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Issues in flood forecasting: ungauged basins, extreme floods and uncertainty

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Abstract Flood forecasts for any location, at times of extreme storms and with uncertainty estimates, embrace three issues that present important scientific challenges and the prospect of improved flood warning. Forecasting for ungauged basins using empirical regionalization of parameters of simplified models has met with mixed success and given little advance to our understanding of hydrological science. Prototype conceptual-physical area-wide model formulations, supported by terrain and soil property data, are trialled here and shown to have advantages for complex responding lowland catchments. Evidence is presented—using case study historical extreme storms and amplified forms of them—that demonstrates the potential value of distributed rainfall–runoff models for flood warning and for identifying flood-prone locations, especially for unusual or extreme storms and for locations that are ungauged. The challenges of model initialization, forecast updating and uncertainty estimation are discussed in relation to these area-wide models, future advances in ensemble rainfall forecasting and the benefits of risk-based decision-support for flood warning.

Key words extreme storm; flood; forecasting; rainfall–runoff model; uncertainty; ungauged basin; warning

Problèmes sur la prévision des crues: bassins non jaugés, crues extrêmes et incertitude

Résumé La prévision des crues pour n’importe quel site en contexte incertain pendant les périodes de précipitations intenses comprend trois aspects qui recouvrent d’importants défis scientifiques et la perspective d’une amélioration de l’annonce de crue. La prévision pour des bassins non jaugés utilisant une régionalisation empirique des paramètres de modèles simplifiés a obtenu des succès mitigés et fourni quelques progrès à notre compréhension de la science hydrologique. Des prototypes de modèles spatialisés à base physico-conceptuelle, s’appuyant sur des données des terrains et des sols, sont ici mis à l’épreuve et montrent leurs avantages pour les bassins de plaine à réponse complexe. Sur la base d’une d’étude de cas d’averses historiques extrêmes et de leur amplification, on peut démontrer le potentiel des modèles pluie-débit distribués pour l’annonce de crue et l’identification des emplacements sujets à inondation, particulièrement en ce qui concerne les averses inhabituelles ou extrêmes et les sites non jaugés. Les problèmes de l’initialisation du modèle, de la mise à jour des prévisions et de l’estimation des incertitudes sont discutés en relation avec la nature de ces modèles spatialisés, les avancées attendues de la prévision des précipitations et les bénéfices de l’aide à la décision fondée sur l’analyse de risque appliquée à l’annonce de crue.

Mots clefs averse extrême; crue; prévision; modèle pluie–débit; incertitude; bassins non jaugés; annonce de crue

INTRODUCTION

What are the key research challenges for improving flood forecasting and warning? Three challenges are selected here for discussion. First is the growing need to forecast at any location where there is a risk of flood damage. Simple extrapolation of forecasts and warnings from gauged sites may no longer suffice. New methods of grid-based area-wide forecasting—supported by digital data sets on terrain, land cover, soil and geology—show promise in providing an integrated approach to modelling for any location, whether gauged or ungauged. The spatial nature of storm rainfall and flood response may also be accommodated through appropriate choices of grid-scale and forms of sub-grid process parameterization.

A second challenge is forecasting an extreme flood, in particular one that is more extreme than those contained in the historical record and now judged more likely as a consequence of climate and/or land-use change. This raises issues related to the nature of extreme storms (of convective, orographic and frontal type), the dominant processes and properties shaping the flood response, and problems of model configuration and calibration.

A traditional focus of modelling for flood forecasting is to improve the accuracy and robustness of the central estimate of the flood hydrograph at future times. A third challenge is the quantification of uncertainty in this estimate and its use in risk-based decision-making related to invoking flood warnings. Issues raised by these three challenges will be reviewed and examples of progress given.

FLOOD FORECASTING AT ANY LOCATION

The challenge of flood forecasting at any location is the classical ungauged problem. It forms part of what is sometimes referred to as the model regionalization or spatial generalization problem. For a rainfall–runoff model, a classical approach is to seek model simplification to obtain a model with few parameters that can be empirically related to catchment properties, either via regression or site-similarity approaches. Methods of model simplification have been reviewed and developed by Wagener *et al.* (2004) whilst Vogel (2006) provides a recent overview of regional parameter estimation methods. Model simplification may involve reducing processes to a dominant set or seeking aggregated process representations. Alternatively, simple forms of transfer function may be sought through data analysis without necessarily seeking clear process representations. Hybrid approaches offer other possibilities.

Seeking relationships between model parameters and catchment properties stimulates activity in two main areas. The first is formulating novel and appropriate catchment properties usually involving aggregation to obtain catchment representative quantities. Second is activity involved in formulating the relation in regression or site-similarity form, and possibly extending this to seek estimates of prediction uncertainty. This second activity can transform a hydrologically-based problem into a statistical one, and become a dominant preoccupation feasting on the rich literature relating to forms of regression and parameter estimation. Model performance is diminished by the reduced form of model employed, the use of properties in catchment aggregated form and the often weak relations of the model parameters with these catchment properties.

Little if any advance in hydrological science and understanding is gained by the application of such methods, although they sometimes can prove of practical value in limited cases.

The crisis in regionalization of rainfall–runoff models by such approaches is highlighted by Vogel's overarching opinion that "*until hydrologists formulate the basic theoretical (physical) relationships between watershed model parameters and watershed characteristics, regionalization will continue to produce mixed results*". An arguable weakness of this statement is its preoccupation with parameters and characteristics defined at the catchment scale, but its broad intent is well directed. It seems most likely that scientific progress will be made by using measures of basic properties that underpin the processes represented in our models. One approach in this direction is the development of distributed model formulations using spatial data sets, at appropriate scales, on basic properties concerned with terrain, soil, land cover and geology. It may be that a catchment aggregated formulation can be derived from the underlying distributed model, if required, as attempted by Todini (1995).

A well recognized dilemma with pursuing the distributed model approach to "regionalization" is that lumped conceptual models can often provide as reliable, if not better, flood forecast performance, at least for gauged sites used in model calibration. This is borne out by the results of the recent DMIP (Distributed Model Intercomparison Project) in the USA (Smith *et al.*, 2004), the earlier "Comparison of rainfall–runoff models for flood forecasting" undertaken in the UK (Moore *et al.*, 2000) and the related assessment of new distributed flood forecasting models (Bell & Moore, 1998b). However, there is growing evidence that simple conceptual-physical distributed models, with process links to basic properties (rather than parameters) and prescribed via spatial data sets, can be of real value for flood forecasting. This appears especially true for the ungauged problem, for forecasting at any location across a domain of interest and for modelling the flood response of unusual and/or extreme storms.

The next section considers a suitable framework for developing and trialling distributed flood forecasting models. Possible prototype formulations are then developed in outline and preliminary results discussed.

MODELLING APPROACHES FOR DISTRIBUTED FLOOD FORECASTING

An important distinction can be made between distributed models that employ a *source-to-sink* catchment approach and ones that employ a *grid-to-grid* (cell-to-cell) area-wide approach (for example, see Olivera *et al.*, 2000). In the grid-to-grid approach, a runoff production scheme operates within each grid-square and generated runoffs are translated from grid to grid using a routing scheme. Figure 1 provides the essential elements of such an approach and serves as a framework for model development and trialling. It highlights model configuration support using digital data sets of terrain, soil, geology and land cover properties, and also the possible use of rainfall climatology information for rainfall pre-processing. Flow paths from grid to grid are delineated with reference to a digital terrain model (DTM). Errors in flow path and catchment boundary delineation can occur as the DTM is normally degraded to the model grid size. Manual and automated methods of delineation and correction are an active area of research (for example, see Fekete *et al.*, 2001; Soille, 2004).

