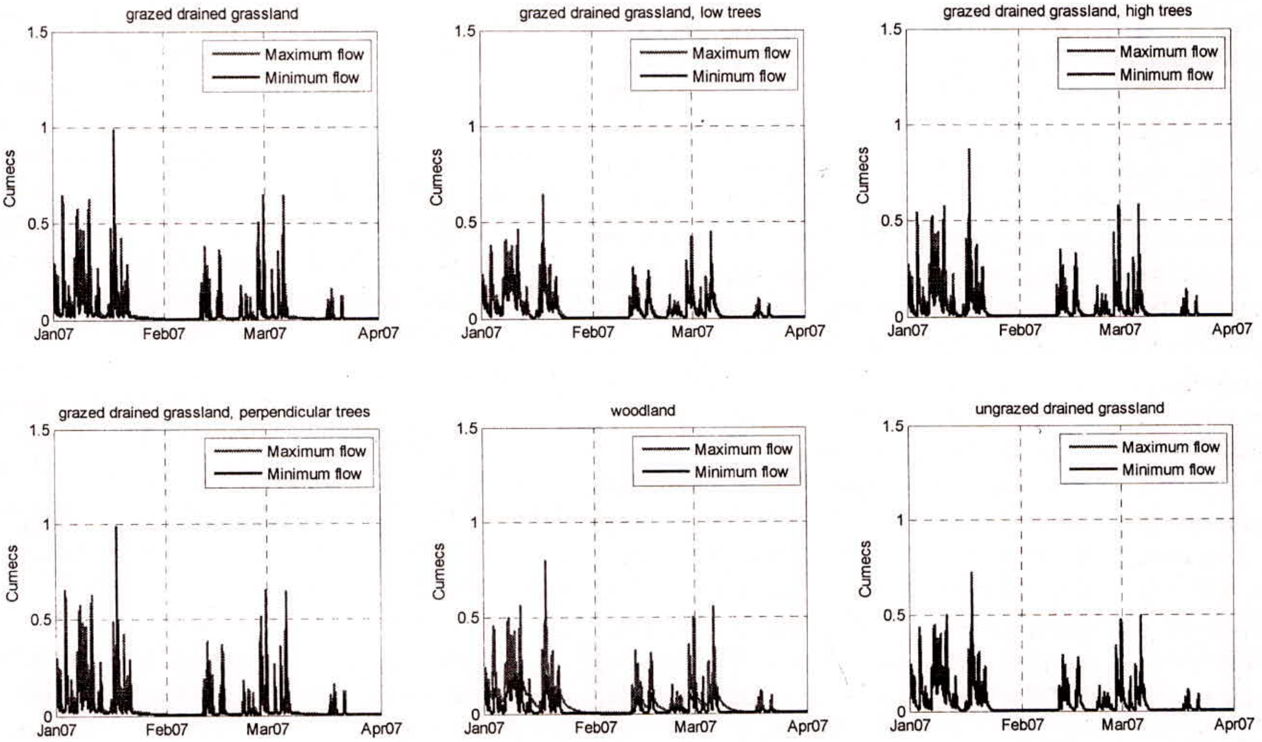


Fig. 3: Field-scale runoff (drain flow + overland flow) for different land use types, with uncertainty bounds

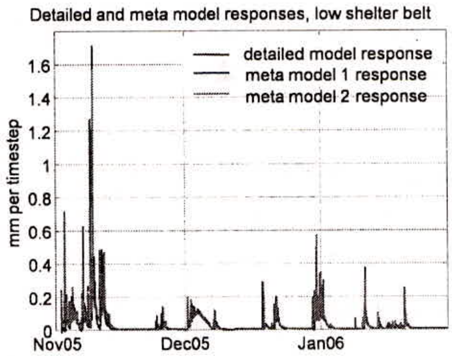


Fig. 4: Representation of detailed model response by alternative conceptual model structures

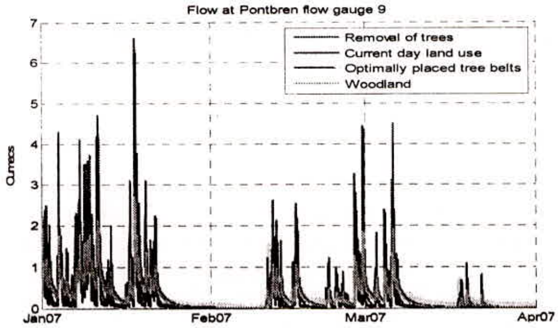


Fig. 5: Catchment-scale response for a 4 km^2 Pontbren sub-catchment for current land use and a set of scenarios: 1990s intensification, further addition of tree shelter belts, and full afforestation

Based on observed data for the period 2005–2008, simulations suggest that the use of tree shelter belts at suitable locations can reduce flood peaks significantly, with more extensive afforestation giving greater reductions. The shelter belt effects are mainly due to a decrease in overland flow, and hence peak intensities of runoff, rather than any significant change in runoff volumes. However, these results are indicative only; more work is needed to confirm model assumptions, to evaluate uncertainty, and in particular to investigate response for the more extreme events of significance for flood design.

These issues are being examined in current research, which also seeks to extend the research to a wider range of upland land management issues and sites, and to larger catchment scales.

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