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Downward approach to hydrological prediction

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Abstract:

This paper presents an overview of the 'downward approach' to hydrologic prediction and attempts to provide a context for the papers appearing in this special issue. The downward approach is seen as a necessary counterpoint to the mechanistic 'reductionist' approach that dominates current hydrological model development. It provides a systematic framework to learning from data, including the testing of hypotheses at every step of analysis. It can also be applied in a hierarchical manner: starting from exploring first-order controls in the modelling of catchment response, the model complexity can then be increased in response to deficiencies in reproducing observations at different levels. The remaining contributions of this special issue present a number of applications of the downward approach, including development of parsimonious water balance models with changing time scales by learning from signatures extracted from observed streamflow data at different time scales, regionalization of model parameters, parameterization of effects of sub-grid variability, and standardized statistical approaches to analyse data and to develop model structures. This review demonstrates that the downward approach is not a rigid methodology, but represents a generic framework. It needs to play an increasing role in the future in the development of hydrological models at the catchment scale. Copyright © 2003 John Wiley & Sons, Ltd.

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INTRODUCTION

Current debate on the development of hydrological models is centred on the relative pros and cons of distributed, physically based models (e.g. based on theories of small-scale processes, large data and computer requirements, large set-up and computational times) versus lumped conceptual models (arbitrary or inappropriate model structures, lack of physical basis, difficulties with calibration, faster in set-up and computational times, more modest in terms of data requirements). However, it is clear that this debate has not provided a way forward. We remain at a loss as to how to improve and validate distributed physically based models for making hydrologic predictions (Beven, 1989; Grayson and Blöschl, 2000a and b). Likewise, although there are numerous conceptual models around and being developed, along with significant improvements in model calibration (Kuczera, 1997; Bastidas *et al.*, 2002), we are still nowhere near solving the problems related to arbitrary model structures and the *a priori* estimation of parameters that hamper predictions.

We are therefore at an impasse! We need new approaches that will help us to move forward, and to enable us to construct hydrological models that can be used for making predictions into the future—in both gauged, and even more importantly, ungauged catchments. If a model is able to reflect the essence of how a catchment functions hydrologically (for the full range of possible states) then we can extrapolate with some confidence beyond the observed conditions and come up with reliable predictions. So the issue of obtaining predictive power for future states in gauged and ungauged catchments is tantamount to acquiring an understanding of

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how the catchment system functions. But just how do we find out? Ideally, on the one hand, these approaches must be based on understanding of climate, soil, vegetation and topographical controls on catchment responses, and, on the other hand, based on interpretation of variability inherent in observed runoff response data.

In the sciences, there have been two avenues to acquire an understanding of how a system operates: the upward and the downward approaches. The objective of this article is to present an overview of the 'downward approach' to hydrologic modelling and how it is set apart from the upward approach, discuss its relevance to current hydrologic research and practice, and attempt to provide a perspective for the various contributions appearing in this special issue.

UPWARD OR BOTTOM-UP APPROACH TO MODEL BUILDING

Blöschl and Sivapalan (1995) presented the generally accepted sequence of steps that are involved in the development of hydrological models of all types, in the context of a particular modelling goal: (a) collecting and analysing data; (b) developing a conceptual model that, in the modeller's mind, describes the important characteristics of a catchment; (c) translating the conceptual model into a mathematical model; (d) calibrating the model to fit a part of the historical data by adjusting the various coefficients; and (e) validating the model against the remaining historical data.

Although the above remains an appropriate way to build models, model development over the past 25 years has increasingly tended to diverge somewhat from this ideal. This has been contributed to in part by significant advances in our understanding of various hydrological processes and the development of sophisticated theories governing individual processes, and in part by the explosion in certain types of data availability (e.g. terrain attributes such as topography, soils, vegetation) and in computational power. Consequently, the two steps involving collection and analysis of hydrological data and the development of conceptual models (in the modeller's mind) that describe the catchment response have tended to be short circuited in favour of approaches that rely exclusively on the description of the many individual processes and an *a priori* perception of how they interact.

