5 Progress and Directions in Rainfall-runoff Modelling

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In hydrology there are many examples of natural systems which have the property, discussed in Chapter 2, that there is a loss of information or a smoothing between inputs and outputs. Hydrological systems are complex and heterogeneous, and yet, for a river basin, their integrated response to climatic inputs is simply represented by the relatively smooth variation of streamflow discharge rate with time. Hence, a wide range of alternative approaches has been taken to hydrological modelling, and in particular to rainfall-runoff modelling, encompassing quite different modelling philosophies.

At the simplest level, all that is required to reproduce the catchment-scale relationship between storm rainfall and stream response to climatic inputs is a volumetric loss, to account for processes such as evaporation, soil moisture storage and groundwater recharge, and a time distribution function, to represent the various dynamic modes of catchment response. However, a spectrum of approaches of varying complexity exists in which component processes can be explicitly represented within a modelling framework with different levels of mathematical and physical approximation and different levels of spatial aggregation..

Set against this spectrum of models is a range of tasks. This includes a set of purely hydrological issues, but increasingly, hydrological models are required as an essential input to the study of wider environmental problems. Hydrological fluxes provide the advective components for solute transport in soils and groundwater systems (Chapter 6), and hydrological pathways

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determine the chemical interactions that characterise streamwater quality (Chapters 4 and 7). The sustainability and productivity of ecological systems is inextricably linked to the hydrological regime (Chapter 10), and impacts of climatic variability and climatic change on the terrestrial ecosystem depend on hydrological response. Indeed, the climate system itself is strongly influenced by the hydrological response of the land surface, and models of the atmospheric general circulation must account for the hydrological boundary conditions for atmospheric processes (Chapters 14 and 16).

For purely hydrological problems, selection of an appropriate level of model complexity for a particular problem is far from straightforward. Apart from the obvious increase in data and computational costs with increasing model complexity, there are important issues concerning the identifiability of parameters or ill-conditioning (Chapter 2) in complex models, the extent to which physical characteristics can be specified a priori, and scale-dependence, for example the extent to which small-scale heterogeneity can be represented by equivalent processes at larger scale.

For the broader range of environmental problems, an essentially similar set of issues must be addressed. Commonly, problems of complexity are exacerbated, as for example where a coupled set of hydrological, chemical and/or biological processes must be considered, and current interest in global modelling (Part IV of this book) for climate change studies is requiring fundamental problems of scale and aggregation to be addressed.

The aim of this chapter is to review the range of available hydrological modelling approaches in the context of known behaviour of hydrological systems and hence to discuss appropriate modelling strategies for a representative range of modelling tasks.

ALTERNATIVE APPROACHES TO HYDROLOGICAL MODELLING

GENERIC MODEL TYPES AND THE HISTORICAL PERSPECTIVE

To a major extent, hydrological model development has been influenced, perhaps overly so, by advances in computing power. In the 1930s, methods of linear systems analysis were developed which could be applied manually. The availability of digital computers in the 1960s led to the ability to combine simplified representations of hydrological processes in a more comprehensive conceptual representation of catchment-scale hydrological systems. As computing power has increased further, the component

descriptions have attempted to move closer to the underlying physics, for example through numerical solution of the nonlinear partial differential equations held to govern water flow in partially-saturated porous media. Thus in the 1970s and 1980s *physics-based* hillslope and catchment models emerged. These modelling approaches can be broadly classified into three generic model types. Following Beck (1991) (although such classifications have significant overlaps), these are metric, conceptual and physics-based. It is however, important to examine critically the impact of this technologically-driven development.

METRIC MODELS

The essential characteristic of metric models is that they are based primarily on observations and seek to characterise system response from those data. The hydrological origin of the metric approach is the development of unit hydrograph theory for catchment-scale simulation by Sherman (1932). Conventionally, the streamflow hydrograph is split into quick $x^{(q)}(t)$ and slow $x^{(s)}(t)$ response components (stormflow and baseflow). The unit hydrograph $h(t)$ is the stormflow response at time t to a unit input of rainfall excess $u(t)$. Rainfall excess is that part of the rainfall which eventually becomes stormflow, that is rainfall minus evapotranspiration losses, changes in storage and baseflow contributions. The original unit hydrograph concept considers only event response, thus eliminating complexities of continuous moisture accounting, evaporation and long-term dynamics. Process nonlinearities are excluded from the model through the separation of a baseflow and rainfall losses. Stormflow is modelled explicitly as a linear, time invariant function of effective rainfall, i.e. its convolution with the unit hydrograph. Thus

$$x^{(q)}(t) = \int_0^t h(t-s)\ u(s)\ ds \qquad (1)$$

and commonly some nominal representation is made of the baseflow component. The model thus synthesises streamflow response to rainfall by a loss function and a linear model, satisfying the basic requirements of hydrological modelling noted earlier. However, a major strength of the method is in analysis. Once the stormflow and effective rainfall components of an observed response have been separated, a unit hydrograph can be derived, characterising the event response. The variability of the unit hydrograph can be established by analysing data from a range of events.

Much research in the 1950s and 1960s focused on alternative conceptual formulations of the linear response functions, and on methods of identification (e.g. Nash, 1960; O'Donnell, 1966). Having characterised a system uniquely through linear analysis, the variation of catchment response with catchment physiographic and climatological characteristics can be explored through regional analysis (e.g. NERC, 1975) and inter-event variability investigated (e.g. Wheater *et al.*, 1982). Hence the unit hydrograph has been extensively used as a regional design tool.

The conventional unit hydrograph methods exclude formal modelling of baseflows and hence simulation between events when stormflow has waned. However, simple extension for such continuous simulation is possible. For example, the CLS model of Natale and Todini (1977) provides two parallel linear response functions with a switch between the two, dependent on aggregated antecedent precipitation. Recently, more general techniques of advanced time-series analysis have been used to extend the concept of metric analysis to linear and nonlinear analysis using algorithms such as the Kalman filter (Beck *et al.*, 1990) and instrumental variable methods (Jakeman *et al.*, 1990). The latter approach will be discussed in the section on hybrid metric-conceptual models.

