13: Pattern, Process and Function: Elements of a Unified Theory of Hydrology at the Catchment Scale

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Catchment hydrology is presently operating under an essentially reductionist paradigm, dominated by small-scale process theories. Yet, hydrology is full of examples of highly complex behavior, including strong nonlinearities and thresholds, and paradoxes that defy causal explanation through these small-scale process theories. There are strong interactions and feedbacks between processes, leading to apparent simplicities in the overall catchment response, yet the laws governing these feedbacks are not well understood. Routine measurements and specialized field experiments have been valuable for observing catchment responses and understanding the underlying process controls, but there has been little progress in extrapolating the local knowledge and understanding gained from these well studied (or gauged) catchments to ungauged catchments. Efforts at generalization are hampered by the lack of an appropriate quantitative framework, for example, a classification system, to help identify interesting and useful patterns in the observations. There are many theories governing different elements of catchment hydrology, but not a unified theory that connects these seemingly disparate elements. This article presents the broad outlines of an emerging new, unified theory of hydrology at the catchment scale, and the approaches being used to develop it. The new theory embraces multiscale heterogeneities as a natural and intrinsic part of catchment hydrology. Instead of relying solely on current process theories, it seeks to discover new catchment-scale process theories that embed within them the effects of natural heterogeneities. Instead of attempting to prescribe in detail the actual patterns of heterogeneity in every catchment, it will seek to incorporate the geomorphic or landforming processes that may have generated them in the first place, and their ecological, pedological, and geomorphological functions. Instead of using our rather meagre observations to calibrate complex models that are based on small-scale theories, the theory will emphasize the use of patterns in the observations to formulate and test alternative hypotheses about the underlying process controls. Instead of using field measurements to learn more and more about individual catchments, it will seek to find connections between observations in different catchments, to identify broad-scale or general patterns. The defining feature of the new theory of catchment hydrology will be a sharp focus on the interconnection and feedbacks between pattern and process, over a range of scales, and their interpretation in terms of their "function", that is, the reason that these connections arise. The renewed focus on pattern, process, and function will revolutionize hydrology, elevate its place within the earth system sciences, and strengthen the scientific foundations of its practice.

INTRODUCTION

Owing to its focus on water, the science of hydrology holds a unique and central place in the field of earth system science, intimately intertwined with other water-related disciplines such as meteorology, climatology, geomorphology, hydrogeology, and ecology. As an applied science, hydrology is highly relevant to the management of the world's water resources and water quality, and for the prediction, prevention, and amelioration of water-related

Encyclopedia of Hydrological Sciences. Edited by M G Anderson.

natural hazards, such as floods and droughts. Thus, hydrology should be an exciting field of study, yet it appears to be fragmented, deeply rooted in empiricism, and struggling to realize its full potential.

Hydrology boasts of many theories, for each of its many constituent processes (e.g. infiltration, evaporation, overland flow, groundwater flow etc.), but there is an almost complete lack of an holistic theory unique to hydrology itself, unifying these many varied theories. In spite of the sophistication of the individual process theories, there has been little progress toward understanding the laws governing the interactions and feedbacks between these processes, so much so that models based on current process theories often cannot explain or reproduce key patterns of observed hydrological behavior (Tromp-van Meerveld and McDonnell, 2005). The reliance on individual process theories, and the lack of a unifying theory governing process interactions and feedbacks, have led to a proliferation of complex hydrological models, which suffer from overparameterization and high predictive uncertainty. As an applied science, hydrology derives many of its methods of analysis and predictive tools from the experience gained through specializations such as engineering hydrology, agricultural hydrology, urban hydrology, and so on. However, there is little, if any, common ground amongst these different perspectives, nor between these perspectives and the advances made in fundamental process understanding. Scientific progress and advances in hydrological practice have both been hampered due to the lack of a unified theory of hydrology at the catchment scale.

There have been frequent calls for a new unified theory of hydrology, as it would considerably improve our understanding of hydrological phenomena, including a more holistic understanding of their function within the entire earth system, and improve the scientific management of water resources, water quality, and water-related natural hazards (Dooge, 1986; Dunne, 1998; Sivapalan, 2003a). There has been an increasing recognition of the presence of natural, multiscale heterogeneities in hydrology, and of the need for an holistic, rather than fragmented description of these heterogeneities in hydrological theory and practice (Gupta, 2000). It has been suggested that with the advent of a new unified theory, we would not need to appeal to different, and often contradictory, conceptual models to explain (physical and chemical) phenomena that coexist in the same catchment (Kirchner, 2003).

This article presents a broad review of the current theoretical foundations of hydrology, the possible approaches to developing a more coherent and unified theory, and a brief survey of the progress that has already been made. On the basis of this review and a survey of current global trends in the scientific arena, the article identifies new opportunities and challenges that may be poised to accelerate the development of a new unified hydrological theory.

Subject Matter of Catchment Hydrology

In this article, we limit ourselves to the theory of hydrology pertaining to catchments, which are widely recognized as being the most fundamental landscape unit for the cycling of water, sediments, and dissolved geochemical and biogeochemical constituents. Catchments integrate all aspects of the hydrological cycle within a clearly defined area in a way that can be studied, quantified, and acted upon (Wagener *et al.*, 2004). It is for this reason that we choose catchments as the building block for the development of a new hydrological theory.

While practitioners of catchment hydrology approach the field from many different perspectives, all of them still have as their basis, the need to understand, manage and/or deal with space-time variability of catchment responses to climatic inputs (water and energy) at the land surface. Understanding of the spatial and temporal variability of hydrological processes aggregated to the catchment scale, their extremes, and their scaling behavior both in time and space, is important for a number of applications: for example, flood estimation, drought mitigation, water resources systems analysis. The pathways that water takes in its passage through the catchment, their spatial and temporal variabilities, and the associated residence times, are important for water quality predictions and for managing the health of aquatic ecosystems.

Hydrologists are also concerned with the need to understand and predict alterations to these hydrological responses due to changes at the earth's land surface and to the earth system as a whole, due to human impacts and any global change. Predicting the effects of human impacts, such as urbanization and deforestation, is important from the perspectives of water resources assessment, mitigation of natural hazards, and water quality management. Exchanges of water and energy between the land surface and the atmosphere, their sensitivity to long-term climate changes, and their impact on global water and energy circulations and teleconnections, are important for the study of global hydrology and of the global climate system. Therefore, improvements to the theory of catchment hydrology will have positive ramifications beyond hydrology, contributing to the sustainable management of land and water resources and aquatic ecosystems, and to managing global change.

Catchments as "Complex Systems with Some Degree of Organization"

Hydrological processes arise as a result of interactions between climate inputs and landscape characteristics that occur over a wide range of space and timescales (*see* **Chapter 3, Hydrologic Concepts of Variability and Scale, Volume 1**). In the time domain, these may range from a few seconds needed to capture turbulent exchanges of mass, energy, and momentum between the land surface and the atmosphere, to intermediate timescales governing runoff generation processes during storm events, for example, overland flow and subsurface stormflow, and long timescales governing deep groundwater flow, seasonal variations of climate and annual water balances, and interannual and interdecadal variabilities. In the space domain, the length scales may range from an individual soil pore, leaf blade or surface gully, to small hillslopes, to river basins as large as the Mississippi, to whole climatic or geographic regions, all the way to the entire globe.

Due to the tremendous heterogeneities in landscape properties and climatic inputs, the resulting hydrological processes are highly variable and complex at all scales. It is not practical, or even feasible, to routinely observe hydrological processes at the scale of a soil pore or a surface gully, or at the scale of a hillslope, in all catchments. For both scientific and practical reasons, routine observations of hydrological processes are made only at the catchment scale, leading to a gap between the scales at which processes actually occur, and the scale at which routine observations are made and predictions are required. Catchments thus qualify as *complex* or *poorly defined* systems. This means that while process understanding at all scales, especially at scales smaller than catchment scale, is very valuable in guiding or underpinning predictions of catchment responses, actual predictions must still be based and/or conditioned on observations at the catchment scale.

On the other hand, the catchment is a self-organizing system, whose form, drainage network, ground and channel slopes, channel hydraulic geometries, soils, and vegetation, are all a result of adaptive, ecological, geomorphic or landforming processes. As a result, they lend themselves to regular geometric patterns, which, if understood and embraced, may actually lead to a simplification of catchment descriptions to be used in analysis and predictions. Dooge (1986) categorizes catchments as "complex systems with some degree of organization" (Figure 1).

Hence a holistic theory of hydrology at the catchment scale must be founded on a synthesis of process understanding and process theories *at all scales*, with empirical theories derived from the analysis of observations at the catchment scale, mediated by theories governing the natural organization and self-similarity underlying the spatial heterogeneities in landscape properties. The next three subsections will give a brief overview of the current status of process theories, empirical theories, and theories relating to natural organization of landscape properties.

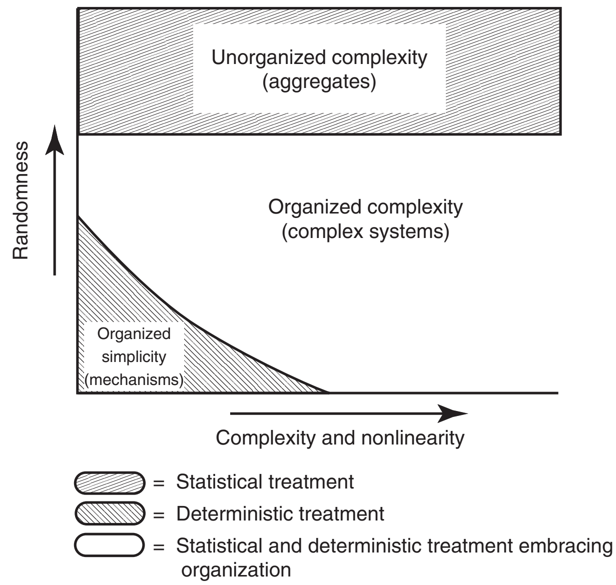


Figure 1 Catchments as complex environmental systems, that is, complex systems with some degree of organization. Adapted from Weinberg (1975) and Dooge (1986)

Current Status of Process Theories

In view of the central role of both water movement and storage in the catchment, which take place on the land surface including in river channels, in various parts of the soil, as well as in vegetation, catchment hydrology currently derives many of its laws from sister disciplines such as open channel hydraulics, soil physics and chemistry, groundwater flow, crop micrometeorology, plant physiology, boundary layer meteorology, and so on. These laws and associated governing equations are used to quantitatively describe hydrological processes such as overland flow, snowmelt, channel flow, infiltration, recharge to the water table and capillary rise, evaporation, root water uptake and transpiration, and contaminant movement. Some examples include Darcy's law, Fick's law of diffusion, Manning and Chezy equations, the Saint Venant equations governing surface flows, Richards equation governing subsurface water movement, and the Penman and Penman–Monteith equations governing evaporation and transpiration. Detailed descriptions of these governing equations and their derivations have been presented elsewhere in this encyclopedia (*see* **Chapter 5, Fundamental Hydrologic Equations, Volume 1**), and in many standard textbooks, and will not be repeated here.

Considerable research has been carried out in the last 50 years toward the development and application of the governing equations, leading to significant advances in the understanding and description of many individual hydrological processes. Sophisticated numerical models have been developed on the basis of these governing equations, and the resulting numerical models have gained the status of physically-based models. However, it is often overlooked that the constituent process theories are essentially derived at the laboratory or other small scales. They are underpinned by assumptions of homogeneity, and uniformity, and time invariance of various flow paths, over the land surface and in channels, and through soils and vegetation (e.g. roots, stems, and leaves). In reality, catchments are highly heterogeneous, dynamic and evolving entities (with respect to vegetation, soil structure, and morphology), responding dynamically to climatic inputs, which also exhibit tremendous variability in both space and time. One way that the catchment response can be modeled is by splitting the catchment into elements that are small and homogeneous enough so that the process theories can still be deemed to be applicable: this is the current paradigm (e.g. Abbott *et al.*, 1986a,b; Wigmosta *et al.*, 1994 and *see* **Chapter 11, Upscaling and Downscaling – Dynamic Models, Volume 1**). Another way is to develop the balance equations for mass, momentum, and energy directly at the catchment scale. Some progress has been made in this direction (Reggiani *et al.*, 1998; Reggiani *et al.*, 1999); however, the needed closure relations at the catchment scale, to replace the current ones based on Darcy's law, Fick's law, and so on still remain to be developed to complete the specification of the governing equations.