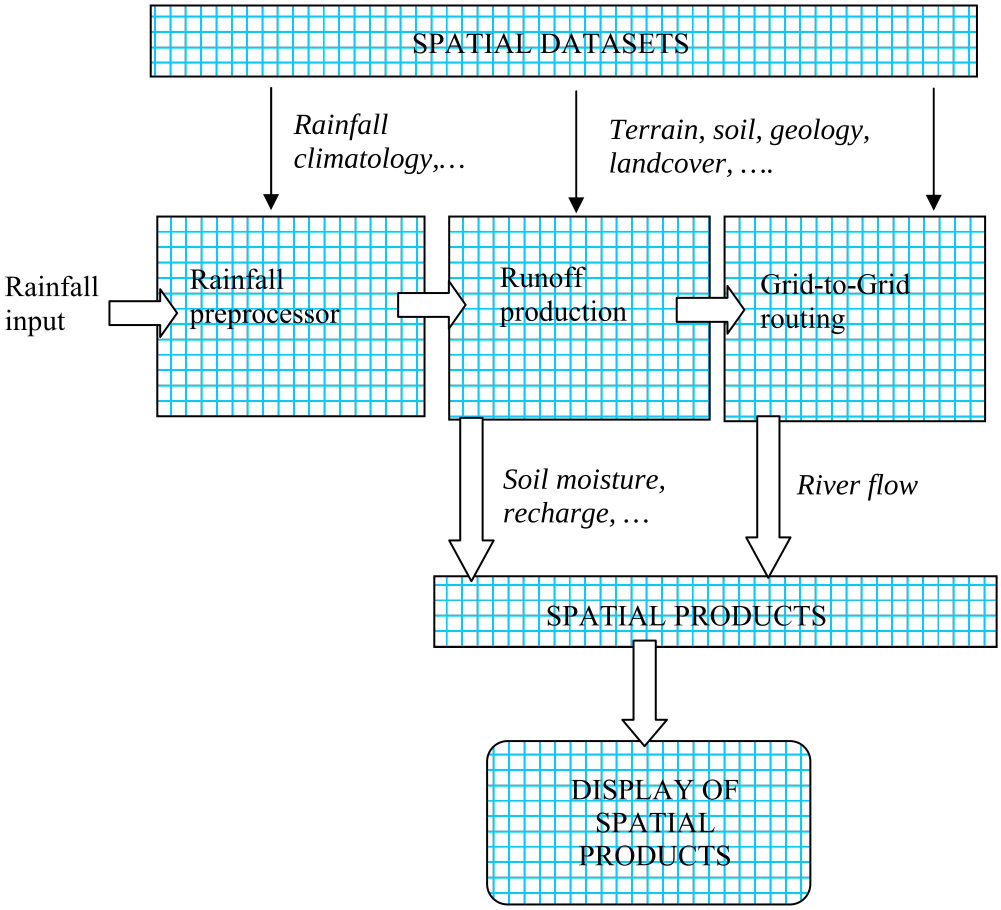


Fig. 1 Framework for a distributed grid-based flood forecasting model.

In the source-to-sink approach to distributed hydrological modelling, the focus is on calculating the river flow at a catchment outlet of interest whilst at the same time representing the distributed nature of runoff formation and translation through the catchment system. This means that efficient calculation schemes can be devised that route flows directly to the catchment outlet without troubling with estimation of flows at intermediate locations. This can be accomplished by using a model grid over the catchment to generate runoffs from each grid-square (the source grids), but using a routing scheme that takes these distributed runoffs and translates them directly to the catchment outlet (the sink). Flows are not routed from grid to grid explicitly. The form of routing can account for the source location of runoff, with runoff from more distance source grids experiencing greater translation. The CEH Grid Model (Bell & Moore, 1998a) provides one example of a source-to-sink model, and employs an isochrone delineation of the catchment which is used to spatially configure a cascade of kinematic routing reaches. Essentially 2-D routing from grid to grid is simplified to a 1-D representation that preserves the effects of distance to catchment outlet when translating source runoffs. Because the spatial resolution of the routing scheme can be finer than the model grid used by the runoff production scheme, within-grid routing effects can be implicitly accommodated. Also, the routing reaches defined via isochrone bands can be inferred from a DTM at its base resolution, and not that of the model grid.

It is clear that the source-to-sink approach is catchment focused. However, because the formulation is distributed in nature it can be configured and calibrated to a gauged catchment, and re-applied to a target set of ungauged catchments. This would most obviously be done for locations within the catchment used for calibration, or a little downstream, but could be applied more widely. Note that the approach is using the topography of the ungauged catchment in configuring the routing model. It is also using any land cover, soil, geology and topography information that features in the formulation of the runoff production function operating within each grid-square. It thus provides a potentially powerful mechanism of information transfer from gauged to ungauged locations. This is also the case for the grid-to-grid area-wide approach.

The grid-to-grid approach is a natural one for providing full national coverage grid estimates of runoffs, routed river flows and inundated areas in support of "first-alert" activities. However, for forecasts of an accuracy required for flood warning at vulnerable locations, the source-to-sink approach is also deserving of consideration. The efficiency of this approach and use of the DTM at its base resolution for flow path and catchment delineation are features that are particularly appealing. Equally, the resolution of the DTM-inferred information may argue for finer scale grid-to-grid modelling. A focus of interest in this paper is the challenge of forecasting at any location, and thus the grid-to-grid (cell-to-cell) area-wide approach is a natural choice. Prototype forms of grid-to-grid model, developed within the framework of Fig. 1, are considered next.

PROTOTYPE GRID-TO-GRID MODELS

Figure 1 highlights the need to consider the choice of two main modelling components: runoff production and grid-to-grid flow routing, and their support by spatial data sets of terrain, soil, geology and land cover properties. A simple formulation for the grid-to-grid flow routing component is considered first, assuming that the runoff production module has served to generate fast ("surface") and slow ("subsurface") runoffs within each grid-square.

Grid-to-Grid flow routing

A simple kinematic wave equation (Moore & Jones, 1978) is used as the basis of the Grid-to-Grid routing scheme. This equation relates channel flow, q, and lateral inflow per unit length of river, u, and is given by:

$$\frac{\partial q}{\partial t} + c\frac{\partial q}{\partial x} = cu \tag{1}$$

where c is the kinematic wave speed and x and t are distance along the reach and time respectively. This equation is applied separately to the two runoffs from the runoff production module so as to represent parallel fast (surface) and slow (subsurface) pathways of water movement. Water is explicitly transferred from one grid to another based on topographic control. Different wave speeds over land and river pathways are accommodated. A *return flow* term allows for flow transfers between the subsurface and surface pathways representing surface/sub-surface flow interactions on hillslopes and in river channels.

The Grid-to-Grid routing scheme equations (Bell & Moore, 2004; Bell *et al*., 2006) in one dimension are:

$$\begin{aligned} &\frac{\partial q_l}{\partial t} + c_l \frac{\partial q_l}{dx} = c_l (u_l + R_l) \\ &\frac{\partial q_{lb}}{\partial t} + c_{lb} \frac{\partial q_{lb}}{dx} = c_{lb} (u_{lb} - R_l) \\ &\frac{\partial q_r}{\partial t} + c_r \frac{\partial q_r}{dx} = c_r (u_r + R_r) \\ &\frac{\partial q_{rb}}{\partial t} + c_{rb} \frac{\partial q_{rb}}{dx} = c_{rb} (u_{rb} - R_r) \end{aligned} \tag{2}$$

where q_l is flow over land pathways, q_r is flow over river pathways, R_l and R_r denote land and river return flow, and u_l and u_r are inflows for land and river, which include runoff generated by a runoff-production scheme. The additional subscript *b* denotes sub-surface ("baseflow") pathways. The wave speed *c* can vary with the pathway and surface-type combination as indicated by the suffix notation.

The four partial differential equations are each discretized using the finite-difference representation:

$$q_k^n = (1-\theta) q_{k-1}^n + \theta \left(q_{k-1}^{n-1} + u_k^n + R_k^n \right) \tag{3}$$

where the dimensionless wave speed $\theta = c\,\Delta t / \Delta x$ and for stability $0 < \theta < 1$. Time, t, and space, x, have been divided into discrete intervals Δt and Δx such that k and n denote positions in discrete time and space. Equation (3) is a recursive formulation which expresses flow out of the nth reach at time k, q_k^n, as a linear weighted combination of the flow out of the reach at the previous time, the inflow to the reach from upstream (at the previous time) and the total lateral inflow (the sum of lateral inflow u_k^n and return flow R_k^n) along the reach (at the same time). For application to two dimensions, the q_{k-1}^{n-1} term, which represents inflow from the preceding grid-cell in space, is given by the sum of the inflows from adjacent grid-cells.