CONCEPTUAL (LINGUISTIC) MODELS

With the development of digital computers, it became possible to design hydrological simulation models of much greater complexity. Thus the Stanford Watershed Model was developed (Crawford and Linsley, 1966) to represent all of the component hydrological processes perceived to be of importance in catchment-scale input-output relationships. Over the succeeding period of nearly three decades, hundreds, at least, of alternative conceptual models have been developed. These models vary considerably in complexity, but are invariably based on a representation of internal storages, generally associated explicity with particular hydrological components. However, hypotheses of catchment-scale response are not often explicitly incorporated, a notable exception being TOPMODEL (Beven and Kirkby, 1979). The essential features of all of these models are that (i) the model structure is specified a priori, according to the perception of the important component processes (hence the analogy with the *linguistic* classification of Beck, 1991); and (ii) parameter adjustment, through calibration against observed data, is required to optimise parameter values to represent the system of interest.

The *system identification* (Chapters 1 and 2) or calibration process requires the definition of a criterion or criteria for the goodness of fit of the simulated and observed responses. An important divergence of philosophy occurs. Manual optimisation uses the skill of the model user to progressively refine parameter sets in a subjective process using *system simulation* (Chapter 2). Often particular features of the output are considered to guide trial and error parameter adjustment. For example volume errors, errors in peak flow and recession rates and errors in low flow values are likely to suggest the need for refinement of different aspects of the model parameterisation. A range of error statistics can be consulted to aid this process. However, the process is never complete; optimisation is stopped when performance is considered *adequate* to meet the particular objectives, constrained by resource availability (usually time).

The alternative approach is to pursue an objective optimisation procedure, using computer algorithms to refine parameter estimates. Thus the optimisation is formalised for n model parameters as the maximisation (or minimisation) of an objective function in a $(n+1)$-dimensional hyperspace. A single criterion of performance must generally be adopted, although this may represent a composite measure. The optimisation problem is complete when a global maximum is identified.

As noted by Wheater *et al.* (1986), the shape of the objective function is determined by three factors: the field observations; the model structure and its parameters; and the type of estimator including assumptions of error structure.

With respect to the second, it has long been demonstrated (Ibbitt, 1970) that common structural features such as thresholds and parameter interdependence create major problems for optimisation algorithms, and the practical consequences are well documented. Thus, for example, Pickup (1977), using a 12-parameter version of the Boughton (1965) model, generated a synthetic error-free data series and, using a least-squares objective function, was unable to recover the *true* parameters using various representative search algorithms. Johnston and Pilgrim (1976), using a nine-parameter version of the same model, were unable, after extensive trials over a 2-year period, to locate a global optimum parameter set.

With respect to the type of estimator, extensive research has been undertaken on different optimisation methods. Alternatives to the sum of squared-errors criterion were investigated by Dawdy and Lichty (1968) and Chapman (1970) among others. Sorooshian *et al.* (1983) and Sorooshian and Gupta (1983) investigated least-squares and maximum likelihood methods, for five and eight-parameter submodels, and demonstrated that poor performance in fitting using maximum likelihood methods was accompanied by improved prediction, usefully illustrating the difference between calibration performance and predictability. However, the authors note that in more complex models, structural problems inhibit the application of likelihood methods. Duan *et al.* (1992) pursued global optimisation procedures in an attempt to overcome the problem of local optima apparent with only a six-parameter model.

Wheater *et al.* (1986) and Kleissen (1990) developed methods which include consideration of field observations in defining subsets of the data for which parameter sensitivity is greatest, analogous to the subjective approach of an experienced model user. However, while all of the above can demonstrate some marginal improvement in optimisation performance under certain circumstances, the overall general problem of lack of convergence to a global optimum for most applications has remained.

The essential problem, as discussed by Wheater *et al.* (1986), Beck *et al.* (1990), and Jakeman and Hornberger (1993), for example, is that the model complexity exceeds the information content of the available data – the ill-conditioning or identifiability problem addressed earlier in Chapter 2. One solution is to reduce model complexity to an appropriate degree, as suggested by Nash and Sutcliffe (1970). This can be achieved by use of identification statistics (e.g. Jakeman *et al.*, 1990), or sensitivity analysis (e.g. Hornberger *et al.*, 1985; Sorooshian and Gupta, 1985), whereby the complexity of the model is reduced by holding insensitive parameters constant or formally re-structuring the model. The effect, of course, especially in the latter case, is to move the model away from its original conceptualisation and towards the metric approach.

The difficulties associated with lack of identifiability of conceptual models have important consequences, and, as discussed by Moore and Clarke (1981), have severely restricted the range of potential application of such models. However, the interface between metric and conceptual models offers scope to address these problems, and is discussed below in the context of hybrid metric-conceptual models.

PHYSICS-BASED MODELS

As computing power has increased, it has become feasible to represent the component processes within hydrological models in a more classical mathematical-physics form, based on continuum mechanics, through numerical solution of the relevant equations of motion using a finite difference (Chapter 4) or finite element spatial discretisation. Freeze (1972) developed the first such model, in which finite difference methods were used

to solve Richards' equation (Chapter 6) for unsaturated flow in two dimensions to represent hillslope processes, and streamflow was represented through numerical solution of the St-Venant equations of gradually varied unsteady flow. More recently, models such as the Institute of Hydrology Distributed Model (IDHM) (Beven *et al.*, 1987) and the Système Hydrologique Européen (SHE) model (Abbott *et al.*, 1986; Bathurst, 1986) have been developed with essentially similar mathematical formulations although with more complete micrometeorological process representation.

Such models are a powerful compilation of the relevant idealised processes, but raise a number of important issues, as articulated by Beven (1989), and earlier by Woolhiser (1971). The major problems are most obvious in the representation of subsurface processes. Natural soils are generally structured and heterogeneous. A scale problem emerges, since within the numerical solution scheme of the above models, soil properties are represented by homogeneous elements, of dimensions which are problem-specific, but may range in typical applications from 10^4 to 10^6 m^2. The extent to which subgrid-scale heterogeneity can be represented by effective properties of a uniform element is still open (see Binley *et al.*, 1989; Binley and Beven, 1989; Zhu *et al.*, 1990). However, indications from this and other recent work are that where strong process nonlinearities are present, as when overland flow is generated from saturated areas, effective parameters cannot represent the ensemble heterogeneous response. An extreme case of heterogeneity is the presence of macropores (e.g. Beven and Germann, 1982) which cannot be directly represented in current, continuum-based model formulations.