The resulting models are often labelled as 'process based' or 'physically based', with the approach to such model development being called variously as 'upward', 'bottom-up', 'reductionist', 'mechanistic', etc. The defining feature of the upward approach is the attempt to predict overall catchment response based on process knowledge acquired on smaller spatial and temporal scales, the common practice being to scale-up small-scale understanding or models to the catchment scale (Klemeš, 1983; Jarvis, 1993). The components representing small-scale (sub) processes are usually based on universal physical laws, such as conservation laws, although empirical relationships for individual processes and their model counterparts have also been used. The hallmark of the upward approach is that

- individual (small-scale) model components are selected (or left out) based on an *a priori* perception of which individual processes are important;
- individual (small-scale) components are combined based on an *a priori* perception of how they interact; and
- it is applicable to any type of model irrespective of its degree of detail and physical basis.

The overall model structure is hence not based on the catchment response data of a particular catchment but based on a prior perception, whereas model parameters are usually partly calibrated to the observed data and partly preset.

In hydrology, the upward avenue has been championed by Freeze and Harlan (1969) in their 'Blueprint for a physically-based, digitally simulated hydrologic response model', and since then numerous modelling studies have followed their paradigm; e.g. see Abbott and Refsgaard (1996). The hope has been that if a model mirrors in detail how the individual parts of a catchment function hydrologically then the resulting predictions at the catchment scale will be reliable, particularly for unobserved states. Unfortunately, this hope has been deceptive, as illustrated by Beven (1989) and Grayson *et al.* (1992) among others, and already anticipated by Freeze and Harlan (1969) themselves.

The main problem seems to be that processes important at one scale may not necessarily be important at other, larger or smaller, scales (Blöschl and Sivapalan, 1995). Indeed, because of the change of dominant processes with changing scales, it can be argued that at large scales not all the complexity embedded in small-scale models is actually necessary (Sivapalan, 2003). For example, soil heterogeneity may average out as we aggregate from the patch to the catchment scale. Conversely, as we go up in scale, processes not observed at the small scale may become important, such as large-scale preferential flow paths in the subsurface. An *a priori* perception of what small-scale processes are important and how they interact can, therefore, be grossly misleading. Another, related, problem seems to be excessive model complexity relative to data availability of the models derived from the upward approach and the associated difficulties with validating the model structure and estimating the parameters. Whereas in the 1970s and 1980s it was sometimes argued that the more complex models may be appropriate with limited data availability (Abbott *et al.*, 1986), the opposite seems to be true: the more complex a model the more data are needed to validate it (Grayson and Blöschl, 2000a,b). Owing to non-existent or inadequate data, many models of this type tend to be over-parameterized, with arbitrary and overly complex model structures leading to the problem of equifinality (Beven, 2000). Young (1978) suggested that while large and complex models have enormous explanatory power and can usually be fitted easily to the meagre time-series data often available, many of the 'estimated' parameters tend to be ill-defined and a smaller subset is often sufficient to explain or mimic the observed system behaviour; also see Jakeman and Hornberger (1993). Consequently, the models have a degree of 'surplus content' that is not supported by data, but is only introduced to satisfy the modeller's preconceived notions of the catchment's functioning. If model parameters are then calibrated based on catchment response data then they become merely 'grist to the calibration mill' and may compensate for model structural errors, resulting in an inaccurate representation of the catchment functioning, or, as Beven (1977) put it, '. . .optimisation may work to accommodate reality, often in a subtle way, to the detriment of the physical basis of theory on which a model is based.'

