

Modelling the hydrological impacts of rural land use change

Neil McIntyre, Caroline Ballard, Michael Bruen, Nataliya Bulygina, Wouter Buytaert, Ian Cluckie, Sarah Dunn, Uwe Ehret, John Ewen, Alexander Gelfan, Tim Hess, Denis Hughes, Bethanna Jackson, Thomas R. Kjeldsen, Ralf Merz, Jong-Sook Park, Enda O'Connell, Greg O'Donnell, Ludovic Oudin, Ezio Todini, Thorsten Wagener and Howard Wheeler

ABSTRACT

The potential role of rural land use in mitigating flood risk and protecting water supplies continues to be of great interest to regulators and planners. The ability of hydrologists to quantify the impact of rural land use change on the water cycle is however limited and we are not able to provide consistently reliable evidence to support planning and policy decisions. This shortcoming stems mainly from lack of data, but also from lack of modelling methods and tools. Numerous research projects over the last few years have been attempting to address the underlying challenges. This paper describes these challenges, significant areas of progress and modelling innovations, and proposes priorities for further research. The paper is organised into five inter-related subtopics: (1) evidence-based modelling; (2) upscaling to maximise the use of process knowledge and physics-based models; (3) representing hydrological connectivity in models; (4) uncertainty analysis; and (5) integrated catchment modelling for ecosystem service management. It is concluded that there is room for further advances in hydrological data analysis, sensitivity and uncertainty analysis methods and modelling frameworks, but progress will also depend on continuing and strengthened commitment to long-term monitoring and inter-disciplinarity in defining and delivering land use impacts research.

Key words | floods, land cover, land management, models, non-stationarity, scenarios

Neil McIntyre (corresponding author)

Nataliya Bulygina

Wouter Buytaert

Department of Civil and Environmental Engineering, Imperial College, London SW7 2AZ, UK

E-mail: n.mcintyre@uq.edu.au

Neil McIntyre

Centre for Water in the Minerals Industry, Sustainable Minerals Institute, The University of Queensland, Brisbane, QLD 4072, Australia

Caroline Ballard

Aqualinc Research Ltd, 11 Deans Avenue, Christchurch 8011, New Zealand

Michael Bruen

School of Civil, Structural and Environmental Engineering, Newstead Building, University College Dublin, Belfield, Dublin 4, Ireland

Wouter Buytaert

Grantham Institute for Climate Change, Imperial College, London SW7 2AZ, UK

Ian Cluckie

Jong-Sook Park

College of Engineering, Swansea University, Swansea SA2 8PP, UK

Sarah Dunn

The James Hutton Institute, Aberdeen AB15 8QH, UK

Uwe Ehret

Karlsruhe Institute of Technology (KIT), Karlsruhe, Kaiserstraße 12, 76131, Germany

John Ewen

Enda O'Connell

Greg O'Donnell

School of Civil Engineering & Geosciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK

Alexander Gelfan

Institute for Water Problems, Russian Academy of Sciences, Moscow 119333, Russia

Tim Hess

Cranfield Water Science Institute, Cranfield University, Cranfield MK43 0AL, UK

Denis Hughes

Institute for Water Research, Rhodes University,
6140 Grahamstown, South Africa

Bethanna Jackson

School of Geography, Environment and Earth
Sciences, Victoria University of Wellington,
PO Box 600, Wellington, New Zealand

Thomas R. Kjeldsen

Centre for Ecology and Hydrology, Wallingford
OX10 8BB, UK

Ralf Merz

UFZ Helmholtz Centre for Environmental Research,
Department of Catchment Hydrology, D-06120
Halle, Germany

Ludovic Oudin

University of Paris 6, Centre National de la
Recherche Scientifique, UMR Sisyphe 7619,
F-75252 Paris, France

Ezio Todini

Department of Earth and Geoenvironmental
Science, University of Bologna, I-40126
Bologna, Italy

Thorsten Wagener

Department of Civil and Environmental
Engineering, Pennsylvania State University,
University Park, PA 16802, USA

and

Department of Civil Engineering,
University of Bristol, Bristol BS8 1TR, UK

Howard Wheeler

Global Institute for Water Security, University of
Saskatchewan, National Hydrology Research
Centre, Saskatoon SK S7N 3H5, Canada

BACKGROUND

Land use and water management are inextricably linked, and it is widely recognised that the link must be duly considered in developing strategies for sustainable, cost-efficient water supply and flood management (O'Connell *et al.* 2007; Wheeler & Evans, 2009). This is demonstrated by the role of land use and hydrology in key European Directives (e.g. Water Framework Directive and Floods Directive) and in European Thematic Strategies (e.g. Soils). Although this includes urban planning considerations, the greatest challenges for hydrological science are those of understanding and predicting the impacts of rural land use change. In general terms, the challenge lies in the difficulty of observing, understanding and predicting complex and heterogeneous hydrological responses in non-stationary environments. The challenge becomes greater still when considering that other factors of importance to water management – sediments, hydrochemistry and hydroecology – are strongly linked to rural land use via the hydrological response; hydrological impacts assessments

must therefore be extended to multiple variables, disciplines and users.

In the context of land use change impacts, hydrological models are used in two general ways. Models can be applied to detect and attribute change in observed hydrological responses, thus adding to an understanding and quantification of factors affecting change. For example, detection of change may be approached by time-variable parameter estimation and assessment of whether the time-variance is significant relative to parameter uncertainty (Wagener *et al.* 2003; Beven *et al.* 2008). To attribute hydrological change to land use, a statistical test of dependency may be employed if suitable land use data are available and the necessary statistical conditions for the test are satisfied. Hydrological models can alternatively be applied to the prediction of possible future responses under land use scenarios by changing the model structure or parameter values to represent physical changes in the catchment properties (Dunn & Mackay 1996; Seibert *et al.* 2010; Ballard *et al.* 2012).

Both types of model application – analysis of observations and prediction – encounter many of the classical environmental modelling challenges. Seeking evidence of the hydrological effects of rural land use change is a primary challenge: where signals of change are expected, they tend to be obscured by other sources of variability and data uncertainty (Beven *et al.* 2008). For example, evidence-based methods of flood and low flow estimation that are widely used in practice in the UK (Holmes *et al.* 2005; Kjeldsen 2007) cannot explicitly allow for rural land use changes due to lack of clear and consistent evidence in national databases. Where inter-comparison of small catchments has revealed land use signals, these cannot be safely extrapolated to different catchments and larger scales (Buytaert *et al.* 2007; McIntyre & Marshall 2010). For larger catchments, seeking evidence of effects is even more of a challenge because of the important role of the channel network in the dispersion of flow signals (O'Donnell *et al.* 2011; Pattison & Lane 2012). The lack of unambiguous evidence of the effects of land use presents a fundamental problem for hydrological modellers who rely on observed evidence to formulate, calibrate and validate their models.

The wide perception that land use management has a considerable role to play in solving our water management problems provides motivation for increasing efforts to meet the scientific challenges. In the past few years, numerous research groups internationally have been conceiving, evolving, discussing and testing new approaches to doing so. Some of the groups at the forefront of this research (represented by the authors of this paper) attended a workshop in London in June 2011 sponsored by the UK Flood Risk Management Research Consortium (FRMRC, www.floodrisk.org.uk) to review progress and current capability, exchange ideas and discuss future priorities. The research, opinions and ideas presented at that meeting are the basis for this discussion paper, focussing on five inter-related topics that are considered to be of greatest potential interest and value to readers: (1) evidence-based modelling; (2) maximising the role of process knowledge using physics-based models; (3) hydrological connectivity; (4) uncertainty analysis; and (5) integrated catchment modelling for ecosystem service management. Within these topics, the main questions discussed in the paper are included in Figure 1. Before

Modelling steps	Main questions addressed in this paper
Observations & knowledge ↓	<ul style="list-style-type: none"> How should evidence be transferred from one region/one country to another? In data-poor regions, what frameworks should be used for incorporating expert knowledge?
Model selection ↓	<ul style="list-style-type: none"> How can we simplify process-based models with minimal loss of predictive power? How can we make sure that complexity of hydrodynamics and hydrological connectivity is sufficiently included?
Parameter estimation ↓	<ul style="list-style-type: none"> Can systematic spatial variations in parameters be used to estimate changes over time? Is Bayesian analysis a suitable way to estimate and update uncertainty?
Inference ↓	<ul style="list-style-type: none"> What model outputs are useful for inference about change? Can we separate land use signals from model uncertainty and climatic noise?
Prediction ↓	<ul style="list-style-type: none"> How do the processes of model simplification and upscaling affect prediction uncertainty? What progress can be made in spatial aspect of land use impacts?
Review of future	<ul style="list-style-type: none"> How should our methods adapt to demands for integrated, ecosystem services analysis? What are the other priorities towards reliable prediction of land use impacts on hydrology?

Figure 1 | Examples of science questions addressed within the five topic areas and their relation to steps of a general modelling procedure.

entering into these discussions, however, some background on the relevant general modelling approaches is useful.

GENERAL MODELLING APPROACHES AND THEIR APPLICABILITY

Discussions about the analysis and prediction of hydrological change inevitably include debate on the relative merits of different approaches to hydrological modelling: top-down (metric or data-based) and bottom-up (mechanistic or physics-based) modelling, or some combination of the two (conceptual modelling).

