using science to create a better place

Rainfall-runoff and other modelling for ungauged/low-benefit locations: Operational Guidelines

Science Report – SC030227/SR2

SCHO0307BMEU-E-P

ea/br/e/sci/v1

The Environment Agency is the leading public body protecting and improving the environment in England and Wales.

It's our job to make sure that air, land and water are looked after by everyone in today's society, so that tomorrow's generations inherit a cleaner, healthier world.

Our work includes tackling flooding and pollution incidents, reducing industry's impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

This report is the result of research commissioned and funded by the Environment Agency's Science Programme.

Published by:
Environment Agency, Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol, BS32 4UD
Tel: 01454 624400 Fax: 01454 624409
www.environment-agency.gov.uk

ISBN: 978-1-84432-694-5

Further copies of this report are available from:
The Environment Agency's National Customer Contact Centre by emailing:
enquiries@environment-agency.gov.uk
or by telephoning 08708 506506.

Author(s):
R. J. Moore, V. A. Bell, S. J. Cole and D. A. Jones

Dissemination Status:
Publicly available

Keywords:
flood, forecasting, hydrological model, ungauged, warning

Research Contractor:
CEH Wallingford
Maclean Building
Crowmarsh Gifford
Wallingford, Oxon
OX10 8BB
Tel: 01491 838800 Fax: 01491 692424
Project manager: Bob Moore Email: rm@ceh.ac.uk

Environment Agency's Project Manager:
Bob Hatton

Science Project Number:
SC030227

Product Code:
SCHO0307BMEU-E-P

Science at the Environment Agency

Science underpins the work of the Environment Agency. It provides an up-to-date understanding of the world about us and helps us to develop monitoring tools and techniques to manage our environment as efficiently and effectively as possible.

The work of the Environment Agency's Science Group is a key ingredient in the partnership between research, policy and operations that enables the Environment Agency to protect and restore our environment.

The science programme focuses on five main areas of activity:

- **Setting the agenda**, by identifying where strategic science can inform our evidence-based policies, advisory and regulatory roles;
- **Funding science**, by supporting programmes, projects and people in response to long-term strategic needs, medium-term policy priorities and shorter-term operational requirements;
- **Managing science**, by ensuring that our programmes and projects are fit for purpose and executed according to international scientific standards;
- **Carrying out science**, by undertaking research – either by contracting it out to research organisations and consultancies or by doing it ourselves;
- **Delivering information, advice, tools and techniques**, by making appropriate products available to our policy and operations staff.

Steve Killeen

Head of Science

Executive Summary

Across England and Wales, the Environment Agency provides only a general Flood Watch service at locations that are ungauged and associated with low benefit from flood warning. Providing an improved, more targeted flood warning service is possible. But strategic guidance is needed on the technical possibilities available: both now as “best practice” and, through the identification of research opportunities, in the future.

Against this background, this document provides an overview of approaches for modelling at ungauged locations to guide operational practice both now and in the future. It also serves as a “roadmap” to the accompanying Science Report where more detail can be found. The emphasis is on the types of modelling problem commonly encountered and the general approaches that can be considered when addressing them. Whilst rainfall-runoff models are the main focus of attention, broader discussion encompasses hydrological channel flow routing models and hydrodynamic river models; simpler empirical models including level-to-level correlation methods are also considered.

Even for specific rainfall-runoff model types, it is unusual for a methodology to be sufficiently well established for its application to be routine for ungauged forecasting purposes. The overview first focuses on the nature of the ungauged problem and the modelling approaches available when considered at a generic level. Subsequent discussions of specific model types serve to illustrate how some of these approaches have been applied and their shortcomings. Possible opportunities for improvement are identified.

An important aspect of ungauged modelling is the ability to utilise digital spatial datasets on properties of the terrain, land cover, soil and geology that will influence the hydrological response. The more useful datasets for use in modelling are identified.

Although not a natural choice for application to ungauged locations, the scope for using purely statistical (empirical) modelling approaches, such as level-to-level and structure function methods, is considered. Similarly, the application of real-time updating techniques at ungauged locations is not immediately obvious, but a number of methods of transferred-error updating are considered as deserving of future attention.

More broadly, the opportunities for improved flood warning for ungauged locations relating to advances in monitoring and uncertain triggers for warning are considered. Topics addressed encompass improved methods of areal rainfall estimation, remote-sensing of land surface properties and river height and width, stage-discharge curve derivation, and flood warning trigger mechanisms incorporating uncertainty and costs of alternative actions.

Each section ends with a set of conclusions and recommendations, some relating to operational practice and others highlighting the need for further research. A closing section provides, through reference to a more detailed appendix in the Science Report, a practical illustration of some ungauged forecasting methods. Some closing remarks highlight ongoing national and international research activities of relevance to flood forecasting and warning for ungauged locations.

Contents

List of Figures

List of Tables

1 Introduction

Across England and Wales, the Environment Agency provides only a general Flood Watch service at locations that are ungauged and associated with low benefit from flood warning. Providing an improved, more targeted flood warning service is possible. But strategic guidance is needed on the technical possibilities available: both now as “best practice” and, through the identification of research opportunities, in the future.

Against this background, this operational guideline aims to provide an overview of approaches for modelling at ungauged locations that can help guide Environment Agency operational practice in the future. An accompanying Science Report provides significant further detail. This guideline serves both as an overview and “road map” to where further information can be found in the Science Report. The emphasis is on the types of modelling and forecasting problem commonly encountered and the general approaches that can be considered when addressing them. Whilst rainfall-runoff models are the main focus of attention, broader discussion encompasses hydrological channel flow routing models and hydrodynamic river models; simpler empirical models including level-to-level correlation methods are also considered.

Even for specific rainfall-runoff model types, it is unusual for a methodology to be sufficiently well established for its application to be routine for ungauged forecasting purposes. The overview first focuses on the nature of the ungauged problem and the modelling approaches available when considered at a generic level (Section 2). Subsequent discussions of specific model types in Section 3 serve to illustrate how some of these approaches have been applied and their shortcomings. Possible opportunities for improvement are identified.

An important aspect of ungauged modelling is the ability to utilise digital spatial datasets on properties of the terrain, land cover, soil and geology that will influence the hydrological response. The more useful datasets for use in modelling are highlighted in Section 4.

Although not a natural choice for application to ungauged locations, the scope for using purely statistical (empirical) modelling approaches, such as level-to-level and structure function methods, is considered in Section 5. Similarly, the application of real-time updating techniques at ungauged locations is not immediately obvious, but a number of methods of transferred-error updating are considered in Sections 6 and 7 as deserving of future attention.

In Section 8, the opportunities for improved flood warning for ungauged locations relating to advances in monitoring and uncertain triggers for warning are considered in broad terms. Topics addressed encompass improved methods of areal rainfall estimation, remote-sensing of land surface properties and river height and width, stage-discharge curve derivation, and flood warning trigger mechanisms incorporating uncertainty and costs of alternative actions.

A set of specific conclusions and recommendations are identified at the end of each section. Through reference to a more detailed appendix in the Science Report, the final Section 9 points to illustrations of the practical application of selected methods of model transfer to ungauged locations using case studies from upland and lowland Britain.

Some closing remarks in Section 9 highlight ongoing national and international research activities of relevance to flood forecasting and warning for ungauged locations, and the need to keep a watching brief on these.

2 Modelling Approaches for Ungauged Locations

2.1 Outline

This section first considers how different levels of data availability impact on the choice of modelling approach to be used for flow forecasting at ungauged locations. It then considers, at a broad generic level, approaches to ungauged modelling as involving some form of information transfer from donor catchments to a target catchment of interest.

The choice of modelling approach as a function of catchment type (headwater, middle and lower, tidal) is then discussed. A set of modelling approaches is identified in more detail for different types of model. A figure (Figure 2.3) provides a structural overview of these approaches, serving as a roadmap to where more detail can be found in the Science Report.

A set of Conclusions and Recommendations relating to modelling approaches for ungauged locations is given at the end of the section.

2.2 Definition of "ungauged" and data availability

An ungauged catchment may have different *levels of data availability*. Classically absence of river level measurement at the catchment outlet defines an ungauged catchment. The presence of rainfall measurements in the catchment would not normally affect such a classification. This guideline recognises different degrees of "ungauged", including consideration of: stage-discharge relations for flow estimation, past historical records but no current ones, the presence of telemetry for real-time data access and availability of data from neighbouring catchments. These levels of data availability impact on the choice of modelling approach, both in terms of process model selection and method of updating. These issues are considered further in Section 2 of the Science Report.

By way of guidance, Figure 2.1 presents a flowchart highlighting which modelling procedures make the best use of the available data at the target and neighbouring sites. The guidance is clearest where there is a full set of data available for model calibration and updating (the fully gauged case), as indicated in the left hand-side of the flowchart. When historical data are available but there is no on-site telemetry for real-time updating, the *process model* may be calibrated for the site, but the user may need to look to neighbouring sites (rivers) for real-time telemetry. If good quality telemetry is available nearby, on-site discharge estimates can be inferred leading to a pseudo-updating scheme for the site. Similarly, if there is no historical data on-site suitable for calibrating the process model, *process model* parameters may be inferred from a model fitted to a nearby catchment. Although the flowchart indicates which set of modelling approaches makes best use of available data, it does not provide