In practice, the routing is implemented in terms of an equivalent depth of water in store over the grid square, S_k^n, where $q_k^n = \kappa S_k^n$, and the inflow and return flow are also parameterized as water depths. The return flow to the surface is given by $R_k^n = r\, S_k^n$, where S_k^n is the depth of water in the subsurface store and r is the return flow fraction. This fraction takes a value between zero and one since it represents the proportion of the sub-surface store content that is routed to the surface, and can differ for land and river paths. For sub-surface routing, the return flow term is modified to subtract from water in store. Note that whilst return flow is normally positive, it can take negative values to represent influent, rather than the more normal effluent "stream" conditions. The flow-routing scheme allows for different values of the dimensionless wave speed, θ, for the different pathway (surface or subsurface) and surface-type (land or river) combinations.

Note that this simple prototype routing scheme is topographically controlled through the DTM-derived flow path network. A more complex form accommodates the effects of terrain slope and roughness on conveyance, allowing information on land cover and channel surveys to be used.

Runoff production

The choice of runoff production function is arguably less straightforward. A simple formulation is that used by the Grid Model (Bell & Moore, 1998a) in which each grid square is assumed to have a maximum water storage capacity, $S_{\max}$, controlled by the average topographic gradient, $\bar{g}$, within the grid square, such that:

$$S_{\max} = c_{\max}\left(1 - \frac{\bar{g}}{g_{\max}}\right) \tag{4}$$

for $\bar{g} \leq g_{\max}$. The parameters $g_{\max}$ and $c_{\max}$ are upper limits of gradient and storage capacity respectively and act as “regional parameters” for the runoff-production function. An estimate of mean slope for each grid square can be obtained from a DTM. In turn, this allows values for the structural parameter $S_{\max}$ for all grid squares to be determined using only the two regional parameters, $g_{\max}$ and $c_{\max}$. Introducing water-storage controlled evaporation and drainage functions allows mass balance calculations of saturation excess runoff, water storage and drainage to be undertaken.

A development of this lumped average representation considers that terrain slope is distributed as a power distribution within a grid square (Bell & Moore, 1998a). Using the capacity-slope relation of equation (4) at a point, derived distribution theory can be used to show that the store capacity, c, has a distribution function of Pareto form, $F(c) = 1 - (1 - c/c_{\max})^b$, with shape parameter $b = \bar{g}/(g_{\max} - \bar{g})$ and $c_{\max}$ = $\bar{c}(b+1)$ where $\bar{c}$ is the mean store capacity over the grid square. The Probability Distributed Model theory (Moore, 1985, 1999, 2006) then shows that the water storage in the grid square can be calculated as:

$$S = \frac{c_{\max}}{b+1}\left[1 - \left(1 - \frac{C^*(t)}{c_{\max}}\right)^{b+1}\right] \tag{5}$$

where $C^*(t)$ is the critical capacity below which all stores of smaller capacity are full and generating surface runoff. Mass balance principles then allow surface runoff, water storage and drainage to be calculated.

Note that both these simple runoff production formulations are entirely topographically controlled and do not explicitly consider the effect of soil/geology and land cover properties. A third, more complex, formulation aims to allow soil/geology property information to be directly used, in addition to terrain properties, as part of the process description. The conceptualization of water storage and transfer for a grid square cell, viewed as a sloping soil column, is depicted schematically in Fig. 2. Conceptually this is best considered as representing the aggregated behaviour of hillslope elements within the grid square. Specifically, the rate of change in soil water

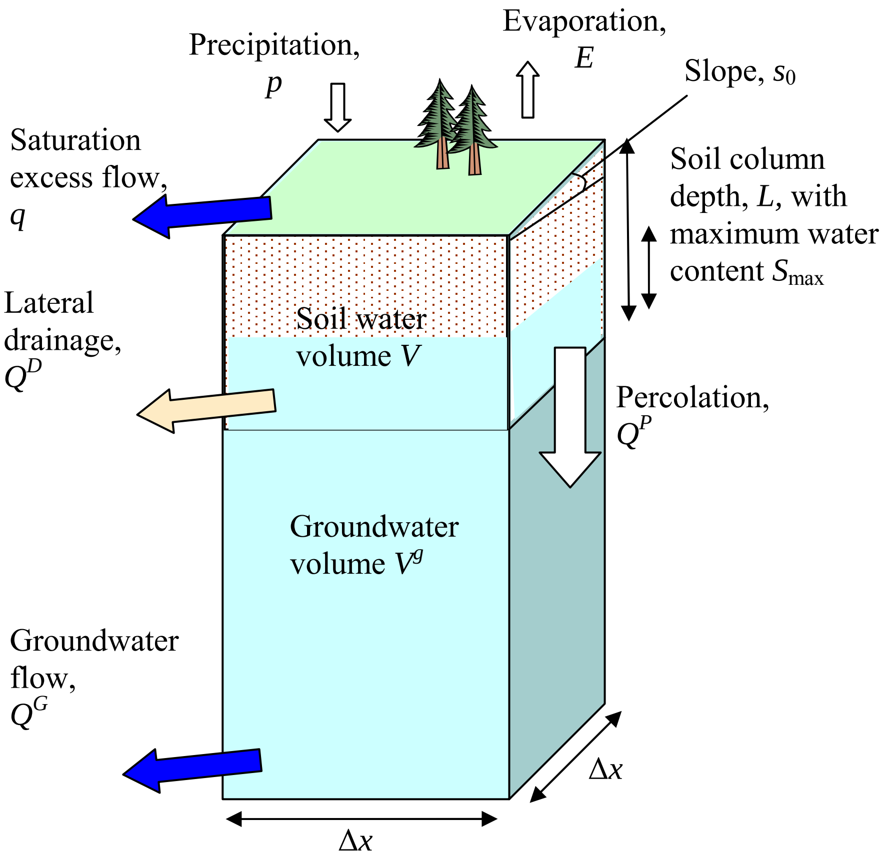


Fig. 2 Conceptual diagram showing runoff production and lateral drainage in a 1-D soil column.

volume, V, is given by:

$$\frac{\partial V}{\partial t} = p\Delta x^2 + Q^I - Q^D - Q^P \tag{6}$$

where p is the rainfall rate falling on a grid square of length Δx, and the Q terms relate to inflow from upstream cells, lateral drainage and downward percolation, respectively. The soil water volume V is related to the water depth S through $V = \Delta x^2 S$ whilst water depth is related to soil moisture content θ and soil depth L via $S = (\theta - \theta_r)L$, where θ_r is the residual content. The maximum water depth $S_{\max} = (\theta_s - \theta_r)L$ where θ_s is the water content at saturation.

Lateral drainage from the cell is given by (Todini, 1995; Liu *et al.*, 2005):

$$Q^D = C\ \Delta x S^{\ \alpha} \tag{7}$$

where the local conveyance $C = Lk_s s_0 / S_{\max}^{\alpha}$ with k_s the horizontal saturated hydraulic conductivity, s_0 the terrain slope and α a pore size distribution factor linked to the Brooks and Corey relation for hydraulic conductivity.