The difficulty, or even fallacy, of the reductionist paradigm that has dominated hydrological science for the past 25 years has been discussed and debated at length in recent times (Beven, 1989a, 1993, 2000a,b, 2001, 2002). For example, it is highly impractical, using current and even future technologies, to describe in full the natural heterogeneity exhibited in catchments; in the unlikely case in which we can, the resulting models will be overly complex, and pose a huge computational burden. In the more likely situation in which the model parameters cannot be estimated *a priori* from observable landscape properties, the resulting models will pose a huge parameter estimation problem (Beven, 1989a).

An even greater difficulty arises from the fact that, on their own, traditional process theories cannot account for processes and process interactions that may occur at the catchment scale in the presence of natural heterogeneities and the natural self-organization underlying these. For example, while our best models are predicated on porous media flow theory based on Darcy's law and Richards equation, we observe non-Darcian flow in the field (Tromp-van Meerveld and McDonnell, 2005) due to the presence of preferred pathways such as macropores. The use of passive tracers, for example, stable isotopes, chloride, and so on has demonstrated in many catchments that while streamflow responds promptly to rainfall inputs, fluctuations in the passive tracers are strongly damped, indicating the stormflow is mostly "old" water (Sklash, 1990; Turner and Macpherson, 1990; Buttle, 1994). The old water paradox – the fact that catchments store water for considerable periods of time and then release it promptly during storm events – cannot be explained by these small-scale process theories (Kirchner, 2003). A variety of concepts have been invoked in attempts to explain this phenomenon – piston flow, kinematic waves, transmissivity feedback, exchange between matrix and macropores (Beven, 1989b; McDonnell, 1990; Bishop, 1991; Kendall *et al.*, 1999), but with limited success. Clearly, mechanisms other than contained in our current process theories, must be at work here.

Current Status of Empirical Theories

Given that hydrological processes vary over a broad range of space and timescales, the business of hydrology is to understand, explain, and characterize hydrological variability, in space and time, including how this variability changes with time or space scale. Usually, this variability is characterized as a space-time field of the quantity of interest, be it streamflow, soil moisture, groundwater table depth, or rates of evaporation. Increasingly, we are also interested in the pathways that the water takes to arrive at the catchment outlet, the distribution of travel times, and the age of the water that exits the catchment as these are indicators of the underlying space-time variability of hydrological processes, and have implications for water quality predictions (Vache and McDonnell, 2005).

In the context of empirical data analysis, the role of theory is to provide a robust, quantitative, and reproducible framework to relate descriptors or *signatures* of hydrological variability to properties of the catchments and climatic inputs, which we might call *predictor variables*. When such robust relationships are established, we can then hope to predict the responses of catchments with confidence, given only the relevant climatic parameters and catchment properties. Therefore, the value of these signatures is not so much what they tell us about individual catchments, which is still considerable, but what they can tell us about differences between catchments. A robust and reproducible theory will evolve only when we broaden the search from ever more detailed explorations of processes *within* individual catchments toward quantitative and causal explanations of the differences *between* catchments.

Descriptors (Signatures) of Hydrological Variability

In order to develop coherent theories to underpin empirical data analysis, we need *signatures* of variability that are physically meaningful, and also useful in a practical context (*see*, **Chapter 3, Hydrologic Concepts of Variability and Scale, Volume 1**). Focusing on streamflow response, some of the commonly used measures of hydrological variability include interannual (between-year) variability of annual streamflow, and intraannual (within-year) variabilities, such as mean monthly variation (i.e. regime curve), the flow duration curve and annual rainfall-runoff relationships. These describe the character of temporal streamflow variability in one catchment, examples of which are presented in Figure 2(a). Other measures of temporal variabilities include the flood frequency curve, and the low flow (drought) distribution. In hydrology we are also interested in between-catchment variabilities of the measures listed earlier in the text, either within the same region, or between different hydroclimatic regions. Figure 2(b) presents the

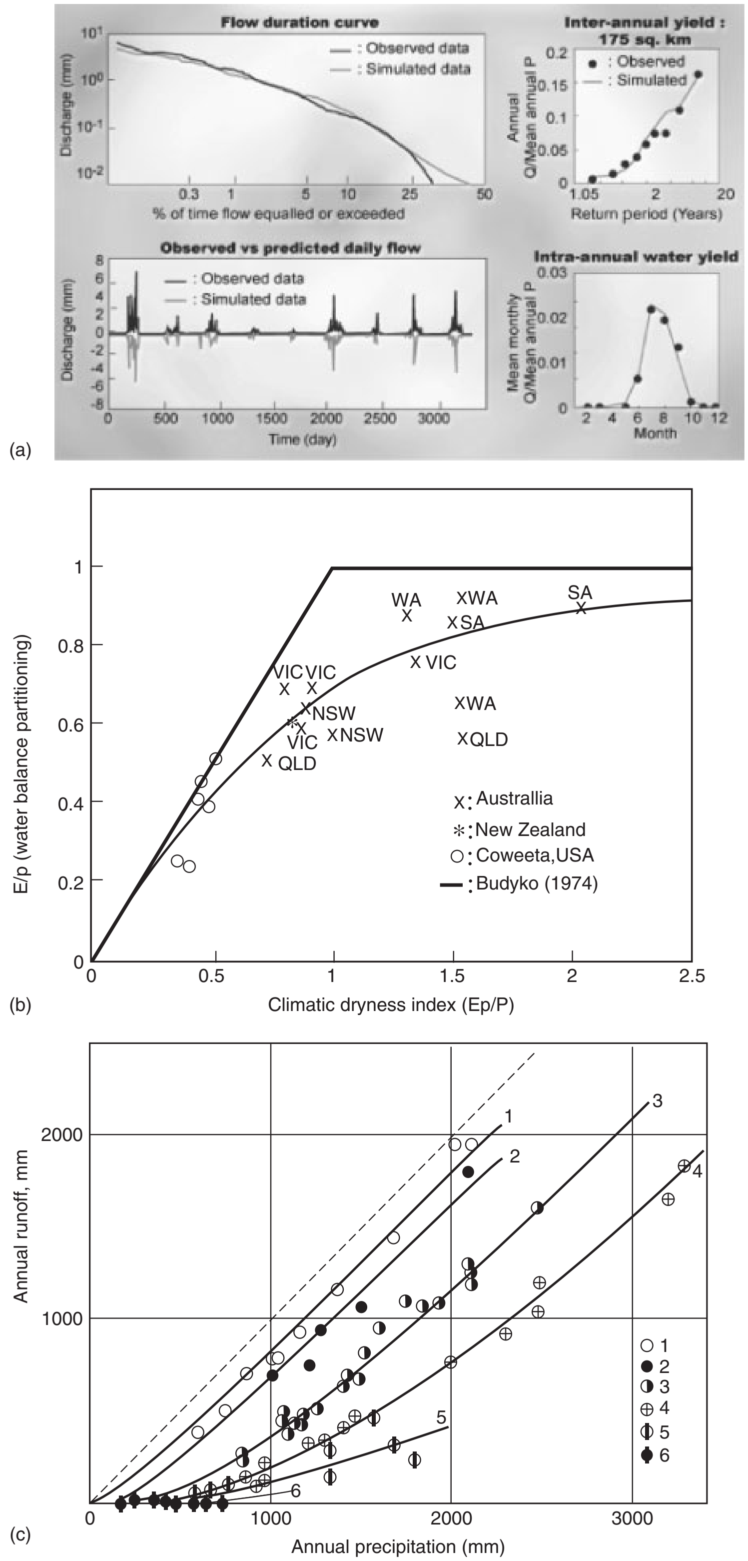


Figure 2 Signatures of hydrological variability: (a) interannual, intraannual (mean monthly variation and flow duration curve); (b) mean annual water balance as a function of the climatic dryness index, E_p/P: crosses refer to locations in Australia and New Zealand; and (c) geographical variation of annual runoff versus annual precipitation for South and South-East Asia: the numbers refer to different vegetation types (Reproduced from L'vovich, 1979 by permission of American Geophysical Union)

geographical variation of E/P, the ratio of mean annual actual evaporation to mean annual precipitation, as a function of the ratio of the mean annual potential evaporation (surrogate for net radiant energy) and annual precipitation, E_p/P. This is known as *the Budyko curve* (Budyko, 1974), and shows that climate, as exemplified by E_p/P, is a good first-order predictor of annual water balance. Geographical variations of the relationship between annual runoff and annual precipitation are presented in Figure 2(c), taken from L'vovich (1979), with the differences between different regions attributed to differences in climate (seasonality, storminess etc.), soils and vegetation, including the way that native vegetation adapts to water stress, such as leaf shedding and deep rooting. Other measures of spatial variability include scaling behavior of flood frequency curves, with respect to the size of catchments in the same region. Analysis of data from around the world has thrown up interesting patterns in many of these signatures. For example, L'vovich (1979) and McMahon *et al.* (1992) have presented a compendium of interhemispherical and interregional comparisons of interannual variability of annual runoff volumes, intraannual variations of streamflow (the regime and flow duration curves), and annual maximum flood peaks. There is tremendous value in exploring their underlying process controls, which will assist in developing a coherent new theory of hydrology.

Other signatures, besides measures of streamflow variability, include distributions of residence time or water age, temperature, isotopic composition, concentrations of tracer chemicals such as chloride or nitrate, although measurements of these are not as widespread as streamflow. Some of these chemical signatures may be strongly distinctive, and diagnostic of important differences between catchments and need to be predicted correctly. Patterns of vegetation cover, in both space and time, can also be excellent indicators of hydrological variability since they provide a window into the underlying water balance (Boer, 1999; Boer and Puigdefábregas, 2005), although, in the past, they have only been utilized as prescribed inputs to hydrological models. In a similar vein, patterns of other hydrological response data such as soil moisture and snow cover have been shown to provide powerful indicators to the understanding of catchment behavior (Grayson and Blöschl, 2000).

Predictors of Runoff Variability

Examples of the *predictors* of catchment responses include, but are not limited to:

- Climate: aridity/humidity, seasonality, especially, the relative seasonality of precipitation and potential evaporation, measures of storminess, ratio of interstorm period to storm duration, nature of within-storm variability of rainfall intensity,and so on;
- Catchment area and shape, drainage density;
- River network: length and shape of channel network;
- Soil properties: soil depth, soil texture (well drained or poorly drained soils, saturated hydraulic conductivity etc.), and their spatial distributions;
- Geology: fractured or monolithic rock, its influence on the subsurface hydrogeology, layering, relationship to topography, and so on;
- Topography: steepness (surface and stream slopes), mean elevation, curvature;
- Vegetation: type and density, spatial patterns, and temporal variability.

At the present time, our ability to infer or learn from observations through systematic data analysis is not well advanced. Progress in developing robust, quantitative relationships between the signatures of hydrological variability described above and the predictor variables (various climate parameters and landscape properties), toward the development of a general and reproducible theory at the catchment scale, has been hampered for a number of reasons. Firstly, the signatures of variability presented above can be thought of as reflecting processes occurring at or below the catchment scale, and providing a window into the interactions and feedbacks between different processes and between the various constituent elements of the catchment. To date, most of these signatures are not yet understood, and have not been explored in terms of the underlying processes. One consequence of this is that, as yet, we are not even able to choose predictor variables with clear, causal connections to the signatures.