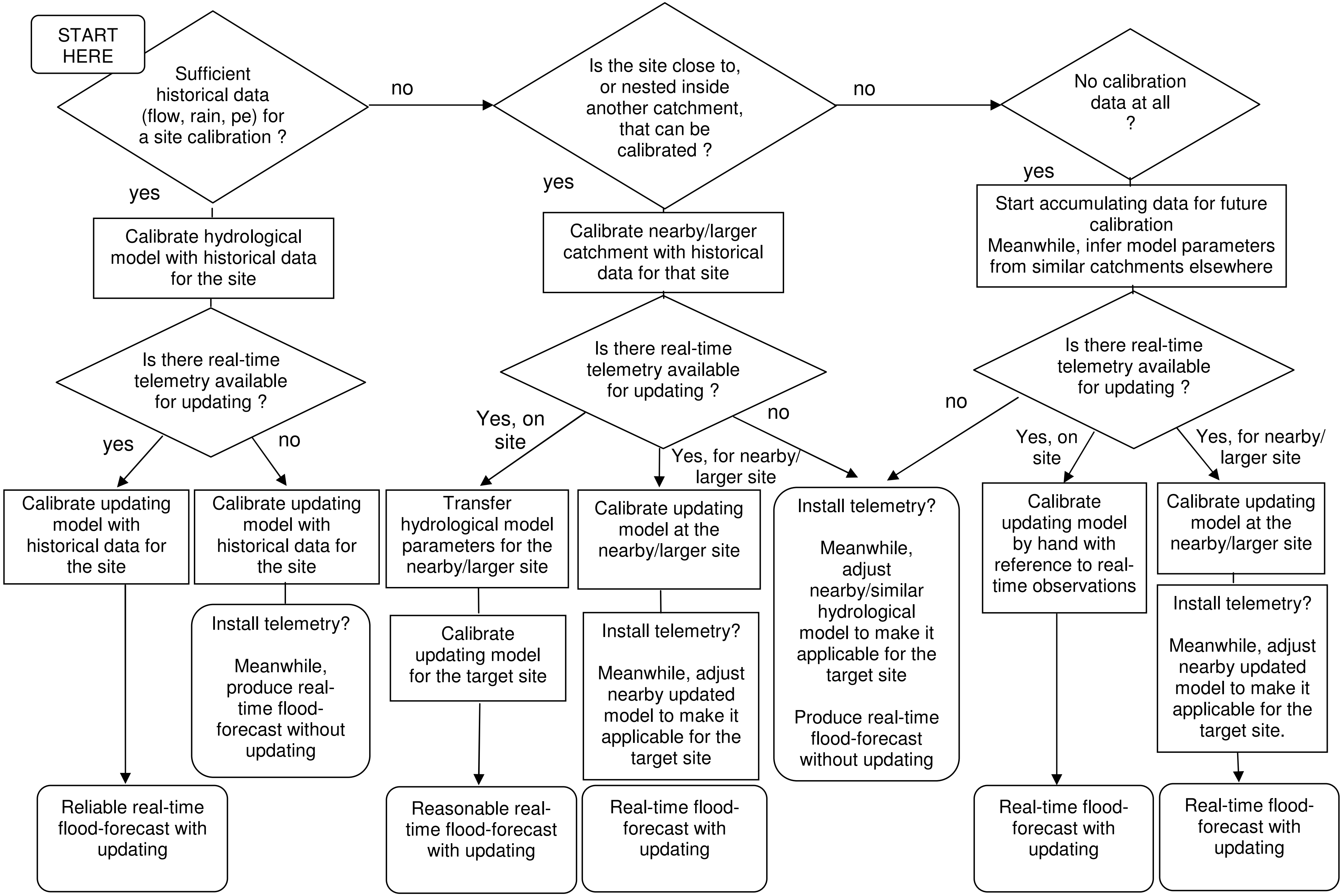


Figure 2.1 Flowchart highlighting modelling needs in response to different levels of data availability

guidance on *which* model to use. This will be discussed in the following sub-sections with the aim of providing outline guidance on the best model to use for different hydrological situations. Section 3 of the Science Report provides further details.

2.3 Ungauged modelling approaches

The *direct modelling* of gauged catchments gives way to *indirect modelling* of *target* ungauged catchments. This involves some form of *information transfer* (of data or model parameters) from donor (neighbouring, nested, downstream or "similar") catchments to the ungauged catchments of interest. Some examples are illustrated in Figure 2.2.

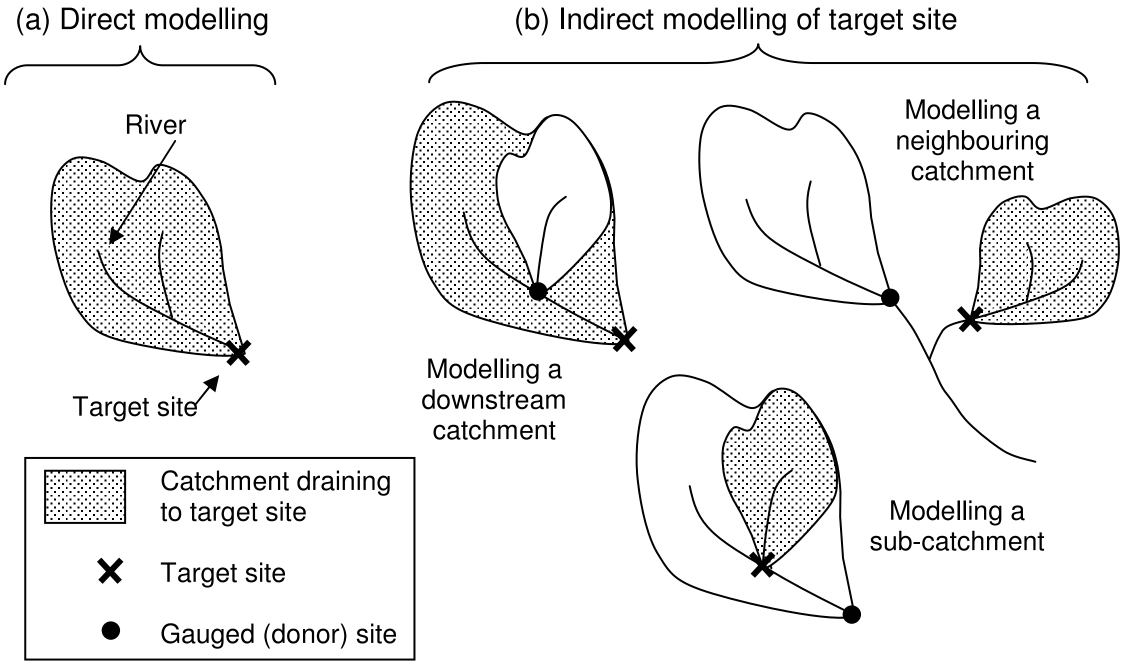


Figure 2.2 Direct and indirect modelling of a catchment, downstream catchment, neighbouring catchment or sub-catchment

The method of transfer may be called the *inference model.* An inference model may relate to the process model, updating method or both. It may also embrace the method of rainfall estimation (such as Thiessen polygon interpolation) used in the construction of the model input. The process model may take a lumped or distributed form. For example, a lumped rainfall-runoff model and a method of parameter regionalisation may constitute the inference model. In the case of a distributed model configured using spatial datasets, this may typically combine runoff production and flow routing schemes on a grid for a prescribed area that embraces some gauged sites, providing a natural inference model for forecasting at ungauged sites. A distributed model of this form is referred to as an *area-wide model* to distinguish it from a *distributed catchment model* that is configured to a bounding river basin. Both can be used as inference models for forecasting at target ungauged sites. For the case of *forecast updating*, errors in the forecasts at gauged sites can be transferred to ungauged sites either via a model state-correction or error-prediction based inference model. There will be a need to down-weight the adjustments to reflect the uncertainty of transfer from gauged to target sites in different hydrological situations.

2.4 Choice of modelling approach

Influence of catchment type

The nature of the catchment will influence the choice of modelling approach to use. Considerations include catchment size, location within a river basin (headwater, middle reach, lower reach), steepness and the influence of tides, backwater or river gate controls. Modelling options for a variety of catchment-types are presented in Table 2.1, working downstream from small headwater catchments to tidal regions. Major rivers are distinguished from minor tributaries, the latter being less likely to be gauged except near the confluence with major rivers. In addition, it is important to consider whether the catchment is rural or urbanised. It can be helpful to forecast the faster, more localised response of urban catchments separately to the rest of a catchment.

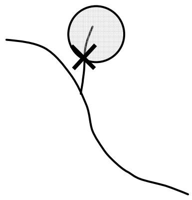
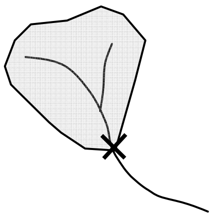
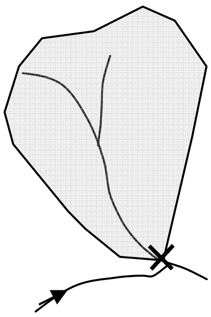
Headwater catchments of small or moderate size are natural candidates for rainfall-runoff models using transferred parameters, or scaled versions of model forecasts from neighbouring or similar catchments.

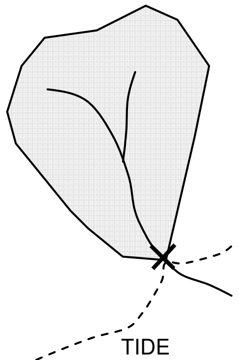
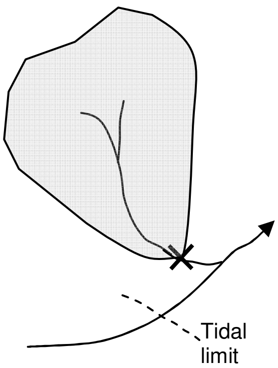
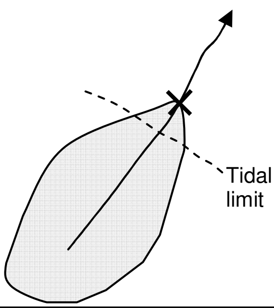
Techniques for use on the middle to lower reaches of more major rivers may vary from simple level-to-level correlation methods or hydrological storage-routing models (extrapolated from gauged sites), to hydrodynamic river models (using survey data for configuration and model parameters transferred from “similar” gauged reaches).

Tidally-influenced rivers may use hydrodynamic approaches or simpler tabular forecasts linked to observations and tide/surge predictions at gauged locations along the river, estuary or coast.

Distributed hydrological models have the ability to mix rainfall-runoff and routing models in an integrated way to allow a unified transfer of information from gauged to ungauged sites whilst using spatial datasets on terrain, soil, land use and geology to support model configuration. They are potentially flexible to the type of catchments being targeted but may not incorporate the detailed modelling capability of hydrodynamic river models developed for tidal- and backwater-influenced rivers.

Table 2.1 Choice of modelling approach

Catchment type	Suggested modelling approaches	Notes
Headwater (steep)-small upstream areas (<10 km^2) 	Consider: *(i) lumped rainfall-runoff model with transferred parameters* *(ii) distributed hydrological modelling*	Less likely to have relevant gauged location nearby. Overflow from minor or major rivers likely to be limited by steep topography. Locations may be affected by overland flows and possible springs.
Headwater (steep)-moderately sized upstream areas (>10 km^2) 	Consider: *(i) lumped rainfall-runoff model with transferred parameters* *(ii) scaling from nearby location with benefit of updating* *(iii) distributed modelling* *(iv) hydrological routing from gauged location upstream*	Fast response times to rain on rural catchment areas. Possibly have relevant gauged location nearby.
Middle and lower catchment 	Minor tributaries: *In addition to treatments for headwater areas:* *(i) override forecast from upstream gauged flows with backwater curve estimate under influence of receiving stream level* *(ii) possible extension of hydrological models to incorporate backwater effects* *(iii) extend hydrodynamic model to include tributaries experiencing backwater effects* Major rivers: *(i) level-to-level correlations* *(ii) hydrological routing from gauged location upstream* *(iii) hydrodynamic models for special cases, in particular, for* urban reaches	Possibly have relevant gauged location nearby, but also possible backwater effects from major rivers. Likely to have gauged flows upstream.