Downward percolation, Q^P, is given by:

$$Q^P = k_P \Delta x^2 \left(\frac{S}{S_{\max}} \right)^{\alpha_P} \tag{8}$$

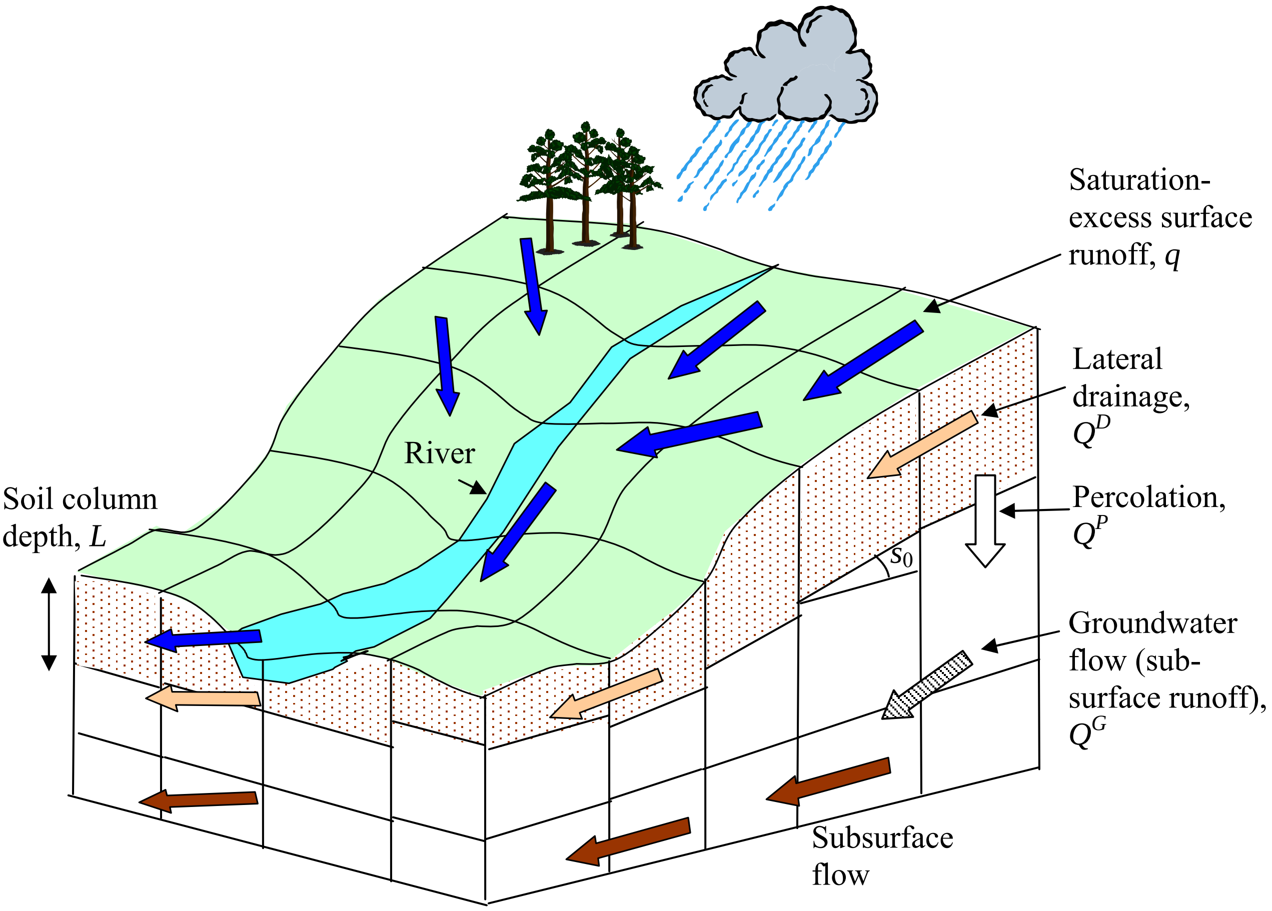


Fig. 3 Key features of a coupled runoff-production and routing scheme.

where k_P is the vertical saturated hydraulic conductivity of the soil (m s^{-1}) and α_P is the exponent of the percolation function.

A water mass balance for the soil column allows the saturation excess flow volume, q, to be calculated and used as input to the Grid-to-Grid routing (surface runoff) component. The water in store is updated, taking into account evaporation losses.

The downward percolation drains as recharge to groundwater and a Darcy-based representation of lateral groundwater flow, Q^G, is used to transfer water out of the cell for input to the Grid-to-Grid routing (subsurface runoff) component. The prototype application is not currently supported by geology property data (bedrock slope and horizontal hydraulic conductivity of the aquifer). Instead, a nonlinear storage representation is used to relate Q^G to the groundwater storage volume, V^G, parameterized by a rate constant and exponent.

Figure 3 shows how the sloping soil column (typical hillslope) representation of runoff production within each grid square is coupled with the Grid-to-Grid flow routing scheme across the modelling domain to provide the basis of area-wide flood forecasting at any location.

Prototype applications

The different forms of the prototype Grid-to-Grid model have been trialled, on simply responding upland catchments and more complex lowland catchments in the UK, with regard to their performance to forecast at ungauged locations (Moore *et al.*, 2006a). Whilst a simple topographic-controlled runoff production formulation has provided good performance for upland catchments, obtaining consistent performance across heterogeneous catchments in lowland Britain has proved impossible unless calibrated to specific catchments of interest.

Introducing soil and geology controls on runoff production through the more complex runoff production formulation described above has highlighted the challenge of using available soil and geology data sets. In the UK, the most readily available source of soil/geology information is via the HOST (Hydrology of Soil Types) classes, which differentiate 29 classes at a 1-km grid resolution on the basis of soil type, hydrological response and substrate hydrogeology (Boorman *et al.*, 1995). A major motivation for developing these classes was their use in rainfall–runoff model regionalization studies—typically using simple unit hydrograph and loss function approaches that lacked a process model base—to derive catchment properties that could be related to model parameters via regression relations. The basic soil property information (such as depth, porosity and hydraulic conductivity) is hidden within this classification as they had little direct relevance to the model parameters requiring regionalization.

In applying the prototype soil-topography controlled runoff production function, preliminary work has been done on combining HOST and SEISMIC (a soil property database) to associate each HOST class with five basic soil properties: the soil water content at 5 and 1500 kPa (related to field capacity and residual water contents), the porosity, the saturated hydraulic conductivity and a measure of soil depth. The lowland application employed catchments in the Upper Thames and paid special attention to two sub-catchments, the Sor at Bodicote and the Cherwell at Banbury where a topographic-controlled runoff production function had failed to provide the basis of a single consistent area-wide model. The two catchments are dominated by radically different HOST classes, 2 and 25, respectively, and the soil property associations indicate that soil depth is the most prominent difference, being twice as deep in the Sor. Figure 4 shows the soil depth inferred from HOST/SEISMIC and highlights the difference for these two sub-catchments. The larger available water storage per unit area (S_{max}) for the Sor catchment leads to a slower response to rainfall, despite its area being half that of the Cherwell (about 88 km^2 compared to 200 km^2). Figure 5 shows how the prototype Grid-to-Grid model can incorporate soil and terrain property spatial data, using a single small set of regional model parameters, to obtain reasonable model performance across a range of catchments. Note that the largest catchment considered, the Thames to Sutton Courtenay, has an area of 3414 km^2. Further work aims to introduce geological property data sets into the application and to improve upon the current use of soil data sets.

The trial application to the Upper Thames catchments has, at this preliminary stage, served to demonstrate how easily and widely the prototype Grid-to-Grid model can be applied to address the ungauged forecasting problem at any location within a chosen