A second problem concerns observability. In principle the parameters of physics-based models are measurable (if only in the context of a model such as Darcy's Law), but in practice this cannot be achieved at the required scale for model discretisation; such measurements are essentially made at a point. In addition, for most purposes, extensive field investigation is impractical (Stephenson and Freeze, 1974). The practical result in application to specific catchments is a very large number of unknown parameters. Their values can be estimated, for example from generalised soil descriptions, but the uncertainties are sufficiently large to encompass a wide range of process responses. If such a model is calibrated to observed input-output data, the degrees of freedom are so large that the parameters cannot be uniquely identified. Even for well-defined laboratory soil column experiments, lack of identifiability can be demonstrated (Abeliuk and Wheater, 1990). Hence, in application to gauged catchments the problems of parameter identification, discussed in the context of conceptual models, are exacerbated.

HYBRID METRIC-CONCEPTUAL MODELS

The aim of this approach is to use observations (the metric paradigm) and other prior knowledge to test hypotheses about the structure of component hydrological stores (the conceptual paradigm) at catchment scale. This could also be viewed as a system identification approach and is one that has not been applied sufficiently in hydrology to examine the credibility of postulated models.

The work presented in Jakeman *et al.* (1990), Jakeman and Hornberger (1993), Beck *et al.* (1990), Young and Beven (1991) and Kleissen *et al.* (1990a) illustrates this approach. To take the first example, the unit hydrograph concept is used in assuming that, after adjustment of rainfall r_k at time step k for losses l_k dependent on antecedent conditions, the total streamflow x_k is a linear response to effective or excess rainfall $u_k = r_k - l_k$. Equation (*1*) is the continuous time version of the linear relationship and importantly it was found that total streamflow, not just stormflow, can be represented by such a linear response to excess rainfall. This negates the need for arbitrary extraction of some baseflow from streamflow for unit hydrograph analysis. The integral equation (*1*) can be approximated by a discrete time transfer function of order (n, m) such that

$$x_k + a_1 x_{k-1} + \ldots + a_n x_{k-n} = b_o u_k + b_1 u_{k-1} + \ldots + b_m u_{k-m} \quad (2)$$

This is a configuration of n linear storages connected in parallel and/or series paths for the transit of excess rainfall to stream. The number of connected storages n and the order m influence the nature of the parallel-series configuration. For example, $n=2$ and $m=0$ corresponds to two storages connected in series, whereas $n=2$ and $m=1$ corresponds to two parallel storages.

The order (n,m), or configuration, and parameter values are determined by statistical identification exercises using time series data on rainfall and streamflow. Estimation of a loss model also requires measured climatic time series related to evapotranspiration, the Celsius temperature t_k being the variable most often available. The loss model developed in Jakeman and Hornberger (1993) calculates an index of catchment storage at each time step k according to

$$s_k = c\, r_k + [1 - 1/\tau_w(t_k)]\, s_{k-1} \quad (3)$$

$$\tau_w (t_k) = \tau_w \exp[(20-t_k)f] \quad (4)$$

The term $\tau_w(t_k)$ is inversely related to the rate at which catchment wetness declines (or potential evapotranspiration); this is arbitrarily defined as a constant τ_w at 20°C. The parameter f is a temperature modulation factor which accounts for fluctuations in potential evapotranspiration. It determines how $\tau_w(t_k)$ changes with temperature. The value of the parameter c in equation (*3*) is set so that the volume of rainfall excess is equal to the total streamflow volume over the calibration period. It is the increase in catchment wetness index s_k per unit rainfall in the absence of any decrease in catchment storage. The effective rainfall u_k and the losses l_k can then be computed using

$$u_k = s_k\, r_k \quad (5)$$

$$l_k = (1-s_k)\, r_k \quad (6)$$

Whether or not such an adjustment for antecedent conditions using the loss model (*3*)–(*5*) is applied, Jakeman and Hornberger (1993) have illustrated that, at least in temperate catchments, only two components (parallel storages) of the linear response in equation (2) to effective rainfall can usually be identified from rainfall, temperature and streamflow time series. Their findings are consistent with the work of Loague and Freeze (1985), Hornberger *et al.* (1985), Beven (1989) and Jakeman *et al.* (1990) who note or show the ability of small parameterisations in rainfall-runoff models to reproduce most of the information in a hydrological record. The study of Jakeman and Hornberger (1993) covers catchments from 490 m^2 to 90 km^2. Subsequently, Jakeman *et al.* (1993a) have also identified only two response components for the much larger basins of Teifi in Wales (894 km^2) and the French Broad River in North Carolina (767 km^2).

When only two parallel storage components are identified, these are called quick and slow flow components, and the associated quick and slow streamflow outputs can be parameterised as

$$x_k^{(q)} = -\alpha_q x_{k-1}^{(q)} + \beta_q u_k \quad (7)$$

$$x_k^{(s)} = -\alpha_s x_{k-1}^{(s)} + \beta_s u_k \quad (8)$$

$$x_k = x_k^{(q)} + x_k^{(s)} \quad (9)$$

The parameter α_q (α_s) describes the rate of decay, or equivalently the time constant τ_q (τ_s) of the quick (slow) hydrograph following a unit input of effective rainfall; $\tau_q = -\Delta/\ln(-\alpha_q)$, $\tau_s = -\Delta/\ln(-\alpha_s)$ where Δ is the time sampling interval. The parameter β_q (β_s) defines the peak of the quick (slow) component of the unit hydrograph. The relative volume v_q (v_s) of water passing through the quick (slow) component is a function of α_q and β_q (α_s and β_s); $v_q = \beta_q/(1 + \alpha_q)$, $v_s = \beta_s/(1 + \alpha_s)$. The quantities c, f, τ_w of the loss model and τ_q, τ_s, $v_q = (1\text{-}v_s)$ of the unit hydrograph are called dynamic response characteristics (DRCs) of the catchment.

OBSERVATIONAL EXPERIENCE OF HYDROLOGICAL SYSTEMS

The above discussion has introduced a diverse set of modelling approaches, embracing quite different modelling philosophies. In this section the interpretation of catchment response from field experimental research is reviewed, to provide an essential perspective from observational experience on appropriate modelling strategies.

CONCEPTS OF CATCHMENT RESPONSE

Early concepts of catchment response were dominated by the ideas of Horton (1933), who hypothesised that a hydrograph could be considered to be comprised of a rapid response component, due to the occurrence of overland flow when rainfall intensity exceeds the soil precipitation capacity, and a slow baseflow response arising from deep percolation to groundwater. This thus conveniently reinforced the concept underlying conventional unit hydrograph analysis. Although alternative ideas of catchment response were proposed in the 1930s (Lowdermilk, 1934; Hursh, 1936), it was not until the 1960s that the Horton model was widely questioned. It became apparent that, at least in many humid, well-vegetated areas, infiltration rates did not exceed infiltration capacity, and extensive overland flow was not observed. Further, overland flow rates are extremely rapid, much more so than the *fast* streamflow response component. Experimental observations (eg. Hewlett and Hibbert, 1963) also indicated that *baseflow* could be explained by slow drainage of shallow soils, without invoking a conventional groundwater response.