Catchment type	Suggested modelling approaches	Notes
Mixed Fluvial/Tidal  	Minor tributaries: *(i) tabular forecast based on forecasts for upstream flows and downstream levels* *(ii) empirical prediction rules constructed to fit results from a full hydrodynamic model* *(iii) hydrological simplification of full hydrodynamic model* *(iv) extend hydrodynamic model to include tributaries and use in real-time* Major rivers: *As (i) to (iii) for minor tributaries* *(iv) hydrodynamic model for use in real-time*	May have relevant gauged location upstream, but certainly tidal effects from major rivers or estuary. Typically will be a relevant gauged location upstream, but certainly tidal effects from estuary or sea.
Tidal   	Need to decide if forecast for tributary should have any fluvial component. For minor tributaries: *(i) tabular forecast based on forecasts for estuary or coast* *(ii) empirical prediction rules constructed to fit results from a full hydrodynamic model* *(iii) hydrological simplification of full hydrodynamic model* *(iv) extend hydrodynamic model to include tributaries and use in real-time* For major rivers*:* *As (i) to (iv) for mixed fluvial/tidal case, but additionally:* *(v) consider 2D hydrodynamic models* *(vi) consider inclusion of wind run-up effects in hydrodynamic models*	Flooding mainly from tidal causes. Maps of area flooded if rivers reach given levels, forecasts based on models for coast or estuary. Hydrodynamic models including representation of extensive flood-plains and washlands. Gauged locations upstream less relevant than in mixed fluvial/tidal case but still need to be used to ensure proper coverage when fluvial conditions are extreme.

Influence of model type

In the five sub-sections that follow, a set of modelling approaches for flow forecasting at ungauged locations are identified for different types of model. Figure 2.3 provides a structural overview of these approaches. It serves as a roadmap to where more detail can be found in the Science Report, through number reference to specific sections. It distinguishes between catchment models and river reach models and identifies a group of five methods of transfer that have applicability to both. Their support by property datasets is indicated. The five methods of transfer are discussed in outline here in Section 2.6, in relation to lumped conceptual rainfall-runoff models. However, they may have broader applicability as suggested in Figure 2.3. Models of distributed form, for both catchment areas and river reaches, more naturally make direct use of property datasets in their specification for flow forecasting at target ungauged locations, as indicated in the figure.

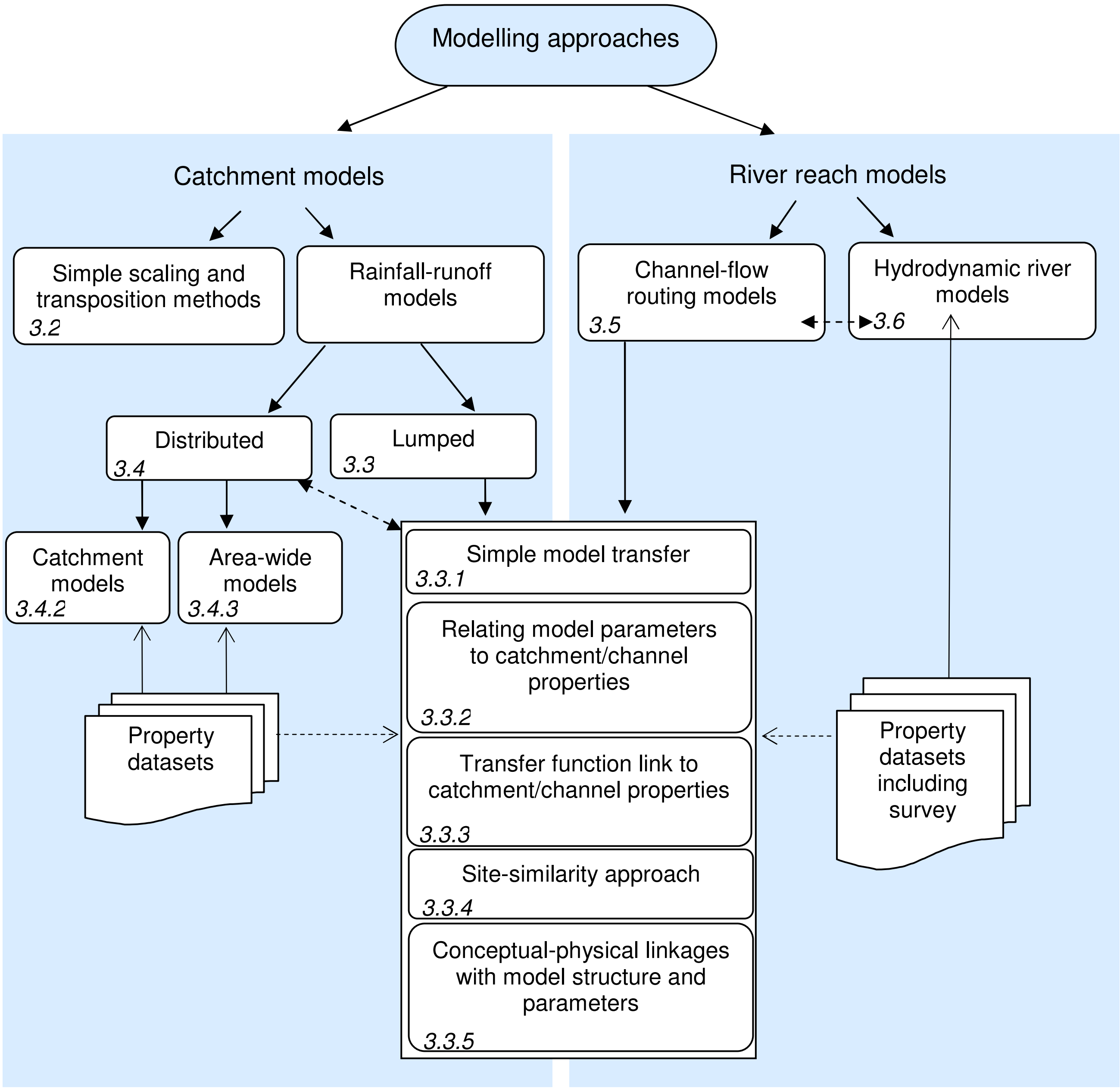


Figure 2.3 Modelling approaches for ungauged locations

2.5 Simple scaling and transposition methods

A distinction can be made between simple scaling and transposition methods. *Simple transposition* involves direct use of gauged flow values for a *source location* at a nearby *target location.* River level values may also be transposed in some instances although a datum adjustment may be required. Proximity and similarity are key factors to the success of simple transposition. One example application is the use of gauged flow to trigger a warning at a nearby flood-prone site.

Simple scaling involves transformation of the gauged values for the source location to the target location to make them more representative. A commonly used scaling factor to use is the ratio of the source and target catchment drainage areas. A refinement of this might use the Standard Average Annual Rainfall (SAAR) as a further ratio factor. Further possibilities, including offset and time-shift forms, are outlined in Section 3.2 of the Science Report.

2.6 Lumped conceptual rainfall-runoff models

A rainfall-runoff model developed for a gauged catchment can be used as the basis of information transfer to a target ungauged catchment. Different approaches present themselves. *Simple model transfer* involves the direct transfer of the model and its parameters, only changing the catchment area and input rainfall to that of the target catchment. This may be appropriate for catchments that are very similar in location, area, terrain, soil, land cover and geology. It may prove better than simple scaling, particularly at times of spatially-varying rainfall for which good areal estimates are available for both source and target catchments.

Where rainfall-runoff models can be calibrated for a variety of gauged catchments, it is tempting to develop regression relations linking model parameters to catchment properties. The approach of *relating model parameters to catchment properties* has proved a popular method of model transfer to ungauged catchments because of its apparent simplicity. In practice, careful attention needs to be given to: (i) possibilities for model simplification to achieve a degree of parameter independence, (ii) choice of appropriate catchment property measures, and (iii) the form of regression methodology to use. The approach can be criticised for its lack of a physical basis, it can be time-consuming to apply in a rigorous manner, and model performance for some target locations may be disappointing. A variant of this approach employs a *transfer function parameter link to catchment properties*. The functional form of the transfer functions and the catchment properties they relate to are predefined and parameters estimated in a one-step calibration process across all gauged catchments. This contrasts with the conventional two-step “model calibration and parameter regression” approach. It may prove more robust and faster to apply. An alternative to the parameter regression on catchment properties approach is to estimate the model parameters for the target site as a weighted combination of those at “similar sites”. This *site-similarity approach* uses the catchment properties to define *similarity* or *distance* (in the catchment property space) *measures* between the target catchment and potential source catchments. These measures are used to identify a set of similar catchments to use as source catchments (the pooling group) and to establish the weights in the weighted average of parameters across the source catchments used to estimate the model parameters at the target site. All these model parameter transfer approaches employ an essentially empirically-based link to catchment properties and are not physically-based.

A scientifically more rigorous approach is to formulate a rainfall-runoff model from the outset that has a structure and parameters that can be linked in a conceptual-physical way to spatial datasets on topography, soil, land cover and geology. The approach of *establishing conceptual-physical linkages to model structure and parameters* has considerable appeal for application to ungauged catchments. Either lumped or distributed forms of model can be developed, lumped models usually being derived from a distributed form that establishes the links to the spatial datasets. Such models normally have a small set of *regional parameters* that allow mapping onto a much larger set of model parameters with the support of the spatial datasets. Gauged sites in the region can be used for calibration of these regional parameters and the overall model used to forecast at ungauged locations in a natural way. Models are normally formulated as distributed hydrological models either in source-to-sink or grid-to-grid form. *Source-to-sink models* are formulated to simulate flow at a catchment outlet (the sink), with runoffs generated from distributed source areas being translated directly to the outlet. In contrast, *grid-to-grid models* route runoff from grid-cell to grid-cell across a predefined area that would generally not correspond to a specific catchment or river basin. For this reason they can be described as *area-wide models*. Using either form of model, it is possible to calibrate the model parameters at gauged locations within the modelled area and to extract flows for interior ungauged locations for forecasting purposes. Such models, whilst essentially distributed in form, can be used as lumped rainfall-runoff models for specific locations. An important advantage is that their model structure and parameters have been derived using property datasets in spatial form as opposed to using empirical relations with catchment-aggregated properties.

2.7 Distributed hydrological models

Distributed models arguably provide the most natural way of flood forecasting at ungauged sites across a region. They embrace runoff-production and flow routing components within a unified framework. The modelled domain can encompass gauged sites supporting model calibration, forecast assessment and updating and ungauged sites requiring flood forecasts. *Physics-based distributed models* classically employ partial differential equation representations of water movement and storage in soil, aquifer and channel systems. Such detailed mathematical description can prove illusory because of (i) the spatial complexity of such systems, (ii) the interest in aggregated flows from larger scale elements (hillslope, catchment, river basin), and (iii) the difficulty of spatial characterisation and measurement of the properties of the propagating media, especially underground. Simpler *conceptual-physical formulations* are commonly sought for forecasting applications for such reasons and because of ease of application and performance issues. Irrespective of the type of distributed model in question, experience suggests that in many situations it is hard to outperform lumped conceptual models in operational use for flood forecasting. Whilst this arguably still applies for gauged catchments, the prospect for improvements in flood forecasting for ungauged catchments via a distributed modelling approach seems much greater.

The *area-wide distributed models* developed for atmospheric modelling purposes, in support of weather forecasting and climate prediction, have emphasised vertical water and heat transfers with the atmosphere. These *land surface schemes* have been developed for national and global application and have elements, supported by global datasets on soil and land cover, that are of some interest to the ungauged problem. However, the focus on vertical transfers of water to the exclusion of horizontal transfers under topographic control means they do not provide a natural starting point for flood forecasting at ungauged sites.