The basic principle of top-down models is that they seek to characterise hydrological response entirely from observations of model input and output variables (Sivapalan 2003; Young 2003). In the present context, the most

important variables for detecting changes in response are catchment-scale rainfall and flow and for attributing change are quantitative measures of change in catchment properties. Using top-down models, the ability to predict hydrological non-stationarity, such as that due to land use change, is limited to extrapolating any signals of change and dependencies that can be identified in that data. As discussed above, such signals are often undetectable or the cause is ambiguous. Signals in hydrological extremes are especially difficult to detect, with traditional frequency analysis unlikely to be capable of detecting land use influences (He *et al.* 2011). Intercomparison of small catchments has led in some cases to basic land use signals, such as land use effects on the runoff coefficient or base flow index, being identified from data. A notable example is that of the experiments conducted by the US Soil Conservation Service in establishing the Curve Number method. Interpreting such data, applying them to new contexts and upscaling to greater scales leads to results with high uncertainty (Bulygina *et al.* 2011). This is not to say that attempting to do so is worthless however, as discussed further below.

In contrast to top-down modelling, physics-based models are built around the best available understanding of the physics of hydrology. A theoretical advantage of this type of model is that if the physical properties of the catchment under existing and changed conditions can be determined, then the effects of physical change can be explicitly represented (Wheater *et al.* 1993, 2012; O'Connell & Todini 1996). In practice, the underlying physics has (necessarily) been derived from small-scale, often laboratory-based, observations. The parameter values are therefore unlikely to apply under conditions and at scales of interest; calibration of scale-adjusted values is generally necessary, including consideration of both space and time-scale (e.g. O'Loughlin *et al.* 2013). The problems of observation uncertainty and model identifiability then arise, leading to large prediction uncertainty. Another practical problem is that to resolve the physics-based differential equations over catchment scales with satisfactory precision may require many days or weeks of simulation on a personal computer. Again, such problems do not necessarily overcome the attractions of this approach, but careful thought is needed about how to manage them.

The final type of hydrological model is the 'conceptual' class. These models abandon the aspiration to entirely specify the model using catchment-scale observations or to entirely specify the model using prior knowledge of the physics. Instead, prior knowledge is used to define a system structure, typically a series of storages and fluxes between storages, while calibration is used to define the parameter values. Problems of non-identifiability have led to a preference in the recent scientific literature for parsimonious models and to the extensive use of Monte Carlo methods to estimate uncertainty. This class of model does not solve the prediction problem; rather, it contains some of the limitations of physics-based modelling (prior specification and non-identifiability) and of data-based modelling (detection of signals in the observations). The focus on uncertainty estimation by many conceptual modellers has also raised the difficult question of characterising and modelling errors (Mantovan & Todini 2006).

The choice between approaches depends not only on the potential errors associated with the methods, but also on practical criteria. A practical requirement, common across all modelling tasks, is the need for the model and its supporting documentation to be simple enough to use within reasonable constraints of expertise, data and human and computer resources, and to provide the outputs needed to solve the problem at hand. Also common to all models is the need to apply good practice modelling procedure (Klemeš 1986; Wagener *et al.* 2004; Jakeman *et al.* 2006; Alexandrov *et al.* 2010), including conceptual design, calibration, testing and review. In addition to these general requirements, the task of land use impacts modelling presents at least four particular requirements. (1) Many land use interventions are made in small areas that are inconsistent with the scales at which flow predictions are needed. This implies the need for a spatially distributed model. (2) The requirement to extrapolate, in other words to make predictions under conditions never yet observed, implies that there must be some reliance on prior knowledge of the physics and hence a role for physics-based models. (3) The difficulty of extrapolating to future land use, and the potential influence that a wrong prediction may have on planning and policy, provide a particular motivation to evaluate and report uncertainty in predictions. (4) It is often the case that the

hydrological model needs to support the prediction of variables other than water storages and fluxes, such as sediment yields, water quality (particularly nutrients) and hydro-ecological variables, which will dictate the modelled variables and hence influence the choice of model (Bruen & Mockler 2012).

EVIDENCE-BASED MODELLING

This section deals with the problem of obtaining useful observations of hydrological responses and using these to identify models that can be used for understanding and predicting land use change impacts. The discussion is restricted to observations of flow at catchment scale (although the issues apply equally to other variables that might be used for model calibration) and their use in conceptual models, and will cover two general approaches to generating evidence required for land use impacts modelling: extracting signals of change over time in one or more selected catchments (non-stationarity analysis); and extracting signals of differences between two or more catchments and using this to understand which land use factors govern flow responses.

Of these two approaches, non-stationarity analysis may be considered preferable because it provides the most direct evidence of impacts. A classical methodology for analysis of non-stationarity using conceptual models follows the sequence: identification of the reference and test periods; calibration (and sometimes validation) of the model on the two sub-periods; simulation on the test period using the parameters obtained on the reference period; and change detection/trend analysis of the model residual on the test period. However, at least three major issues are encountered: (1) the confounding effect of climate variability in pre- and post-change periods, which can lower the significance of the results (Lørup *et al.* 1998); (2) the impact of many land use changes is gradual, potentially taking many years to reach some new equilibrium response, which is more difficult to identify than a step change (see Ashagrie *et al.* 2006; Andréassian 2012); and (3) long-term records are needed for the periods before and after land use changes to derive statistically meaningful changes in response, particularly when analysing distributions of extremes.

An obvious solution to these problems is investment in long-term high-precision monitoring of catchments that are subject to significant and observable changes in rural land use. Arguably, that is essential for major scientific progress to be made in understanding non-stationarity. However, a parallel and more immediately practicable route to progress is modelling methods that aim to more effectively distinguish between signals and noise. Examples of such routes are the focus on response indices that are most susceptible to change (Archer *et al.* 2010) and the use of cross-validation and ensemble techniques to evaluate the influences of climatic variability and parameter uncertainty. For example, Kjeldsen (2009) investigated the ability of a conceptual model to detect and predict the impact of urban land use change using an event-based cross-validation procedure. Schreider *et al.* (2002) and Andréassian *et al.* (2003) calibrated an ensemble of parameter sets for a sequence of sub-periods from a long observation record. Using the parameter set from each sub-period, a simulation is performed on the entire record from which estimations of catchment response indices are derived, giving an idea of the significance of transient catchment behaviour relative to the noise.

The general lack of unambiguous evidence of a link between land use and hydrological non-stationarity in individual catchments means that the alternative source of evidence – differences between catchments – is the most commonly applied to impacts studies. This may be paired catchment studies, where there is some element of experimental design in terms of which factors are varied between the catchments and which are considered to be constant between the two catchments. The major problem is that, in reality, catchments are unique and everything changes between the two catchments, not just land use; interpreting any difference in response is not straightforward. Results are also difficult to safely generalise, being conditional on the pair of catchments used. Regional analysis is the alternative approach that aims to include information from a large number of catchments (from a whole region or country or even continent), inevitably with a greater number of non-land-use factors varying significantly.

If the hydrological response or the parameters of a model can be successfully generalised over space using regional analysis (e.g. Figure 2), then there is some basis for generalising the model over future land use scenarios

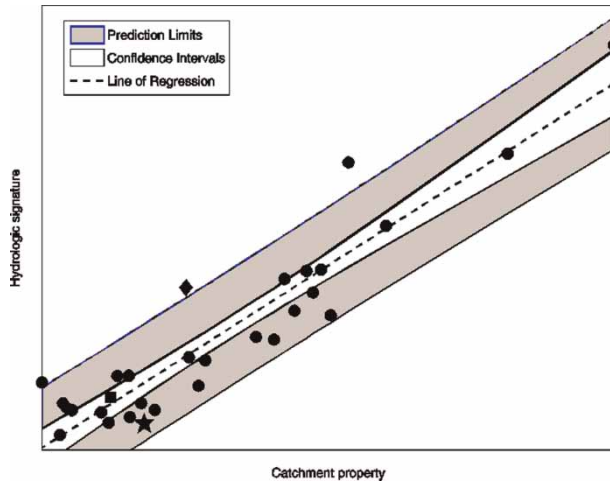


Figure 2 | A regional spatial signal in hydrological response that can be applied to the time domain to look at land use impacts (adapted from *Yadav et al. (2007)*).

in what might be called a ‘trading space for time’ approach (*Merz & Blöschl 2009; Oudin et al. 2010; Buytaert & Beven 2011; Singh et al. 2011; Wagener & Montanari 2011*). Various problems arise, however: the well-known difficulty of, and uncertainty in, generalising model parameters over space (*McIntyre et al. 2005; Wagener & Wheater 2006; Oudin et al. 2010*); signals of rural land use are weak or non-existent within most regionalisation studies (*Merz & Blöschl 2009; Merz et al. 2011*) or do not cover all scenarios of interest (*McIntyre & Marshall 2010*); and there is an incompatibility of scale between regionalisation studies (usually catchment scales of at least several kilometres squared) and the scales at which land use change is implemented, for example field scale. Nevertheless, given the limitations of other approaches, regional analysis may be the best applicable source of evidence. Several projects have taken this view and approaches which attempt to address the three main problems listed above have been proposed (*Yadav et al. 2007; Merz & Blöschl 2009; Bulygina et al. 2011; Singh et al. 2011*).