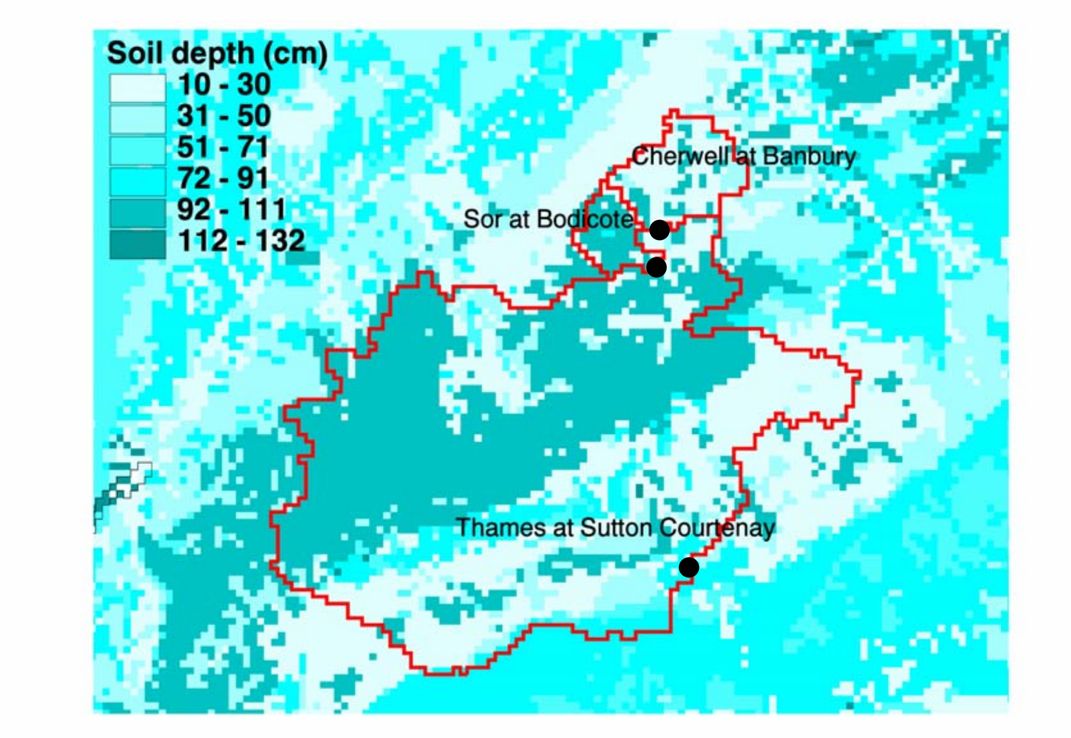


Fig. 4 Maps of soil depth (cm) over the Upper Thames catchments derived from HOST/SEISMIC.

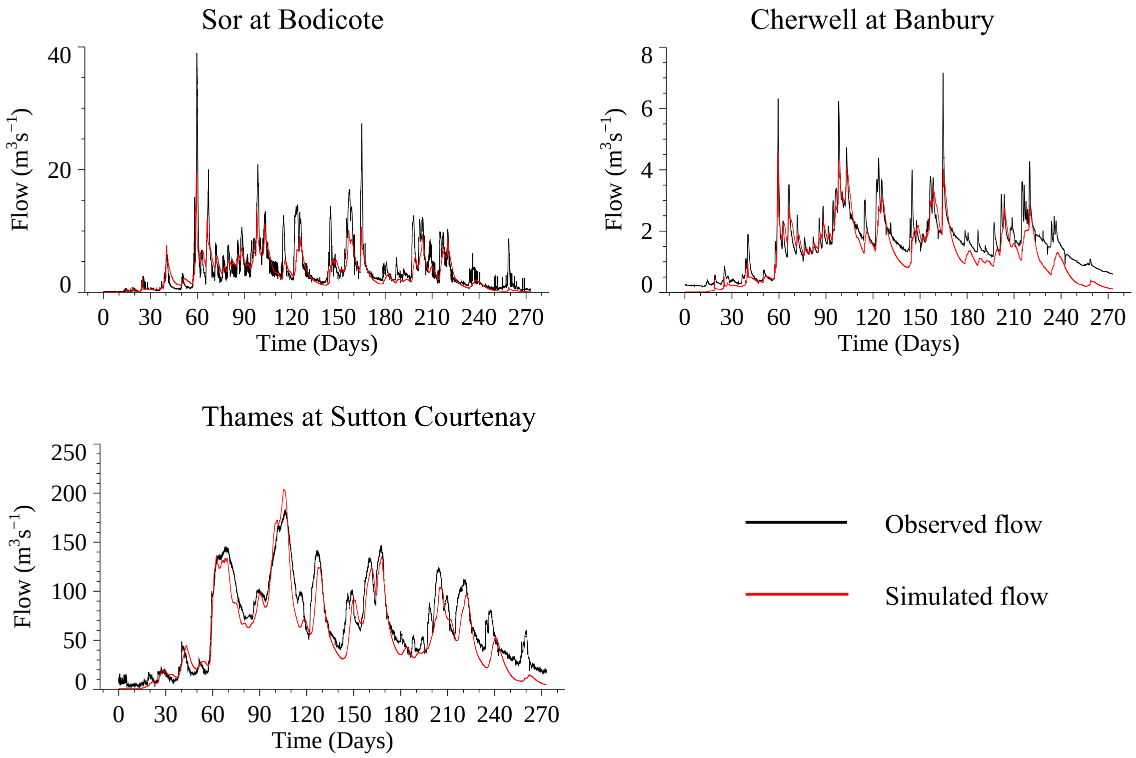


Fig. 5 Model performance obtained from a prototype Grid-to-Grid model: flow hydrographs for the Upper Thames catchments, 1 September 2000 to 1 June 2001.

model domain. Process simplification and scaling issues, relating to both the property data and model resolution, clearly will complicate the successful application of such models. Whilst regional scaling and offset transformations of the property data may be required in some cases, the information on spatial patterns of variability in these data sets provides a valuable support to distributed model configuration. The resulting model requires only a small number of regional parameters for application across large areas. It also provides a scientific framework within which the hydrological response to storm rainfall can be understood, in a spatial-temporal context, in relation to the shaping of the flood hydrograph by terrain, soil and other properties of the landscape.

FORECASTING EXTREME FLOODS

What makes an extreme storm an extreme flood? The shaping mechanisms of an extreme flood from storms of differing kind and catchments of varying form are important to understand, both from a scientific and practical viewpoint. Such an understanding will help identify locations vulnerable to flooding to be identified, even prior to them experiencing an extreme flood for the first time, and allow contingency measures to be planned and put in place. Extreme storms of convective, orographic and frontal origin have different properties that will influence the type of locations that are vulnerable to flooding. Flood genesis is influenced by the complex interplay of storm properties, catchment form and antecedent conditions. Modelling this interplay is a key challenge to successful forecasting of unusual or extreme floods and in the early recognition of flood-prone locations.

An investigative framework for extreme flood recognition, encompassing the evaluation and improvement of rainfall–runoff model performance under extreme storm conditions, has recently been set down and developed (Moore *et al.*, 2006b). This framework first selects historical storms of different meteorological origin and identifies case study catchments that they affect. The storms are first characterized in terms of return period for their critical rainfall depth and duration and other storm properties. The flood response over a catchment is assessed for flood peak return period and modelled using lumped and distributed approaches. Comparison with observed hydrographs can expose shortcomings in model formulation and serve as a catalyst for model improvement and greater understanding of extreme flood genesis. Areal rainfall estimates for catchment and grid-square areas, used as model input, are obtained from weather radar and by multiquadric interpolation methods applied to raingauge data alone or in combination with weather radar data. Shortcomings of stage–discharge ratings affecting implied model performance are taken into account in the evaluation.

A rainfall transformation tool is applied to the historical storms to change their speed and direction of travel, their magnitude and their shape to create artificial storms of greater return period. The modelled flood response is then investigated for catchments co-located with the storm and, by invoking storm transposition, to other catchments of different form. Exposing hydrological models to storm conditions greater than those contained in the historical record can reveal previously unseen weaknesses in the model formulations. The rainfall transformation tool can also be used to explore the genesis of a flood in relation to the causal rainfall and antecedent conditions. When a distributed model is used, it can identify locations within a catchment that may be particularly vulnerable to flooding, providing support to extreme flood recognition in advance of one occurring. The selection of case studies that follow illustrate some of the insights that can be gained on rainfall–runoff model performance and flood recognition for extreme storms.