DOWNWARD OR TOP-DOWN APPROACH TO MODEL BUILDING

The downward approach is an alternative to the upward route of finding a meaningful conceptualization. This special issue focuses on the 'downward approach' to hydrological model development. The 'downward approach' is considered as synonymous with 'top-down' and has been defined by Klemeš (1983) as the route that 'starts with trying to find a distinct conceptual node directly at the level of interest (or higher) and then looks for the steps that could have led to it from a lower level'. In other words, any explanation and/or generalization is achieved *by fingering down into the (smaller-scale) processes from above* (i.e. catchment scale), and this is why models developed in this way are also called 'top-down' models (Jarvis, 1993). The defining feature of the downward approach to hydrologic modelling is the attempt to predict overall catchment response and the catchment functioning based on an interpretation of the observed response at the catchment scale, i.e.

- individual model components are selected (or left out) based on the analysis of catchment response data in a particular catchment;
- individual model components are combined based on these data as well; and
- it is applicable to any type of model irrespective of its degree of detail and physical basis, although rather simple models are usually preferred as justified by the data.

The important difference to the upward approach is that the model structure, including what processes to include and in which way, is inferred from the data rather than being preconceived. Model parameters ideally are also derived from the data analysis, although sometimes they are also partly calibrated to the observed data and partly preset.

The downward approach, by its very nature, is amenable to systematic learning and hypothesis testing. In interpreting the observed data obtained at the catchment scale, or patterns in the data, there is an opportunity to formulate alternative hypotheses about the underlying causes, developing appropriate causal models and then testing these model predictions against the data in an iterative manner. The downward approach, therefore, is often applied in a stepwise mode. It can also be applied in a hierarchical manner, starting from exploring first-order controls in the modelling of catchment response, and model complexity then being increased in response to deficiencies in reproducing observations at different levels.

In hydrology, the downward avenue was introduced by Klemeš (1983). It seems to have its roots in the systems approach, or systems theory, which was first proposed by the Austrian biologist von Bertalanffy in the 1940s (von Bertalanffy, 1968) and became the cornerstone of cybernetics (Ashby, 1956). In the 1970s, systems theory acquired additional momentum by the increased interest in ecologic systems at the global scale (de Rosnay, 1979; Capra, 1996). Whereas the mechanistic or reductionist approach emphasizes the individual components or processes that make up the whole, the systems approach emphasizes the whole (Heylighen and Joslyn, 1995). Also, recognizing that the properties of the individual processes are not intrinsic properties of the whole system, any study of the properties of the individual processes or components is carried out only from the point of view of understanding the whole system, and the focus is much more on the interactions, feedbacks, and functional relationships between the various parts of the whole. In other words, the systems approach focuses more on networks or patterns or linkages between the various components of the whole rather than on the individual components themselves.

In hydrology, the systems approach attracted a lot of interest in the 1960s and 1970s (e.g. Yevjevich, 1971) but, interestingly, tended to focus on deriving input–output relationships from data in a most efficient manner, often based on formal optimization procedures (Rogers and Fiering, 1986), with little interest in what is happening within the system and why this is happening. In his 'Linear theory of hydrologic systems', Dooge (1973: 5–6) states: 'In systems analysis, we are concerned only with the way in which the system converts input to output. If we can describe this system operation, we are not concerned in any way with the nature of the system—with the components of that system their connection with one another, or with the physical laws which are involved'. This statement clearly defines the differences and similarities of the systems approach and the downward approach in hydrology. Apart from the common roots in biology and cybernetics, the similarity is the emphasis on the whole. The important difference is that the downward approach is concerned with inferring the components of the system and their connection with one another, whereas the systems approach in hydrology is not. The essence of the downward approach is to explain or interpret the input–output relationships in terms of internal characteristics or processes occurring at finer scales, whereas the systems approach limits itself to deriving the input–output relationships in an optimum way. The systems approach usually works well for the conditions for which the input–output relationship has been derived from the data, but it may not work well for extrapolations beyond the data. The reasoning in support of the downward approach is that an understanding of the internal characteristics or finer scale processes will facilitate extrapolations beyond the observed states, which is a key goal in hydrologic prediction.