2.8 Channel flow routing models

Channel flow routing models are used to translate a flow hydrograph from an upstream site to one downstream. Where the downstream flow influences this translation via backwater control, this situation is treated separately here under hydrodynamic river models. A modelled river reach is normally sub-divided into sub-reaches with nodes at their boundaries. Assigning a boundary node to a target ungauged location provides a simple example of the use of a channel flow routing model as an indirect modelling approach for ungauged forecasting. Ungauged lateral inflows commonly bring further complexity and lessen forecast accuracy. Simple scaling methods or rainfall-runoff models may be used to represent such ungauged lateral inflows.

A lesser form of “ungauged problem” is where only river level measurements are available and a stage-discharge relation cannot readily be established via a current metering field programme. The stage-discharge relation may be embedded within the channel flow routing model and its form and parameters calibrated along with those of the routing model.

Some channel flow routing models can be linked directly to the St. Venant equations of open channel flow and through them to the properties of the river channel and its floodplain. This can provide a direct basis for application to ungauged sites but, on account of the simplifications involved, is likely to benefit greatly from experience gained in modelling similar river reaches that are gauged.

2.9 Hydrodynamic river models

Hydrodynamic river models, through their direct link to channel and floodplain form and formulation as equations in terms of both flow and level, at first sight appear immediately suited to the ungauged forecasting problem. They are particularly suited to rivers under backwater influence from tides, river confluences and river controls. Simplification of processes, reduction to one dimension, poor definition of lateral inflows and roughness parameters requiring a degree of calibration are some of the reasons for application not being straightforward for ungauged sites. Experience of model application for similar river reaches will invariably prove invaluable. The simplest and most successful use of hydrodynamic models for ungauged forecasting will be for model node locations within a river reach gauged at its upstream and downstream boundaries, and without significant ungauged lateral inflows. Standing water level on the floodplain, off the main river channel, may also form a target ungauged forecast requirement. The extent of the modelled region may be extended to encompass tributaries under the backwater control of the main river with ungauged locations requiring flood forecasts.

2.10 Conclusions and Recommendations

The following conclusions and recommendations can be made with regard to "Modelling approaches for ungauged locations".

(1) The appropriate choice of modelling approach will depend on the nature of the ungauged location and the extent and type of data available.

(2) Simple scaling and transposition approaches are well established, routinely used and may suffice in some situations.

(3) Application of rainfall-runoff models to ungauged locations for flood forecasting is not routine. Well developed methodologies are rare.

(4) Simple transfer of rainfall-runoff models from neighbouring or similar sites can prove practical. Experience needs to be gained through trial transfers, using gauged sites as if they are ungauged, for given areas of application.

(5) Relating rainfall-runoff model parameters to catchment properties via regression is a popular method used in flood design applications. However, the performance may not be acceptable for use in flood forecasting and warning, particularly for more complex responding catchments. This results from model simplification and often rather weak empirical regression relations. Using a site-similarity-approach, in place of regression, makes little difference.

(6) Rainfall-runoff models developed to have more direct physical-conceptual links to land properties (terrain, land cover, soil, geology) are seen as the way forward. Such model formulations do not suffer from the need to start with catchment-aggregated properties commonly referred to as "catchment characteristics".

(7) Physical-conceptual distributed models employing a grid-to-grid flow routing structure and kinematic representations of lateral soil drainage, surface and subsurface runoff and channel flow are naturally suited for area-wide hydrological forecasting across both gauged and ungauged locations. It is recommended that further research on this type of model should be undertaken.

(8) Channel flow routing models normally result from simplifications of the St. Venant equations for open channel flow. This provides a theoretical basis for relating model structure and parameters to properties of the river channel and its floodplain for application to ungauged river reaches. However, on account of the simplifications involved and the essentially empirical nature of roughness, there is a need to complement the theory with experience of a model's application to similar river reaches.

(9) Hydrodynamic river models are normally applied where backwater influences are significant, such as in tidal rivers, in the vicinity of river controls and where a forecast location is on a tributary under the backwater control of the receiving river. Models of this type are configured to make direct use of geometry and material properties of the river and are naturally suited to application to ungauged river reaches. However, experience with gauged reaches is likely to prove very valuable in setting roughness parameters and for compensating for simplifications in model configuration.

(10) The accuracy of channel flow routing and hydrodynamic river models can be greatly influenced by the method of estimation of ungauged lateral inflows. Suitable methods may include simple scaling of a nearby gauged tributary inflow or a rainfall-runoff model for the ungauged inflow catchment.

3 Some Specific Modelling Tools

3.1 Introduction

Consideration is given in this section to specific modelling tools of potential use for forecasting at ungauged locations. Attention is particularly focussed on models in operational use by the Environment Agency and reviewed in more detail in the accompanying Science Report. The specific modelling tools are treated thematically under the headings: simple scaling methods, lumped rainfall-runoff models, distributed hydrological models, channel flow routing models, hydrodynamic river models and flood mapping tools. Figure 3.1 provides an overview of these specific tools within the structure of modelling approaches presented previously in Figure 2.3. Through numbered reference to sections of the Science Report, it serves as a roadmap to where more detail can be found relating to a specific model. The section concludes with a set of conclusions and recommendations relevant to the application of these specific modelling tools to ungauged locations.

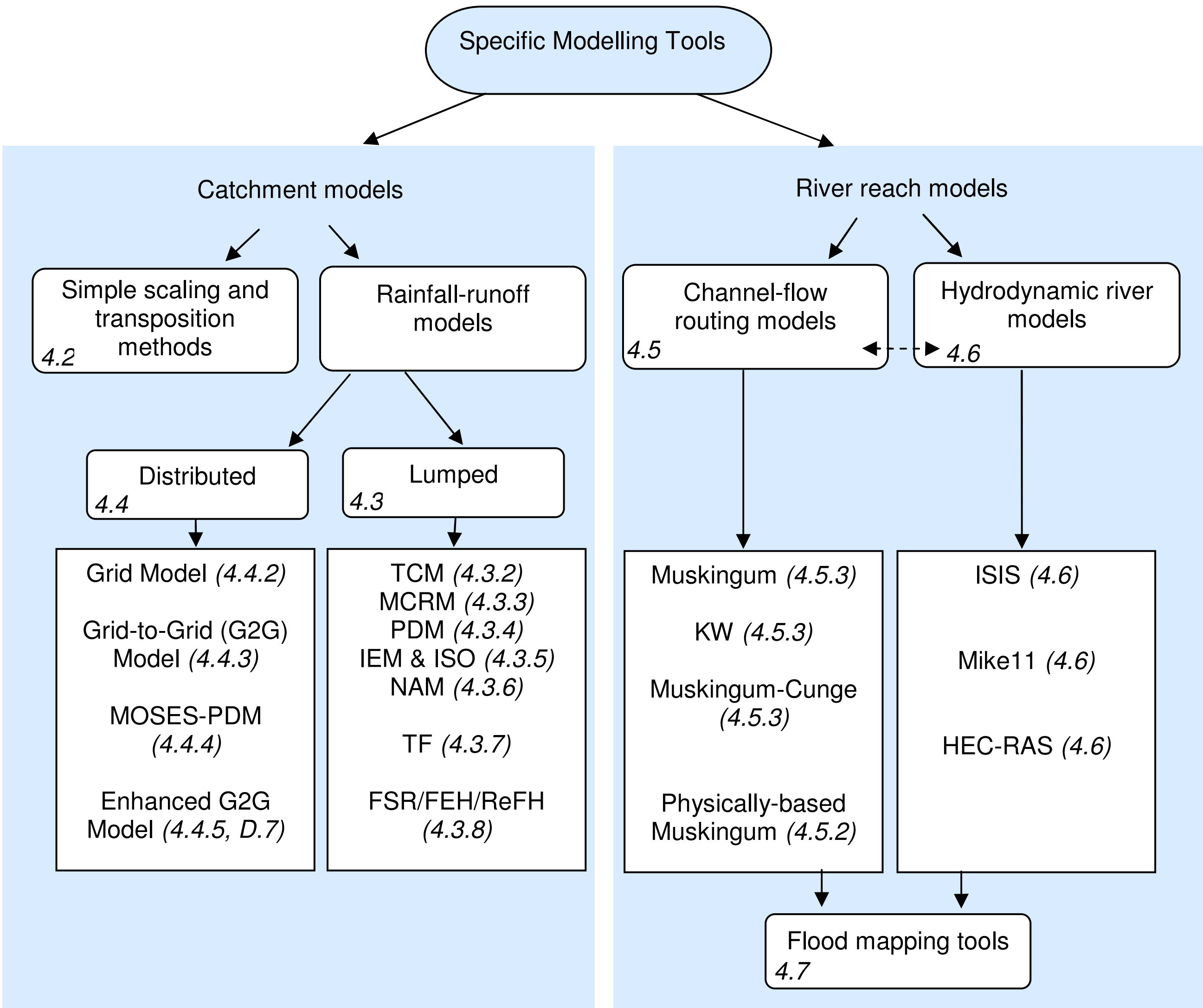


Figure 3.1 Some specific modelling tools

3.2 Simple scaling methods

Simple scaling methods, typically involving Area/SAAR weighting factors for the gauged source catchment and ungauged target catchment, are rather general in nature and are not discussed further with respect to specific modelling tools.

3.3 Lumped rainfall-runoff models

Specific rainfall-runoff models in use by the Environment Agency for flood forecasting include: the Thames Catchment Model (TCM or Catchmod, and available within the Penman Store Model or PSM), the Midlands Catchment Runoff Model (MCRM), the PDM (Probability Distributed Model), the Isolated Event Model (IEM, and available within the PSM), the ISO (Input-Storage-Output) model, forms of Transfer Function (TF) model, and the NAM model.

It is not commonplace for specific models like the above to have well defined routine procedures for application to ungauged sites. Rather, there are methodologies that can be utilised to develop such procedures for particular applications and geographical areas. For forecasting applications and over England and Wales, such methodologies have rarely been invoked in a comprehensive way.

Some lumped rainfall-runoff models are more suitable than others for application to ungauged sites. However, many share common elements and are rather similar with regard to their suitability and approach for application to ungauged catchments. The accompanying Science Report reviews each of the above models in terms of its suitability for ungauged catchments, and others. Some models, such as the TCM, appear more complex and having large numbers of model parameters. However, they can be reduced to simpler forms and a smaller set of dominant parameters, albeit at the expense of flexibility in the modelled response. The more complex forms may have closer ties to measurable quantities, and map information, that can support model configuration and calibration and application to ungauged catchments. Experience with their application across a region will give the modeller increasing confidence to formulate models for similar ungauged catchments, in terms of choice of configuration and parameter values.

Regional application of the “regression of model parameters on catchment properties approach” in the case of the MCRM, led to identifying subsets of sensitive parameters for this 22 parameter model, invoking a stepwise regression procedure, and using judgement to guide the development of plausible relations and the rejection of outlier catchments. An earlier attempt focussed on model simplification to reduce model parameters, simplifying the regression step, and resulting in the “Simple MCRM”. In both cases, the results failed to be convincing overall for operational use on ungauged catchments, although good results were obtained in some situations with the Simple MCRM.