Alternative hypotheses were required, and a debate ensued on the role of throughflow (i.e. lateral flow within the soil profile). Freeze (1972), in a two-dimensional numerical analysis of hillslope behaviour, concluded that

lateral flows were insignificant for the range of hydraulic conductivities conventionally associated with representative soil types, which supported a number of field observations. For example, Dunne and Black (1970) noted that, at a site in the Eastern USA, subsurface flows were too small, too slow, and too insensitive to supply stormflow to the channel hydrograph.

Where throughflow was not significant, an alternative hypothesis was required, and studies by Hewlett and Nutter (1970), Dunne and Black (1970) and others identified variable source areas for runoff generation. Such areas tend to develop at the base of slopes, and in thin soils, where downslope drainage, enhanced by topographic convergence, tends to maintain soils near saturation. During a storm event, surface saturation of these areas can rapidly occur, leading to runoff generation from incident precipitation and downslope return flows. Such areas were observed to expand during storm events, and to vary seasonally according to antecedent conditions.

On the other hand, Whipkey (1965), in a study of a forested slope in Ohio, showed that large and responsive sub-surface flows could occur when a perched water table developed within the soil profile, and his data implied extremely high effective permeabilities from near-surface soils. This raises the issue of macropores, reviewed by Beven and Germann (1982), which can arise from a variety of causes, particularly, in the case of forested soils, decayed roots, earthworms and other animal activity. Other forest experiments have similarly demonstrated rapid downslope transmission (e.g. Wheater *et al.*, 1987) and in other environments where macropores are known to occur, extremely rapid flow rates have been observed (e.g. Muscutt *et al.*, 1990).

Reviews such as Chorley (1978) define a spectrum of hydrological response mechanisms. Hortonian overland flow certainly occurs under particular circumstances and in certain environments, most notably arid and semi-arid areas. In humid areas, variable source area concepts are generally held to apply, although the importance of throughflow is acknowledged under certain circumstances.

However, such neat categorisation may be simplistic. A study by Pilgrim *et al.* (1978), on a small, apparently uniform, grassed hillslope at Stanford, California, clearly demonstrated that each of the hypothesised modes of response was observed to occur. There was, however no way of determining a priori, without detailed site monitoring, which mode would predominate in practice. Forested hillslope sites in Scotland studied by Wheater *et al.* (1990a), were all dominated by highly spatially variable throughflow, believed to be arising from macropore response. Response of a 10 km^2 moorland catchment in Scotland, reported in detail by Wheater *et al.* (1991a), demonstrated both the emergence of downslope drainage as seeps at locations of highly localised topographic convergence and the occurrence of rapid throughflow. A small 4 ha moorland catchment in mid-Wales, intensively monitored over a 6-year period, displayed a complex combination of rapid throughflow in natural pipes, extensive overland flow and slow throughflow (Muscutt *et al.*, 1990). Again, it was not possible a priori to predict the relative contribution of the various modes of response to the streamflow hydrograph.

The above discussion has disturbing implications for modelling, as noted by Pilgrim *et al.* (1978). There is a strong implicit suggestion that, at least at small scale, subsurface stormflows are essentially chaotic, and that the ensemble response cannot necessarily be predicted a priori or as an aggregation of spatial components.

SIMULATION OF EFFECTS OF SCALE AND HETEROGENEITY

It will be evident from the preceding discussion that a fundamental problem of observability of hydrological systems exists. Intensive monitoring can only be undertaken at small (plot) scale; at larger (catchment) scales, observations of inputs and outputs provide insufficient information to identify the spatially variable response which is occurring at sub-observation scale. There is thus no means through direct observation of investigating the heterogeneity of response which is generating the catchment-scale output. We cannot observe hydrological *truth* at catchment scale (a problem that will recur in Chapters 6 and 7).

One alternative route to explore hydrological behaviour is to generate a detailed spatially variable response through simulation, and analyse the results. This presupposes, of course, that the model is an appropriate representative of the component processes at the scale under consideration! This exercise has been undertaken by Wood *et al.* (1990) using a conceptual model (TOPMODEL) which embodies two important features of upland catchments, namely an exponential decrease of soil transmissivity with water table depth below surface, and the effects of topographic convergence on soil moisture spatial distribution, derived from digital terrain analysis. The model was used to investigate simulated catchment runoff as a function of discretisation scale. At fine scales of discretisation (less than 1 km^2), highly variable response occurred from the individual spatial elements. At larger scales than this, a marked decrease in variability occurred, thus supporting the hypothesis that an area of the order of 1 km^2 could be postulated as a 'representative elementary area' (REA), analogous to the 'representative elementary volume' (REV) required for the application of a continuum

description of groundwater transport processes as defined by Bear (1979).

The results have a number of important implications. The consistency of response at scales in excess of the REA has obvious consequences for regional analysis of catchment behaviour. However, to extend the analogy between the REA and the REV, it can be noted in the groundwater context that the REV is the smallest scale at which the continuum approach holds. The intriging inference of this analogy is that the REA is similarly the smallest spatial element that can be used in a distributed hydrological representation. This does not imply that this is also the scale at which lumped catchment parameters can be used. The macroscale (> REA) model of Wood *et al.* (1990) remains firmly based on the use of distribution functions (in their case of topography, soil characteristics and rainfall intensities) to represent catchment responses.

SPATIAL VARIABILITY OF PRECIPITATION

The above discussion of variability has been primarily concerned with the heterogeneity of the terrestrial components of hydrological response at catchment scale. However, the spatial variability of inputs, in particular precipitation, must also be considered, and is of major importance in particular environments and at certain scales. (This bias of streamflow gauging measurements is another source of model error).