Secondly, a prerequisite for making inferences from observations is the availability of a physically meaningful classification system, which can be used to guide empirical data analysis, to organize the data in such a way as to elicit interesting and useful patterns. Such a classification system, and a theory of inference based on the analysis of patterns in the observed data, is almost nonexistent in catchment hydrology at the present time (McDonnell and Woods, 2004; Woods, 2002). Dooge (1986) has suggested that hydrology is in the same position of confusion as the field of hydraulics had been before the Reynolds and Froude numbers were proposed; almost two decades on, there has been no real advance in this direction, notwithstanding the work of Milly (1994).

Much of the data analysis that is presently carried out is model focused, for example, during the calibration of models based on small-scale process theories, constrained by assumptions about processes upon which the models are based. This may explain why data analyses in the past have not been very revealing, and possibly even why there are too many models. Indeed, it can be said that the increasing sophistication of models based on small-scale process-based theories and the increasing power of computers may even have contributed to a neglect of systematic and thoughtful data analyses, and the role of data has been relegated to its use in model calibration only.

Current State of Theories Regarding Organization

The role of organization in catchment response has been widely acknowledged over the years (e.g. Blöschl *et al.*, 1993; Blöschl and Sivapalan, 1995). At the most fundamental level, climate acts as the unifying global force in the coevolution of landscapes and vegetation. An illustration of this, is the fact that the world's broad vegetation classes can be predicted by the combination of just two climatic variables: temperature and rainfall (Figure 3a, Shuttleworth, 1983; Woodward, 1987). Observed precipitation patterns demonstrate space-time variability over a wide range of scales, including but not limited to such definable units as cells, small mesoscale areas, large mesoscale areas,

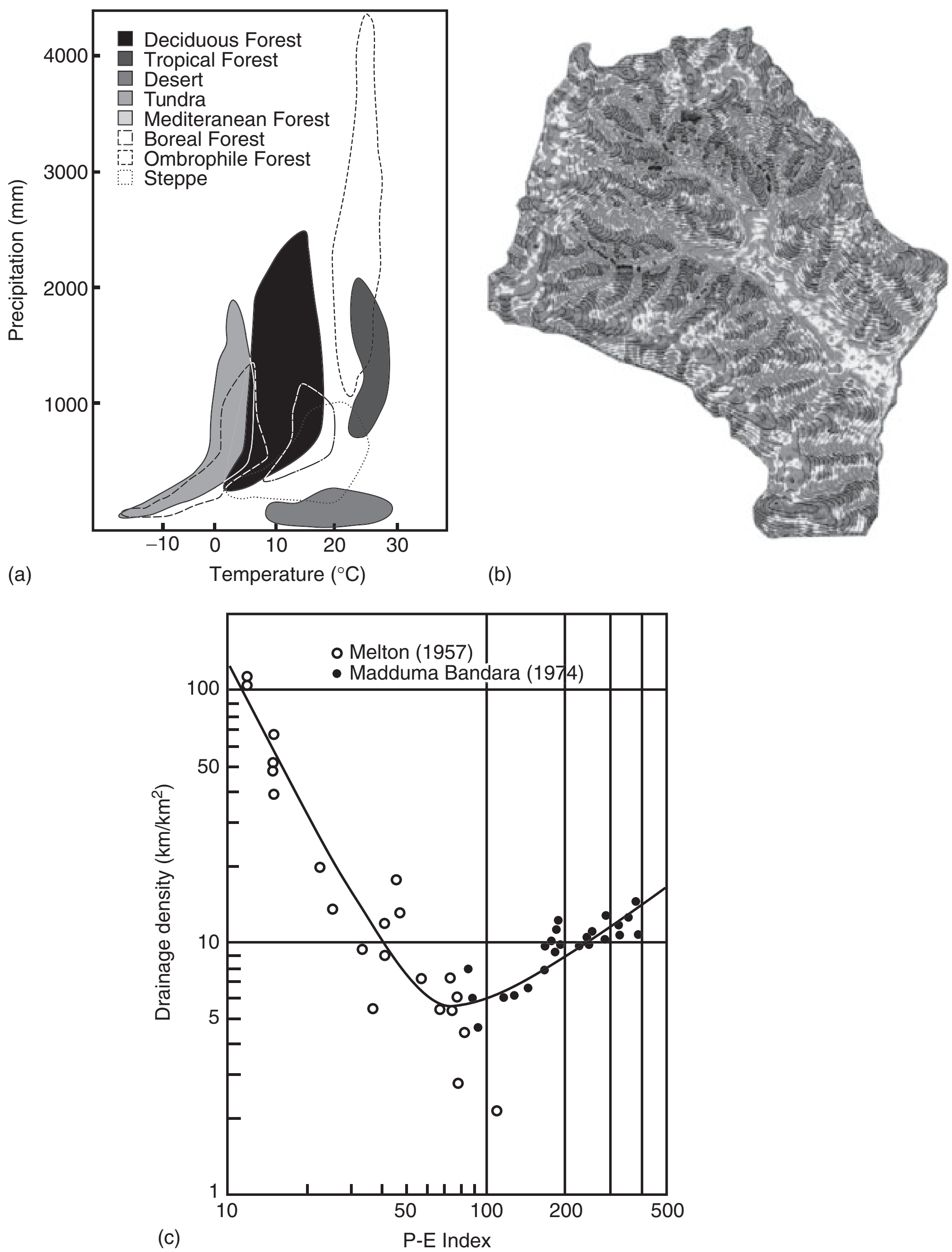


Figure 3 Patterns of landscape properties due to self-organization: (a) climatic influence on major vegetation zones of the world (from Shuttleworth, 1983); (b) soil catena – simulated patterns of soil depth within a catchment (from Dietrich *et al.*, 1995); (c) global relationship between drainage density of landforms against the precipitation–evaporation (P-E) index (Reproduced from Abrahams, 1984 by permission of American Geophysical Union)

synoptic areas, and so on as they develop, mature, move, and dissipate. Rivers carve the landscape into intricate shapes called *river networks*, which appear to embody a deep sense of symmetry (Rodriguez-Iturbe and Rinaldo, 2000). Soils tend to develop in response to state controls such as topography, with different parts of a basin (nose, slope, hollow) being formed by different processes and having different functions (e.g. concentration, storage, and evapotranspiration of water). The resulting soil patterns (soil catena) exhibit a common form of organization and symmetry, with water movement clearly being an active agent in their formation (Figure 3b, Dietrich *et al.*, 1995). Drainage densities observed around the world in different hydroclimatic regions demonstrate a robust relationship with the so-called precipitation–evaporation (P–E) index, the difference between annual precipitation and evaporation (Abrahams, 1984), the particular U-shape of this relation, and its minima (Figure 3c) being caused by the armoring imparted to the soil by the presence of vegetation roots.

The interactions between climate, soils, vegetation, and topography thus contribute to the generation of the interesting patterns that we see in natural catchments, which must contain valuable information about the way they function. Therefore, a fundamental aim of theoretical hydrology must be to recognize these patterns, decipher the underlying order or symmetry occurring over a wide range of scales, and explore the mechanisms that may have generated them. The field of hydrogeomorphology is attempting to discover the mechanisms underlying the order or symmetry in terms of quantitative measures of drainage network composition (Rodriguez-Iturbe and Rinaldo, 2000). In a similar vein, theories and associated models of soil formation, shallow landsliding, and erosion have been pursued in order to explain the observed patterns in soil properties (Jenny, 1941; Willgoose *et al.*, 1991; Dietrich *et al.*, 1995). On the other hand, the field of ecohydrology is attempting to discover rules or organizing principles governing spatial patterns of vegetation density and type, linking these to underlying water and energy balances, consistent with a Darwinian natural selection process that is optimal for growth and reproduction within the prevailing climate and geology (Rodriguez-Iturbe *et al.*, 1999; Eagleson, 2002). However, to complete the development of a theory of catchment hydrology, current understanding of self-organized patterns in landscape properties must be extended to produce insights into the interactions and feedbacks between hydrological processes at the catchment scale. Progress would be made, for example, when such natural self-organization in landscape properties could be confirmed to be the cause of simple process descriptions or closure relations extracted from observations at the catchment scale (Savenije, 2001).

The most that has been done to accommodate the natural self-organization has been with respect to the choice of model structure, that is, the way the various components of the landscape are organized and interconnected, that underlies many current hydrological models. For example, a typical model structure may consider a catchment to consist of a population of hillslopes, of different sizes, shapes and steepnesses, wrapped around the stream network, which is its most distinctive element (Troch *et al.*, 2003). The channel hydraulic properties, collectively known as *hydraulic geometry* (*HG*), may be allowed to vary systematically with flow at a single site, as well as in the downstream direction. In the vertical direction, the catchment (and the associated hillslopes) is assumed to consist of the land surface, and the soil and bedrock beneath it, including any vegetation that is contained within it. The subsurface is further characterized by an unsaturated zone, underlain by one or more saturated zones, underlain by bedrock. In larger catchments, to account for large-scale spatial variations of climatic and landscape properties, the catchment may be divided into a number of subcatchments which are hierarchically organized around the stream network, before being further divided into hillslopes (Gupta and Waymire, 1998; Reggiani *et al.*, 1998). Recent work has suggested that the treatment of hillslopes as monolithic entities suppresses important functional variations that may occur within them, and has advocated their partitioning into upland and riparian zones (McGlynn and McDonnell, 2003). Other studies have advocated the introduction of a hyporheic zone between the riparian and the stream zones.

However, this kind of representation is essentially a static stratification of the landscape, and does not necessarily recognize or incorporate the dynamic mechanisms that sustain those subsystems. In particular, the processes that occur within these subsystems continue to be described in terms of small-scale process theories. The effects of the natural self-organization of soil properties, vegetation, and topography have not been embedded in the process conceptualizations that appear in most current hydrological models. Notable exceptions to this are the body of work that led to the development of TOPMODEL (Beven and Kirkby, 1979; Sivapalan *et al.*, 1987) and the related TOPOG model (O'Loughlin, 1986). In this case, the two models captured the effects of topographic convergence through the use of a topographic wetness index, along with assumptions made to characterize in a simple way the interactions between upslope and downslope regions of hillslopes, including the accumulation of water near the stream zone and the generation of dynamic saturation areas generating saturation excess runoff. The kind of spatial organization of soil moisture assumed in TOPMODEL has since been supported, to some extent, through a number of field studies at the small catchment scale (e.g. Western *et al.*, 1999), although spatial patterns have also been observed which are not consistent with TOPMODEL predictions. Another example of the use of organization in developing appropriate process conceptualization is the now popular Xinanjiang or variable infiltration capacity model (Zhao *et al.*, 1980; Wood *et al.*, 1992; Liang *et al.*, 1994; Sivapalan *et al.*, 1997). In this case, the self-organization present within the catchment is expressed in terms of a statistical distribution of soil depths or infiltration capacity, which implicitly also accounts for the position on the hillslope. A third and final example is the development of the geomorphological instantaneous unit hydrograph (GIUH) of catchments on the basis of the organization present within the stream network in the form of, for example, Horton's order ratios (Rodriguez-Iturbe and Valdes, 1979; Rinaldo *et al.*, 1991; Snell and Sivapalan, 1994; Saco and Kumar, 2002). In this case, the dispersion imparted to the incoming rainfall by the stream network is quantified in terms of measures of the drainage network structure.

Status of Theories of Catchment Hydrology: Impasse!