Notwithstanding these difficulties, a similar approach was attempted for design application at ungauged sites for the PDM model. The research focussed on model simplification, different regression techniques (including sequential regression) and choice of catchment properties. The simplified form compromised performance overall and use of regression relations for parameter estimation at ungauged sites caused further deterioration. Rather similar results were obtained using a site-similarity approach for parameter estimation instead of regression. Whilst rather straightforward to apply, it is not clear that the performance of these empirical approaches would be acceptable for flood forecasting and warning purposes.

The physical-conceptual nature of the PDM and its intermediate level of complexity do offer the prospect of using the approach of “establishing conceptual-physical linkages with model structure and parameters”. Such an approach could capitalise on the use of spatial datasets on terrain, soil, land cover and geology at their basic resolution rather than via catchment-aggregated properties used in the regression approach. To date, this approach has not been pursued although some first steps are considered in the Science Report (under Future Opportunities in Section 4.3.4). The use of a distribution function of absorption capacity in the PDM to control water storage and runoff production lends itself to explore links to terrain, soil and land cover data. One formulation is based on invoking a linear relation between terrain slope and absorption capacity which leads to a Pareto distribution of absorption capacity defined through slopes calculated from a Digital Terrain Model. An alternative approach is to use soil survey data, such as the Integrated Air Capacity of the Soil Survey, to characterise absorption capacity and its spatial distribution. The canopy component of absorption capacity, if judged important, can be introduced through use of land cover data. Hybrid forms of these approaches can be considered.

Flow routing in the PDM, via fast (typically channel) and slow (typically groundwater) pathways, is represented by variants of the Horton-Izzard equation including simple linear storages in series. A body of theory exists that links the time constants and power exponents in these equations to properties of the channel and aquifer units involved. Some of the relevant theory has been summarised here to point the way forward in support of application to ungauged catchments. However, there are problems to be overcome in the appropriate use of spatial data on relevant properties, particularly on account of the lumped catchment-aggregated form of the PDM’s routing functions. One approach is to consider distributed routing formulations as a means of arriving at effective parameters for the lumped routing components used in the PDM.

Similar considerations are relevant to applying the IEM and ISO models to ungauged catchments as their model structures encompass forms of the Horton-Izzard equation. The IEM with only four model parameters is arguably a good candidate for the “regression of model parameters on catchment properties” approach, although this has yet to be undertaken. The shortcomings of this empirical approach need to be borne in mind to avoid false expectations and possible disappointment in a forecasting context.

The NAM model has 16 parameters and the User Guide does not offer advice on its application to ungauged catchments. Remarks made already for the MCRM are probably as applicable to the NAM and parameter/property regression approaches are likely to encounter similar difficulties. Experience of applying it on gauged catchments is likely to provide a “feel” for how to apply it to similar ungauged catchments, as discussed for the TCM.

The TF (Transfer Function) model, including UH (unit hydrograph) forms, when viewed purely as black-box models do not appear to be immediately suited for application to ungauged catchments. However, they can be subject to conceptual-physical interpretation as deriving from configurations of linear storages allowing links to be established with physical properties. Parameter parsimonious forms, including ARMA (autoregressive-moving average) and triangular UH functions, can also ease the task of establishing parameter regressions on catchment properties. However, in their restricted forms they only address the routing process and usually require add-ons to accommodate the runoff production mechanism and its control on flood volumes. The triangular UH of the Flood Study Report (FSR) and Flood Estimation Handbook (FEH) developed for use in design provides a good example. This has recently been revised to have a kink in the recession limb and combined with a PDM type of runoff production function and a linear reservoir representation of groundwater. This revision is called the ReFH model and is provided with explicit parameter regressions on catchment properties for application to ungauged catchments. In some cases the parameter regressions on catchment properties are rather weak and the overall approach may not be good enough for flood forecasting purposes. It is possible that the regressions might prove a useful guide for modellers trying to apply the PDM, and forms of TF and UH model, to ungauged catchments.

3.4 Distributed hydrological models

The classical *physically-based distributed models* in hydrology employ nonlinear partial differential equation descriptions of key physical processes that are solved numerically using, for example finite difference or finite element schemes. Well known examples are the SHE (Systéme Hydrologique Européean) and the IHDM (Institute of Hydrology Distributed Model). The fundamental equations employed are the Richard's equation for subsurface flow, the Boussinesq equation for groundwater flow and the St. Venant equations for overland and channel flow. Their success as useful tools for flood forecasting applications has been limited. Reasons for this include the real complexity of hydrological systems, much of which is unobservable below ground, issues of scale of representation, and the necessary approximations involved in process representation and numerical solution. For gauged catchments, simpler formulations are easier to apply and model calibration can result in as good if not better performance. Even for ungauged catchments, the complexity of model formulation can raise false expectations of model accuracy. The utility of distributed hydrological models is greater in design and planning contexts where the hydrological response to a change in catchment conditions needs to be understood.

The difficulties associated with classical physics-based distributed hydrological models have led to simpler *physical-conceptual models* being developed and linked to spatial datasets on controlling properties. These commonly use simpler, aggregated representations of key processes. Examples are the Grid Model (developed by CEH for the Environment Agency for flood forecasting purposes) and the Grid-to-Grid Model (developed by CEH for the Ministry of Defence for indicative area-wide flow forecasting and for Defra in support of climate change flood impact studies). These two models provide contrasting examples of source-to-sink and grid-to-grid (area-wide) approaches to distributed hydrological modelling. Both have structures well-suited to the ungauged problem and can accommodate the effects of topography, soil, land cover and geology in physically sensible ways. The Grid Model's source-to-sink method of routing is computationally more efficient than grid-to-grid routing and can more readily utilise terrain data at sub-grid resolutions. The Grid-to-Grid Model area-wide formulation offers a more flexible approach to forecasting at any grid outlet location, gauged or ungauged. There are significant opportunities to develop either approach as a basis for ungauged flood forecasting.

A further category of distributed hydrological model is offered by the *land surface scheme models* developed for interfacing to atmospheric models for national, regional and global application. A good example is offered by MOSES (Met Office Surface Exchange Scheme) and its development as MOSES-PDM to incorporate a Probability-Distributed Model of soil water capacity as an extension of the Richard's equation control of soil moisture. It has also been coupled to the Grid-to-Grid Model routing scheme to obtain area-wide indicative estimates of river flow. A strength of this approach for ungauged flood forecasting is that its formulation naturally lends itself to employ soil property information although this has not been fully exploited in practice. However, the model's use of a rather detailed vertical description of water movement, no explicit link to topographic control on runoff production, and absence of groundwater representation makes it of limited interest as an approach for ungauged flood forecasting purposes at catchment scales. The UK-wide grid-square estimates of runoff and river flow may have value in a Flood Watch context for providing a spatial indication of potential "hotspots", although at a coarse resolution. A more hydrologically-tailored distributed model approach is clearly called for to meet the requirements of flood forecasting for ungauged catchments.

A unified approach based on a kinematic wave representation of lateral soil drainage, saturation overland flow, channel flow and groundwater is being considered as one way forward, invoked as a variant of the Grid-to-Grid Model. The formulation allows for direct use of spatial datasets on properties of terrain, soil, land cover and geology. Model equations reduce to a simple nonlinear reservoir form applied within each grid-cell with parameters defined as physical properties appropriate to the process being represented. Prototyping of this approach is in progress as a possible area-wide approach to flood forecasting for gauged and ungauged locations. Provisional results are reported in Appendix D.7 of the Science Report.

3.5 Channel flow routing models

Hydrological and hydrodynamic approaches to channel flow routing can usually be shown to have a common basis in the St. Venant equations, and though them to the physical properties of the river channel and its floodplain. As a consequence, application to ungauged river channels has a natural physical basis. However, even for the most refined hydrodynamic river model, channel geometry simplification and the inherently empirical nature of roughness normally means there is benefit in model calibration for gauged sites and transfer of the experience gained for application to ungauged reaches. Hydrological approaches combine simple mass balance water storage accounting with a simplified momentum equation linking channel storage to water level or flow. The simplifications involved can make the links to channel properties less direct in physical terms, but can ease practical application and the building up of experience for use in modelling ungauged reaches. Simpler hydrological approaches are normally preferred where backwater influences from tides, river controls and confluences are not dominant. The hydrodynamic approach is sometimes distinguished by models providing estimates of both river flow and level for situations where there is no unique relation between these two quantities. However, the distinction between hydrological and hydrodynamic (hydraulic) approaches is largely artificial with a spectrum of levels of simplification.

A popular method of hydrological routing is provided by the Muskingum scheme in which reach storage is a linear function of a weighted combination of the reach inflow and outflow. It is possible to relate this back to the underpinning St. Venant equation and in this way establish relations with channel properties applicable to ungauged reaches. There are different ways of doing this leading to different variants. For example, the Muskingum-Cunge method chooses a weighting that matches the numerical and physical diffusion whilst the mixing-cell approach uses a variable space-step to eliminate the diffusion term. As previously discussed, experience gained with "calibration" at similar gauged reaches will benefit application at ungauged reaches. Kinematic wave routing schemes can also be linked back to channel properties.

3.6 Hydrodynamic models

A number of off-the-shelf hydrodynamic models have been employed by the Environment Agency, but only ISIS and Mike11 are used in real-time to support flood warning. Whilst channel and floodplain property information can be used to set up a model for an ungauged reach, much can be gained from experience of model configuration and calibration for gauged reaches. This is particularly true of roughness parameters, initially inferred from field inspection in relation to published tables and photographs, where parameter calibration can prove of great benefit. This may also apply to other essentially empirical parameters such as weir, bridge and gate contraction coefficients.

Care needs to be exercised when transferring a hydrodynamic model developed for design studies to use in real-time, for both gauged and ungauged reaches. The full range of flows should be adequately modelled, computational problems should not arise at very low flows or during rapid fluctuations of river level, and opportunities for simplifying the model configuration need to be borne in mind.

Of major relevance to ungauged forecasting using hydrodynamic models is the need to pay appropriate attention to the modelling of ungauged lateral inflows. A false expectation of accuracy from the detailed configuration of a hydrodynamic model may arise if ungauged lateral inflows are significant and poorly represented. Methods for their estimation encompass the scaling, rainfall-runoff and channel flow routing approaches discussed previously.

3.7 Flood mapping tools

Flood mapping tools facilitate the mapping of water levels continuously over an area so the ungauged location is most typical. The tool may serve wholly as a visual display facility with the information mapped deriving from observed (remotely-sensed imagery) and/or modelled sources. The mapping tool may be provided as an intrinsic component of a 1-D or 2-D hydrodynamic river modelling system.

There is a developing opportunity for area-wide hydrological models to map inundation extent and depth at an indicative level and with UK coverage. The river flow volume along the entire river network can also be mapped in intensity-coded line form. Simple geomorphological relations on channel geometry linked to grid-to-grid flow routing models and DTMs provide the modelling support to such products.

3.8 Conclusions and Recommendations

The following conclusions and recommendations can be made with regard to "specific modelling tools" and their relevance for forecasting at ungauged locations".