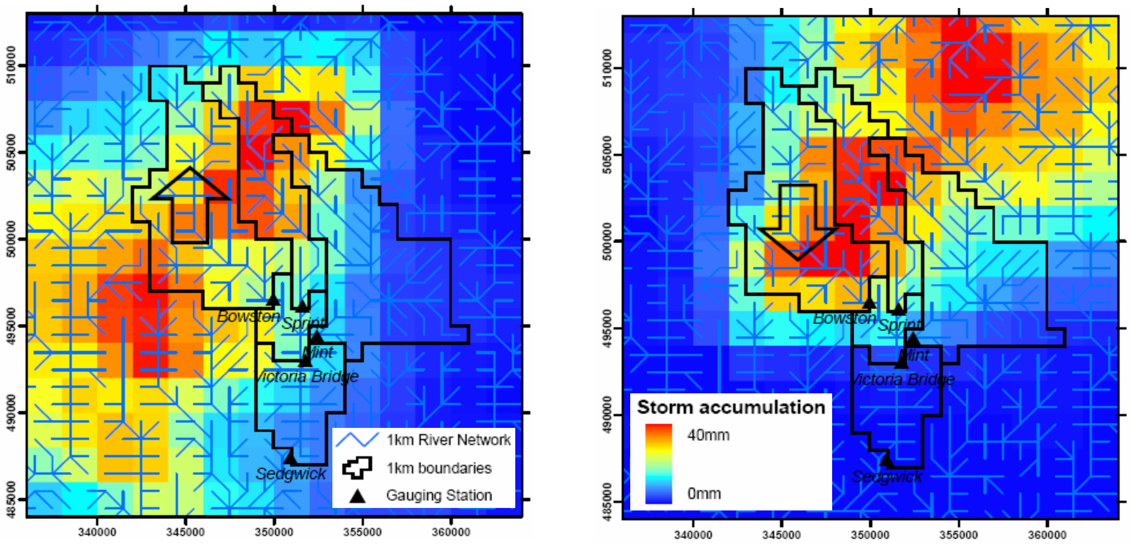
Case studies

An interesting case study concerns a fast-moving extreme convective storm that failed to produce an extreme flash flood over the catchments it traversed. At Carlton-in-Cleveland in northeast England a fall of 49.1 mm in 15 minutes was recorded and assessed to have a return period of *c*.600 years. The storm has been transposed to the Kent catchment to Sedgwick (in the English Lake District), reduced in speed and re-orientated to align with the river network. Both lumped and distributed models have been used to obtain simulated flood responses. The top half of Fig. 6 shows the different spatial rainfall totals on a 2-km grid produced by assuming a northerly and southerly track for the storm. Also shown are the 1-km resolution river network and catchment boundaries used by the distributed model. These have been derived from a 50-m DTM using the method of Fekete and further refined by hand correction. The two artificial storms result in rainfall fields that have a similar catchment average rainfall and a return period of 15 years.

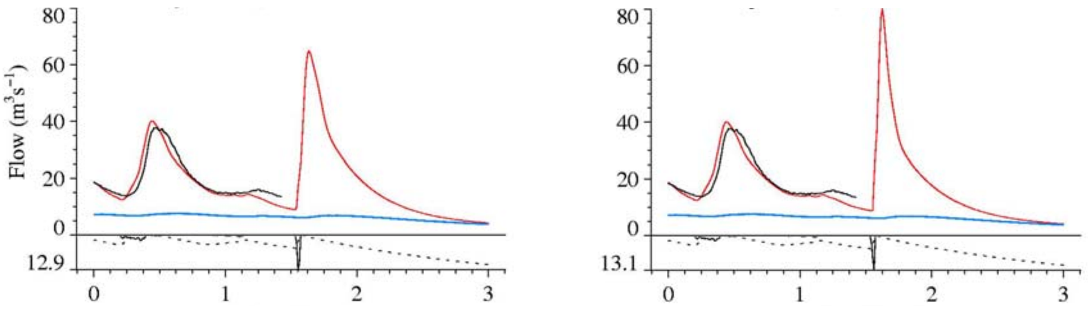
Modelled flood hydrographs produced by the two artificial storms using distributed and lumped rainfall–runoff models are shown in the lower part of Fig. 6. Note that the artificial storm rainfalls have been appended to a period of historical record for the Kent catchment to provide a starting condition for the rainfall–runoff model (the historical flow hydrograph is shown in black). The higher and sharper flood hydrographs produced by the distributed model (the topographic-controlled Grid-to-Grid model outlined earlier), especially for the southerly tracking storm moving down valley, seem to be the more plausible. There is little change in the lumped model response, reflecting the similar catchment average rainfalls, and this is consistent with the spatially uniform assumptions that underpin the model structure. The more extreme flood response obtained from the distributed rainfall–runoff model, relative to the lumped one, serves to highlight the potential value of distributed models when subjected to storms that are extreme or have unusual characteristics.

Animated images of flood forecasts with area-wide coverage, obtained from the distributed model, provide insight into the space–time shaping of the flood by the catchment form. This has particular relevance to flood warning for ungauged locations and also in identifying locations vulnerable to flooding under different meteorological conditions. For an orographic storm that affected the Kent catchment on 3 February 2004, Fig. 7 shows a spatial mapping of the modelled flood flows down the river network at two times separated by 2½ hours. The four-day catchment total for this storm was assessed to have a return period of 39 years. The river reach flow profiles in the lower half of Fig. 7 show that, at 10:00 hours, the flood had just peaked at Victoria Bridge (Point A) in the town of Kendal. Downstream at Sedgwick (Point B), the flood peaked 2½ hours later at 12:30 hours.

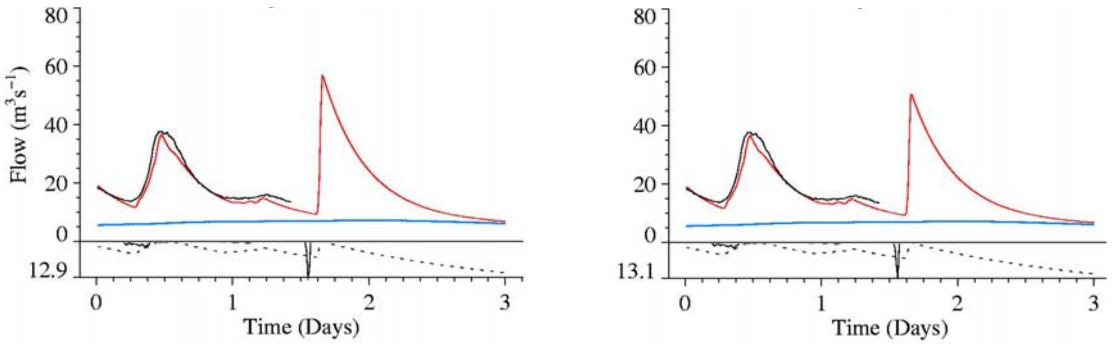
(a) Northerly storm track (b) Southerly storm track



Distributed Model



Lumped model



Above axis: ——— Observed flow ——— Simulated flow ——— Simulated baseflow

Below axis: ——— Rainfall ······· Simulated soil moisture

Fig. 6 Sensitivity to changing storm track direction of lumped and distributed rainfall–runoff models. Tranposition of the Carlton-in-Cleveland convective storm over the Kent catchment. The value below the axis indicates the maximum catchment rainfall in mm over a 15-minute interval.