The paradigm underpinning current hydrological theories at the catchment scale is shown in Figure 4, and is essentially *reductionist*. In this framework, the natural organization present within catchments is partly embraced through model structures that may reflect the presence of a stream network, a set of hillslopes or subcatchments organized around this network, distinct saturated and unsaturated zones, and a further possible partitioning of the hillslopes into upland, riparian, and hyporheic zones. However, the conceptualizations of hydrological processes are still dominated by small-scale process theories, unrelated and unconnected to the nature of self-organization present within the catchment. A set of balance equations at the scale of a representative catchment, and respecting the natural organization that is present within catchments has been presented

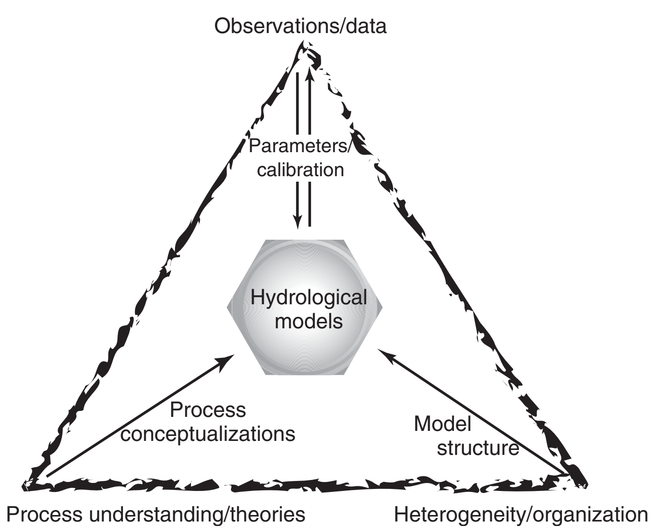


Figure 4 Current state of theory in catchment hydrology – reductionist with a reliance on calibration

recently (Reggiani *et al.*, 1998, 1999); the lack of appropriate catchment-scale closure relations to close this set of equations is hampering efforts to turn these into a new blueprint for distributed modeling at the catchment scale (Lee *et al.*, 2005; Zehe *et al.*, 2005). Even the best models based on current process theories are found to be inadequate to predict catchment responses since they demand complete knowledge of climatic inputs and landscape (soils and vegetation) characteristics, which is not routinely available. In fact, due to the strong heterogeneities of climatic landscape and climate properties, hydrology is replete with examples of highly complex behavior, including strong nonlinearities and threshold behavior, and paradoxes that defy causal explanation by models based on small-scale theories.

Catchments being "poorly defined systems with some degree of organization", predictions of catchment responses must be conditioned or founded on empirical observations. Yet, in the current framework, the main role of observations and data appears to be, with a few exceptions, to assist in the calibration of models that are based on small-scale process theories, and *a priori* model structures, that is, "grist to the calibration mill" (Sivapalan, 1997). Indeed, hydrologists have not demonstrated the collective will, skill in experimental design, and the required clarity in posing scientific hypotheses and testing them on comprehensive datasets. The lack of holistic process theories and the inadequacies of current small-scale process theories, have meant that data collection to formulate alternative hypotheses has been limited and the analyses of existing datasets have not been so revealing. We do not yet have a sound quantitative framework, for example, a classification system, based on a set of predictor variables and governed by the understanding of underlying process controls, that can help us recognize interesting patterns in the data.

Because of the overparameterization in relation to the meagre datasets against which they are calibrated, current models suffer from the problem of equifinality (Beven, 1989a, 2001, 2002; Savenije, 2001), which expresses the fact that infinite combinations of parameters can give rise to model predictions that provide a good match to the observations. The lack of a holistic theory at the catchment scale has led to a plethora of alternative models that are overly complex, overparameterized, and uncertain. The end result is confusion not clarity, and stagnation and not real progress, in spite of the explosion of new knowledge related to various individual hydrological processes.

It is clear that catchment hydrology is trapped in a dead-end track, a theoretical impasse! We urgently require a new holistic and unified theory that overcomes the limitations of the current theories in dealing with processes, organization, and data analysis.

TOWARD A NEW UNIFIED HYDROLOGICAL THEORY AT THE CATCHMENT SCALE

Scope of a Unified Theory of Catchment Hydrology

In the discussions that follow, we will adopt a simple, but overarching definition of *theory* as the set of ideas or concepts that is best able to describe or explain the system of interest, the catchment, its presence in the landscape, its behavior, and its function in relation to other systems. In this context, theory is seen as more than the sum total of all knowledge, but as *distilled* knowledge, and, as knowledge that is causally interlinked, that is, every piece of knowledge must make sense with regard to all other pieces. Theory helps to connect the specific to the general, the local to the global, and the past to the future. Theory provides a framework to assess what we know and what we do not know. Theory provides the avenues to seek the knowledge that we do not possess.

Given the ubiquitous nature of hydrological variabilities at multiple space – time scales, the main role or purpose of a coherent hydrological theory is then to:

- help explain observed patterns of hydrological behavior over multiple space-timescales in terms of the underlying climate, soil, vegetation, and topography interactions, in this way providing a robust framework for a dialogue with nature;
- guide us to make appropriate measurements to further improve our understanding and our ability to generalize or extrapolate in space and time, and assist with the design of observational networks and/or focused field experiments; and
- guide us to make better predictions, into the future or to other points in space, that are based on *a priori* understanding and not just calibration, and in this way help establish the practice of hydrology on firm scientific foundations.

Given the nature and basis of hydrological science and its place at the center of a number of earth science disciplines, the desired hydrological theory at the catchment scale will combine ideas and concepts from:

- natural sciences such as physics, chemistry, and biology: examples include Newton's laws of motion, the 2^{nd} law of thermodynamics, biological laws including theories of evolution, chemical laws of reaction and transformation;
- earth sciences, because of the overlap and interactions with other branches of earth system science: examples include theories of soil physics, micrometeorology, open channel hydraulics, geomorphology, ecology;
- empirical science: hydrology is fundamentally an empirical science, and depends crucially on inferences made from observations at all scales, all the way from laboratory to global;
- applied science: hydrology is also an applied science and elements of hydrological theory may derive from the sharing of experiences from its applications, for example, in agricultural hydrology, engineering hydrology, forest hydrology, and so on.

Hydrological theory will thus derive from the actual practice of the science, as natural science, empirical science, earth system science, and as applied science. Hydrological theory will not arise through mere speculation of the human mind, or, as Klemeŝ (1986) put it, "... the logic of hydrological processes cannot be deduced from algebra". By the same token, we cannot postpone the practice of the science of hydrology until a theory is ready.

Approaches to a New Unified Theory of Hydrology at the Catchment Scale

The observed patterns of variability of hydrological behavior at the catchment scale arise out of interactions between space-time variability of climatic inputs, for example, precipitation, solar radiation, atmospheric humidity, wind, and so on, the natural multiscale heterogeneity of landscape properties, such as the soils, vegetation, topography, and so on, and any alterations to these due to human impacts. The natural heterogeneities of the landscape properties, in turn, themselves arise through geomorphic (i.e. landforming), and ecological processes that occur over a much longer period of time, compared to the typical timescales of hydrological processes.

The new unified hydrological theory must ultimately consist of a set of organizing principles or natural laws governing:

- the ways that catchments are organized in space and time, in terms of their constituent landscape elements, including the geomorphic and ecological processes that may have led to them;
- the ways that catchments respond to climatic inputs and the nature of the interactions between the heterogeneities in the climatic inputs and the landscape properties;
- the resulting fundamental hydrological processes, their space-time variabilities, including the pathways, fluxes and stores of water, energy and other constituents, and the interactions between them;
- the way that the different constituent parts of the catchments, and the catchments as a whole, function, interact with, and feedback on each other; and
- the way that catchments respond to human-induced changes in the climate inputs and the landscape properties, in terms of both their form and function (e.g. storage of water, primary production etc.), in the short-term and in the long-term.

Considering the self-organized aspect of catchments, their constituent landscape elements, the processes that generated them in the first place, the way they interact and feedback on each other, and the resulting impact on hydrological processes at all scales, it is clear that feedbacks between pattern and process, must be the defining feature of any new, unified theory of catchment hydrology. It is also clear that the feedbacks between pattern and process are highly relevant in different contexts also, due to the critical role played by water in climatological, ecological, geomorphological, and pedological processes. Therefore, the ecological, geomorphological, and other "function" of the feedbacks between hydrological patterns and processes is essential for a deeper understanding of hydrological variability. For this reason, it is argued that pattern, process, and function must be the key elements of a new theory of hydrology at the catchment scale.

Pattern: instead of using observations and data for calibration of *a priori* constructed models, seek and identify patterns (both within-catchment and between-catchment) in the data or observations, to formulate and test hypotheses about processes, process interactions and feedbacks, including the mechanisms that contribute to natural self-organization;

Process: discover or explore new processes, process interactions, and feedbacks at all scales, and descriptions that embrace or embed within them explicitly or implicitly the effects of landscape and climatic heterogeneities, including any simplification that comes about due to the feedbacks and self-organization underlying these heterogeneities;

Function: investigate the processes that lead to the heterogeneities and self-organization exhibited by landscape properties, and explore the laws or organizing principles governing their ecological, geomorphological, or pedological "function", with the idea that these laws could act as constraints to both the process descriptions (within-catchment), and broad-scale patterns of behavior (between-catchment, regional etc.).

An example of an ecological function is the provision of physical habitat, or of food supply. The geomorphological function of watercourses may be the efficient movement of water and sediment. This function entails both conveyance and storage, which are critical to the healthy functioning of the stream. A stream may attain a shape, form, or pattern that permits the necessary movement of water and sediment with the energy available (i.e. slope). The landscape functioning may be related to maintaining the stability of the landscape, it may develop pipe flow as a mechanism for fast release of water to prevent too frequent landslides. It may develop a vegetation-soil association to keep erosion to a minimum.

By combining pattern, process, and function, the new theory will lead to process descriptions that respect patterns of observed behavior, it will lead to more parsimonious models with much-reduced parameterizations, it will encourage a scientific culture of learning from observations, instead of using them for calibration, and it will encourage the formulation of rigorous hypotheses to underpin future experimental campaigns and data collection exercises. By branching out to embrace organizing principles or natural laws from neighboring disciplines such as geomorphology, pedology, and ecology, it will also broaden and enrich the hydrological perspective.

Downward and Upward Approaches to Theory Development

Klemeŝ (1983) proposed two alternative approaches for pursuing the organizing principles or laws that might constitute the theory of hydrology at the catchment scale: the "upward or bottom-up approach" and the "downward or top-down approach", and the eventual reconciliation of the outcomes of these two approaches. Dooge (1986), in a similar vein, proposed parameterization of microscale effects (upward), and the search for general laws at the macroscale (downward) as alternative approaches to the discovery of hydrological laws at the catchment scale. Acknowledging the need for a reconciliation of these two approaches and considering the importance of scale and the adaptive or self-organized character of catchments, Dooge argued for the discovery and exploration of scaling laws in hydrological behavior as a third, alternative method that helps to find links across catchments of different sizes.

These ideas also resonate with recent developments in other related fields, as exemplified by the theoretical vision for earth system science proposed by Harte (2002). Harte considered systems having characteristics that apply equally well to catchments: poorly defined, unique, and continuously evolving; self-organized, characterized by strong feedbacks and interdependencies; requirement not just to characterize but also to generalize and extrapolate, so that the behavior in response to climate changes and/or land use changes can be predicted. Similar to Dooge, Harte proposed a theoretical framework that involves a combination of (i) simple falsifiable models, (ii) a search for patterns and laws, and (iii) the science of the place. Harte (2002) characterizes this theoretical framework as a synthesis of the Newtonian and Darwinian worldviews, combining "particularity and contingency, which characterize the ecological sciences, and generality and simplicity, which characterize the physical sciences".