(a) Lumped rainfall-runoff models

(1) The main rainfall-runoff models employed for flood forecasting by the Environment Agency, and given special attention here and in the Science Report, are: Thames Catchment Model or TCM, Midlands Catchment Runoff Model (MCRM), the PDM (Probability Distributed Model), the Isolated Event Model (IEM), the ISO (Input-Storage-Output) Model, the NAM model, and forms of Transfer Function Models. Some rainfall-runoff models developed for design use in the UK - associated with the Flood Studies Report, Flood Estimation Handbook and follow-on work – have also been given special consideration.

(2) Many brand-name rainfall-runoff models share common elements. Thus rather general conclusions relating to their suitability for application to ungauged areas can be made.

(3) Conceptual rainfall-runoff models that can accommodate a range of hydrological behaviours normally contain a reasonable number of parameters. These parameters are often interdependent and only weakly related to aggregated catchment properties ("catchment characteristics"). Simple empirical "regionalisation" procedures - based on forms of regression or site-similarity methods linking model parameters to catchment characteristics – can be limited in the performance they can achieve, particularly for more complex catchments. Such methods have been applied to simplified forms of the MCRM and PDM models.

(4) Only one of the models considered in detail, the TCM, is configured to have spatial response zones within which a hydrological response model operates. This formulation is used to represent parallel flow responses from say aquifer, clay and riparian areas. The result is an overall model with many parameters and having great interdependency across zones. However, application to ungauged areas is less difficult than might be imagined as the response zones can be made to operate in hydrological sensible ways in the hands of an experienced modeller. Transfer of experience from modelling similar catchments in the same region can prove particularly valuable. Digital datasets can be used to support assignment of response zone areas.

(5) The physical-conceptual nature of the PDM and its intermediate level of complexity offer some hope of successful application to ungauged sites. Each of the model parameters has a clear physical meaning that invites attempts to establish physically-based linkages with data on soil and geological properties, land cover, topography and stream network topology. However, to date, there has been no systematic attempt to do this. Only simple empirical regionalisation approaches using aggregated catchment properties have been considered: these have achieved some success, but usually where the catchment response is relatively simple. Some ideas for advancement have been set down and are recommended for further investigation. These ideas also have relevance to other forms of conceptual rainfall-runoff model, both of lumped and distributed form.

(6) The Transfer Function or TF model when viewed as a pure black-box model is arguably the antithesis of a suitable model for ungauged catchments. However, simple

forms of TF model can be related to physical-conceptual models representing the storage and release of water in soils, groundwater and river channels. This can be used to support parameter estimation using properties of soil, geology and topography. Also simple forms of TF model, including certain unit hydrograph (UH) forms, are characterised by a small number of basic characteristics that lend themselves to empirical regionalisation approaches. However, progress is more likely to be made by recognising that TF and UH models provide the storage routing function of a more complete conceptual rainfall-runoff model incorporating runoff production and the principle of water mass balance. The ReFH, as a reformulation of the FSR and FEH rainfall-runoff method for design use, provides a good example of such an approach. It combines a simple kinked-triangle UH routing function with a PDM-type runoff production function. However, empirical regionalisation of the ReFH parameters has proved rather weak.

(b) Distributed hydrological models

(1) Physically-based distributed models, such as the SHE and the IHDM, employ nonlinear partial differential equation descriptions of key physical processes that are solved numerically on a finite difference grid or finite element mesh. Their performance will necessarily be constrained by the real complexity of hydrological systems above and below ground, the data support available, and the approximations involved in the process representation and numerical solution. Experience with models of this type indicates their value is greatest where there is a need to understand the impact of some future change within a catchment, particularly relating to land cover or land management. Application of such models for real-time flood forecasting is less likely to prove worthwhile. The complexity of model formulation can raise false expectations of model accuracy. Simpler physical-conceptual distributed models are easier to apply, can give as good if not better performance, and are generally preferred for flood forecasting application.

(2) The CEH Grid Model is a distributed physical-conceptual rainfall-runoff model configured on a regular square grid. It uses a source-to-sink formulation in which water flows are routed directly to the basin outlet: it is efficient to apply to specific catchments. In contrast, the CEH Grid-to-Grid Model uses an area-wide formulation in which water flows are routed from grid to grid making it easy to output water flows at any set of locations, gauged or ungauged. In other respects the models are similar and provide modelling environments within which alternative runoff production functions operating within each grid-square can be formulated and trialled. Both flow routing and runoff production formulations are chosen to be physical-conceptual in nature so that they can be supported by digital datasets on elevation, soil and geological properties, and land cover. When configured on the weather radar network grid, such models can exploit the benefits of grid-square radar rainfall estimates to the full. Models of this type provide an attractive way of addressing the ungauged forecasting problem. It is recommended that further work is undertaken on alternative formulations leading to a prescription for operational use. Some ideas for improved model formulations, relating especially to lateral drainage and groundwater, have been identified as deserving of further research. Prototyping of an extended form of the Grid-to-Grid model incorporating these ideas is ongoing: preliminary trial results are reported in Appendix D.7 of the Science Report.

(3) The land surface scheme, MOSES-PDM, used in combination with the Grid-to-Grid flow routing scheme provides estimates of soil moisture, evaporation, runoffs and routed river flows with UK-coverage on an operational basis. Although not well-suited to the ungauged forecasting problem at a detailed level, these estimates are likely to prove of value in a Flood Watch context.

(4) Ideas for improved runoff production and flow routing schemes that enjoy physically based linkages with topography (though the influences of terrain slope and water pathway topology), soil properties and land cover are considered in some detail in the Science Report. New kinematic representations of lateral soil drainage, surface runoff and channel flow together with consideration of groundwater transfers need to be investigated further within the Grid-to-Grid modelling framework. This is an area where real progress on the ungauged forecasting problem can be made. It can be seen as a move away from the empirical regionalisation approaches towards one with a sounder scientific basis and more robust and accountable performance.

(c) Channel flow routing models

(1) Channel flow routing models have a common basis in the St. Venant equations and their simplification. This provides a formal link to channel properties, concerning geometry and resistance (roughness), and a sound basis for application to ungauged channel reaches. Simplifications of representation and of channel geometry, together with the essentially empirical nature of roughness, means that there will normally be benefit in model calibration at gauged sites and transfer of this experience to ungauged sites. This applies even for the most refined hydraulic models.

(2) A new Mixing–Cell variant of the Muskingum Method is introduced in the Science Report as a good example of a simplified routing scheme derived from the St. Venant equations that is well suited for application to ungauged river reaches. The model is configured using the following channel properties: bottom slope, roughness, cross-section shape and reach length. The practical application of this method deserves further investigation, and compared with the commonly used Muskingum-Cunge method.

(d) Hydrodynamic models

(1) The Environment Agency has commissioned a number of investigations under the "Benchmarking of Hydraulic Models" project (e.g. Crowder *et al.*, 2004) to which the reader is referred for more detail of the differences between different model codes. The main model codes adopted for use by the Environment Agency are ISIS, Mike-11 and HEC-RAS. The main differences, apart from computational methodology, affect the handling of river channel water transfers, sinuosity, static water bodies, channel roughness, wind drag, river structures and out-of-bank flows. Because of their sound physical basis, they are well suited for application to ungauged rivers. However, the simplification of flow process representation and configuration combined with the essentially empirical nature of roughness makes model calibration desirable at gauged sites, transferring the experience gained to ungauged site applications.

(2) The method of estimation of ungauged lateral inflows to river reaches represented by a hydrodynamic model may prove critical to forecast performance, if these inflows account for a significant water volume in relation to those in the receiving stream. The detail of the hydrodynamic modelling may raise false expectations of model performance in such situations.

(3) Special considerations need to be applied when transferring a hydrodynamic model configured for design use to one to be used in real-time flow forecasting. This includes ensuring good performance is maintained over the full flow range, possibly requiring the addition of nodes and river structures to deal with low river-levels, and the removal of detail important only to the design study.

(e) Flood mapping tools

(1) Animated spatial displays of observed and modelled water levels are useful to depict the spatial extent and severity of flood inundation. It is common for some form of GIS (Geographical Information System) to be used to provide this functionality. The degree to which the GIS itself is used for inference of mapped information or an external model or observations will depend on the detail of the application.

(2) While flood mapping tools are commonly used with 1-D, 2-D and 3-D hydrodynamic model outputs, there is also great scope to use distributed hydrological forecasting model outputs to produce spatial maps of river flow, flood inundation and related quantities over time. Some early prototyping of these opportunities has been done using the Grid-to-Grid hydrological model. Model outputs in gridded form are exported to HYRAD and displayed as animated images of river flows propagating down the modelled river network along with fields of soil moisture deficit and local runoff. Also, time-series hydrographs can be extracted and viewed for any location (gauged or ungauged) down the river network. Further work leading to operational implementation is recommended here.

4 Digital datasets to support modelling ungauged locations

4.1 Overview

Over the last decade the increased availability of digital spatial datasets on terrain and properties of soil, land cover and geology has revolutionised what is possible in hydrological modelling. The old practice of using time-consuming mapwork to derive properties, usually simplified to “catchment characteristics” to make the task bearable, had a huge influence on what could be done. Ungauged modelling approaches tended to be limited to lumped rainfall-runoff models and parameter regressions on catchment characteristics, which proved arduous but practical. As digital datasets became increasingly available, particularly Digital Terrain Models (DTMs), the first applications focussed on automating catchment characteristic derivation. There was inertia in moving on from the parameter regression approach which was now much easier to implement and opened up many opportunities to invent new characteristics aggregated to the catchment scale. The complexity of physics-based distributed models and disappointments in their performance for forecasting purposes were further reasons for digital datasets not being used as fully as possible in model formulation. There are now great opportunities to explore new conceptual-physical formulations linked directly to spatial datasets rather than to derived characteristics at the catchment scale.

Tables 5.1, 5.2 and 5.3 of the Science Report provide an inventory of spatial datasets that may be of value in support of modelling for ungauged flood forecasting purposes. These concern datasets on soil and geology, land cover and terrain respectively. The most useful soil datasets with England and Wales coverage are held by the National Soil Resources Institute (NSRI). Those of most interest to a physics-conceptual approach to modelling concern the more basic soil properties of saturated hydraulic conductivity, water content at field capacity, pore space, Integrated Air Capacity, and van Genuchten parameters. The HOST (Hydrology of Soil Types) are of lesser interest and emerged as a requirement of the “catchment characteristic” era of ungauged flood modelling, for which they continue to have value. Notable omissions from the list of advertised products are total soil depth and residual soil moisture content. These datasets are available at resolutions of 1, 2 or 5 km but only under license. A combination of HOST and SEISMIC datasets have been used by CEH to derive basic properties on a 1 km grid for ungauged modelling purposes; an example, for soil depth over the Upper Thames and Stour catchments, is shown in Figure 4.1. Hydrological modellers only able to utilise free products, or with global modelling interests, usually turn to the IGBP soil dataset with ~9 km resolution over the UK. This contains soil water content at field capacity and wilting point, available water capacity, saturated hydraulic conductivity and Van Genuchten parameters. Model performance at the catchment scale in flood forecasting applications is likely to be compromised if the NSRI datasets are not used.