There are, of course, a number of problems or caveats with the downward approach. Since the downward approach attempts to identify processes directly at the scales of interest and interprets these in terms of properties and processes occurring at finer scales, it requires an ability to determine the net effect of small-scale interactions and feedback mechanisms. However, there will exist a limit to how far we can 'finger down' towards introducing causality into patterns in observed catchment response without, in fact, changing over to the upward approach and introducing assumptions not justified by the data. This limit is usually reflected in a limit on the model complexity justified by the data. This is in line with the principle of Occam's razor, also termed the principle of parsimony, which states that one should not make more assumptions than the minimum needed, i.e. when choosing from among models with equal explanatory power the simplest model is more likely to be correct (Forster, 2000). As data are usually rather limited, it is often rather simple models that are justified by the data (Young, 1978). Another problem with the downward approach is the difficulty with generalizations, which is also shared with applications of the systems approach in other disciplines, such as ecology (Harte, 2002). In fact, hydrologists have faced generalization problems since the science began (Dooge, 1986). Although, that to date, there is no final answer to these issues, a number of suggestions have been proposed in the literature specifically address the generalization problem. One possibility is to move beyond the notion of 'trying to model everything' and develop methods to identify dominant processes that control hydrological response in different environments (landscapes and climates) and at different scales, and then develop models to focus on these dominant processes (a notion we might call the 'dominant processes concept' (DPC), Grayson and Blöschl, 2000a,b; Woods, 2002). This involves some sort of classification or typological approach that is consistent with a downward avenue to hydrologic prediction.

So far, we have discussed the advantages and disadvantages of the upward and downward approaches. However, it is important to consider them as complementary, and not competing, approaches to the modelling of catchment responses. There is considerable benefit to be gained by using a combination of both approaches in developing hydrological models appropriate to specific applications. Similarly, the downward approach can also benefit from some of the systematic and standardized data analyses and interpretations inherent to the systems approach. The main advantages of the downward approach of isolating how the catchment system operates at the catchment scale are illustrated below, through a number of examples from the literature.

EXAMPLES OF THE DOWNWARD APPROACH IN HYDROLOGY

A first and classical example in hydrology was provided by Klemeš (1983). Klemeš related monthly precipitation to monthly runoff in a 39 000 km^2 basin in Canada. Klemeš found a poor relationship and went back to hypothesize about the reasons. He consequently included the effect of evaporation, gravity storage and tension storage in steps. At each step he tested the hypothesis by examining the data and could finally separate the effects of gravity and tension storage. It is important that these results have been arrived by analysis rather than by postulating them *a priori*.

Analysis of observed streamflow recessions has been used for many decades to obtain an appreciation of groundwater storage. The main advantages of the recession analysis are that rainfall can be assumed to be zero, or at least small (so difficulties with any errors in catchment rainfall estimation are avoided), and that the hydrograph represents an aggregate measure of catchment behaviour. A recession analysis is framed as a downward approach if different alternatives of how aquifers and the vadose zone interact with the stream are tested based on the observed hydrographs. One example is the recession flow analysis of Brutsaert and Nieber (1977), who estimated the catchment-scale saturated hydraulic conductivity and the mean aquifer depth from the recession curves. As noted by Troch *et al.* (1993), when estimating the catchment-scale hydraulic conductivity by the Brutsaert–Nieber technique, the resulting values are generally one to two magnitudes larger than their laboratory-derived counterparts. This is because the catchment-scale estimates incorporate the effect of preferential flow, flow in macropores, and the possible high spatial autocorrelation of the conductivity values in certain directions, clearly a result one would not be able to obtain by the upward approach. A related example is the TOPMODEL approach of Beven and Kirkby (1979), which involves estimating hydrologically effective soil depths from the recession curves (e.g. Ambroise *et al.*, 1996). Another example is provided by Wittenberg and Sivapalan (1999), who obtained a non-linear relationship between groundwater discharge and storage in shallow unconfined aquifers from recession analysis and were able to estimate the depletion of groundwater by evapotranspiration.