Figure 5 illustrates the application of the downward and upward approaches, seeking connections between patterns and processes. Within-catchment investigations deal with specific catchments, and attempt to explain the temporal patterns of variability in terms of the underlying process

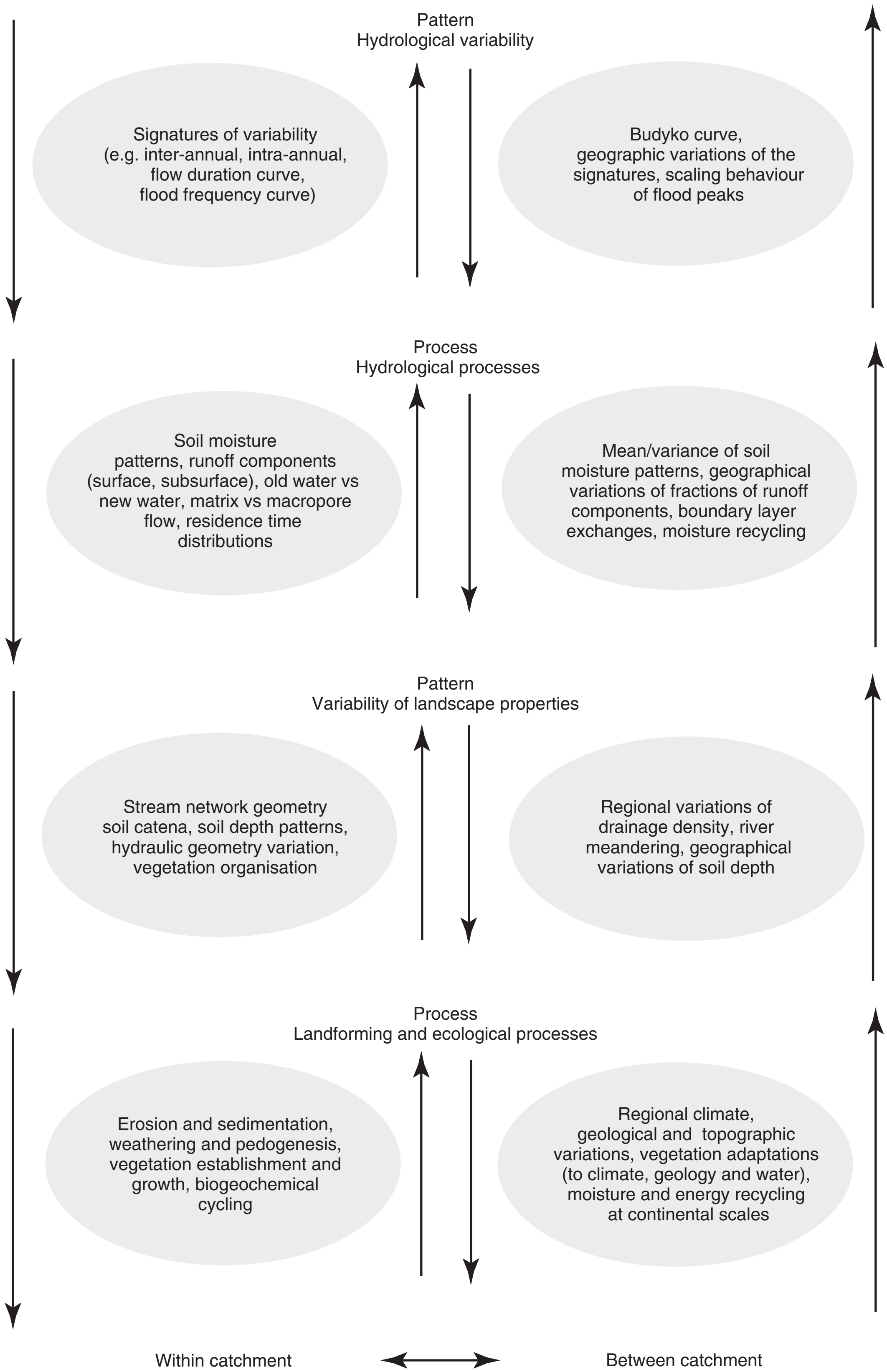


Figure 5 Downward and upward approaches to theory development in catchment hydrology – exchanges of knowledge and understanding at multiple levels

controls, and *vice versa*. In an analogous manner, between-catchment studies deal with spatial patterns, that is, differences between catchments located in the same region, or in different regions. Particular attention must be paid to scaling behavior exhibited by hydrological variables, both in the space and time domains.

Klemeŝ (1983) defines the downward approach 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" (*see* also Sivapalan *et al.*, 2003a; and *see* **Chapter 134, Downward Approach to Hydrological Model Development, Volume 3**). Along this downward path, we start at the patterns of observed hydrological variability at the catchment scale, and characterize these using appropriate measures of variability, as outlined before. The role of hydrological theory then is to explore the underlying process controls behind these patterns. At the next level, the approach will first involve observing hydrological processes at multiple space scales, not just the catchment scale, but both smaller and larger scales, and characterizing their variability through appropriate measures. The next step is to interpret the observed process variabilities in terms of the underlying heterogeneities in landscape properties, for example, soils, vegetation, topography, network geomorphology, HG and so on, and climate inputs. At the final, deeper level, the approach is to first characterize the natural spatial heterogeneities in the landscape properties, and quantify the heterogeneities through appropriate quantitative measures. The role of hydrological theory then is to explore the underlying, that is, hydrological, landforming, and ecological, process controls.

On the other hand, Klemeŝ (1983) defines the upward approach as "the route that attempts to combine, by mathematical synthesis, the empirical facts and theoretical knowledge available at a lower level of scale, into theories capable of predicting events to be expected at a higher, in our case hydrological, level". Along the upward path, we start at the deeper level, utilize existing knowledge about hydrological, landforming, and ecological processes toward development of process-based models capable of generating realistic patterns of landscape heterogeneities and validate these against observed patterns. At the next higher level, the approach will characterize the spatial heterogeneities in the landscape and climate properties, for example, soils, vegetation, topography, HG, network geomorphology and rainfall, and combine these with available small-scale process theories. Theory development will proceed by testing the predictions of the models against any observations of hydrological processes at the catchment scale. At the final level, the approach will observe and characterize hydrological processes at a wide range of scales, and aggregate these to generate patterns of hydrological variability at the catchment scale. The hydrological theory will evolve through testing or matching these predictions against patterns of behavior observed in the field.

Reconciliation Between the Upward and Downward Approaches

It is clear that the development of the catchment-scale theory will involve, at each level, almost symmetrical exchanges, upward in scale as well as downward, of both knowledge and understanding between observed patterns and the underlying process controls on the one hand, and between observed processes and the underlying patterns, on the other. As indicated previously in Figure 5, in the downward direction, theory development involves:

1. knowing the observed patterns, testing hypotheses about alternative processes that may have led to them, and
2. knowing the observed processes, testing hypotheses about alternative patterns that may have contributed to them.

In the upward direction, theory development involves:

1. knowing the processes, learning through constraining the patterns that they produce to match observed patterns, and
2. knowing the patterns, constraining the processes that they generate to match those that are observed.

The methodologies associated with the application of the downward and upward approaches, and the role of data, are presented in Figure 6. The upward approach starts with complex process descriptions and patterns, and whittles away the complexity and/or heterogeneity by constraining the model predictions using observed patterns and processes (Dooge, 1986; Sivapalan, 2003b). When the upward approach is repeated in different catchments, the descriptions will therefore evolve from specific to general catchment behavior. The downward approach involves identifying patterns of behavior or global relationships at the larger scale, for example, catchment scale, and looking for the processes that may have produced them, trying to connect the identified patterns or global relationships ultimately to such factors as soils, vegetation, drainage networks, and rainfall patterns (Dooge, 1986). Typically, the downward approach will start with simple process descriptions or patterns, and gradually adds complexities, through learning from observed patterns and/or process complexities. As we add more details in this way, the resulting models and process descriptions will evolve from the general or universal behavior toward behavior of specific catchments.

These objectives of the upward and downward approaches to the development of a new theory of catchment hydrology bear remarkable resemblance to equivalent themes reflected in the fields of ecology. In a recent review, Levin (1992), an ecologist, suggested, *inter alia*, that:

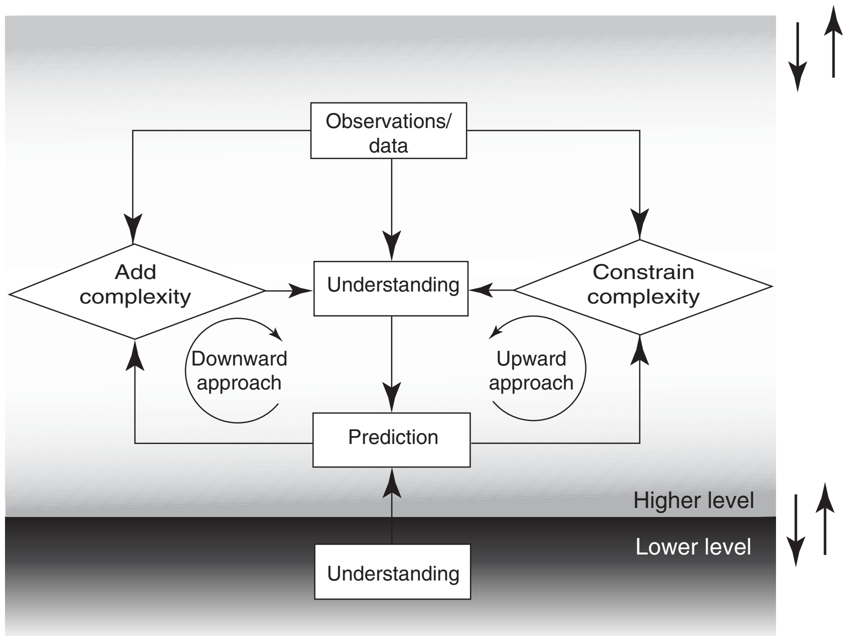


Figure 6 Methodologies of the downward and upward approaches to theory development. Adapted from Dooge (1986)

> "To scale from the leaf to the ecosystem to the landscape and beyond ... we must understand how information is transferred from fine scales, and vice versa. We must learn how to aggregate and simplify, retaining essential information without getting bogged down in unnecessary detail. The essence of modeling is, in fact, to facilitate the acquisition of this understanding, by abstracting and incorporating just enough detail to produce observed patterns... the objective of a model should be to ask how much detail can be ignored without producing results that contradict specific sets of observations, on particular scales of interest".

Clearly, there is much to learn from neighboring disciplines such as ecology, geomorphology, and pedology; the issues and the challenges are remarkably similar across the disciplines.

In fact, there is no reason for us not to use both the upward and downward approaches to generate and test *analogous* hypotheses regarding hydrological behavior at catchment scale. Independent application of the upward and downward approaches may, however, throw up conflicting outcomes, as illustrated schematically in Figure 7, which might still require reconciliation. One possibility is to altogether abandon any pretence to smaller scale process theories, and look for laws that may be sufficient to explain processes and/or patterns at the larger scale (Hatton *et al.*, 1997). Another possibility is that such conflicts or paradoxes might trigger further investigations leading to discoveries of new concepts or laws underpinning hydrological mechanisms that transcend multiple space-timescales, such as laws governing the ecological or geomorphological or pedological *function* of the catchment or parts of it, and in this way bring about the needed

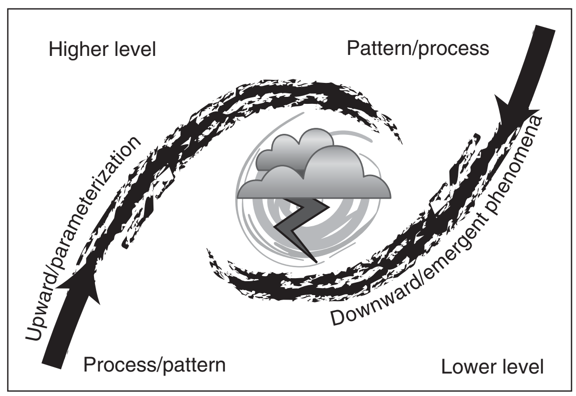


Figure 7 Reconciliation of downward and upward approaches – break or transition from a reliance on averaging and parameterization of lower level features to a culture of discovery and explanation of emergent phenomena at the higher level. A color version of this image is available at http://www.mrw.interscience.wiley.com/ehs

reconciliation. Examples of organizing principles or natural laws that are currently debated in earth system science include, principle of minimum energy expenditure in geomorphological systems (Rodriguez-Iturbe and Rinaldo, 2000), ecological optimality in vegetation systems (Eagleson, 1978a,c,g, 1982, 2002; Cowan and Farquhar, 1977; Cowan, 1982; *see* **Chapter 12, Co-evolution of Climate, Soil and Vegetation, Volume 1**), maximum entropy production in climate change and climate-vegetation feedbacks (Ozawa *et al.*, 2003; Kleidon, 2004; Bejan, 2000), and self-organized criticality in general complex systems (Bak, 1996; Rodriguez-Iturbe and Rinaldo, 2000; Hallet, 1990; De Boer, 2001). Any discoveries of this type can only come about through a broadening of the hydrological perspective to include multidisciplinary perspectives. These will also require or could be triggered through radically new observations that throw light on hitherto unknown mechanisms. Clearly, there is a lot of room for innovation and creativity; while the necessary conditions for breakthrough can be thus prescribed, success itself is *a priori* not predictable or guaranteed.