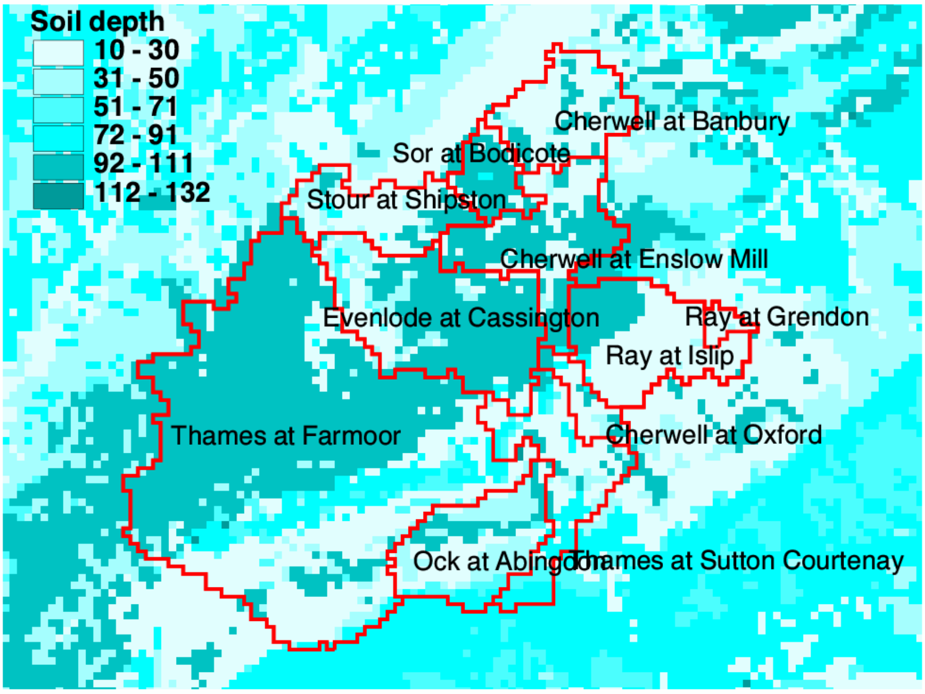


Figure 4.1 Map of soil depth (cm) over the Upper Thames and Stour derived from HOST/SEISMIC

For land cover, the CEH land cover dataset available at 25m or 1 km resolution would be the first choice for use over England and Wales. Spatial-temporal datasets on remotely-sensed land properties are becoming available from operational satellites. Of particular interest to hydrological modelling is the MODIS/Aqua Leaf Area Index, updated every 8 days on a 1 km grid. This can have value in modelling seasonal variations in evaporation loss, for example from growing crops, that impact on the water balance and runoff production.

For terrain data, the natural choice for hydrological modelling over England and Wales is the IHDTM (Integrated Hydrological Digital Terrain Model). It is provided on a 50m grid and includes elevation, flow directions, cumulative drainage area and surface type. Figure 4.2 provides a good example of its use to depict relief and to automatically infer river networks and catchment boundaries. It also shows the derivation of approximate river paths and catchment boundaries for use with 1km grid-based hydrological models, such as the Grid-to-Grid Model. The example is for the River Kent to Sedgwick gauging station, just south of Kendal in the Lake District; four sub-catchments are also delineated.

For hydrodynamic river modelling and floodplain mapping purposes the Environment Agency's LIDAR elevation dataset at 2m resolution has great value. The new NEXTMAP DTM at 5m resolution is of potential interest, and its utility for modelling requires investigation

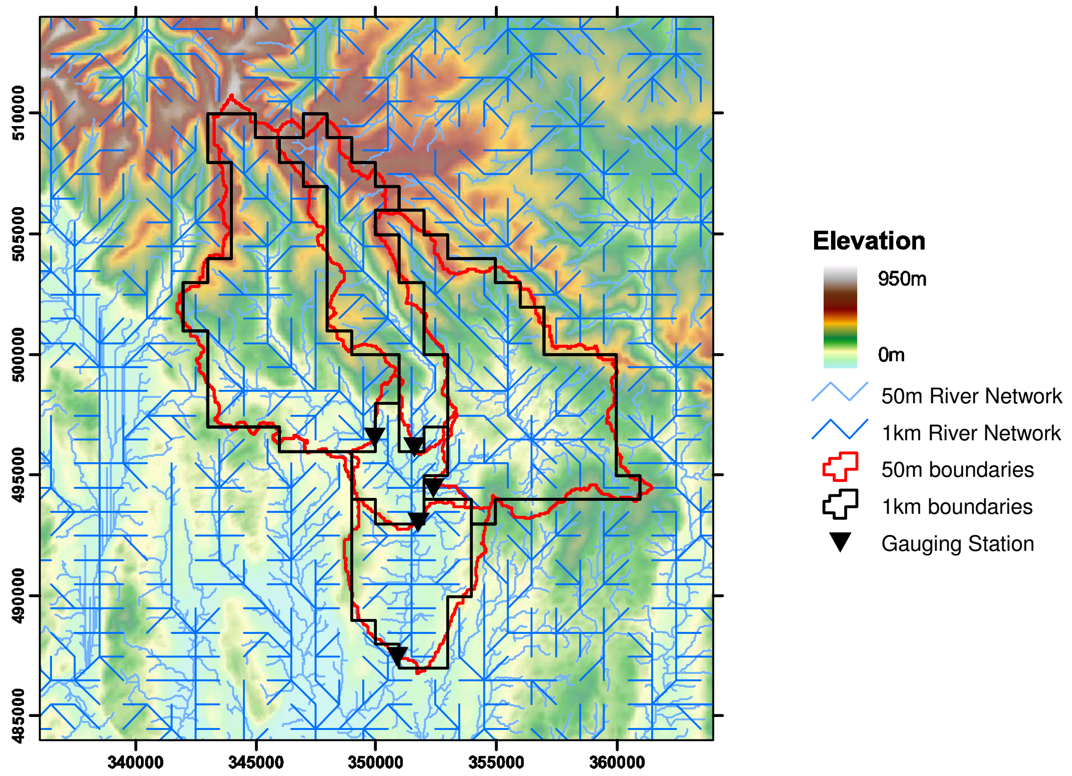


Figure 4.2 1km and IHDTM 50m resolution flow directions and catchment boundaries: River Kent catchment, Northwest England.

4.2 Conclusions and Recommendations

The following conclusions and recommendations can be made with regard to “Digital Datasets to Support Modelling Ungauged Locations”.

(1) A key growth area is the use of spatial digital datasets on elevation, soil and geology properties and land cover to underpin the configuration and parameterisation of process-based hydrological forecasting models, making them suited for application to ungauged locations.

(2) A review of relevant spatial datasets is provided in support of this modelling activity in the accompanying Science Report. These extend to include certain space-time datasets from satellite sensors: for example leaf area index (relevant to seasonal land cover effects on water balance) and processed images of flooded areas (useful for inundation model assessment purposes). New and improved datasets are appearing every year. It is recommended that a review of these be maintained in relation to their relevance to ungauged flood forecasting.

5 Statistical methods for forecasting

5.1 Overview

Statistical methods of forecasting are understood here to be empirical approaches leading to flexible forecasting rules with parameters that are calibrated using available data. They cover level-to-level correlation schemes, more generalised empirical forecasting schemes (including autoregressive flow predictors and neural network approaches) and the statistical simplification of hydrodynamic models (e.g. predictors based on tabulated “structure functions” obtained from a hydrodynamic river model) and hydrological models.

Statistical forecasting methods are not natural candidates for forecasting at ungauged locations, since they depend on observations for parameter calibration and forecast construction. They will not be considered further here in this overview. Some further consideration is given in Section 6 of the Science Report and in the conclusions and recommendations below.

5.2 Conclusions and Recommendations

The following conclusions and recommendations can be made with regard to “Statistical methods for forecasting” relevant to flood forecasting at ungauged locations.

(1) Statistical methods for forecasting are understood here to involve empirical model building resulting in a flexible forecasting rule with parameters that are calibrated using available data. They are essentially empirical methods, in contrast to the hydrological and hydrodynamic process-based mathematical models. Because of their dependence on observed data, they are not immediately applicable to ungauged forecasting: methods of transfer to the ungauged target site are required.

(2) Level-to-level correlation is arguably one of the best known and simplest statistical methods for forecasting, and usually focuses on forecasting peak river levels. When applied to gauged reaches upstream and downstream of a target ungauged location, a transfer method based essentially on interpolation (possibly incorporating a datum adjustment and time shift) can be devised for ungauged forecasting.

(3) Empirical forecast rules need not be limited to those based on linear functions, and may extend to embrace neural network methods for example.

(4) A hydrodynamic model configured for a river reach using known channel properties can be used to produce river level/flow outputs for ungauged locations from which a simplified empirical forecasting model may be derived. The simple predictive relationships so-derived may be of value in bringing computational savings or as the

basis of a back-up manual forecasting procedure. The methodology can also be used to extend the range of extremes experienced beyond those contained in historical records. Tabular “Structure Functions” derived from hydrodynamic model runs can be of value in forecasting peak water levels along a tidal estuary from upstream river flow and downstream peak tidal level.

6 Real-time updating techniques

6.1 Overview

Observations of river flow in real-time allow modelled flows for future times to be improved upon via real-time updating techniques. The most popular approaches are *state-correction* (where forecast errors are used to adjust model state values to achieve better agreement with observations) and *error prediction* (where dependence in errors over time is used to predict future errors). Updating normally requires observations being available for the target forecast site. However, it is feasible to consider the transfer of information from a gauged site to an ungauged target forecast site. This may involve the transfer of forecast errors at the gauged site to adjust forecasts from a model at the ungauged target site. There is clearly a risk in applying such *transferred-error* (inferred-error) updating schemes. In general, such schemes are best avoided until some successful experience in their use is first gained; a number of research opportunities are identified in the Science Report.

An important exception to the above general advice is where a simple scaling or transposition approach is used as the inference model. The simple scaling of past flow observations and updated forecasts at a source gauged location to provide flow estimates at an ungauged target location is straightforward, but needs to be undertaken with care and caution. The scaling factor can be defined in terms of the relative areas of the two catchments (and possibly SAARs). If the scaling factor is large, then the danger of amplifying forecast errors is likely to be greater and argue against use of the method.

The situation where transferred-error updating schemes are most likely to work is where an indirect modelling approach is used for the target ungauged location, where this location forms only part of a more extensive modelled area also containing river gauging stations. Any correction to modelled states for gauged sites are likely to form a useful basis for adjustment at ungauged sites, particularly if there is a physical basis to the model.

One updating approach identified as particularly deserving of further investigation, and applicable to transferred-error updating for ungauged locations, is the *two-pass state-correction* approach. This has potential for both rainfall-runoff and hydrological flow routing models. The approach is in some ways intermediate between error-prediction and state-correction schemes, and as such is particularly suited to situations where errors from conventional state-correction schemes are correlated over time (i.e. serially-correlated). The approach can also continue to correct model-states forward in time from the forecast time-origin. In the first pass, the model is run without state-correction to obtain simulation-mode error forecasts. The second pass includes state-correction based on an additive adjustment to the current state-set using a weighted sum of these simulation-mode errors. The corrected model states are used in the construction of forecasts at an ungauged location for which a similarly structured simulation model is applied.