The method of *Bulygina et al. (2011)* encompasses ideas from all these groups. They condition a conceptual field-scale model using regionalised values of flow response indices: the baseflow index from the Hydrology of Soil Types (HOST) soils classification system (*Boorman et al. 1995*) and the Curve Number from the US Department of Agriculture (USDA) soil classification system (*USDA 1986*). The indices are used to condition parameters of the model using

Bayes’ equations, giving posterior parameter distributions for a given land use scenario while taking into account not just the expected value of the index but the probability distribution of the index derived from these sources. Trading space for time, the posterior distribution of parameter values is propagated to uncertainty in predictions under land use scenarios. In validation tests, the regionalisation gave hydrograph outputs broadly consistent with observed differences (*Bulygina et al. 2009, 2011*) although with high uncertainty. A major limitation of this approach is the incomplete and uncertain information about field-scale land use effects contained in the USDA and HOST databases; *Bulygina et al. (2012)* recommended that additional sources of information, including spot gauging and physics-based modelling, are incorporated within the method. Uncertainty is also introduced in translating evidence of regional variations into speculations of future time variations. *Bulygina et al. (2011)* and *Holman et al. (2011)* discuss this in the context of how to apply the US Curve Number system to UK impacts studies and *Buytaert & Beven (2009)* propose including an additional term in the Bayes equation to formally include this evidence translation error.

The problem of course changes depending on the availability of data to support regionalisation. In cases where hundreds of well-gauged catchments are available to support regionalisation (*McIntyre et al. 2005; Wagener et al. 2007; Oudin et al. 2008; Merz & Blöschl 2009; Sawicz et al. 2011*) the role of prior knowledge in parameter estimation may be relatively small. In more typical cases however, the specification of the model and its parameter uncertainty may rely heavily on the expert’s prior knowledge. *Kapangaziwiri et al. (2009, 2012)* describe the challenge in South Africa of predicting under environmental change, where the collection and formalisation of expert knowledge into realistic ranges of parameter values is crucial; they describe a procedure for comparing and combining this knowledge with regionalised indices.

UPSCALING TO MAXIMISE THE USE OF PROCESS KNOWLEDGE AND PHYSICS-BASED MODELS

Given the numerous limitations of relying on catchment-scale evidence, a theoretically attractive approach to

modelling land use impacts is physics-based modelling. This involves discretising the catchment into many elemental units (e.g. Ewen *et al.* 2006; Park *et al.* 2009; Gelfan 2010) and integrating the elemental responses into a catchment-scale response, explicitly accounting for process non-linearity, heterogeneity and non-stationarity. In design at least, this approach allows physical changes associated with land use scenarios to be represented as perturbations in and/or trajectories of model parameters values (Hashemi *et al.* 2000; Kuchment & Gelfan 2002; Park & Cluckie 2009). However, as previously noted the inherent problems with physics-based models means that data requirements are high, results can be highly uncertain and catchment-scale modelling can be computationally expensive. For example, in the recent work at Pontbren in Wales, UK in order to resolve the physics acceptably, it was deemed necessary to use a 1 m^2 grid in the x - y plane with a 1 cm vertical discretisation (Jackson *et al.* 2008), resulting in personal computer run-times of several hours to cover a 1-month simulation period over a $20,000\text{ m}^2$ field. However, the required grid size depends on the non-linearity of the specific case and the accuracy criteria used; for example, when applying the Topkapi model (Todini & Ciarapica 2001) over larger scales, Martina & Todini (2008) concluded that 10–1,000 m grid sizes can be sufficient.

The need to lower the expense but preserve the capability of physics-based models leads to the idea of metamodelling (Ballard 2011; Razavi *et al.* 2012; Wheater *et al.* 2012). Here, metamodelling is taken to mean the substitution of a physics-based model by a conceptual model that maintains the same basic hydrological principles as the physics-based model and also closely replicates its responses under a range of relevant climate and land use scenarios (Figure 3). Previous applications of this general idea in hydrology are few, the closest being the ‘UP’ framework of Ewen (1997) and the emulation framework of Young (2010). The method, as applied by Wheater *et al.* (2008) and Ballard (2011), allows uncertainties associated with data, models and the upscaling procedure to be propagated through to predictions using Monte Carlo simulation. These authors considered the method to have considerable merit for predicting impacts of land use change on flood flows. However, uncertainty was high, especially where the physics-based models were developed without supporting small-scale measurements. In one case study, the errors in predicted changes in peak flows due to the metamodelling step had magnitudes of 0–20% at small scale and 0–10% at 260 km^2 catchment scale (Ballard 2011), on top of uncertainty in the physics-based model. As with the alternative regionalisation approach, in many cases the potential

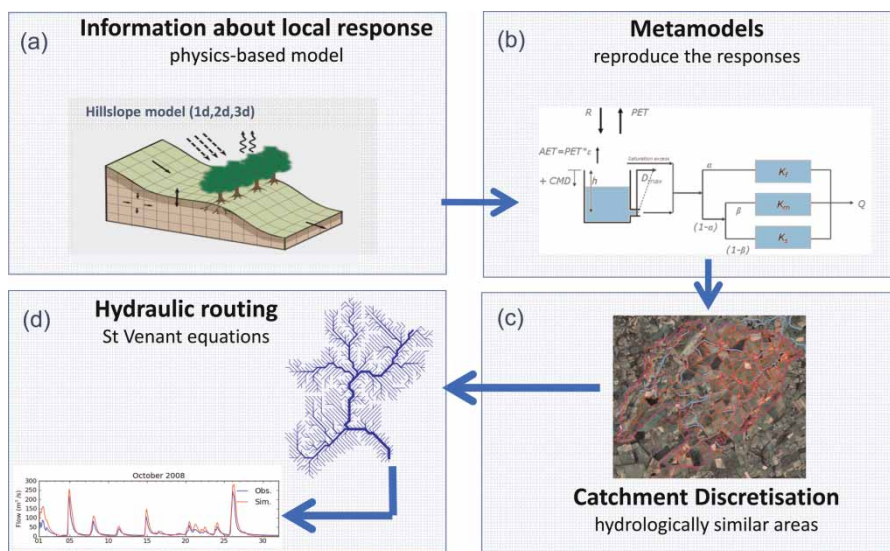


Figure 3 | A metamodelling and hydraulic routing procedure to upscale local-scale impacts of land use change: (a) local- (field or pixel) scale responses estimated by a physics-based model; (b) a simple conceptual-type model is identified that closely replicates selected responses; (c) the catchment is discretised into units (pixels or fields) and an identified metamodel is applied to each unit class; and (d) the responses from each unit are upscaled using a channel network model.

errors were much larger than the predicted change (Bulygina *et al.* 2012).

The metamodelling approach requires that the conceptual model retains as much of the relevant hydrological processes as possible. Using the Topkapi model, Martina *et al.* (2011) illustrated the strong hysteresis that can exist in the soil moisture-saturated area relationship for both hillslopes and large catchments, and the importance of saturation excess processes after rainfall. They also illustrated that typical conceptual models, which usually have unique and lumped relationships between soil wetness and runoff, will produce inaccurate runoff predictions. They then showed how such hysteresis may be included to produce more satisfactory results. Such attention to knowledge of physical processes, as well as emulating the outputs of the more complex model, is arguably essential to the development of metamodelling (and conceptual modelling more generally) to improve confidence in predictions beyond the range of training data.

REPRESENTING HYDROLOGICAL CONNECTIVITY IN MODELS

The term 'hydrological connectivity' is sometimes used in different ways (Bracken & Croke 2007), but here we consider it as the networking of surface and subsurface preferential hydrological pathways including macropores, pipes, rills, ditches, streams, river channels and floodplains. Networks influence travel time distributions, shifting them from Gaussian to skewed distributions (the former are only present under well-mixed conditions) and act as integrators of the space-time runoff response patterns. In particular, the river network governs how local runoff responses translate into catchment-scale flows. While the detail of the travel time distribution may be unimportant for water supply applications, for flood studies it is expected to be a critical part of the analysis, especially at and beyond the lower meso-scale (defined here as greater than 10 km²; Pattison & Lane 2012). According to Dooge (1986), such catchments are systems of organised complexity whose hydrological response is strongly and non-linearly controlled by structural and topological characteristics of landscape

characteristics such as topography, vegetation, soil properties, connective flow structures and their interaction with forcing and system states (Zehe & Sivapalan 2009). Preferential connected hydrological pathways can be found in almost any catchment and across all scales. This is not by chance; rather, their self-reinforced development and maintenance may be regarded as a manifestation of the fundamental tendency of nature to dissipate gradients as fast as possible (Kleidon *et al.* 2012).