LEARNING FROM PATTERNS – METHODOLOGY OF THE DOWNWARD APPROACH, AND EXAMPLES

The methodology of the downward approach (Figure 6) may include the following steps: (i) identify an interesting pattern of behavior or an aspect of process observable at the catchment scale; (ii) devise alternative hypotheses, which may be potential explanations, or organizing principle, for the observed pattern or process characteristic; (iii) build the simplest possible predictive model based on this explanation or organizing principle; (iv) devise a numerical experiment (or several of them) with the simple numerical model, make a prediction of the pattern or process, and compare the predictions against data available at the higher scale; (v) on the basis of this test, either confirm or falsify the organizing principle or explanation as being correct or not; (vi) recycle the above steps, depending on the outcomes, making alternative hypotheses, or making further subhypotheses or sequential hypotheses to help resolve the possibilities that remain, developing a new numerical model and experiment to reflect the alternative hypothesis, or add more complexity to the previous model to reflect the subhypothesis or sequential hypothesis, and testing their predictions against the same data or additional data at the higher scale. Two examples are presented below as illustrations of the downward approach.

Pattern to Process: Spatial Scaling Behavior of Flood Frequency

The quantity of interest here is the annual maximum flood peak, and its dependence on catchment area. Empirical studies around the world have revealed that the annual flood peaks of a given return period T, Q_T, scale with catchment area, A, in terms of a relationship of the type $Q_T = cA^{\theta}$, with an exponent θ in the range between -0.10 and -0.40 (Jothityangkoon and Sivapalan, 2001). The power function relationship, and the exponent θ, can be seen as emergent behavior, that integrates information about complex rainfall–runoff–flood processes operating within a given region, how these change with increasing catchment size (Gupta and Dawdy, 1995; Robinson and Sivapalan, 1997a; Jothityangkoon and Sivapalan, 2001; Gupta, 2004), and about how the underlying process controls differ between different regions.

A number of studies have attempted to explore the physical basis of this scaling relationship, through the use of simple models that nevertheless captured the dominant process controls. Robinson and Sivapalan (1997a) approached this problem with the use of a simple rainfall-runoff model based on the unit hydrograph concept, with rainfall inputs that were scale-dependent, a mean catchment residence time also dependent on catchment area. With the use of this model, they showed that the interactions between two timescales, namely, rainfall duration and catchment response time, lay at the heart of the observed scaling relationship. Subsequent work by Robinson and Sivapalan (1997b) found that the observed apparent log–log linearity of the relationship between annual maximum flood peaks and catchment area is in fact caused by more complex interactions. At small catchment scales, within-storm patterns of rainfall variability interacted with the associated small mean resident times to increase the flow peaks. At large catchment scales, within-storm patterns were not important; instead, longer timescales in the rainfall field such as seasonality and the carry-over of storage between storms interacted with the longer residence times and again increased the magnitude of the flood peaks. Thus, the observed log–log linearity of the $E[Q_p]$ versus A relationship is a result of a "resonance" between the increasing catchment response time and the changing timescales associated with rainfall variability. Figure 8, adapted from Robinson and Sivapalan (1997b) illustrates this phenomenon. On the other hand, the spatial scaling of the rainfall intensities had a small but nevertheless significant contribution at all scales.

This then gives rise to a phenomenon which can be described as representing a *space to time connection* – an apparently simple spatial scaling behavior, an emergent property, being generated by complex interactions and feedbacks in the time domain between rainfall and runoff processes (Jothityangkoon and Sivapalan, 2001). The situation is further complicated when the relationship of the catchment response time to A depends on the relative dominance of hillslope and channel network in controlling the response time (Robinson *et al.*, 1995; Jothityangkoon and Sivapalan, 2001). Where the hillslope response time is dominant, θ approached zero, whereas in catchments where hillslope residence time is small, θ approached -0.40, an exponent in the relationship between channel length and A. Jothityangkoon and Sivapalan (2001) also demonstrated that the space-time connection and θ were also affected by the underlying long-term water balance regime, through its control of the antecedent soil moisture. Blöschl and Sivapalan (1997) found that the effects of resonance and the space-time connection, while important in a given hydrological setting, tend to be swamped by the other factors in larger, nonhomogeneous regions. They classified the

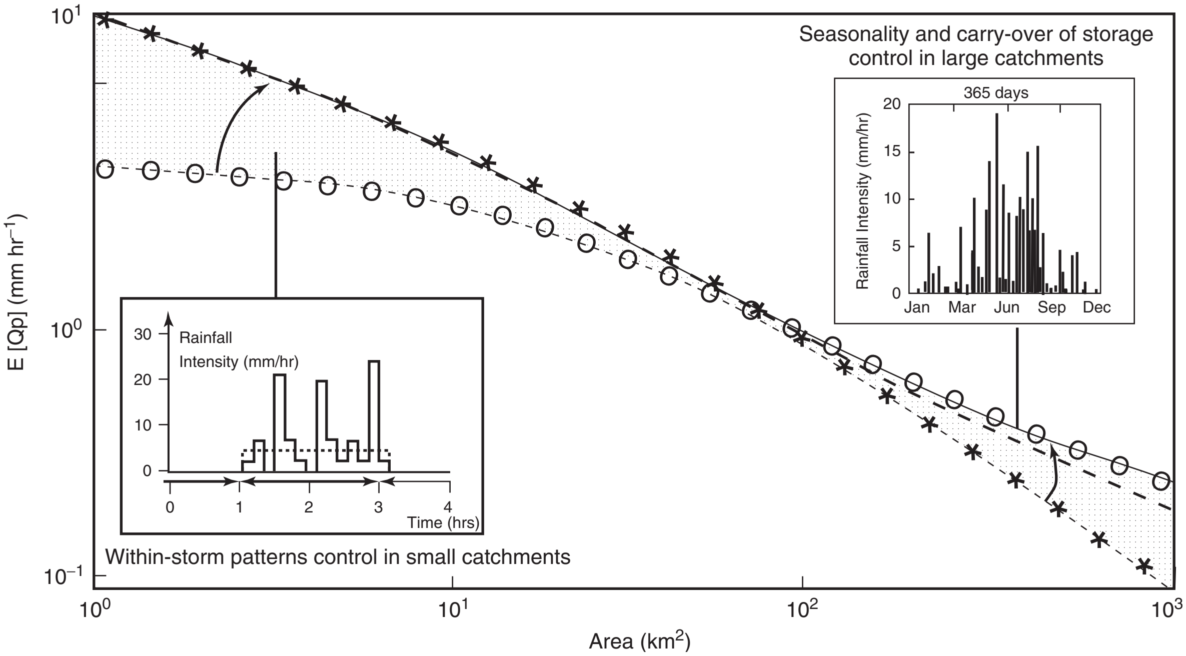


Figure 8 Process controls on scaling behavior of flood frequency. Power law relationship of mean annual flood with catchment area as an emergent property – complex interactions in the time domain leading to apparently simple pattern of behavior at the catchment scale

scaling behavior in Austria in terms of the differences in the underlying hydrological regime, which encapsulates the long-term water balance in a region.

A downward route for explaining the change of the flood frequency curve with catchment scale has also been taken by Merz and Blöschl (2003). They classified 12 000 flood peaks in Austria into long-rain floods, short-rain floods, flash-floods, rain-on-snow floods and snowmelt floods and then examined the flood statistics separately for each of the groups. They found that the coefficient of variation (*CV*) of the snowmelt flood type exhibited the flattest decrease with catchment area, which is consistent with the usually large extent of snowmelt. The *CV* of the flash-flood process type, however, tended to increase with catchment area, which was interpreted as being related to the nonlinearity of runoff generation associated with fast hillslope response.

These studies have demonstrated: (i) that apparently simple behavior may come about due to complex process interactions, and therefore the critical importance of these interactions; (ii) the power of simple models to elucidate the underlying process controls; and (iii) the use of these simple models to decipher broad-scale patterns and explain them in term of the underlying process controls.

Pattern to Process: Scaling of Hydraulic Geometry and Links to River Meandering

The dependence of channel hydraulic properties on streamflows have been known for a long time, and empirically described by the notion of HG introduced by Leopold and Maddock (1953). HG refers to the power law relationships relating the channel width, mean flow depth, and mean velocity to streamflow (discharge). These power law relationships have been observed to hold either for different discharges at a single cross section (called *at-a-station HG*), or for different downstream locations related through characteristic discharges having a constant frequency of occurrence (denoted as downstream *HG*). In their original work, Leopold and Maddock (1953) looked at HG in an *average* sense, ignoring the scattering around the proposed power laws.

Recently, Dodov and Foufoula-Georgiou (2004a) carried out extensive work on the *HG* relationships, paying particular attention to the scatter in the observed power laws. Through careful analysis, they showed that the exponents of the at-a-station *HG* systematically depended on catchment area, and that the exponents of downstream *HG* depended on the frequency. To quantify this empirical finding, they presented a lognormal multiscaling model, which was used to derive revised at-station HG whose coefficients are now explicit functions of catchment area. This generalized HG model was fitted to 85 gaging stations in Oklahoma and Kansas, and shown to reproduce the empirical trends extremely well. These revised HG relationships, being caused by streamflows in a self-organizing manner, therefore, represent an example of an emergent property, a phenomenon that only emerges at the catchment scale, possibly due to complex process interactions and feedbacks.

Subsequent work by Dodov and Foufoula-Georgiou (2004b) set out to explore the underlying process controls of the empirically determined and statistically described scale-dependence of at-site *HG*. They presented an analysis of fluvial instability (Parker, 1976) as a function of catchment area, and showed that channel planform geometry (e.g. sinuosity, curvature, and wavelength) and, particularly, the transition between straight and meandering channels, are scale-dependent. To relate channel planform geometry and channel shape, they used the numerical river model of Johannesson and Parker (1989) to calculate the bed topography of representative meander bends of a given Strahler order, and subsequently the *HG* of these bends. In this way, Dodov and Foufoula-Georgiou (2004b) showed that the at-site *HG* that emerges from this physical model is scale-dependent, and agrees with the empirical trends and the proposed multiscaling statistical model. On the basis of these findings, they concluded that the scale-dependent *HG* is caused by the systematic increase of channel asymmetry downstream, induced by scale-dependent fluvial instability; an example of an apparently simple and useful relationship being brought out by complex process interactions at smaller scales.

LEARNING FROM MODELS – METHODOLOGY OF THE UPWARD APPROACH, AND AN EXAMPLE

The upward approach starts with the most complex model based on the most current or appropriate process descriptions. The objective then is to discover natural rules or organizing principles that may act to constrain the combinations of parameters or process interactions, into permissible ranges that are consistent with observed patterns in real catchments. The methodology of the upward approach, as presented in Figure 6, may include the following steps: (i) choose or identify the most detailed or appropriate process model for the problem and catchment of interest; (ii) devise alternative hypotheses regarding parameter combinations or process interactions; (iii) devise a numerical experiment (or several of them) with the chosen model, constrain the combination of model parameters or process interactions; (iv) compare the resulting model predictions against observations available at the higher scale; (v) on the basis of the above, confirm, or falsify the organizing principle as being correct or not; (vi) recycle the above steps, depending on the outcomes, making alternative hypotheses, or making further subhypotheses or sequential hypotheses to help define the possibilities that remain.