For many arid and semi-arid areas, rainfall is predominantly convective and of highly localised spatial extent. Dense raingauge networks in the south western United States, monitoring rainfall at a spatial scale of the order of 100 km^2, have revealed a spatial structure in which rain-cell correlation is negligible for distances greater than 10 km (Jacobs *et al.*, 1988). At a larger observation scale, raingauge networks with an intergauge spacing of 8 – 10 km, based on catchments in south western Saudi Arabia of up to 5000 km^2, have shown the highly localised occurrence of such convective rain cells (Wheater *et al.*, 1991b). Hence the spatial scale of rainfall variability is much less than catchment scale for most practical problems, and is extremely difficult if not impossible to characterise using conventional raingauge networks. This leads to ambiguity of process interpretation from data recorded with such networks.

Spatial rainfall thus provides a further example of the importance of sub-observation scale variability in hydrological systems, and although illustrated here as a particular problem for arid areas, there are more general implications, for example in the context of climate modelling, discussed below.

APPLICABILITY OF MODELS

The above comments provide the context in which hydrological models must be applied, and in this section the implications for appropriate modelling strategies are discussed, based on a representative set of modelling problems. These include the classical hydrological problems of modelling gauged and ungauged catchments, and modelling catchment change. To consider hydrological models in a broader context, two further problems are considered, namely hydrogeochemical modelling in the context of surface water acidification, and the representation of hydrological processes within atmospheric general circulation models .

SIMULATION OF GAUGED CATCHMENTS

All of the generic model types are capable of broadly matching observed catchment response, and most have a long record of application. Metric methods, in the form of the conventional unit hydrograph, have been applied for over 60 years to simulate event response. For continuous simulation (i.e. between as well as during events), conceptual models are most widely used, and in the present context, prediction performance is of greater concern than identifiability *per se*.

For physics-based models, there is an obvious lack of identifiability of model parameters, and with up to hundreds of degrees of freedom in a distributed, physics-based representation, it would be surprising if a good fit to calibration data were not assured. However, the lack of identifiability means that alternative combinations of parameter values can yield equivalent model performance and, as would be expected, examples are known to have occurred where inappropriate process representation has resulted from the calibration process (Anderson and Burt, 1990; Fawcett, 1992; Fawcett *et al.*, in preparation).

Conceptual models tend to have far fewer parameters, but still generally suffer from a lack of parameter identifiability. A reduction in model complexity is likely to lead to improved identifiability, but at the possible expense of goodness of fit. Mandeville *et al.* (1970) demonstrated that it is relatively easy, with a simple model, to explain 75% of data variance. Of course, what is required is high performance quality in prediction on independent data sets not used for model calibration and, as noted earlier, this may have implications for optimisation procedures.

Intercomparisons could be expected to reveal the strengths and weaknesses of alternative models, but, in general, have failed to identify clear guidelines

for model selection. The WMO (1975) intercomparison, for example, demonstrated that a range of widely different models could provide similar performance in humid catchments. In drier climatic regimes, the modelling task becomes more difficult, and increased model complexity is required to represent adequately soil moisture and evaporation processes, provided that data quality and availability can support that increased complexity.

A useful quantitative performance comparison of the whole range of model types cannot therefore be presented. However, it has been found that simpler models perform equally well or at least are not substantially outperformed by more complex models (Loague and Freeze, 1985). As far as we are aware, the hybrid model type discussed in the previous subsection has undergone more performance analysis than any other. It is relevant to review briefly aspects of its performance here.

The hybrid model (*3*)–(*9*), and a similar version with a simpler nonlinear loss model, is a good predictor of streamflow, not only matching streamflow records quite well in calibration periods but also in 'validation' periods (Jakeman *et al.* 1990, 1991, 1993a, 1993b; Littlewood and Jakeman, 1992). From experience of application to over 50 catchments to date, the model more often than not accounts for greater than 80% of streamflow variance on calibration data sets. On validation data sets where the model has been calibrated on other records, this variance drops by between 1 and 10% compared to a calibrated model performance on those validation data sets.

For the 767 km^2 French Broad River Basin, Wood *et al.* (1992) applied a simple conceptual (VIC) model and Jakeman *et al.* (1993a) a very similar model to the hybrid one above. On a validation period, the VIC model explained 54% of daily streamflow variance. Jakeman *et al.* (1993a) studied the performance of their model when calibrated on nine other periods of similar length to Wood *et al.* (1992). On the same validation period as Wood *et al.* (1992) the average of the streamflow variance explained by the nine models was 74% and the standard deviation was 3%. These results are encouraging given that rainfall data used for the modelling came from only one gauge.

If a rainfall-runoff model is to simulate changes in streamflow and evapotranspiration losses from time series of climatic inputs, then the model parameters should not be substantially related to the climate sequence in calibration records (or at least the relationship should be predictable). In a simulation study, Gan and Burges (1990), for example, found that parameters of the Sacramento model were climatically related to the sequence of observations used to calibrate the model. Jakeman *et al.* (1993a) studied the relevant performance of their hybrid model on the French Broad River, taking percentage runoff or basin yield as the best single indicator of climate in calibration periods. Their analysis quantified the variability of their model parameters over 20 three-year calibration periods and the general lack of relationship between any parameter and percentage runoff.

Uncertainties in any rainfall-runoff model will depend upon several factors including: the coverage of contributing areas within the catchment being modelled by the raingauge network; the temporal nature of the incident rainfall; the properties of the streamgauge errors; the length of data available for model construction; and, not least of all, the underlying nature of the catchment response characteristics. The results for the French Broad River Basin give an indication of the level of performance that can be expected in the presence of such uncertainties. Improved performance could be expected with better raingauge coverage of the basin. The variability of the model parameters estimated are also a useful guide to the lower bounds that can be expected with the use of more highly parameterised models.

SIMULATION OF UNGAUGED CATCHMENTS

In principle, physics-based models should be suited to the simulation of ungauged catchments provided that data are available to determine the required physical characteristics. In practice, a number of problems arise, as discussed earlier. For conceptual models, the essential difficulty is that at least some, if not most, of the parameters have no readily identifiable interpretation in terms of physical catchment properties. In principle, experience can be gained by model application to many catchments, and the variation of parameter values between catchments analysed in terms of physiographic and climatological variables. In practice, the problems of lack of uniqueness in parameter values have been overwhelming. Thus Johnston and Pilgrim (1976) failed to regionalise the Boughton model for Australian data, and NERC (1975) failed to regionalise a simple event model for UK data.

The problem of non-uniqueness of parameters is only fully resolved for metric models, albeit at a perceived cost of model simplification. With 'unique' determination of parameters, regional analysis of parameter variability can be undertaken successfully. Thus, for example, the UK Flood Studies Report (NERC, 1975) produced regression relationships which allow a catchment unit hydrograph to be synthesised as a function of stream length and slope, urban area and climate, and the event runoff coefficient as a function of soil type, rainfall and antecedent conditions and this and similar methods are extensively used in flood design.