The research that has followed the development by Rodríguez-Iturbe and Valdés (1979) of the geomorphological instantaneous unit hydrograph (GIUH) concept is a notable example of the downward approach. This work has been driven by a desire to understand the pattern of hydrologic response at the event scale, and to interpret instantaneous unit hydrographs (IUHs) obtained from observed streamflow data in terms of the elements of catchment structure and functioning '*that could have led to it*' (Klemeš, 1983). These interpretations have shed light on the geometric features and component processes operating at lower scales that govern the shape of the IUHs, especially the relative roles of channel network topology, at-site and downstream hydraulic geometry, channel network hydraulics and the nature of hillslope responses. The thrust of the subsequent research has centred on the most physically realistic and parsimonious ways with which to capture the shape of the IUH, tests of the assumption of linearity and any departures from it, and their dependence on catchment size. The topology of its channel network was represented initially by Horton order ratios, with the channel network response being represented by conceptual models that idealized the channels of each order as simple linear reservoirs. Subsequent work on GIUHs attempted to improve the descriptions of network topology by replacing the Horton order ratios with the network width function (Mesa and Mifflin, 1986; Snell and Sivapalan, 1994) and the reservoir routing models of channel responses with more sophisticated models that included elements of channel hydraulics (Mesa and Mifflin, 1986; Rinaldo *et al.*, 1991). Later, work by Robinson *et al.* (1995) introduced the effects of hillslope responses into this formalism, and investigated the relative roles of channel network geometry, channel hydrodynamics and hillslope response on the shape of the resulting IUH, focusing especially on its first two moments. Later, work by Rinaldo *et al.* (1995), using the width function as a measure of network topology, looked at the coefficient of skewness of the IUH, suggesting that hillslope contributions were an important contributor to the positive coefficient of skewness of observed IUHs. Although this question has not been resolved conclusively, and work is progressing, the systematic search for the geometrical and hydraulic controls on the shape of the IUH of the kind presented above has led to a deeper understanding of its physical basis than we had before. This is likely to lead to an improved ability to estimate the IUH for ungauged basins based on physical properties alone, or to extrapolate it from gauged to ungauged basins using a combination of measured streamflows and physical properties.

Budyko (1974) derived a simple relationship describing annual evapotranspiration as a function of annual energy supply (i.e. net radiation) and precipitation, known as the Budyko curve. Studying this simple pattern at the annual time scale and watershed (space) scale is a fine example of the downward approach, as it can provide insights into the dynamic interactions between climate, soils and vegetation and their controls of water balance. Milly (1994a) presented a simple mathematical framework to explain the climate, soil, and vegetation controls on the shape of the Budyko curve. He hypothesized that long-term water balance is determined by interactions of fluctuating water supply and demand, mediated by water storage in the soil. The bucket model that Milly used to investigate the climate and landscape controls on annual water balance is far simpler than the sophisticated process-based models used by Eagleson (1978), and yet it was able to capture most of the spatial variability of the annual water balance in the study region. Choudhury (1999) proposed an alternative explanation that attributes the Budyko curve to the effects of spatial variability of precipitation and energy supply. Later, work by Milly (1994b) investigated the effects of climate seasonality on the resulting annual water balance, using the same simple bucket model. Another attempt at interpreting the Budyko curve was made by Zhang *et al.* (2001), who developed a simple two-parameter model that relates mean annual evapotranspiration to rainfall, potential evapotranspiration, and to plant-available water capacity. The model suggests that long-term average annual evapotranspiration under the same climatic conditions is determined by vegetation characteristics, and any differences thereof are attributed to the way different kinds of vegetation use soil water. Work on the Budyko curve is continuing using a number of approaches.