6.2 Conclusions and Recommendations

The following conclusions and recommendations can be made with regard to "Real-time updating techniques" relevant to flood forecasting at ungauged locations.

(1) Transferring forecast errors from gauged to ungauged catchments is not recommended for routine use at the present time. Research is required on possible techniques leading to recommendations for operational use. One exception to this is the use of transferred-errors where the target location is modelled using a simple scaling or transposition approach. Even in this case, care needs to be exercised in the choice of suitable situations and the method of application.

(2) Research needs to be carried out on transferred-error updating schemes to gain experience that can be carried through to operational use. A particular priority is to investigate the two-pass state-correction approach to forecast updating. This provides an intermediate approach between error-prediction and state-correction and can be used to continue to correct states forwards in time from the time-origin of the forecast. It is applicable to both rainfall-runoff and channel flow routing models.

(3) The promise of improved forecasting at ungauged locations using physical-conceptual distributed models configured on a gridded domain encompassing gauged sites argues for research on real-time updating techniques for such models. There has been little progress to date in this challenging area.

7 Monitoring, forecasting and warning

7.1 Overview

Whilst the main attention in this guideline relates to modelling for ungauged locations, a few topics related to monitoring and flood warning deserve special mention in relation to ungauged areas. These concern areal rainfall estimation, remote-sensing, stage-discharge relations and trigger mechanisms for flood warning.

Areal rainfall estimation

The method of areal rainfall estimation for catchment and grid-square domains can be of significant importance to forecast accuracy, for both gauged and ungauged areas. One aspect is the monitoring of rainfall by raingauge and weather radar networks, their quality control (QC) and their best use as separate or combined sensors of rainfall. A further, and related, aspect is the method of interpolation over space used to construct catchment and grid-square estimates of rainfall needed as input to lumped and distributed hydrological forecasting models. The Met Office Nimrod QC product provides a state-of-the-art rainfall product for Environment Agency use whilst CEH's Hyrad system provides facilities to visualise and to interface this rainfall product to modelling and forecasting systems. Methodologies for areal rainfall estimation, based on multiquadric surface fitting (and with links to Kriging methods), are reviewed in the Science Report (Appendix C) and shown to reduce to simple linear weightings of the rainfall sensor values for the spatial areas of interest (catchments or grid-squares).

Remote sensing

Weather radar is a ground-based form of remote sensing configured for rainfall measurement. There are other important forms of monitoring by remote-sensing that are satellite-based. Some have already been commented on, especially as a source of elevation and land cover data. Whilst these datasets are often considered static, there is now increasing availability of time-history spatial datasets of leaf area index, snow cover, area of flood inundation and surface soil moisture. These have relevance both to the monitoring and modelling/forecasting of ungauged areas.

An exciting prospect is the ability to remotely sense river level (and width) from which to develop flow discharge estimates. However, the state-of-the-art suggests some progress with optical imagery for the larger rivers of the world but probably limited applicability for the scale of river encountered in the UK. A combination of GPS (global positioning system) technology and a tethered floating buoy has been investigated in field trials and through computer simulation of anticipated satellite position systems. This is now seen as emerging technology that has potential use for some ungauged locations in the UK as the supporting satellite network improves.

Stage-discharge relations

Stage-discharge relations for ungauged locations have importance in a number of situations, including their potential use with the remote sensing of river levels discussed above. Flow from a hydrological model of an ungauged site may require conversion to river level for flood warning purposes. A rating may need to be inferred from a hydrological model for a “level-only site” in order to calibrate the model and to use the levels for forecast updating in real-time. Procedures for embedding a stage-discharge relation within a hydrological model are available within CEH’s Model Calibration environment. Standard procedures for extending rating curves at gauging stations, by hydraulic-geometry extrapolation and using hydrodynamic river models, have been reviewed by Ramsbottom and Whitlow (2003) for the Environment Agency. These procedures also have relevance for developing ratings at ungauged locations.

Flood warning trigger mechanisms

A key component of the flood warning operation is the *trigger mechanism* used to stimulate action in advance of flooding occurring. The mechanism might involve the crossing of a critical condition (e.g. bankfull discharge) at a location that is ungauged. The action may be to disseminate a flood warning or to upgrade the level of flood surveillance. The quality of the methods of forecasting for an ungauged site will clearly impact on the success of the action. Knowledge of the *uncertainty* associated with the forecast, and consideration of the *costs of alternative actions*, can form the scientific basis of effective *decision-making* for flood warning operations. Developing such an approach to decision-making is seen as an important future challenge and relevant to both gauged and ungauged locations at threat from flooding and requiring effective warning.

7.2 Conclusions and Recommendations

The following conclusions and recommendations can be made with regard to aspects of “Monitoring, Forecasting and Warning” relevant to flood forecasting at ungauged locations.

(1) The method of areal rainfall estimation can be a major influence on the performance of rainfall-runoff models. Correction (quality-control) of radar data and their combination with raingauge data can significantly improve the robustness and accuracy of rainfall estimates for catchment and grid-square areas. Some procedures for combining raingauges alone, and radar data in combination with raingauges, are reviewed in the Science Report for guidance when applying rainfall-runoff models.

(2) Remote sensing has proved particularly valuable in providing elevation and land cover data with wide-area coverage and improved resolution and accuracy. These data are invaluable to the configuration and parameterisation of flood forecasting models in ungauged areas. Some space-time satellite datasets can be of value to model assessment (flood inundation extent for example) and in support of time-varying parameterisations (leaf area index for example).

(3) The remote sensing of water level offers the prospect of remotely inferred river levels and flows of use in flood forecasting for any location. There has been some progress of use for the larger rivers of the world but the approach has little applicability for UK conditions at the present time. GPS technology used in combination with a

tethered buoy offers the potential of a low-cost gauging method: satellite developments in the future may eventually make this worth considering for application in the UK.

(4) An ungauged site may have no measurement at all or a measurement of river level but no rating curve (a level-only site). Where a rating is required then the Environment Agency's best practice guidance manual on "Extension of rating curves at gauging stations" provides a convenient reference source for developing rating curves using simple hydraulic techniques or computational hydraulic models. The CEH Model Calibration Environment supporting the KW, PDM and PSM (TCM and IEM) models also provides facilities to embed an unknown rating curve within the model formulation.

(5) The Environment Agency's "A best practice guide to the use of trigger mechanisms in fluvial flood warning" provides advice on setting a trigger mechanism to stimulate action in advance of a flood. The information used may concern observations and/or forecasts of river level or flow. Such information may be provided for ungauged sites using the methodologies outlined here and in the Science Report, with the appropriate degree of caution. This highlights the need for research on assessing the uncertainty of forecasting at ungauged sites, on the costs of alternative actions, and on placing decision-making for flood warning on a sounder scientific footing.

8 Closure

8.1 Practical illustration of some ungauged forecasting methods

To conclude this operational guideline, it is pertinent to consider providing an illustration of the practical application of selected methods of model transfer to ungauged catchments. The focus of this guideline, and the accompanying Science Report, has been on reviewing existing methods, as well as considering new improved ones, and not in providing examples of their practical application.

To provide more practical guidance, Appendix D of the Science Report considers a selection of methods of model transfer to ungauged catchments and uses case study catchments to illustrate their application. This appendix thereby serves to provide practical guidance on the application of a selection of methods considered here, some in prototype form.

It does not aim to be comprehensive and is limited to examples of rainfall-runoff model transfer and their simulation performance, excluding consideration of the real-time updating of flood forecasts by transfer methods.

8.2 Closing remarks

The ungauged flood forecasting problem is at the heart of hydrological science and its application. As such, it is a problem that is being addressed by many researchers and practioners across the globe in different ways. A recent perspective on issues in flood forecasting for ungauged basins, with UK applications, was presented at the Kovacs Colloquium on 'Frontiers in Flood Research' (Moore *et al.*, 2006).

One mechanism for co-ordinating this global activity has been provided by the International Association of Hydrological Sciences (IAHS) declaring 2003-2012 as the IAHS Decade on Predictions in Ungauged Basins with the acronym PUB. The PUB forum provides an opportunity to share ideas at specialist workshops, such as that held in Perth in February 2004 (Franks *et al.*, 2005). Conclusions of this workshop, of particularly relevance here, were the need for (i) data at nearby or similar sites, (ii) improved process-based models to reduce the reliance on data elsewhere, (iii) intercomparison and integration of diverse techniques as a means of improving estimation, and (iv) quantification of uncertainty of estimates to assess their worth for application.

Of especial interest to improvements in modelling is the DMIP (Distributed Model Intercomparison Project) in the USA (Smith *et al.*, 2004) which has now entered a second phase.

In the UK, the Natural Environment Research Council's FREE (Flood Risk from Extreme Events) initiative has ungauged flood forecasting as an important component of its 5 year Science Plan with implementation starting in 2006.

It will be important to engage in and monitor such national and international activities to ensure knowledge transfer of useful outcomes to operational practice in flood forecasting and warning for ungauged locations.

References

Crowder, R.A., Pepper, A.T., Whitlow, C., Sleigh, A., Wright, N. and Tomlin, C. 2004. Benchmarking of hydraulic river modelling software packages: Project Overview. *R&D Technical Report W5-105/TR0*, Environment Agency, Bristol, 14pp plus Appendix.

Franks, S.W., Sivapalan, M., Takeuchi, K. and Tachikawa, Y. (eds.) 2005. Predictions in ungauged basins: international perspectives on the state of the art and pathways forward. *IAHS Publ. 301*, 348pp.

Moore, R.J., Bell, V.A., Cole, S.J. and Jones, D.A. 2006. Rainfall-runoff and other modelling for ungauged/low-benefit locations. Science Report – SC030227/SR, Research Contractor: CEH Wallingford, Environment Agency, Bristol, 246pp.

Moore, R.J., Cole, S.J., Bell, V.A. and Jones, D.A. 2006. Issues in flood forecasting: ungauged basins, extreme floods and uncertainty. In: I. Tchiguirinskaia, K. N. N. Thein & P. Hubert (eds.), Frontiers in Flood Research, 8th Kovacs Colloquium, UNESCO, Paris, June/July 2006, *IAHS Publ. 305*, 103-122.

Ramsbottom, D.M. and Whitlow, C.D. 2003. Extension of rating curves at gauging stations. Best Practice Guidance Manual. *R&D Manual W6-061/M*, Research Contractor: HR Wallingford in association with Eden Vale Modelling Services, Environment Agency, 254pp

Smith, M.B., Georgakakos, K.P., and Liang, X.(eds.) 2004. The Distributed Model Intercomparison Project (DMIP). Special Issue, *J. Hydrol.*, **298**(1-4), 1-334.

We are The Environment Agency. It's our job to look after your environment and make it **a better place** – for you, and for future generations.

Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

The Environment Agency. Out there, making your environment a better place.

Published by:

Environment Agency
Rio House
Waterside Drive, Aztec West
Almondsbury, Bristol BS32 4UD
Tel: 0870 8506506
Email: enquiries@environment-agency.gov.uk
www.environment-agency.gov.uk