There are important hydraulic elements to the integrating role of the river network: (1) the accumulated flows from the various parts of the catchment interact at network confluences; (2) the stage and other hydraulic properties of the accumulating flows are modified by the very act of overcoming the friction and inertia of open-channel flow; and (3) in extreme cases, the flows themselves can modify the effective properties of channels by over-bank flow or by channel erosion or blockage by debris. Any change in land use management will affect the integration directly by affecting the space-time pattern of runoff and thus the accumulation of flows. There is, however, a further effect in that there can be knock-on effects on the hydraulic elements (1–3) above. For example, a major change in land use management may increase the possibility of steep rising hydrographs or over-bank flows.

To understand the role of the channel network in the downstream propagation of the effect of changes in land use management, it is first necessary to understand the integrating role of the network in the generation of hydrographs. This amounts to an understanding of: the Saint-Venant equations (e.g. Chow 1959; Henderson 1966); routing techniques used by hydrologists (e.g. Singh 1996; Beven 2001); how the basic features of the integration can be viewed as macroscopic (i.e. catchment-scale) dispersive processes (hydrodynamic dispersion: Chow 1959; White *et al.* 2004; geomorphologic dispersion: Rinaldo *et al.* 1991; Botter & Rinaldo 2003; and kinematic dispersion: Saco & Kumar 2002a, b); and geomorphology (Piégay & Gurnell 1997; Thorne *et al.* 2011). This understanding can be used to create models for the generation of hydrographs, such as lumped or distributed rainfall-runoff models. The problem then faced is to validate these models for use in estimating the impact of changes in land use management, which involves demonstrating that they have appropriate

sensitivities to the model parameters that are modified to represent the effect of a change in land use management (Ewen et al. 2006; O'Connell et al. 2007). In practice, direct validation is not possible because this would need data to be collected for a catchment twice for exactly the same storm (i.e. with and without the change in land use management having been implemented). This leaves indirect validation (Ewen & Parkin 1996). The potential inaccuracy of sensitivity estimates is a major problem. For example, parameters in lumped models usually have no physical basis and therefore unphysical sensitivities. One major problem in distributed models is false dispersion generated erroneously in numerical procedures associated with the mathematics of the numerical scheme, the time step and the computational cell size. False dispersion can easily dominate over actual dispersion, and so can mask or enhance dispersion in the propagation of the effects of changes in land use management.

Putting to one side the question of whether the sensitivities are correct, one area where progress has been made recently is the use of distributed modelling in the spatial decomposition of the sensitivity of hydrograph peaks downstream to spatial patterns of changes in land use management upstream. For each computational cell (or pixel) in a distributed model, the sensitivity of the peak discharge rate to changes in the model parameters that control land use management can be estimated efficiently and accurately using algorithmic differentiation. In algorithmic differentiation, the entire source code for the model is differentiated mathematically (Griewank 2000; Hascoët & Pascual 2004). Sensitivity maps have been created using this approach (e.g. O'Donnell et al. 2011), and there has been some experimentation with the decomposition of downstream impacts to give impact maps that show the source of impact, pixel by pixel, down to pixel sizes of 10 m (Ewen et al. 2013).

Impact maps have been generated for the upland Hodder catchment (260 km²), NW England, which is undergoing extensive changes in land use and management including reductions in stocking densities, planting of woodland in the riparian corridors and the blocking of drainage channels in peatland (Ewen et al. 2010). Using extensive sets of field data, a model of the catchment was developed that comprises a detailed hydraulic model

(Ewen et al. 2013) embedded within a grid-based runoff generation model (Ballard 2011; Bulygina et al. 2011). The most obvious features of impact maps for rainfall events are that they show the relative importance of the various spatial patterns used in the modelling. The main pattern is for the change in land use management, and this interacts with the underlying patterns for rainfall, accumulated evaporation, soil type, land management, land cover, topography and travel distance from the point of runoff generation to the flood site. The contributions of the underlying patterns and the integrating effects of the river network are studied using test simulations (Figure 4). It is not yet clear how valuable this approach will be operationally, but it does give a systematic way to assess the likely impact of proposed spatial patterns of changes in land use and management, albeit with various limitations such as the assumption that sensitivities are represented correctly in the distributed model.

Another area where significant progress is being made is conceptualising the networks of flow pathways. This recognises that in general meso-scale catchments are likely to be too large for physics-based models: such a reductionist approach would require high-resolution data on surface

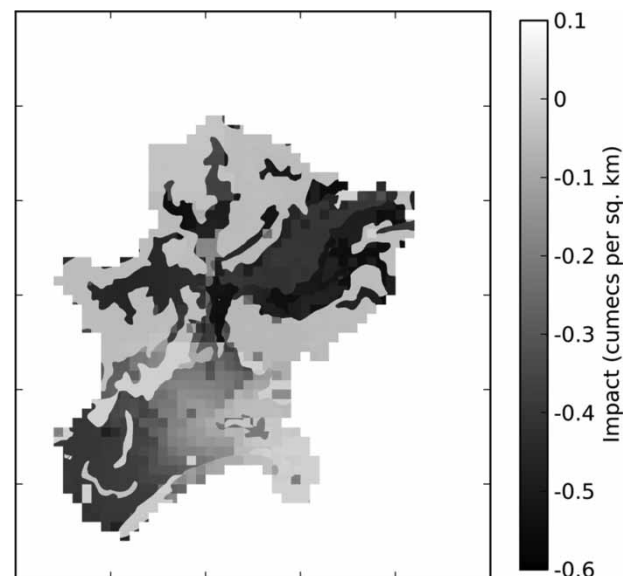


Figure 4 | Impact map for an event on 18 November 2009 for a hypothetical extreme scenario in which there are widespread changes in land use management across the entire Hodder catchment that tend to reduce the flashiness of runoff (observed flood peak 217 m³ s⁻¹; simulated reduction in peak 56 m³ s⁻¹).

and subsurface catchment architecture and flow paths, on top of the challenge of achieving accurate numerical solutions. On the other hand, the real spatial architecture of the hydrological system conceptualised by effective states, effective parameters and effective fluxes is not adequately represented by most conceptual models. A potential solution is to combine the advantages of conceptual models and avoid the disadvantages of physics-based models by aiming for a realistic conceptual representation of the surface and subsurface architecture, especially the explicit representation of preferential flow paths (e.g. Klaus & Zehe 2011), but in a parsimonious way such that data requirements and numerical issues do not preclude its application. This can be assisted by the incorporation of new types of observations such as hydrological tracers, geophysical exploration and remote sensing by basing the model concepts on observable states, structures and properties rather than effective parameters and lumped process representations. Achieving such realistic representations, particularly of the subsurface pathways, is one of the great challenges currently under investigation, e.g. in the CAOS project (Catchments as Organized Systems, www.caos-project.de).

UNCERTAINTY ANALYSIS

Hydrological model uncertainty analysis has become a mainstream research topic, and now also attracts considerable interest from model users. The uncertainty arises from climate inputs and other boundary conditions, model equations and their parameter estimates and initial conditions. All these apply to land use impact predictions, but of particular interest is uncertainty associated with lack of and ambiguity in information about how the model equations and parameters respond to land use change. This applies to the change immediately associated with a land use change and to any subsequent gradual re-adjustment. As previously discussed, the information about change is generated by regionalisation of catchment scale observations or through upscaling of small-scale process knowledge. The former suffers from lack of relevant and unambiguous evidence of effects, and the latter suffers from uncertainty in process knowledge and the upscaling procedure.

The most commonly applied approach to managing these uncertainties is simply to put some caveats on the predictions without attempting quantification. There is increasing interest in running land use change predictions within quantitative uncertainty frameworks, however (Kapangaziwiri *et al.* 2012). Almost all these will use some form of ensemble modelling where lack of, variability of, or ambiguity in information (of both the quantitative and qualitative types) is quantified and mapped to ranges or probability distributions of model parameters, and samples from these ranges/distributions are taken to produce an ensemble of models and hence predictions. Questions that must be addressed when applying such an uncertainty framework include: what information to consider as uncertain; how to estimate and express its uncertainty; how to map information uncertainty to parameter uncertainty; and how to refine (increase or reduce) uncertainty as more information becomes available. Beyond parameter uncertainty lies the still greater challenge of whether and how to represent model structure uncertainty.

The solutions depend upon the situation at hand; nevertheless, general frameworks have been proposed to allow for different cases. Jackson *et al.* (2008) and Ballard (2011) use the established Generalised Likelihood Uncertainty Estimation (GLUE) method (Beven & Binley 1992) to estimate uncertainty in small-scale model parameters, then again apply a GLUE-type method in their metamodelling procedure of fitting conceptual models to the small-scale models. The framework of Bulygina *et al.* (2012) uses a formal Bayesian framework for integrating multiple sources of uncertain information together into the model parameter estimates. This has shown some promise although is limited by the necessary assumptions about the nature of the priors, the nature of the uncertainty in and inter-dependencies between the information sources and the nature of model equation error. One especially interesting problem is ensuring pre- and post-change dependencies are sufficiently represented: a pair of parameter sets representing pre- and post-change conditions can give seemingly sensible results when applied separately, but the difference between the results may be wrong. Unfortunately, observations of change that would allow analysis of this problem are rare, and little attention has been paid to it in the regionalisation literature (with a few exceptions, e.g. Bulygina *et al.* (2009)).