The use of models in this manner renders them "virtual reality models" (Weiler and McDonnell, 2004; Wood *et al.*, 2005), used to gain insights and generate hypotheses that can be tested with observations, and thus lead to gains in understanding. This is quite different from traditional calibration exercises aimed at choosing the parameter combination that produces the best match to observations, which are not meant to generate understanding. One example involving the upward approach is presented in the next section as an illustration of the method.

Process to Patterns: Climate-soil-vegetation Interactions and Ecological Optimality

The interactions between climate, soils, and vegetation in controlling a catchment's water balance and subsequently the drainage characteristics have been highlighted earlier through the Budyko (1974) curve (*see* Figure 2b), which suggests that in spite of differences in geology, soils, and vegetation, the annual water balance is governed, to a large extent, by climate, indicating that the soils and the vegetation that develop in a catchment are already adapted to the climate. Figure 3(c) from Abrahams (1984) was equally suggestive of the role of vegetation in controlling drainage density, through the role of soil armoring through vegetation roots. In other words, there are strong feedbacks between climate, soil and vegetation, through both the water balance and erosional stability.

Eagleson (1978a,b,c,d,e,f,g) carried out a pioneering study of climate-soil-vegetation controls on annual water balance, and feedbacks that develop between climate, soil and vegetation; his work represents the best example of the upward approach. For this, Eagleson utilized a comprehensive hydrological (water balance) model consisting of physically-based conservation equations governing each of the constituent processes: infiltration, exfiltration, transpiration, percolation to groundwater, and capillary rise from the water table. The climate inputs were intermittent rainfall events, separated by interstorm periods. Because all of the surface and subsurface fluxes depend on soil moisture content, which is time variable in response to the climatic inputs, an equilibrium soil moisture concentration s_0, which represents the spatially and temporally averaged state of the soil, was chosen as the state variable, and all fluxes were estimated in terms of the assumed equilibrium moisture content. By solving the resulting annual water balance equation, the unknown equilibrium moisture content s_0 was estimated as a function of the climatic variables and the soil and vegetation characteristics. The problem was cast within a statistical-dynamic framework by introducing the probability density functions of the climatic inputs, and Eagleson derived probability distribution functions of the annual water balance components: surface runoff, evaporation, and groundwater runoff.

These distribution functions expressed the mean water balance partitioning in terms of the independent climatic variables (rainfall intensity, duration, and interstorm period), and the soil hydraulic properties (mainly

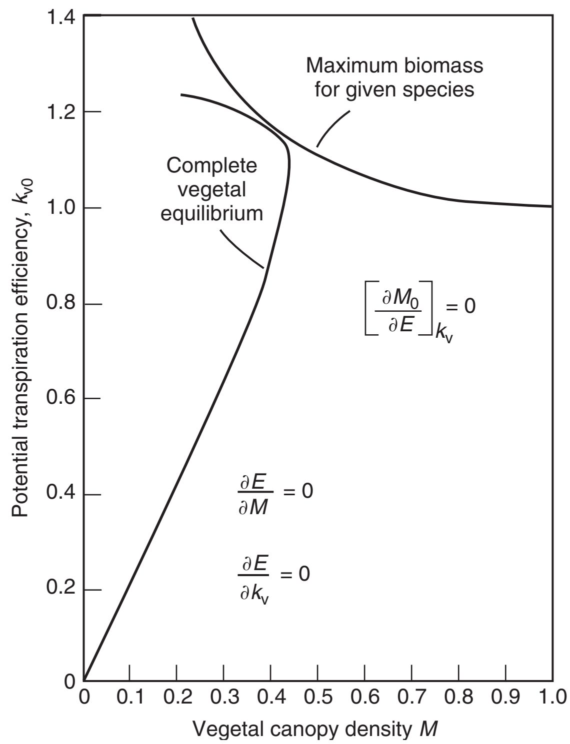


Figure 9 Ecological optimality constraints on climate-soil-vegetation interactions and the resulting water balance, and thus narrow down the space within which vegetation and soil parameters of a complex process-based model can vary (adapted from Eagleson, 1982)

the saturated hydraulic conductivity) and vegetation characteristics (density M, and species type k_v). In principle, according to the model, any combination of climate, soils, and vegetation is possible; apart from the climate inputs and process constraints, no constraints apply as yet to the soil-vegetation combinations that can be included in the model. In line with the methodology of the upward approach, Eagleson (1978d,e,f) invoked three constraints regarding the expected state of vegetation in a natural undisturbed ecosystem in an equilibrium state, which he called *the ecological optimality hypotheses* (*see* Figure 9).

Hypothesis 1: Over short timescales the vegetation canopy density, M, will equilibrate with the climate and soil parameters to minimize the water stress of the component plants, which is equivalent to a maximization of the equilibrium soil moisture, s_0.

Hypothesis 2: Over long timescales, species will be selected whose transpiration efficiency, k_v, maximizes the equilibrium soil moisture, s_0, which is equivalent to minimizing the total evapotranspiration, E.

Hypothesis 3: Over much longer timescales, vegetation will alter soil properties (saturated hydraulic conductivity, K_s, and the pore disconnectedness index, c, to maximize the optimal canopy density, M_0, derived from Hypothesis 1.

The invoking of these ecological constraints effectively limits the set of climate-soil-vegetation combinations to a small subset of the entire set of climate-soil-vegetation combinations that are possible in principle. Furthermore, through the invoking of the ecological optimality constraints, the theory can now be inverted; given the observed water balance in a given climate, the properties of the soil-vegetation system can be derived through an inversion procedure. Eagleson's ecological optimality hypotheses thus represent a predictive and testable theory (Hatton *et al.*, 1997; Kerkhoff *et al.*, 2004). Eagleson successfully tested his theory using observed data from catchments in different climates. In subsequent work, Eagleson (1982) argued that, with time, vegetation modifies (moderates) the hydraulic characteristics of parent material toward values which maximize vegetation production, that is, sandy soils become richer and more water-retentive; clayey soils become more porous and conductive. His ecological optimality hypotheses are capable of reproducing these observed features.

When confirmed on a wide variety of catchments, the ecological optimality hypotheses could constitute the elements of the new theory of hydrology. While recent analysis of the theory have cast doubts on the three ecological optimality hypotheses (Kerkhoff *et al.*, 2004) based on ecological considerations, they do not invalidate the approach adopted.

SUMMARY AND FUTURE PERSPECTIVES

The foregoing review has highlighted the difficulties with the reductionist paradigm that underpins the current theory of hydrology at the catchment scale. Current process theories using the derivatives of mass, momentum and energy balances, along with empirically derived closure relations, such as Darcy's law and Manning's equation, are sufficient to capture only a small fraction of all the hydrological variability that occurs within catchments. Due to the uniformity assumption underlying the small-scale process theories, the resulting distributed models are highly complex, data hungry, and overparameterized compared to the meagre observations on which they can be calibrated. This reductionist framework and the focus on calibration leads hydrologists to study specific catchments in ever more detail, instead of exploring, and learning from, differences between catchments. In spite of the high level of model complexity and the inputs of enormous amounts of data on climatic variables and landscape properties, the models based on current theories still cannot reproduce some key or defining aspects of observed behavior; the old water paradox is just one example. Paradoxes like this abound in hydrology, and in the absence of a new theory of hydrology that can unify the different perspectives, different experiences, and observations made in different contexts, models are being made more and more complex to accommodate these differences. Current textbooks on hydrology propagate the same fragmented vision of hydrology, organized by process, and written in the form of recipes, for example, 10 different formulas for estimating infiltration, potential evaporation, and so on. The situation is literally analogous to "a cacophony of noises ... not a harmonious melody" (Sivapalan, 1997; Sivapalan *et al.*, 2003b). There is a clear and urgent need to develop a new, unified, and holistic theory of hydrology at the catchment scale that overcomes these limitations.

Elements of the New Unified Theory of Hydrology

On the basis of this review, it is clear that feedbacks will play a central, defining role in the new theory of hydrology at the catchment scale. These include feedbacks between different processes, between patterns and processes, between different parts of catchments, and feedbacks in time (through memory effects). With that focus on feedbacks, the new theory will include the following basic elements:

Pattern: The new theory will seek and identify patterns (both within-catchment and between-catchment) in the data or observations as part of the learning process, to formulate and test hypotheses about underlying processes, process interactions and feedbacks, including the mechanisms that contribute to natural self-organization. Increased attention will be given to structured learning from observations and data.

Process: The new theory will seek to discover or explore new processes, process interactions, or mechanisms at all scales that embed within them either explicitly or implicitly the effects of landscape and climatic heterogeneities, including any simplification that might come about due to natural self-organization that may underlie these heterogeneities.

Function: The new theory will investigate the processes that lead to heterogeneities and the natural self-organization exhibited by landscape properties, and explore the laws or organizing principles governing their ecological function, with the idea that these laws will act as constraints on both the process descriptions (within-catchment), and broad-scale patterns of behavior (between-catchment, regional etc.).

Holistic: The new theory will be holistic, treating pattern, process, and function as parts of a whole continuum – processes lead to patterns, which in turn lead to other processes, with the interactions and feedbacks between pattern and process being mediated by "function", a seemless transition between these three elements, as illustrated schematically in Figure 10.

Multiscale: The new theory will accommodate heterogeneities and variabilities of the catchment system and its responses over multiple space and timescales. It is not limited to making connections between just two scales, a small scale (microscale) and a larger scale (macroscale), but to

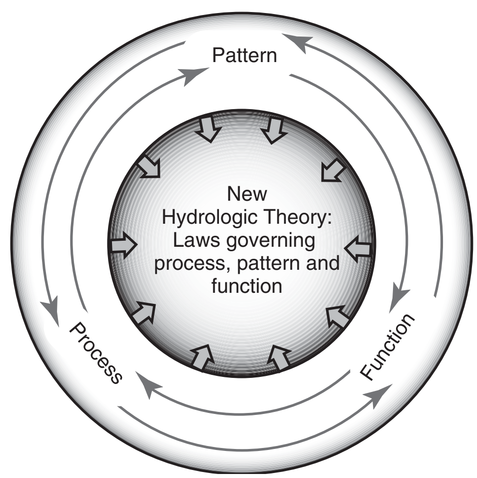


Figure 10 Pattern, process and function, feeding back on each other – elements of a new holistic theory of hydrology at the catchment scale

Old		New
Fragmented Description	→	Holistic Description
Narrow hydrological perspective	→	Broad multidisciplinary perspective
Individual processes	→	Process interactions and feedbacks
Calibration	→	Falsification
Data is grist to a calibration mill	→	Data is a source of learning
Effects of heterogeneity: Averaging and parameterization	→	Effects of heterogeneity: Emergent phenomena
Heterogeneity as a problem to be endured	→	Heterogeneity provides window into catchment functioning
Equi-finality is a curse	→	Equi-finality is a blessing
Models calibrated on limited observations	→	Models serve as virtual hydrological laboratories for hypothesis testing

Figure 11 Paradigm shifts accompanying new theory of hydrology at the catchment scale

identifying and quantifying patterns that span a wide range of scales, and to exploring mechanistic explanations for and the common concepts behind these patterns.

Multidisciplinary: By broadening the nature of scientific inquiry to deal with "function", the new theory will necessarily deal with issues and questions that are at the interface between hydrology and neighboring disciplines such as geomorphology, ecology, pedology, and climatology. In this way, it will necessarily involve a broadening of the hydrologic perspective to include multidisciplinary perspectives.

Combination of "place-based" and comparative studies: Most studies exploring processes must be conducted in actual catchments, in real places. Studies of pattern require observations in many catchments, in the same region, and/or in different regions. Exploration of function underlying pattern and process will therefore require a combination of both place-based and comparative studies.

The development of a new theory of hydrology will therefore require nothing short of fundamental or paradigmatic shifts in both research and practice, as illustrated in Figure 11.