The necessary model simplification has led to a focus on catchment

response to individual storm events, and in particular the stormflow or quick response component. In synthesis for design some simplified representation of the slow component may be recommended as a final stage of calculation. However, recent developments in metric analysis now provide the possibility of identifying both fast and slow components of catchment response.

Indeed the hybrid methodology (described earlier) involving the parsimonious and, with experience to date, effective representation of total streamflow response to rainfall in terms of dynamic response characteristics (DRCs) offers other advantages over previous metric analyses. The methodology is capable of producing an estimate of the covariation among model parameters. This is essential for any regionalisation studies where relationships between model parameters (DRCs) and physical catchment descriptors (PCDs) are to be identified. The model parameters also are valid for a wide range of climatic inputs, hence the relevance of the terminology (dynamic response) characteristics. Jakeman *et al.* (1992) propose examination of the relationships of DRCs to PCDs in large numbers of catchments as a way forward to determining soil moisture status, evapotranspiration, quick and slow streamflow on a dynamic basis in ungauged catchments.

SIMULATION OF CATCHMENT CHANGE

Conceptual models have long been used to predict effects of catchment change, particularly in the context of urban development (e.g. James, 1965). The essential problem with such applications is that the calibrated parameters are assumed to be uniquely associated with particular hydrological components (which they will not be) and the uncertainty in parameterisation is not carried through to estimate the associated predictive uncertainty. Urban development is a change which can, for the most part, be explicitly modelled through representation of paved surfaces and associated overland flow and storm sewer routing. Effects of parameter uncertainty are likely to be greater for more subtle, less explicitly represented, changes than urbanisation; for example, changes in agricultural practice or climate change.

Physics-based models are, in principle, ideally suited to predict change. They arguably embody the best physical representation of component processes currently available, and are as such ideally suited to speculative simulation (what-if scenarios) to predict changes on *hypothetical* catchments which can be uniquely parameterised. For use with real catchments, however, all of the problems of non-uniqess of parameter (and possibly, by association, process) uncertainty recur. Underlying these issues is, however, the question of whether the physics is indeed appropriate at the scale of application.

The metric approach allows the effect of factors such as urban development to be identified through regional analysis (Espey *et al.*, 1969; Brater and Sherrill, 1975). Such statistical relationships, obtained from regional analysis, are commonly used in design (strictly an incorrect association of cause and effect) to estimate flood hydrograph changes post-development. However, more subtle changes in catchment response may not be identifiable in the variability associated with regional analysis, at which point the conventional metric approach fails.

Of course, subtle changes may not be of interest. In any case, improved regionalisation results should be possible with methods which model the total streamflow response (i.e. including baseflow) objectively and quantify and utilise the covariation among model parameters. Small land cover changes in two Balquhidder catchments in Scotland were examined by Jakeman *et al.* (1993b) in terms of changes in dynamic response characteristics before and after the land cover alteration. Any DRC changes were felt to be within the natural variability of parameters estimated from pre-change records. More recent work by Post *et al.* (1993), however, on the Melbourne water supply catchments in Australia, quantifies the changes in model parameters following substantial deforestation. The aim of future work is to consider large numbers of catchments and quantify how changes, in land cover only, affect DRC values and streamflow response.

SIMULATION OF HYDROGEOCHEMICAL RESPONSE

The emergence of the problem of *acid rain* has provided a powerful stimulus to the development of hydrogeochemical models (not least as demonstrated in Chapter 7). Quantification of the sensitivity of surface waters to acid deposition, and quantification of likely recovery associated with emission control strategies are required for policy decisions of major economic importance.

The catchment-scale response to acidic inputs is an integration of the effects of hydrological pathways and the chemical interactions associated with those pathways (Chen *et al.*, 1983). The resulting modelling problem is extremely complex. In addition to all of the problems of hydrological characterisation, discussed in previous sections, the geochemical processes are themselves subject to unknown spatially distributed properties, and processes of weathering and ion exchange which are poorly understood. The history of model application to this problem offers an instructive illustration

of both the strengths and limitations of models (e.g. Christophersen and Wright, 1981; Goldstein *et al.*, 1984; Cosby *et al.*, 1985a,b; Neal *et al.*, 1986; Hooper *et al.*, 1988; de Grosbois *et al.*, 1988).

The essential problem underlying conceptual hydrological models recurs in this hydrogeochemical context. Even though there is increased information available in terms of input-output chemical signals to aid model identification, this is insufficient to characterise the internal system processes, as demonstrated by Kleissen *et al.* (1990a), for example. The conceptual model has an important role to play as a formalisation of hypotheses, and this formalisation can be tested for consistency with observations. However, a unique solution to the inverse problems cannot be obtained, so that a rigorous basis for hypotheses testing does not exist. These models must therefore be seen as an intellectual aid, analogous to the 'linguistic' categorisation of Beck (1991). Nevertheless, conceptual models have made an important contribution to acidification management. For example, extensive trials have shown a consistency of response for different models, indicating robustness in prediction (Rose *et al.*, 1991a,b) and regional distributions of parameters have yielded regional distributions of water quality consistent with those observed (Hornberger *et al.*, 1989).

One solution to the problem of lack of identifiability has been to follow the metric approach, and reduce the level of model complexity to that which can be sustained by the available data. This has been achieved by the use of 'mixing' models, whereby, given an a priori assumption (or measurement) of the concentration of conservative chemical indicators associated with the primary source waters contributing to stream chemical concentrations, inverse modelling can uniquely identify the fluxes associated with those 'end-member' constituents (Christophersen *et al.*, 1990; Hooper *et al.*, 1990; Kleissen *et al.*, 1990b). This limits the analysis to chemical species that can be reasonably approximated as conservative, but provides a powerful tool for systems analysis. It also assumes that significant changes along flow paths do not take place, which has, at least in one small, intensively monitored catchment, been shown not to be the case (Chapman *et al.*, 1993).

The role of physics-based hydrological models in direct extension to geochemical problems must be seen at present as in the realm of speculative research. Uncertainties in flow modelling have been discussed above. Uncertainties in the representation of transport processes will be greater, and to these must be added the uncertainties in geochemical properties and processes. It is worth noting that in two basins, intensively studied over 5 years, stream chemistry was strongly controlled by waters of uncertain origin (Wheater *et al.*, 1990b; Chapman *et al.*, 1993). A priori simulation of water quality will inevitably fail in such circumstances.