The uncertainty estimation problem becomes increasingly fascinating when looking at gradual non-stationarity, where the solution would entail ensembles of parameter value trajectories rather than step changes. While continuous-time land cover models have been coupled with hydrological models (Quillet *et al.* 2010), the uncertainty in this interaction remains a relatively unexplored area.

Another innovation towards managing the computational requirements of physics-based models, while including Monte-Carlo-based uncertainty analysis for the purpose of flood risk assessments, is the specific censoring procedure of Gelfan (2010). This approach uses dynamic-stochastic modelling (Kuchment & Gelfan 1991), which couples a deterministic physics-based model with a stochastic weather generator. A very large number of samples of weather inputs is generated, but these are censored so that only those that have the potential to pose a flood risk are run through the model. Such censoring/screening of Monte Carlo samples may have valuable potential for managing land use impacts uncertainties, as well as climate variability.

However they are assessed, a major issue is the communication of these uncertainties to decision-makers and managers. Surveys in the flood forecasting area confirm that managers do want to have this uncertainty information, but are unclear about how it should be presented and used. There are considerable differences in how this is done in European countries, e.g. Bruen *et al.* (2010).

INTEGRATED CATCHMENT MODELLING FOR ECOSYSTEM SERVICE MANAGEMENT

The preceding discussion highlights some of the difficulties in demonstrating the benefits of various land use practices for managing water hazards. This may make it difficult to justify expenditure on changes in land use because the cost effectiveness is difficult to quantify, and interventions are subject to more uncertainty than traditional 'hard' engineered solutions (dams, stopbanks, river dredging, etc.).

In practice, land management activities may have multiple effects above and beyond those that are being targeted, for example through modifications to sediment or pollutant transport, carbon sequestration and greenhouse gas emissions, ecological responses and biodiversity. Some of these

other responses may be easier to quantify and the multiple benefits that the land use changes deliver may become easier to justify on economic grounds. Similarly, the cost of hard engineered solutions to flood risk may be more prohibitive when the potentially detrimental effects of such solutions on other service (for example, floodplain habitats), and their corresponding costs, are quantified. This calls for implementation of an ecosystem services approach that takes a holistic overview of all of the processes occurring and their various roles in providing services (Millenium Ecosystem Assessment 2005; Morris *et al.* 2005; Jackson *et al.* 2012).

Examples of land use activities that might have multiple benefits include temporary flood storage zones (Environment Agency 2012). As well as attenuating a flood peak through slowing the movement of water through the catchment, flood storage ponds often provide suitable conditions for deposition of sediment and associated particulate pollutants, such as phosphorus. The wetland environment created can also be valuable for decreasing nitrate concentrations through enhanced de-nitrification. Finally, wetland environments often bring biodiversity benefits and can be visually appealing. Set against this, potential negative factors also need to be considered. For example, enhancement of the de-nitrification process will generate increased greenhouse gas production and, if sediments are allowed to accumulate in the storage pond, they may be remobilised at a later date, causing enhanced pollutant transport at different times.

Similarly, tree planting can have significant impacts on multiple environmental services which may be positive or negative depending on the geomorphic and climatic regime in which they are placed, the species utilised and the vegetation type they replace. Their placement in agricultural locations generally tends to be beneficial, however. For example, where trees replace modern grasses, root depth and organic matter content will usually significantly increase, in turn enhancing soil water holding capacity, infiltration capacity and sequestration of carbon. They can also protect against erosion and reduce the amount of sediments and nutrients entering a fluvial system. However, their capacity to provide flood mitigation and sediment and water quality benefits is highly influenced by their positioning in the landscape and thus their influence on hydrological connectivity; they can only capture and filter significant

amounts of water, sediments and chemicals if they are located in zones of topographical convergence. Many other land management activities such as riparian management, minimum tillage and drain blocking will also affect more than one aspect of the water environment, pointing to the need for consideration of multiple responses.

Another issue is that many land use interventions (such as those that might be implemented by a land owner) are typically quite small, meaning that on their own they would be ineffective at achieving any measurable changes in catchment responses. However, where multiple activities are undertaken, their combined effectiveness could become valuable (Balana *et al.* 2012). This calls for a catchment approach to address land use and a holistic overview to identify synergistic activities or potential conflicts. Consideration of all of these aspects clearly makes the modelling challenge much more complex, but ultimately is more likely to deliver sustainable management practices that are both efficient and cost-effective in their outcomes. Furthermore, it highlights the need for buy-in from land managers as well as dialogue and collaboration between managers, scientists, policy makers and other stakeholders if land use management techniques are to become effective in mitigating against environmental hazards.

The more general case for development of generic frameworks and suites of models to support decision-making under change (land use or otherwise) was stressed by the recent *Millennium Ecosystem Assessment* (2005). Although this area of research is still in its infancy, some recent progress has been made and a handful of frameworks and/or suites of models have been developed with the aim of meeting this need. These include the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) tool described in Nelson *et al.* (2009) and Tallis *et al.* (2011), Polyscape (Jackson *et al.* 2012), the Artificial Intelligence for Ecosystem Services (ARIES) tool (Bagstad *et al.* 2011) and Envision (Bolte *et al.* 2007; Hulse *et al.* 2008). The first three all include consideration of the impact of land management on flood peaks as well as on other ecosystem services, and flood management is now a component of current development for the last. Each differs in the scales considered, data scarcity and computational constraints, and uses different methodological and philosophical approaches to balancing conflicts between users, science and data (these being general issues surrounding development of integrated models linking land use with bio-physical

processes and socio-economic considerations; van Delden *et al.* 2011). There are also a wide variety of site-specific multi-service ecosystem valuation applications in the literature which include consideration of the impacts of land use on water services (e.g. Rutledge *et al.* 2008; Sieber *et al.* 2008; van Delden *et al.* 2010; Britz *et al.* 2011). It is likely that in the next few years, as these frameworks and site-specific applications progress, successes, failures and lessons learned from this and similar research will lead us closer to models that can robustly inform decisions on sustainable land management, with flood mitigation one of many services considered and enhanced.

CONCLUSIONS

Modelling the water-related impacts of rural land use change requires us to face all the general challenges of environmental modelling, including: observability of relevant variables; complexity, non-linearity and heterogeneity of natural systems; model identifiability and uncertainty estimation; and the need for interaction of models and modellers across objectives and disciplines. In the land use impacts context, these general challenges manifest themselves in more specific manners, for example: the need to synthesise evidence of land use impacts from sources that have questionable relevance to the problem at hand; the need to upscale knowledge of local land use change impacts to catchment scales; the need to consider non-stationarity of vegetation, soils and geomorphology, both as step changes and as gradual re-adjustment effects; the need to isolate land use effects from effects of climate variability and model uncertainty; and the increased challenges brought by the need to consider impacts on hydrology-driven variables, such as nutrients and sediments.

This paper has identified and reviewed these challenges and discussed a sample of recent methodological and tool developments. Of the many concluding comments that might be made, the following aim to address each of the questions posed in Figure 1.

- The lack of evidence of land use impacts prompts us to draw upon evidence across regions and nations, and recent work has illustrated quantitative methods of

doing so and the high uncertainty involved. There is a need for greater testing of transferability of data on land use influences.

- Prior knowledge of experts is critical in data-poor regions, and uncertainty frameworks have been proposed to integrate and compare this knowledge with whatever information is available from observations and regionalisation.
- Metamodelling and emulation of physics-based models have rarely been applied in the land use impacts context. Recent work is promising, but careful attention is required to maintain the important non-linear processes and the ability to represent change in the simplified models.
- Connectivities of hydrological pathways, and how they are affected by changing land use, are key controls on flood responses. If connectivity can be quantified using catchment properties and hydrological and hydrochemical observations, this may constitute a large step forward in predictability of land use change impacts. Accurate modelling of the non-linear hydrodynamics is important to ensure land use signals are not inaccurately modified in the upscaling process.
- It has become common to 'trade space for time', in the sense of using identifiable systemic spatial variation of catchment-scale parameters to estimate how these parameters will vary under land use change. However, except where dramatic land use differences exist at catchment scale, the dominant spatial signals are not associated with land use and the search for the more subtle signals is proving challenging.
- Bayesian analysis provides a formal and transparent framework for combining information sources about land use change impacts and for including uncertainty associated with random variability of data and unknowns about the future. However, a careful review of what is omitted or simplified in the analysis is always required.
- The search for evidence of land use impacts on hydrology cannot rely on arbitrary flow statistics applied over arbitrary periods. Progress in detecting change is likely to require a focus on hydrological variables, indices or modes of response most sensitive to change.
- While analysis methods have been developed to separate signals from noise, with positive results in relatively small catchments, observed hydrological change at meso- and large-catchment scales cannot, with very few exceptions, be confidently attributed to land use change due to the

integrating and smoothing effect of the catchment, and the confounding effects of measurement uncertainty and climatic variability.