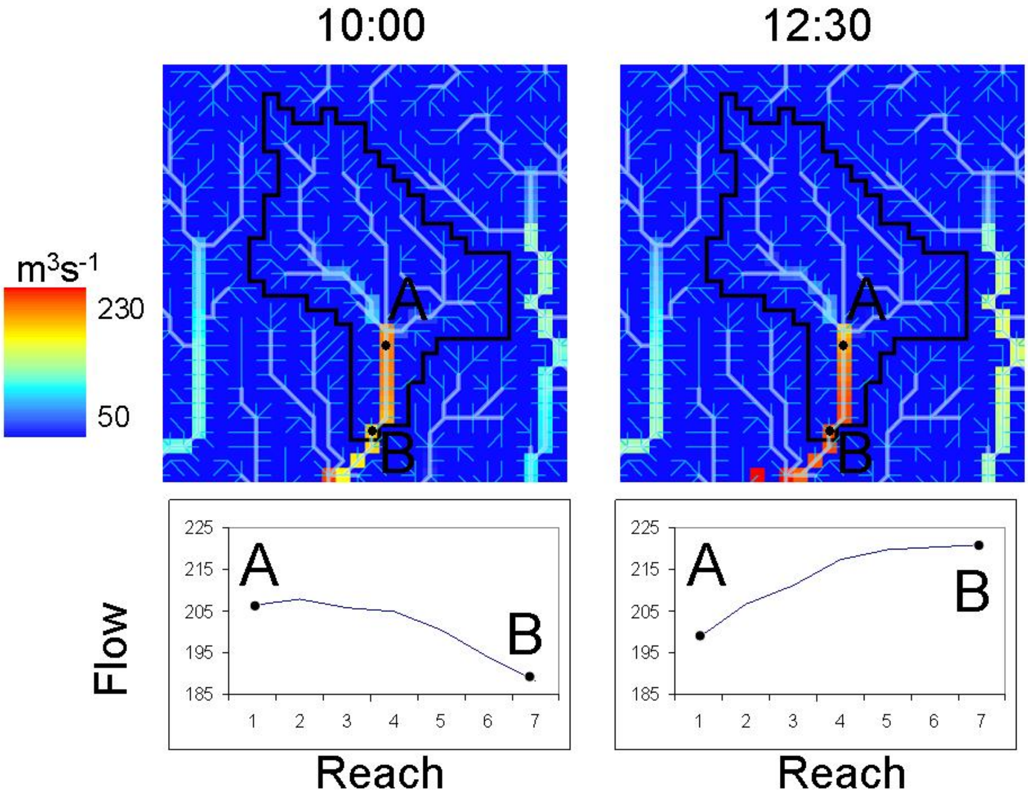
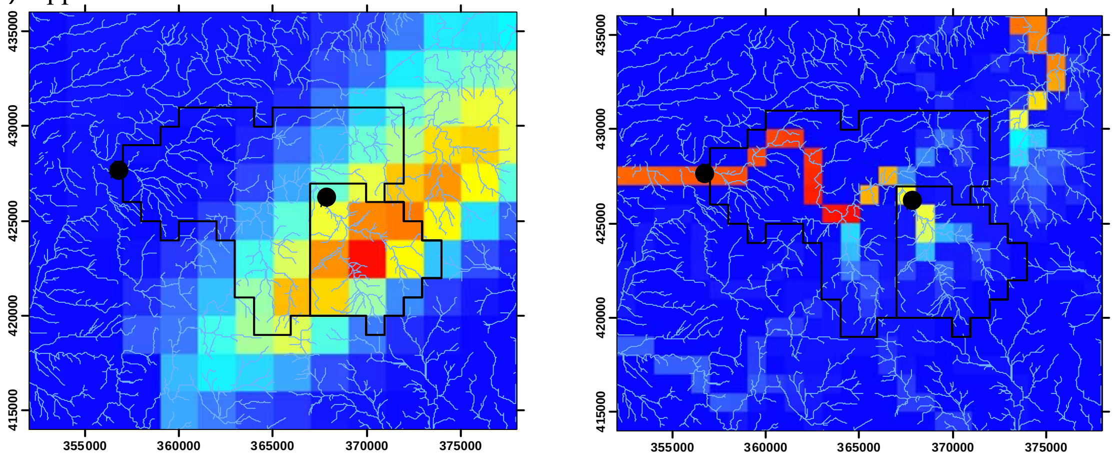


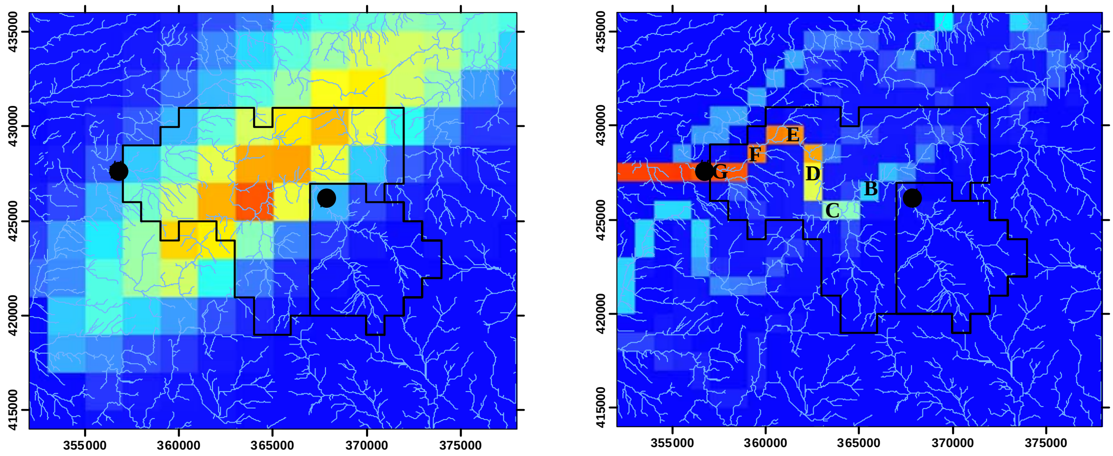
Fig. 7 River flow along a river network modelled using the Grid-to-Grid model. River Kent at Victoria Bridge (A) and Sedgwick (B). Flood response to orographic storm at 10:00 and 12:30 3 February 2004.

The effect of storm position in relation to flood severity at different locations within a catchment can be very important for convective storms. The left side of Fig. 8 shows the Boscastle storm transposed to the Darwen catchment near Blackburn in northwest England. The real storm caused devastating flash flood damage to the small village of Boscastle in North Cornwall (southwest England) on 16 August 2004 and received international press coverage. At Lesnewth, a raingauge estimate of 181 mm in 4 hours was assessed to have a return period of *c*.4500 years. Transposition to the Darwen catchment is done so that the centre of the storm total field is located first over the upper catchment (to the southeast), second over the lower catchment closer to the outlet at Blue Bridge (to the northwest), and third with a stretched transformation giving a more catchment-wide rainfall coverage. The storms were also upscaled to have 4-hour, 100-year return periods for the catchment (61.8 mm). The right column of Fig. 8 shows the modelled flood peak value in each square (at different times) for the three artificial storms. For the storm positioned in the upper catchment the flood peak is greatest towards the centre of the catchment, diminishing towards the catchment outlet at Blue Bridge (return period *c*.1000 years), despite the larger contributing area. The storm located in the lower catchment shows an increase in the flood peak from the centre of the catchment downstream. The catchment-wide storm also shows a general increase in the flood peak as one travels downstream from the centre of the catchment in line with an increasing contributing area. However, the return period at Blue Bridge is reduced to *c*.500 years.

(a) Upper catchment storm



(b) Lower catchment storm



(c) Catchment-wide storm

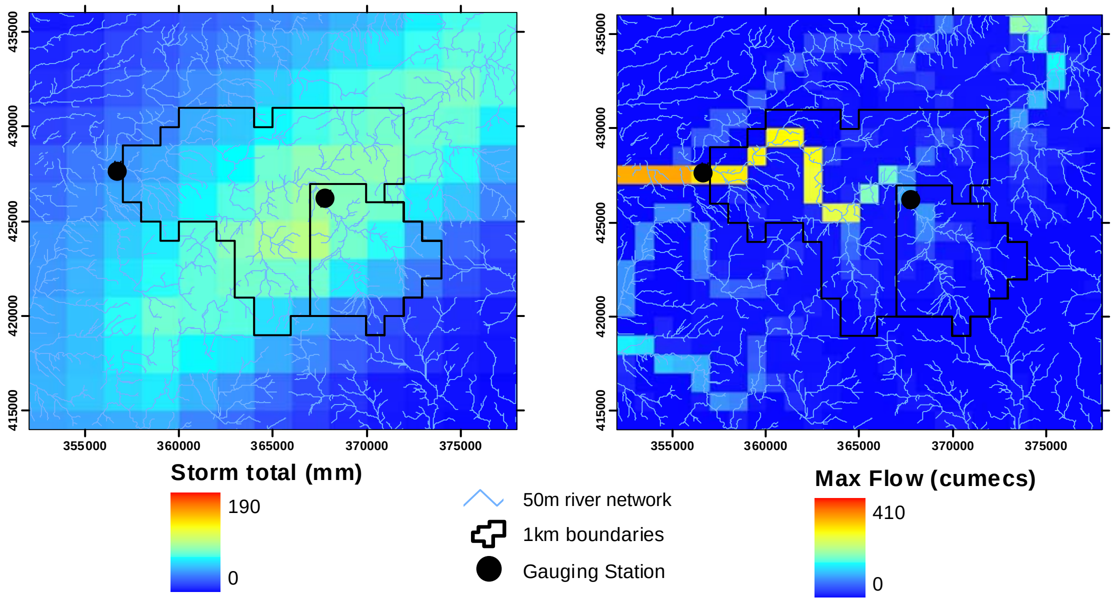


Fig. 8 Modified storm totals (left hand column) and maximum simulated river flow from the Grid-to-Grid model (right hand column) over the River Darwen catchment. The storm modified is the Boscastle convective event.