HYDROLOGICAL SIMULATIONS FOR CLIMATE MODELLING

As in the case of acid rain, issues of climate change have provided an impetus for modelling development which in turn has highlighted a number of the central issues underlying the application of hydrological models.

General Circulation Models of the atmosphere (GCMs) require appropriate representation of the hydrological conditions at the earth's surface to provide the boundary conditions for climatological modelling (Chapter 16). These are primarily water and energy fluxes at the earth's surface. However, simulation of runoff is also important. In some environments, such as major wetlands, water and energy fluxes are determined by river inflows. There is also a general need to obtain estimates of freshwater discharges to seas and oceans. And river flows provide a method of evaluating the adequacy or otherwise of earth surface parameterisations through comparison of observed and simulated discharges.

A central problem for earth surface parameterisation is the scale of discretisation of GCMs. This is currently of the order of 10^5 km^2 for a grid element, although this is decreasing rapidly with advances in computing power (Chapters 14 and 15). An important set of modelling problems at these scales is concerned with subgrid variability (Eagleson, 1986; Shuttleworth, 1988; Wood, 1991). The parameterisation of surface properties must represent the spatially integrated response of heterogeneous areas, and be based on available global data. In addition, the modelled rainfall at grid-scale is physically unrealistic, and disaggregation is required to give an effective representation. An associated, but currently unresolved, problem concerns the lack of any memory of the spatial location of rainfall occurrence within a grid square (Shuttleworth, 1988).

As discussed in Chapter 16, early attempts to include a hydrological representation within GCMs were based on a simple, single bucket model, similar to the upper-storage of many conceptual hydrological models, with no explicit representation of vegetation (Manabe, 1969). Subsequent developments introduced a stronger physical basis to the representation of surface energy and water vapour exchange through the explicit incorporation of plant physiological response using resistance analogies (Dickinson *et al.*, 1986; Sellers *et al.*, 1986; Chapter 16).

The trend with time and increasing computing power has been to pursue increased complexity, for example by the introduction of multiple layers to represent vegetation canopy processes, and to represent heat and water fluxes in the soil profile (Abramopoulos *et al.*, 1988; Gregory and Smith, 1990). There is an apparent underlying presupposition that a more complex and more 'physically realistic' formulation is intrinsically preferable. While the potential importance of surface heterogeneity (Milly and Eagleson, 1987) and rainfall spatial variability (Milly and Eagleson, 1988) has been indicated, an appropriate modelling strategy would seek to balance the complexity of physical process representation with these spatial uncertainties. This has been recognised by Entekhabi and Eagleson (1989), for example, but for lack of data at appropriate scales, analyses have been limited to sensitivity studies.

Hydrological data, in the form of river flows, can be used to investigate the performance of land surface parameterisations in GCMs, as for example Kuhl and Miller (1992) and Wood *et al.* (1992), and also to provide a more general means of analysis of modelling issues. Thus Jolley and Wheater (1993) have investigated the performance of a grid-based parameterisation using river flow data. The results suggest that: a priori specification of water balance components is possible with good accuracy for the climatic regime considered using a relatively simple, physics-based approach, but that subsurface routing effects can only be identified a posteriori, through metric analysis; and that spatial variability of rainfall is likely to outweigh differences in surface properties and their parameterisation.

OPPORTUNITIES FROM ENHANCED HYDROLOGIC DATA

Reliable, purposeful, and informative data are essential for scientific advances through modelling. As pointed out by Dozier (1992), future progress in hydrologic data collection, and hence modelling and hydrologic understanding, should result from:

(i) coordinated experiments where diverse efforts are pooled; recent examples include the International Satellite Surface Climatology Program's (ISLSCP) First Field Experiment (FIFE), the Boreal Ecosystem-Atmosphere Study (BOREAS), the Global Energy and Water Cycle Experiment (GEWEX), the Storm-Scale Operational and Research Meteorology's Project (STORM) and the Water, Energy and Biogechemical Budgets (WEBB) Program of US Geological Survey;
(ii) intensified efforts in the design of monitoring networks and examination of data quality and compatibility;
(iii) new forms of analysis in isotope geochemistry and paleohydrology;
(iv) greater interaction between observations and models as should be fostered by improved information systems (see Chapter 23); and
(v) technological advances in fields such as remote sensing and instrumentation.

Remote sensing, which involves measurements of the reflection or emission of radiation in the electromagnetic spectrum from satellites, aircraft or the surface, offers perhaps the greatest potential for improved hydrologic modelling, understanding and prediction. It can be used to infer properties which characterise the surface and subsurface landscape, and in some cases, to measure hydrologic variables. Engman and Gurney (1991) review applications of remote sensing to hydrology and current research thrusts. They examine the state-of-the-art by focusing on individual fluxes and storages; that is precipitation, evaporation, runoff and soil moisture.

Advances will require the development of improved relationships, between properties of the landscape and its electromagnetic signature. However, these relationships may be complicated and their construction requires the solution of difficult inverse problems (Dozier, 1992).

FUTURE PROGRESS IN RAINFALL-RUNOFF MODELLING

There are severe difficulties in the characterisation of hydrological response. With currently available technology, it is not possible to monitor internal processes at catchment scale, and hence ambiguities arise in extrapolation of point and plot-scale observations. From catchment-scale observations alone, the information content is insufficient to allow the identification of complex internal processes. However, issues of major scientific, economic and social importance require that hydrological systems be characterised in a modelling framework, and that the implications of change are addressed.

Of the modelling tools available, the metric approach has arguably been the most successful in characterising catchment-scale response. The major qualifications of the method in principle (and these qualifications presently apply to all other methods in practice) are that prior data are required, that only relatively simple models can be identified, and that methods derived from data analysis cannot be extrapolated outside the observed range of response. However, in practice, the unique characterisation of system response has allowed extrapolation to ungauged catchments and quantification of the effects of change through regional analysis. Conventional methods of metric analysis have focused on storm runoff response, but more sophisticated analytical tools are available, as discussed above, and their more widespread use will generate greater insight into the physiographic and climatological controls on runoff processes in due course.