- Upscaling is essential because most realistic land use changes occur on relatively small areas of a catchment. The process of upscaling requires careful attention. As well as errors in data and small-scale process conceptualisation, significant error in the upscaling process is inevitable. Continued research on upscaling, and the reporting of uncertainty due to upscaling, is called for.
- Identifying where in a catchment land use change would lead to the greatest downstream flow impacts would usually involve perturbing the relevant parameters for each pixel of a distributed model. Instead, new applications of algorithmic differentiation can be used to provide rapid and accurate estimates of the sensitivity of key model outputs.
- In order to extend an analysis of land use impacts to evaluate the full range of ecosystem services that are coupled to water and all the variables, interactions and observations that would involve, the modelling challenges of pure hydrology would be multiplied by orders of magnitude. Extension of the progress made within the hydrological modelling domain to inter-disciplinary modelling of land use impacts is therefore perhaps the greatest challenge for the next decade, and perhaps provides the greatest scope for progressing the value of our models.

Despite the scope for further progress in modelling land use change impacts, as included in the list above and discussed at length in the rest of the paper, it is clear that substantial progress in understanding and prediction can only come with investment in monitoring land use change and hydrological responses, both in the form of intensely monitored experimental catchments and as part of routine monitoring. Some experimental programmes are addressing this concern; it is hoped that these will continue, additional programmes will be established and the value of national monitoring capacity will be recognised. Developments in remote sensing and other measurement technology will also be essential to support improved monitoring, especially in terms of spatial properties (e.g. Lakshmi *et al.* 2011). The greatest challenge, encompassing many theoretical and

practical hurdles, will be moving on from pure hydrological monitoring and modelling to the inter-disciplinary programmes that are needed to support the analysis of interdependencies between hydrology and other science disciplines, supporting a more integrated approach to land use impacts management.

ACKNOWLEDGEMENTS

This paper represents the proceedings of an international workshop held at Imperial College London during 10–12 June 2011. The workshop was sponsored by the Flood Risk Management Research Consortium Phase 2 (www.floodrisk.org.uk), Engineering and Physical Sciences Research Council grant EP/F020511/1. A variety of funders supported the research presented at the workshop.

REFERENCES

- Alexandrov, G. A., Ames, D., Bellocchi, G., Bruen, M., Crout, N., Erechtkoukova, M., Hildebrandt, A., Hoffman, F., Jackisch, C., Khaiteer, P., Mannina, G., Matsunaga, T., Purucker, S. T., Rivington, M. & Samaniego, L. 2010 Technical assessment and evaluation of environmental models and software: letter to the editor. *Environmental Modelling and Software* **26** (3), 328–336.
- Andréassian, V. 2012 Visualising the hydrological signature of an unsteady land cover – an application to deforested and afforested catchments in Australia, the USA and France. *Revisiting Experimental Catchment Studies in Forest Hydrology*. IAHS Publ. **353**, 125–134.
- Andréassian, V., Parent, E. & Michel, C. 2003 A distribution-free test to detect gradual changes in watershed behavior. *Water Resources Research* **39** (9), 1252.
- Archer, D. R., Climent-Soler, D. & Holman, I. P. 2010 Changes in discharge rise and fall rates applied to impact assessment of catchment land use. *Hydrology Research* **41**, 13–26.
- Ashagrie, A. G., de Laat, P. J. M., de Wit, M. J. M., Tu, M. & Uhlenbrook, S. 2006 Detecting the influence of land use changes on discharges and floods in the Meuse River Basin – the predictive power of a ninety-year rainfall-runoff relation? *Hydrology and Earth System Sciences* **10** (5), 691–701.
- Bagstad, K. J., Villa, F., Johnson, G. W. & Boigt, B. 2011 ARIES – Artificial Intelligence for Ecosystem Services: A guide to models and data, version 1.0. ARIES report series n.1. <http://www.ariesonline.org/docs/ARIESModelingGuide1.0.pdf>.
- Balana, B. B., Lago, M., Baggaley, N., Castellazzi, M., Sample, J., Stutter, M., Slee, B. & Vinten, A. J. A. 2012 Integrating economic and biophysical data in assessing cost-effectiveness of buffer strip placement. *Journal of Environmental Quality* **41**, 380–388.
- Ballard, C. 2011 *The Role of Physics Based Models for Simulating Runoff Responses to Rural Land Management Scenarios*. PhD Thesis, Imperial College London, 340 pp.
- Ballard, C., McIntyre, N. & Wheeler, H. 2012 Modelling the effects of peatland management on peak flows. *Hydrology & Earth System Sciences* **8**, C3721–C3726.
- Beven, K. J. 2001 *Rainfall-Runoff Modelling: The Primer*. Wiley-Blackwell, Chichester.
- Beven, K. J. & Binley, A. M. 1992 The future of distributed models: model calibration and uncertainty prediction. *Hydrological Processes* **6**, 279–298.
- Beven, K., Young, P., Romanowicz, R., O'Connell, E., Ewen, J., O'Donnell, G., Homan, I., Posthumus, H., Morris, J., Hollis, J., Rose, S., Lamb, R. & Archer, D. 2008 Analysis of historical data sets to look for impacts of land use and management change on flood generation. Defra R&D Final Report FD2120, Defra, London.
- Bolte, J. P., Hulse, D. W., Gregory, S. V. & Smith, C. 2007 Modeling biocomplexity – actors, landscapes and alternative futures. *Environmental Modeling and Software* **22** (5), 570–579.
- Boorman, D., Hollis, J. & Lilly, A. 1995 *Hydrology of Soil Types: A Hydrologically-based Classification of the Soils of the United Kingdom*. Institute of Hydrology, Wallingford.
- Botter, G. & Rinaldo, A. 2003 Scale effect on geomorphologic and kinematic dispersion. *Water Resources Research* **39** (10), 1286.
- Bracken, L. J. & Croke, J. 2007 The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes* **21** (13), 1749–1763.
- Britz, W., Verburg, P. H. & Leip, A. 2011 Modelling of land cover and agricultural change in Europe: combining the CLUE and CAPRI-Spat approaches. *Agriculture, Ecosystems & Environment* **142** (1–2), 40–50.
- Bruen, M. & Mockler, E. 2012 A variable structure catchment model as the engine for a water quality decision support tool facilitating scientific debate and collaboration. *Proceedings of iEMSS 012, International Congress on Environmental Modelling and Software*, Leipzig, Germany.
- Bruen, M., Krahe, P., Zappa, M., Olsson, J., Vehvilainen, B., Kok, K. & Daamen, K. 2010 Visualising flood forecasting uncertainty: Some current European EPS platforms – COST731 Working Group 3. *Atmospheric Science Letters* **11** (2), 92–99.
- Bulygina, N., Ballard, C., McIntyre, N., O'Donnell, G. & Wheeler, H. 2012 Integrating different types of information into hydrological model parameter estimation: application to ungauged catchments and land use scenario analysis. *Water Resources Research* **48**, W06519.
- Bulygina, N., McIntyre, N. & Wheeler, H. 2009 Conditioning rainfall-runoff model parameters for ungauged catchments and land management impacts analysis. *Hydrology and Earth System Sciences* **13**, 893–904.