CONTRIBUTIONS OF THIS SPECIAL ISSUE

We next present the specific contributions of the papers appearing in this special issue and summarize how they relate to the various aspects of the downward approach discussed above. The first paper, by Wittenberg (2003), presents an application of the analysis of baseflow recessions to separate direct flow and groundwater flow, and to carry out diagnostic analyses of the data in a systematic manner, along the lines of Wittenberg and Sivapalan (1999). This inverse approach is applied to daily streamflow data of rivers in different climate zones (Germany, Western Australia, Turkey) under different influences. Wittenberg (2003) finds that streamflow recession characteristics are subject not only to seasonal variations and changes due to evapotranspiration, but also to abstractions from groundwater. In one case, recession analysis and baseflow separation are utilized to detect and quantify changes in groundwater flow due to leaky sewer lines.

The next three papers explore the notion of hydrologic signatures in a downward context. Eder *et al.* (2003) present the application of the downward approach for extracting appropriate model structures by systematic analysis of rainfall-runoff relationships in the Upper Enns catchment in the Austrian Alps. As in Jothityangkoon *et al.* (2001), the methodology followed involves a stepwise adjustment of model structure to capture the observed streamflow variability progressively at the annual, monthly, and then on to daily time scales. The main difference to previous work is the application to humid, snow-melt-affected catchments. Throughout the paper, Eder *et al.* (2003) focus on emergent properties of the hydrological system at the various time scales, as detected in key signature plots and hydrographs, and model complexity is kept to the minimum required. The downward approach presented leads to parsimonious water balance models, with a good balance being achieved between model performance and complexity. Struthers *et al.* (2003) implement the downward approach (as described above) to develop a conceptual model of deep drainage through the bottom of a large (2600 m^3) free-draining lysimeter constructed in a *Pinus sylvestris* plantation forest in Colbitz, Germany. The lysimeter has been monitored daily since 1974 with the objective of understanding the effects of afforestation upon groundwater recharge. A simple capacitance model is developed based on information extracted from the observed annual and inter-annual trends using a simple representation of vegetation growth. An important limitation of the capacitance approach (i.e. conceptual bucket model) in simulating the timing of drainage at sub-annual time scales is identified, which could not be overcome by adding further complexity to the model basis. The authors suggest that an alternative formulation is required to account for the time delay between precipitation inputs and drainage generation. Along similar lines, Atkinson *et al.* (2003) extend their previous application of the downward approach (Atkinson *et al.*, 2002) and generate *hourly* streamflow predictions not only at the catchment outlet but also at locations internal to a catchment. At each step, they attempt to provide insights into the relative importance of catchment and climatic properties (rainfall, soil, vegetation, topography), their spatial variability, and their influence on the spatial and temporal variability of streamflows. Eight model types originating from a simple conceptual model design, with complexity ranging from lumped to fully distributed, are tested over summer and winter periods at the Mahurangi Catchment, New Zealand. The analyses show that the required model complexity is a function of the season (summer versus winter), and a fully distributed representation is required for predictions that are accurate under all seasonal climate conditions.

The following paper by Young (2003) focuses on the parsimony and identifiability of the models, drawing parallels between previous applications of the downward approach (e.g. Jothityangkoon *et al.*, 2001) with similar activity in the environmental (e.g. Young, 1978; Beck, 1987) and ecosystems (e.g. Silvert, 1981) literature of the 1970s and early 1980s following the systems approach. Young (2003) then presents examples of an alternative, objective and statistical approach, called a data-based mechanistic (DBM) approach, to modelling ‘poorly defined systems’ that avoids the danger of placing too much confidence in *a priori* causal perceptions about the nature of the catchment system. The DBM approach to modelling has been developed as a stochastic, downward alternative, within the system theoretic framework, to the problems associated with reductionist approaches. Using catchment-scale rainfall-runoff modelling as an example, this paper then compares the inductive DBM approach with its hypothetico-deductive, deterministic alternative (Jothityangkoon *et al.*, 2001) and shows how it can be used to identify and estimate low-order, nonlinear models of the rainfall-runoff dynamics in the River Hodder catchment of northwest England based on a limited set of rainfall-runoff data. Similarly parsimonious approaches are examined by Kokkonen *et al.* (2003) by investigating regionalization approaches to daily streamflow prediction for 13 catchments in the Coweeta Hydrologic Laboratory, North Carolina, using a conceptual rainfall-runoff model of low complexity. Regionalization of model parameters considering differences in physical catchment descriptors is argued as fitting the downward approach, in the sense that factors controlling parameter variability are identified first within the entire region under study and then such information is exploited to predict runoff in a smaller sub-region. Their regionalization results reveal that consideration of interrelationships between parameters improves the performance of regression as a regionalization method. Breaking the parameter correlation structure inherent to the model, and merely exploiting relationships between model parameters and catchment characteristics, can result in a significant decrease in regionalization performance. Kokkonen *et al.* (2003) also find that high significance of regression between values of model parameters and catchment characteristics does not guarantee a set of parameters with a good predictive power.