Conceptual models allow a more complex representation of internal processes, but this is accompanied by a loss of identifiability. Given that there is generally uncertainty concerning the constituent model hypotheses, and that this cannot be rigorously evaluated, it is easy to be sceptical about

conceptual model applications. However, possibly their major strength is as an aid to the modeller's mental process which provides a formal statement of hypotheses which can be used with insight to address a wide range of problems, including catchment change. Nevertheless, lack of identifiability has seriously restricted regionalisation and the ability to quantify uncertainty associated with model predictions.

The strength of physics-based models lies in their potential to represent an integration of our detailed understanding of hydrological processes and hence to explore implications of change in a way which is consistent with the known physical process constraints. However, a number of difficult issues arise. Some processes have a physics-based conceptualisation which is relatively uncontroversial, for example overland and stream flow, and for which the implications of different levels of model complexity are well understood. Micrometeorological and plant physiological processes have a generally accepted physical conceptualisation, developed from detailed point process observations, although problems of observability are only now being overcome (by intensive cooperative experiments) to address the problems of spatial variability. As already noted, the issue of complexity of point process representation versus spatial uncertainty is not yet resolved. The more severe problems relate to subsurface processes. Flow processes in homogeneous soils are well understood, but there are major process uncertainties in the characterisation of the heterogeneous soils which comprise most natural systems, and a lack of observational data at the scales of model representation. The extent to which a conventional continuum approach can represent near-surface response at those scales has been questioned, which casts doubt on the conceptualisation of current models. In addition, there is sufficient uncertainty in parameter values to encompass quite different modes of nonlinear response.

Opportunities for improved charactisation of hydrological response will be afforded by enhancements in hydrologic data collection and management. Advances in remote sensing measurement technology should provide data on more spatially intensive scales. There are, however, substantially difficult inverse modelling problems to be solved to relate these data to physical properties in the landscape, as has been revealed in studies of the inverse problem for relatively linear groundwater systems.

In the highly nonlinear problems of near surface hillslope and catchment responses, there have been few, perhaps surprisingly few, studies that have made use of spatially distributed variables in the calibration of distributed models. Some of the reasons for this have been discussed by Beven (1987, 1989). The classic study of Stephenson and Freeze (1974) is perhaps indicative of the uncertainties that might be expected in the prediction of internal state variables. This has similarly been demonstrated in the well controlled hypothetical simulations of Binley and Beven (1990). This problem urgently needs further study but is dependent on the availability of good, intensively monitored, field process experiments at the catchment scale. There appear to be very few data sets, if any, worldwide that would allow a proper study of the calibration (and limited validation) of the spatial predictions of distributed models of surface and subsurface flow processes.

In fact, the limitations of the various generic model types suggest that the hydrological modeller should show much greater concern with predictive uncertainty and its relationship with parameter calibration. This relationship is well understood for linear models (see Young, 1984, and Beven and Jakeman, 1990) but has received only limited study in the nonlinear models common in the environmental sciences. Such studies as there have been in hydrology have commonly been based on a linearisation of the uncertainty associated with parameter values of boundary conditions (e.g Garen and Burges, 1981; Kuczera, 1988; Harlin and Kung, 1992; and Melching, 1992 in the context of conceptual models; and Jensen and Mantoglou, 1992, for a physics-based model of unsaturated flow). This implies that some 'modal' parameter set, characteristic of a particular system can be identified around which the uncertainty in predicted responses can be examined.

However, results based on very large numbers of simulations presented in Duan *et al.* (1992) and Beven (1993) show that this may not be a very good assumption. There may in fact be very many different parameter sets from different parts of the parameter response surface that may be equally good at representing the system within the limitations of a particular model structure. Duan *et al.* (1992) conclude that this situation makes life very difficult for parameter optimisation techniques, but proceed to suggest a new scheme robust to such difficulties. Beven (1993) suggests that it might be worth abandoning the concept of an 'optimal' parameter set altogether and proceed to discuss Monte Carlo simulation as a way of coping with the possibility of equifinality of parameter sets in simulating the behaviour of a particular catchment with a particular model structure.

The 'generalised likelihood uncertainty estimation' (GLUE) technique of Beven and Binley (1992) is one example of this approach. Parameter sets are chosen randomly within specified ranges. Each set is evaluated as to how well it reproduces the behaviour of the catchment in terms of a likelihood function. Only those simulations with an acceptable likelihood value are retained in making model predictions. The predictions from each retained parameter set are weighted by their associated likelihood value in calculating the predictive uncertainty of the model. The likelihood values may be updated as more observations become available by application of Bayes'

rule. The GLUE methodology implicitly accounts for interactions between parameters, for the fact that different parameter sets may be 'optimal' for different periods of record, and for the possibility that equally good simulations might be produced by different modes of response in the model. The technique can be applied when there are multiple measures of predictibility for distributed models (for example both discharges and water table levels in the case of Binley and Beven, 1991). Computing constraints still tend to limit the number of Monte Carlo simulations that can be made for physics-based distributed models, although the advent of parallel computing systems, for which Monte Carlo methods are very well suited, is making such an approach more generally applicable.

There are other similar approaches that also reject the notion of an optimal parameter set. A notable example is based on set theory (see Keesman and van Straten, 1990; van Straten and Keesman, 1991). Fuzzy set measures may well be useful in this context as a non-probabilistic approach towards predictive uncertainty. One important characteristic of these approaches is that if a consistent measure of performance is used, then it is possible to compare the uncertainties associated with different model structures. It is also possible to determine the value of additional data in constraining uncertainty (Beven and Binley, 1992). One question that remains to be addressed is the value of different types of data in constraining predictive uncertainty. Are hydraulic conductivity measurements of greater value than a number of water table measurements of profiles of soil moisture content? How many sets of such measurements will still add value to the predicability of the system, or do model structural errors dominate as a source of uncertainty? These questions remain to be answered for different scales of prediction in different environments, but the techniques to address the question are beginning to become available.

In looking to the future, each of the generic model types will be subject to further development and technical refinement. Metric models will benefit from improved identification algorithms, and wider application. For conceptual models, greater computing power will generate new methodologies for parameter estimation, hypothesis testing and the quantification of uncertainty. For physics-based models, problems of effective parameterisation will be addressed through experimental and numerical research. However, new techniques are needed, for example in the stochastic representation of spatial variability of precipitation as well as terrestrial properties, in the recognition of effects of spatial uncertainty in model parameterisation, and in observational methods. Perhaps the most exciting opportunities are still a glimmer on the horizon. A clear recognition of the strengths and weakness of alternative approaches will hopefully lead to a more productive juxtaposition of alternative approaches and the development of a new set of hybrid models.

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