- Bulygina, N., McIntyre, N. & Wheater, H. 2011 Bayesian conditioning of a rainfall-runoff model for predicting flows in ungauged catchments and under land use changes. *Water Resources Research* **47**, W02503.
- Buytaert, W. & Beven, K. 2009 Regionalisation as a learning process. *Water Resources Research* **45**, W11419.
- Buytaert, W. & Beven, K. 2011 Models as multiple working hypotheses: hydrological simulation of tropical alpine wetlands. *Hydrological Processes* **25** (11), 1784–1799.
- Buytaert, W., Iñiguez, V. & De Bièvre, B. 2007 The effects of *Pinus patula* forestation on water yield in the Andean páramo. *Forest Ecology and Management* **251**, 22–30.
- Caldar, I. R. 1990 *Evaporation in the Uplands*. Wiley, Chichester, UK.
- Chow, V. T. 1959 *Open-Channel Hydraulics*. McGraw-Hill, New York.
- Dooge, J. C. I. 1986 Looking for hydrological laws. *Water Resources Research* **22** (9), 46–58.
- Dunn, S. M. & Mackay, R. 1996 Modelling the hydrological impacts of open ditch drainage. *Journal of Hydrology* **179** (1–4), 37–66.
- Environment Agency 2012 Greater working with natural processes in flood and coastal erosion risk management. EA Report. Available online at <http://publications.environment-agency.gov.uk/PDF/GEHO0811BUCI-E-E.pdf>.
- Ewen, J. 1997 'Blueprint' for the UP modelling system for large scale hydrology. *Hydrology and Earth System Sciences* **1** (1), 55–69.
- Ewen, J. & Parkin, G. 1996 Validation of catchment models for predicting land-use and climate change impacts. 1. Method. *Journal of Hydrology* **175**, 583–594.
- Ewen, J., Geris, J., O'Donnell, G., Mayes, W. & O'Connell, E. 2010 Multiscale experimentation, monitoring and analysis of long-term land use changes and flood risk, SC060092: Final Science Report. Newcastle University, Newcastle upon Tyne, UK, 133.
- Ewen, J., O'Donnell, G., Bulygina, N., Ballard, C. & O'Connell, E. 2013 Towards understanding links between rural land management and the catchment flood hydrograph. *Quarterly Journal of the Royal Meteorological Society* **139**, 350–357.
- Ewen, J., O'Donnell, G., Burton, A. & O'Connell, E. 2006 Errors and uncertainty in physically-based rainfall-runoff modelling of catchment change effects. *Journal of Hydrology* **330**, 641–650.
- Gelfan, A. N. 2010 Extreme snowmelt floods: frequency assessment and analysis of genesis on the basis of the dynamic-stochastic approach. *Journal of Hydrology* **388**, 85–99.
- Griewank, A. 2000 *Evaluating Derivatives: Principles and Techniques of Algorithmic Differentiation*. Society for Industrial and Applied Mathematics, Philadelphia, USA.
- Hascœt, L. & Pascual, V. 2004 *TAPENADE 2.1 User's Guide*. Institut National de Recherche en Informatique et en Automatique (INRIA), Sophia-Antipolis, France.
- Hashemi, A. M., Franchini, M. & O'Connell, P. E. 2000 Climatic and basin factors affecting the flood frequency curve: Part I – A simple sensitivity analysis based on the continuous simulation approach. *Hydrology and Earth System Sciences* **4**, 463–482.
- He, Y., Bárdossy, A. & Zehe, E. 2011 A review of regionalization for continuous streamflow simulation. *Hydrology and Earth System Sciences* **15**, 3539–3553.
- Henderson, F. M. 1966 *Open Channel Flow*. Macmillan, New York.
- Holman, I. P., Hess, T. M. & Rose, S. C. 2011 A broad-scale assessment of the effect of improved soil management on catchment Baseflow Index. *Hydrological Processes* **25** (16), 2563–2572.
- Holmes, M. G. R., Young, A. R., Goodwin, T. H. & Grew, R. 2005 A catchment-based water resource decision-support tool for the United Kingdom. *Environmental Modelling and Software* **20** (2), 197–202.
- Hulse, D., Branscomb, A., Enright, C. & Bolte, J. 2008 Anticipating floodplain trajectories: a comparison of two alternative futures approaches. *Landscape Ecology* **24** (8), 1067–1090.
- Jackson, B., Pagella, T., Sinclair, F., Orellana, B., Henshaw, A., Reynolds, B., McIntyre, N., Wheater, H. & Eycott, A. 2012 Polyscape: a GIS mapping toolbox providing efficient and spatially explicit landscape-scale valuation of multiple ecosystem services. *Urban and Landscape Planning* **112**, 74–88.
- Jackson, B. M., Wheater, H. S., McIntyre, N. R., Chell, J., Francis, O. J., Frogbrook, Z., Marshall, M., Reynolds, B. & Solloway, I. 2008 The impact of upland land management on flooding: insights from a multiscale experimental and modelling programme. *Journal of Flood Risk Management* **1** (2), 71–80.
- Jakeman, A. J., Letcher, R. A. & Norton, J. P. 2006 Ten iterative steps in development and evaluation of environmental models. *Environmental Modelling and Software* **21**, 602–614.
- Kapangaziwiri, E., Hughes, D. A. & Wagener, T. 2009 Towards the development of a consistent uncertainty framework for hydrological predictions in South Africa. In: *New Approaches to Hydrological Predictions in Data-sparse Regions* (K. Yilmaz, I. Yucel, H. V. Gupta, C. Neale, J. Pomeroy, H. Savenije, T. Wagener & D. Yang, eds). IAHS Press, IAHS Publ., Wallingford, UK, 333, pp. 83–94.
- Kapangaziwiri, E., Hughes, D. & Wagener, T. 2012 Incorporating uncertainty in hydrological predictions for gauged and ungauged basins in southern Africa. *Hydrological Sciences Journal* **57** (5), 1000–1019.
- Kjeldsen, T. 2007 The revitalised FSR/FEH rainfall-runoff method – a user handbook. Flood Estimation Handbook Supplementary Report No. 1, Centre for Ecology and Hydrology, Wallingford, UK.
- Kjeldsen, T. R. 2009 Modelling the impact of urbanisation on flood runoff volumes. *Proceedings of the ICE – Water Management* **162** (5), 329–336.
- Klaus, J. & Zehe, E. 2011 A novel explicit approach to model bromide and pesticide transport in connected soil structures. *Hydrology and Earth System Sciences* **15**, 2127–2144.
- Kleidon, A., Zehe, E., Ehret, U. & Scherer, U. 2012 Thermodynamics, maximum power, and the dynamics of

- preferential river flow structures on continents. *Hydrology & Earth System Sciences* **9**, 7317–7378.
- Klemeš, V. 1986 Operational testing of hydrological simulation models. *Hydrological Sciences Journal* **31** (1), 13–24.
- Kuchment, L. S. & Gelfan, A. N. 1991 Dynamic- stochastic models of rainfall and snowmelt runoff. *Hydrological Sciences Journal* **36**, 153–169.
- Kuchment, L. S. & Gelfan, A. N. 2002 Estimation of extreme flood characteristics using physically based models of runoff generation and stochastic meteorological inputs. *Water International* **27**, 77–86.
- Lakshmi, V., Hong, S., Small, E. E. & Chen, F. 2011 The influence of the land surface on hydrometeorology and ecology: new advances from modeling and satellite remote sensing. *Hydrology Research* **42** (2–3), 95–112.
- Lørup, J. K., Refsgaard, J. C. & Mazvimavi, D. 1998 Assessing the effect of land use change on catchment runoff by combined use of statistical tests and hydrological modelling: case studies from Zimbabwe. *Journal of Hydrology* **205**, 147–163.
- Mantovan, P. & Todini, E. 2006 Hydrological forecasting uncertainty assessment: incoherence of the GLUE methodology. *Journal of Hydrology* **330** (1–2), 368–381.
- Martina, M. L. V. & Todini, E. 2008 Watershed hydrological modelling: toward physically meaningful processes representation. In: *Hydrological Modelling and the Water Cycle* (S. Sorooshian, K. Hsu, E. Coppola, B. Tomassetti, M. Verdecchia & G. Visconti, eds). Springer, Berlin, Heidelberg, pp. 229–241.
- Martina, M. L. V., Todini, E. & Liu, Z. 2011 Preserving the dominant physical processes in a lumped hydrological model. *Journal of Hydrology* **399** (1–2), 121–131.
- McIntyre, N. & Marshall, M. 2010 Identification of rural land management signals in runoff response. *Hydrological Processes* **24** (24), 3521–3534.
- McIntyre, N., Lee, H., Wheeler, H., Young, A. & Wagener, T. 2005 Ensemble predictions of runoff in ungauged catchments. *Water Resources Research* **41**, W12434.
- Merz, R. & Blöschl, G. 2009 A regional analysis of event runoff coefficients with respect to climate and catchment characteristics in Austria. *Water Resources Research* **45**, W01405.
- Merz, R., Parajka, J. & Blöschl, G. 2011 Time stability of catchment model parameters: implications for climate impact analyses. *Water Resources Research* **47**, W02531.
- Millennium Ecosystem Assessment 2005 *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington DC.
- Morris, J., Hess, T. M., Gowing, D. G., Leeds-Harrison, P. B., Bannister, N., Vivash, R. M. N. & Wade, M. 2005 A framework for integrating flood defence and biodiversity in Washlands in England. *International Journal River Basin Management* **3** (2), 1–11.
- Nelson, E., Mendoza, G., Regetz, J., Polasky, S., Tallis, H., Cameron, D. R., Chan, K. M. A., Daily, G. C., Coldstein, J., Kareiva, P. M., Lonsdorf, E., Naidoo, R., Ricketts, T. H. & Shaw, M. R. 2009 Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Frontiers in Ecology and the Environment* **7** (1), 4–11.
- O'Connell, P. E. & Todini, E. 1996 Modelling of rainfall, flow and mass transport in hydrological systems: an overview. *Journal of Hydrology* **175**, 3–16.
- O'Connell, P. E., Beven, K., Carney, J. N., Clements, R. O., Ewen, J., Fowler, H., Harris, G., Hollis, J., Morris, J., O'Donnell, G. M. O., Packman, J. C., Parkin, A., Quinn, P. F., Rose, S. C., Shepher, M. & Tellier, S. 2004 Review of Impacts of Rural Land Use and Management on Flood Generation, R&D Technical Report FD2114/TR, Defra, London, 152 pp.
- O'Connell, P. E., Ewen, J., O'Donnell, G. & Quinn, P. 2007 Is there a link between agricultural land-use management and flooding? *Hydrology & Earth System Sciences* **11**, 96–107.
- O'Donnell, G., Ewen, J. & O'Connell, P. E. 2011 Sensitivity maps for impacts of land management on an extreme flood in the Hodder catchment, UK. *Physics and Chemistry of the Earth, Parts A/B/C* **36**, 630–637.
- O'Loughlin, F., Bruen, M. & Wagener, T. 2013 Parameter sensitivity of a watershed-scale flood forecasting model as a function of modelling time-step. *Hydrology Research* **44** (2), 334–350.
- Oudin, L., Andreassian, V., Lerat, J. & Michel, C. 2008 Has land cover a significant impact on mean annual streamflow? An international assessment using 1508 catchments. *Journal of Hydrology* **357**, 303–316.
- Oudin, L., Kay, A., Andréassian, V. & Perrin, C. 2010 Are seemingly physically similar catchments truly hydrologically similar? *Water Resources Research* **46**, W11558.
- Park, J. S. & Cluckie, I. D. 2009 Modelling the impact of land use change in a strategic wetland with a fully distributed model. *Proceedings of 8th International Conference on Hydroinformatics*, Concepción, Chile, 12–16 January 2009, 2, pp. 1368–1377.
- Park, J. S., Ren, Q., Chen, Y., Cluckie, I. D., Butts, M. & Graham, D. 2009 Effectiveness of complex physics and DTM based distributed models for flood risk management of the River Tone. *UK IAHS Red Book* **331**, 114–121.
- Pattison, I. & Lane, S. N. 2012 The link between land-use management and fluvial flood risk: a chaotic conception? *Progress in Physical Geography* **36** (1), 72–92.
- Piégay, H. & Gurnell, A. M. 1997 Large woody debris and river geomorphological pattern: examples from S. E. France and S. England. *Geomorphology* **19**, 99–116.
- Quillet, A., Peng, C. & Garneau, M. 2010 Toward dynamic global vegetation models for simulating vegetation-climate interactions and feedbacks: recent developments, limitations, and future challenges. *Environmental Reviews* **18**, 333–353.
- Razavi, S., Tolson, B. A. & Burn, D. H. 2012 Review of surrogate modeling in water resources. *Water Resources Research* **48**, W07401.