The remaining papers of this special issue are concerned with the downward approach in the context of spatial patterns of catchment response. Chirico *et al.* (2003) argue that it is most effective to design a model proceeding from the analysis of the field data, with a level of complexity specifically suited to the kind of research objectives and to the amount of field data available for process and parameter identification. They proceed along the downward route in three steps. In a first step they identify the dominant hydrologic processes and their conceptualizations from initial field data analysis using a detailed data set consisting of six spatial soil moisture patterns, 12 soil moisture time series and flow at two internal subcatchments, collected during the MARVEX experiment at Mahurangi in New Zealand (Woods *et al.*, 2001). Runoff is identified as being produced mainly by saturation excess across the entire monitoring period, despite the high-intensity rainfall observed in that area. In a second step they identify the model parameters by comparing simulated time series of streamflow and soil moisture with observations and by comparing simulated spatial soil moisture patterns with observed patterns. In a third step they examine the need for increasing model complexity. The analysis of the flow data at the hourly scale suggest the need for a more complex subsurface transmissivity function in order to produce lateral stormflow with a larger range of celerity. As a simple solution the authors modify the decay of the lateral transmissivity with the soil moisture content by adding a second component activated only for soil moisture close to saturation. This data-driven approach to identifying the model conceptualization and parameters results in a distributed model capable of reproducing the observed catchment behaviour while minimizing model complexity. Although downward approaches generally tend to lead to rather simple model structures, this paper is an example that shows the feasibility of the downward approach to identify the structure and parameters of a more complex distributed model.

Schulz and Beven (2003) present a top-down approach to sub-grid-scale land surface parameterization, and show that the complexity of currently used, 'physically based' soil vegetation–atmosphere transfer (SVAT) schemes may not be supported by the calibration data available. By comparing three SVAT schemes of differing complexity within the Generalised Likelihood Uncertainty Estimation (GLUE) framework (see also Beven (2001)), Schulz and Beven demonstrate the utility of simpler, rather than more complex, models when calibrated against flux data from various intensive field campaigns. A more robust calibration is achieved for a simple evaporative fraction approach by allowing the feasible parameter ranges to be more strongly conditioned by the available data. They argue that a top-down (dominant mode) predictive model based on a database of such robustly estimated parameter values would result in no greater uncertainty at the scales of application.

Simple models of groundwater flow have limited capability to represent spatial waterlogging or salinization due to the mismatch in scale between model cell size and process conceptualization and actual process scale. Petheram *et al.* (2003a) present a method for utilizing available high-resolution digital elevation data to develop a sub-grid parameterization for groundwater discharge and surface waterlogging. This enables simple groundwater models to represent the actual areas of waterlogging and salinization better. The approach utilizes a 'zero-piezometric surface' (i.e. a planar surface that passes through the lowest point of each element in a groundwater model). The difference in elevation between the 'zero-piezometric surface' and a high-resolution digital elevation model (DEM) provides a distribution of depth to the 'zero-piezometric surface' (at the DEM scale) for each element in the model. Traditional methods for evaluating surface discharge can then be applied at the DEM cell scale to the distribution of depth to the 'zero-piezometric surface' to derive a relationship between depth to the piezometric surface and the net recharge or discharge for each element in the model. Petheram *et al.* (2003b) assess the extent of information that can be transferred between hydrogeologically similar catchments by investigating in detail one set of similar catchments. In particular, five examples of a class of deeply weathered, fractured rock aquifers are used as the basis for this assessment. The catchments chosen encompass a wide variety of scales, gradients, and climatic zones. The five catchments are modelled using the simple FLOWTUBE model. Catchment parameter values, catchment response to incremental reductions in recharge and the similarity of the catchments are compared. The results suggest that there is a considerable range in parameter values but that this is smaller than the range for all aquifer types. However, given the sensitivity of the model to transmissivity and specific yield, the range of values is considered too high to allow the transfer of 'averaged' values to other hydrogeologically similar catchments with confidence. Evaluation of a dimensionless similarity parameter G for each of the five catchments indicates that the transmissivity, specific yield, length and head may be interrelated.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