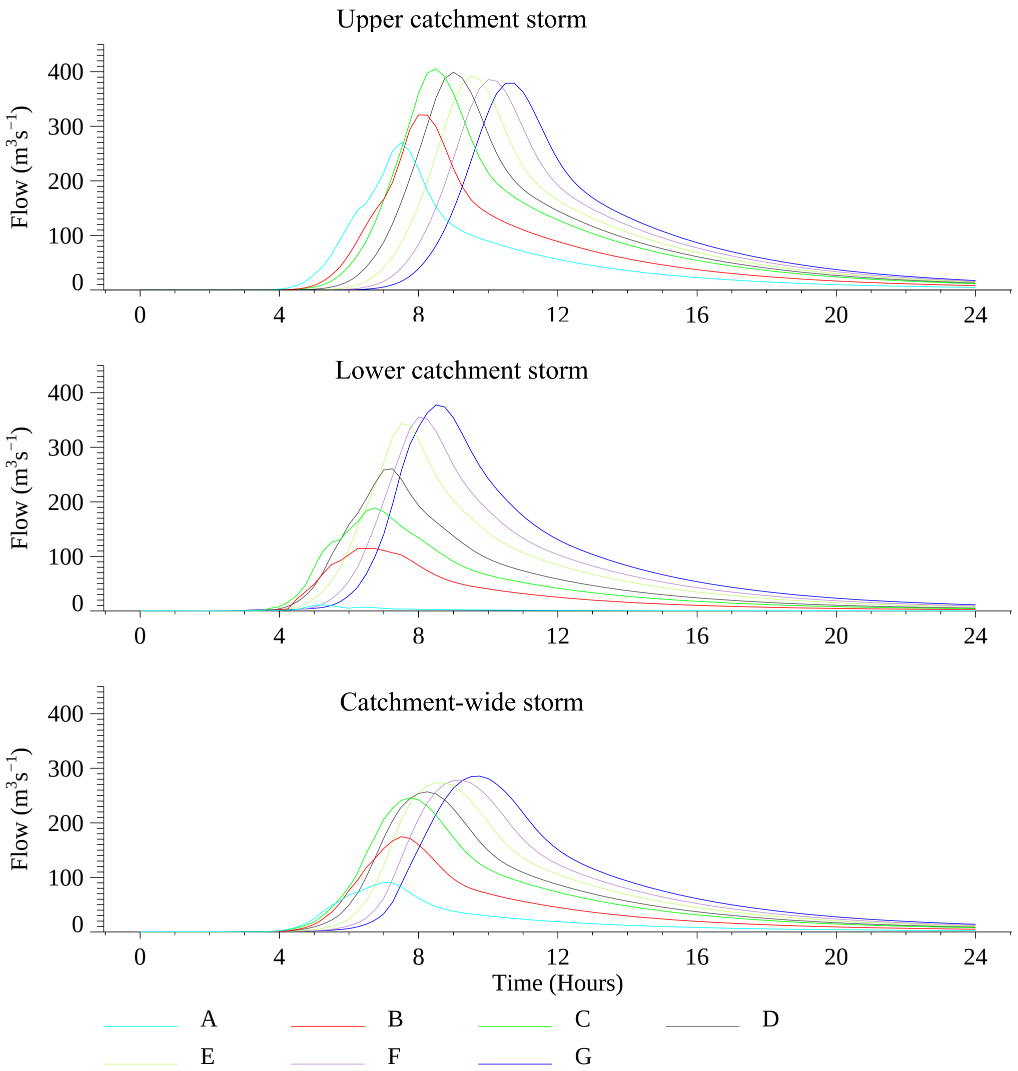


Fig. 9 Grid-to-Grid model simulations at a sequence of grid squares between the modelling point for the River Darwen at Ewood (Point A) and that for the River Darwen at Blue Bridge (Point G). The points are marked in Fig. 8. The storm modified is the Boscastle convective event.

This pattern is reinforced in Fig. 9 by the flood hydrographs at seven chosen locations within the catchment, but also reveals the change in timing of the flood peak with location. Location C is exposed as particularly vulnerable to flooding for a convective storm positioned in the headwaters of the Darwen, the flood dissipating downstream despite an increasing catchment area. This is not the case for the storm positioned closer to the outlet, where the flood peak increases downstream with increasing catchment area; position G (the gauged outlet at Blue Bridge) has the largest peak. This is also the case for the catchment-wide storm. Location C is particularly vulnerable to a headwater convective storm as it has a shorter time-to-peak than the flood peaks experienced at the catchment outlet. Timely flood warning may prove especially difficult.

Note that the flood hydrographs obtained from the lumped model at Blue Bridge (not shown) are similar for all three storms and have a return period of *c*.500 years. The flood response of such lumped models, when applied over responsive catchments and for short duration events, is dominated by the storm total and not the spatio-temporal storm pattern. It is this changing pattern for each storm that is creating the differences in the flood response from the distributed model, and only for the more uniform catchment-wide storm is it similar to the lumped model response. This has obvious repercussions when interfacing hydrological models to ensemble rainfall forecasts, particularly if convective storms are predicted.

The value of the investigative framework for extreme flood recognition and for model performance evaluation is borne out by the above examples. It also served as a catalyst for model improvement of the topographic-controlled Grid-to-Grid model for use in more complex lowland catchments. The failure to obtain consistent area-wide forecasts for the Upper Thames catchments, using storms of predominantly frontal origin, has been improved upon by using the topographic-soil model prototype, outlined previously in the context of forecasting at any location.

CLOSING DISCUSSION: FORECAST UNCERTAINTY

The challenges presented by ungauged and extreme flood forecasting combine to argue for a renewed effort on developing practical distributed flood forecasting models supported by spatial data sets on terrain, soil, geology and land cover. Case studies modelling the flood response of extreme storms, and amplified forms of them, have highlighted the value of distributed models in unusual and extreme situations. The growing need to forecast at any location, gauged or ungauged, has also demonstrated the potential value of area-wide distributed models in this respect. Lumped models will continue to prove appropriate, especially at gauged locations and in situations where the storm conditions and flood response can be said to be "normal". In such situations, the effect of model simplification on forecast performance is helped by site-specific model calibration coupled with real-time updating. The ease of doing this for lumped models is also an advantage.

The use of distributed models for real-time flood forecasting requires attention to model initialization, data assimilation and uncertainty estimation. Whilst the initialization and updating of lumped rainfall–runoff models is well developed and there are many operational examples (Moore *et al.*, 2005), this is not the case for distributed models. Process-based model initialization may be helped by the improved use of spatial property data supporting model configuration. There is an urgent need to explore different forecast updating methods—including state-correction, error-prediction and hybrid forms of these—in relation to new area-wide distributed models. Advances in spatial data assimilation, such as those being made for meteorological application, deserve detailed consideration in this context.

The issue of providing uncertainty estimates on flood forecasts remains a challenge for models of both distributed and lumped forms. At least for higher lead times and smaller catchments, a dominant source of uncertainty is in the rainfall forecasts used in obtaining extended lead-time forecasts. Ensemble rainfall forecasts are beginning to become available to support research on probabilistic flood forecasting (Pierce *et al*., 2005). The ensembles are normally developed as stochastic extensions of radar extrapolation methods, possibly in combination with numerical weather prediction (NWP) forecasts with increasing lead time. Advances in computing and NWP modelling are promising to offer forecasts at finer resolution down to 1.5 km, more frequent forecast updates with data assimilation from new weather radar variables, and forecasts in ensemble form. This is being driven by the importance of convective storm prediction for flash flood forecasting, and the uncertain nature of the initiation and development of such storms.

Major challenges that lie ahead are to explore the value of such advances in weather prediction for flood forecasting at any location and during extreme storms. Providing estimates of forecast reliability, encompassing meteorological and hydrological uncertainty, and using these with cost functions and decision theory to decide on "if, when and where" to issue flood warnings will require much research, interdisciplinary co-operation and stakeholder involvement.

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