- Rinaldo, A., Marani, A. & Rigon, R. 1991 **Geomorphological dispersion**. *Water Resources Research* **27**, 513–525.
- Rutledge, D. T., Cameron, M., Elliott, S., Fenton, T., Huser, B., McBride, G., McDonald, G., O'Connor, M., Phyn, D., Poot, J., Price, R., Scrimgeour, F., Small, B., Tait, A., Van Delden, H., Wedderburn, M. E. & Woods, R. A. 2008 **Choosing regional futures: challenges and choices in building integrated models to support long-term regional planning in New Zealand**. *Regional Science Policy & Practice* **1** (1), 85–108.
- Saco, P. M. & Kumar, P. 2002a **Kinematic dispersion in stream networks 1. Coupling hydraulic and network geometry**. *Water Resources Research* **38** (11), 261–2614.
- Saco, P. M. & Kumar, P. 2002b **Kinematic dispersion in stream networks, 2, Scale issues and self-similar network organization**. *Water Resources Research* **38** (11), 271–2715.
- Sawicz, K., Wagener, T., Sivapalan, M., Troch, P. A. & Carrillo, G. 2011 **Catchment classification: empirical analysis of hydrologic similarity based on catchment function in the eastern USA**. *Hydrology Earth System Science Discussion* **8**, 4495–4534.
- Schreider, S. Y., Jakeman, A. J., Letcher, R. A., Nathan, R. J., Neal, B. P. & Beavis, S. G. 2002 **Detecting changes in streamflow response to changes in non-climatic catchment conditions: farm dam development in the Murray-Darling basin, Australia**. *Journal of Hydrology* **262** (1–4), 84–98.
- Seibert, J., McDonnell, J. J. & Woodsmith, R. D. 2010 **Effects of wildfire on catchment runoff response: a modelling approach to detect changes in snow-dominated forested catchments**. *Hydrology Research* **41** (5), 378–390.
- Sieber, S., Müller, M., Verweij, P., Haraldsson, H., Fricke, K., Pacini, C., Tscherning, K., Helming, K. & Jansson, T. 2008 **Transfer into decision support: the sustainability impact assessment tool (SIAT)**. In: *Sustainability Impact Assessment of Land Use Changes* (K. Helming, M. Perez-Soba & P. Tabbush, eds). Springer-Verlag, Berlin, pp. 107–128.
- Singh, V. P. 1996 **Kinematic Wave Modeling in Water Resources: Surface-Water Hydrology**. Wiley, New York.
- Singh, R., Wagener, T., van Werkhoven, K., Mann, M. & Crane, R. 2011 **A trading-space-for-time approach to probabilistic continuous streamflow predictions in a changing climate**. *Hydrology Earth System Science Discussion* **8**, 6385–6417.
- Sivapalan, M. 2003 **Process complexity at hillslope scale, process simplicity at the watershed scale: is there a connection?** *Hydrological Processes* **17**, 1037–1041.
- Tallis, H. T., Ricketts, T., Guerry, A. D., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Lonsdorf, E., Kennedy, C., Verutes, G., Kim, C. K., Guannel, G., Papenfus, M., Toft, J., Marsik, M. & Bernhardt, J. 2011 **INVEST 2.0 Beta User's Guide**. The Natural Capital Project, Stanford.
- Thorne, C., Wallerstein, N., Soar, P., Brookes, A., Wishart, D., Biedenham, D., Gibson, S., Little, C., Mooney, D., Watson, C. C., Green, T. & Coulthard, T. 2011 **Accounting for Sediment in Flood Risk Management, Flood Risk Science and Management**. Wiley-Blackwell, Oxford.
- Todini, E. & Ciarapica, L. 2001 **The TOPKAPI model**. In: *Mathematical Models of Large Watershed Hydrology* (V. P. Singh & D. K. Frevert, eds). Water Resources Publications, Littleton, Colorado.
- USDA 1986 **Urban hydrology for small watersheds**. United States Department of Agriculture, TR 55, 1–164.
- van Delden, H., Stuczynski, T., Ciaian, P., Paracchini, M. L., Hurkens, J., Lopatka, A., Shi, Y., Gomez Prieto, O., Calvo, S., Van Vliet, J. & Vanhout, R. 2010 **Integrated assessment of agricultural policies with dynamic land use change modelling**. *Ecological Modelling* **221** (18), 2153–2166.
- van Delden, H., van Vliet, J., Rutledge, D. T. & Kirkby, M. J. 2011 **Comparison of scale and scaling issues in integrated land-use models for policy support**. *Agriculture, Ecosystems & Environment* **142** (1–2), 18–28.
- Wagener, T. & Montanari, A. 2011 **Convergence of approaches toward reducing uncertainty in predictions in ungauged basins**. *Water Resources Research* **47**, W06301.
- Wagener, T. & Wheeler, H. S. 2006 **Parameter estimation and regionalization for continuous rainfall-runoff models including uncertainty**. *Journal of Hydrology* **320** (1–2), 132–154.
- Wagener, T., McIntyre, N., Lees, M., Wheeler, H. S. & Gupta, H. 2003 **Towards reduced uncertainty in conceptual rainfall-runoff modeling: dynamic identifiability analysis**. *Hydrological Processes* **17** (2), 455–476.
- Wagener, T., Sivapalan, M., Troch, P. & Woods, R. 2007 **Catchment classification and hydrologic similarity**. *Geography Compass* **1** (4), 901–931.
- Wagener, T., Wheeler, H. & Gupta, H. V. 2004 **Rainfall-Runoff Modelling in Gauged and Ungauged Catchments**. Imperial College Press, London.
- Wheeler, H. & Evans, E. 2009 **Land use, water management and future flood risk**. *Land Use Policy* **26S**, S251–S264.
- Wheeler, H. S., Ballard, C., Bulygina, N., McIntyre, N. & Jackson, B. M. 2012 **Modelling environmental change: quantification of impacts of land use and land management change on UK flood risk**. In: *System Identification, Environmental Modelling, and Control System Design* (L. Wang & H. Garnier, eds). Springer-Verlag, London, pp. 449–481.
- Wheeler, H. S., Jakeman, A. J. & Beven, K. J. 1993 **Progress and directions in rainfall-runoff modelling**. In: *Modelling Change in Environmental Systems* (A. J. Jakeman, M. B. Beck & M. J. McAleer, eds). Wiley, Chichester, pp. 101–132.
- Wheeler, H. S., Reynolds, B., McIntyre, N., Marshall, M., Jackson, B., Frogbrook, Z., Solloway, I., Francis, O. J. & Chell, J. 2008 **Impacts of upland land management on flood risk: multi-scale modelling methodology and results from the Pontbren experiment**, FRMRC Research Report UR 16, Imperial College & CEH Bangor, 163 pp.

- White, A. B., Kumar, P., Saco, P. M., Rhoads, B. L. & Yen, B. C. 2004 Hydrodynamic and geomorphologic dispersion: scale effects in the Illinois River Basin. *Journal of Hydrology* **288**, 237–257.
- Yadav, M., Wagener, T. & Gupta, H. 2007 Regionalization of constraints on expected watershed response behavior for improved predictions in ungauged basins. *Advances in Water Resources* **30**, 1756–1774.
- Young, P. C. 2003 Top-down and data-based mechanistic modelling of rainfall-flow dynamics at the catchment scale. *Hydrological Processes* **17**, 2195–2217.
- Young, P. C. 2010 The data-based mechanistic approach to the emulation of large dynamic hydrological process models. In: *Role of Hydrology in Managing Consequences of a Changing Global Environment* (C. Kirby, ed.). Proceedings of British Hydrological Society Third International Symposium, Newcastle, 19–23 July 2010.
- Zehe, E. & Sivapalan, M. 2009 Threshold behaviour in hydrological systems as (human) geoeosystems: manifestations, controls, implications. *Hydrology and Earth System Sciences* **13** (7), 1273–1297.

First received 12 September 2012; accepted in revised form 7 February 2013. Available online 27 March 2013