In spite of its obvious merits, the downward approach has so far not reached its full potential in hydrology. But, in time, the downward approach should become an important component of the toolkit for data analysis and hydrological model development. It is an important genuine way of learning from the data. From the perspectives presented above, we believe that future advances in hydrologic prediction will likely come from the use of the downward approach in the following areas.

Key signatures of hydrologic variability should be analysed, in their own right, similar to the extensive work done on the GIUH and the flood frequency curve in the 1970s and 1980s. Examples include the Budyko curve, inter-annual and mean monthly variability of water balance, flow duration curves, and the spatial organization of these signatures (Jothityangkoon *et al.*, 2001). These are the key signatures that embody the hydrologic organization or hidden order, and a quest for identifying them seems promising, as noted by Rodríguez-Iturbe (2000): 'Can we reproduce some of the observed, strikingly visual, patterns? Is there hidden order in the space–time evolution which models could help to uncover?'

There is potential in the increasing use of surrogate measurements, such as groundwater table variations, soil moisture, and mapping of binary patterns, such as saturated areas and snow cover (Blöschl, 2001; Grayson *et al.*, 2002). Also, increasing use of chemical signatures, such as isotopic composition, concentrations of chloride and nutrients in streamflow, and the use of multiresponse data simultaneously for model improvement and validation seems to be promising (Seibert and McDonnell, 2002). These surrogate measurements are probably particularly valuable if they provide an indication of the spatial patterns of hydrological response, as voiced by Klemeš (1986): 'It also seems obvious that search for new measurement methods that would yield areal distributions, or at least reliable areal totals or averages, of hydrologic variables such as precipitation, evapotranspiration, and soil moisture would be a much better investment for hydrology than the continuous pursuit of a perfect massage that would squeeze the nonexistent information out of the few poor anaemic point measurements...'

It would be worth adopting the downward approach in a comparative mode in many catchments around the world in different climatic and hydrologic settings. This will allow the methodology, and the insights gained, to be shared around the world for the advancement of the models' predictive capabilities. Ideally, the order of these settings could come from a typology approach, perhaps similar to that proposed by Woods (2002): 'Perhaps we are realizing that while hydrology operates within a stunningly complex world for which we have developed very sophisticated techniques, we have no common framework in which to place our data and models. Where is the hydrological classification system? Classification is not a central pillar of today's hydrology science, but perhaps this Dominant Processes Concept suggests that it should be'. A typology or classification system ideally blends with the downward approach of learning from the data.

Finally, and perhaps most importantly, we believe that what Klemes (1983) stated 20 years ago is still very valid today. '...the most promising route to significant new discoveries in hydrology is to combine the upward and downward search based on the existing facts and knowledge as well as on imagination and intuition, to form testable hypotheses—i.e. to apply the time-honoured scientific method'. Or, as Harte (2002) put it, in a broader Earth Sciences context: 'Physicists seek simplicity in universal laws. Ecologists revel in complex interdependencies. A sustainable future for our planet will probably require a look at life from both sides'. We anticipate that, in the near future, studies that address the same problem by both approaches at the same time will make a significant impact on a better understanding of hydrologic prediction issues.

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