Process of Theory Development and Needed Infrastructure

Exploration of Puzzles and Paradoxes

A new theory will come about through answering specific questions regarding catchment behavior in real places, and solving what appear to be puzzles or paradoxes, that is, through a "dialogue with nature". Hydrologists have become very proficient at solving the "what" and "how" questions, but a new theory requires the answering of broader "why" type of questions related to "function". Examples of some unsolved puzzles or paradoxes include, but are by no means limited to the following questions.

- The old water paradox (Kirchner, 2003): How do catchments store "old" water for long periods, but then release it rapidly during storm events, and vary its chemistry according to the flow regime?
- Nature is replete with preferential flow at many scales, ranging from fingering, macropores, fractures, rills and gullies, all the way to the river network. What is the ecological or landscape function of these preferred pathways? Can we predict their occurrence and their spatial densities in terms of the underlying climate and geology alone?
- Why do landscapes evolve under the movement of water into intricate shapes, for example, river networks, soil catena, a signature of which is also present in vegetation and soil moisture patterns? What are the rules underlying their natural symmetry? What is their function?
- How does natural vegetation evolve and adapt itself to limitations of water, energy, and nutrients? What are the underlying organizing principles? Can the natural vegetation pattern and its functioning be predicted on the basis of climate, soils, and the water balance? Can the observed vegetation pattern in space and time give us clues to the underlying water balance?
- How does vegetation and other biotic elements generate and modify the soils to maximize their own ecological functioning? What are the underlying organizing principles?

Hydrological Infrastructure

Explorations of these puzzles and paradoxes will require sustained, painstaking work by individual hydrologists, perhaps working in small groups (but not in committees!). Nevertheless, this kind work will benefit from the presence of a supportive infrastructure, which helps to multiply and link the work of individual hydrologists. Infrastructure and organization focused on observations, new measurement technologies, and advances in modeling capability, all aimed at predictions in ungauged catchments worldwide will help advance fundamental theory development, as illustrated schematically in Figure 12.

Hydrological observatories: A number of highly focused, and detailed field experiments must be carefully designed and carried out in different regions of the world, in *nested* fashion, in order to observe the multiscale hydrological processes at the plot, hillslope and basin scales, assemble the necessary internal and surrogate data needed to make inferences about the underlying mechanisms over a wide range of scales, and their connections to landscape and climatic heterogeneities. By definition, these have to be established, and maintained over of long periods of time; this can only be done at the regional, national, or international level.

New measurement technologies: One of the difficulties that has hampered the development of a unified theory of hydrology has been the inability to observe processes over a wide range of scales, and at the same time, monitor internal variables such as soil moisture storage, groundwater levels, saturation areas, and so on, so that catchment water balance can be closed with confidence. Inadequate data resolution leads to incomplete or even wrong theories, and partly explains the stagnation in the development of a unified theory. There is a crying need for breakthroughs in measurement technology, on the ground as well as through remote sensing (e.g. radar, satellite, geophysical instruments, tracers). Along with new sources and types of data, we also need a revolution in techniques for data processing, and for identifying patterns in the data, extending beyond the present standard methods, such as cluster or principal component analysis, fractal analysis, artificial neural networks, and so on.

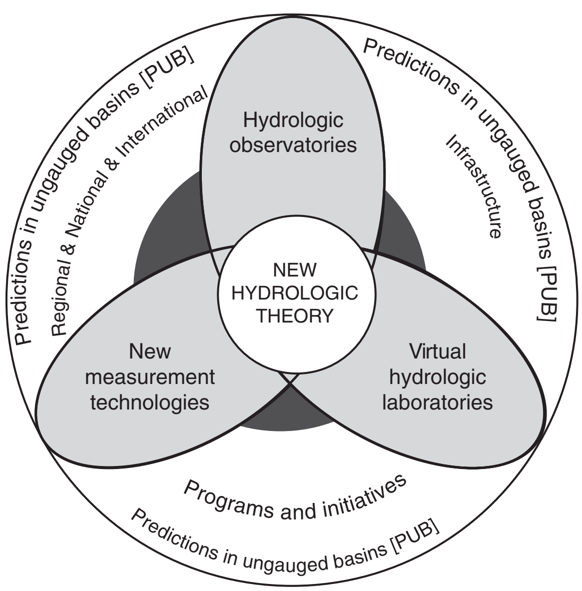


Figure 12 National and international initiatives provide the motivation and urgency toward theoretical advances in catchment hydrology

Virtual hydrological laboratories: In hydrology, we already have access to some of the most detailed, distributed, physically-based hydrological, hydrometeorological, ecohydrological and landform evolution models, containing within them the most up-to-date process descriptions currently available. There is much to gain from their use as "virtual reality models", by implementing them to test alternative hypotheses about the constraints that need to be imposed on the underlying heterogeneities of landscape properties to match observed patterns of behavior. This kind of intellectual activity can play a critical role in the development of a new theory of hydrology, and along the way it will lead to improvements of the models for predictive purposes because of the possibility that such constraints will lead to a simplification of the models.

Methodological Framework

Two approaches, upward and downward, and their reconciliation, were outlined for the development of a new theory. Along the downward route, we begin with observed patterns at the catchment scale and explore the underlying process controls. Along the upward route, we combine existing knowledge about hydrological, landforming, and ecological processes in complex hydrological models, and explore their ability to reproduce observed patterns. Both methods, systematic data analysis and modeling investigations, require organization and a commonality of purpose. In this respect, we include three community level activities that are crucial to the success of the theory development effort.

Catchment classification: The downward approach involves, essentially, making inferences from patterns in the observations. To make progress, in order to decipher meaningful patterns in the observations, hydrology requires a globally agreed classification system capable of predicting, to first order, the dominant controls on water fluxes and pathways from amongst the entire range of mechanisms that are possible. The classification system, a prerequisite for any attempt at theory development, must be established urgently as part of a broad community effort, even though it will evolve with time as the field matures (Dooge, 1986).

Such a classification system would itself provide an important organizing principle, complementing the concept of the hydrological cycle and the principle of mass conservation (McDonnell and Woods, 2004; Woods, 2002). To provide meaningful distinctions between catchments, the classification scheme should be based on characteristic measures of fluxes, storages, and response times: a measure of climate dryness such as the ratio of mean annual potential evaporation to rainfall, E_p/P; the average volumes of water stored in different compartments, that is, snow and glaciers, pore water (in soils, and rocks), and in open water (lakes, wetlands, river channels); and characteristic response times of these catchment stores (Skøien *et al.*, 2003).

New balance equations for nested river basins: To make progress along the upward route to conceptualization, the new theory of hydrology must embrace a quantitative framework that is able to connect components of the hydrological cycle and the catchment system across multiple space-timescales. A primary requirement of this framework is that it be distributed, explicitly respecting the self-organized river network structure that connects different parts of the catchment, including the organized and random heterogeneities that develop within it (e.g. topography, soil catena, vegetation). This quantitative framework should be in the form of a set of coupled balance equations for mass (water), momentum and energy, that is consistent with the organized heterogeneities that are present within the catchment. The most obvious natural building blocks for the derivation of the balance laws are a nested set of subcatchments associated with individual stream links, although other building blocks may also be considered (Troch *et al.*, 2003). Gupta and Waymire (1998) presented a coupled set of mass balance equations for flow within a stream network, and for runoff processes within associated subcatchments, all expressed in the form of a set of hierarchical (nested) difference equations. Reggiani *et al.* (1998, 1999) derived a more complete set of coupled mass, momentum, and energy balance equations for the stream network and associated subcatchments, which they called *the representative elementary watersheds* (*REWs*). These are indeed significant advances toward a consistent quantitative framework that is required for catchment hydrology. Nevertheless, the balance equations derived in these studies must still be supplemented with numerous closure relations for various exchange fluxes (Lee *et al.*, 2005). The determination of such closure relations, reflecting the natural self-organization that is present within catchments, is a significant and as yet incomplete element of the new theory of hydrology (Zehe *et al.*, 2005).

Scaling laws in hydrological behavior: Observed patterns of heterogeneity of climatic inputs landscape elements and hydrological behavior are based on information from disparate sources: experimental plots, field surveys, weather radar reflectivities, and satellite data. Increasingly, much information relevant to hydrology is able to be extracted from satellite remote sensing, including aspects such as soil moisture and vegetation patterns. Coarser, larger-scale field surveys may reflect processes occurring over longer timescales. For example, tree rings and paleobiological and paleohydrological data may unearth information about past changes over very long timescales (Harte, 2002). If simple, robust scaling patterns exist among these variabilities, they will let us connect and extend insights between different scales. Fractals, multifractals, and random cascades are modern stochastic techniques, which exploit concepts such as geometric and statistical self-similarity to quantify the relationship between the variabilities present at different scales, and have the power to describe apparently complex forms of heterogeneity occurring over a wide range of scales with a small number of parameters (Lovejoy and Schertzer, 1995). Multifractal concepts have already been used successfully to characterize space-time variability of rainfall fields and the structure of stream networks, and are already beginning to be used to describe spatial patterns of soils and vegetation, soil moisture, and a number of other geophysical and biophysical phenomena. The search for scaling laws is a key component of the development of a new theory of hydrology (Dooge, 1986; Levin, 1992; Harte, 2002; West and Brown, 2004), and must happen independently of the other two approaches.

Predictions in Ungauged Basins (PUB)

The development of a new theory of hydrology receives additional impetus due to the urgent need to predict catchment behavior, for the sustainable management of water resources and water quality, and the prevention and amelioration of water-related natural hazards such as floods and droughts. The International Association of Hydrological Sciences (IAHS) has launched the IAHS Decade on Predictions in Ungauged Basins (2003–2012), or prediction of ungauged basins (PUB), a new global initiative, aimed at formulating and implementing appropriate science programs to engage and energize the scientific community toward achieving major advances in the capacity to make predictions in ungauged basins (Sivapalan *et al.*, 2003b). PUB emphasizes (i) improved understanding of multiscale variabilities of hydrological behavior at catchment scale, (ii) increased use of advanced technologies, and (iii) development and application of sophisticated numerical models that depend less on calibration and more on understanding. The urgency engendered by PUB forces us to challenge and critically evaluate existing approaches to making hydrological predictions. In addition, a number of other ongoing national and international initiatives act as strong catalysts toward triggering significant theoretical breakthroughs (*see* **Chapter 203, A Guide to International Hydrologic Science Programs, Volume 5**). Parallel national programs are needed in many individual countries and in regions to provide the necessary infrastructure and funding for the associated research activities.

Current Intellectual Environment Surrounding Hydrology

Three contemporary scientific movements are providing a supportive environment for the theoretical advances in catchment hydrology, providing coherence and respectability to the efforts in this direction, as depicted schematically in Figure 13: (i) global change science, which provides support toward comparative hydrology on a global scale, helping to monitor large-scale patterns and understand the causes of these patterns; (ii) ecohydrology and earth system science, which help broaden the nature of hydrological inquiry, through exploration of process interactions and feedbacks, including interactions between hydrological, ecological, geomorphological, pedological, and climatological processes; and, (iii) complex systems science, an emerging interdisciplinary field spanning many fields, including mathematics, statistics, physics, ecology, and earth system science, which helps to generate new mathematical or analytical tools to deal with pattern dynamics and emergent phenomena that arise from nonlinear interactions and feedbacks in complex systems.

Apart from these scientific trends, the thrust toward a new theory of hydrology is also considerably aided by advances in technology: (i) vast improvements in our ability to measure and monitor hydrological parameters and state variables (and even fluxes through indirect methods) at large scales over the whole earth: these include satellite remote sensing, geophysical, and electronic measurements of increasing capability to plumb the subsurface hydrological condition, increasing sophistication of environmental isotope and chemical tracers to measure and monitor fluxes and state variables at the catchment scale; and (ii) increasing speed and storage capacity of digital computers that will enable hydrologists to run massively complex numerical models, in virtual reality mode, and improved methods of communication and sharing of data and results through the Internet which allows scientists to more easily cooperate and interact amongst large groups.

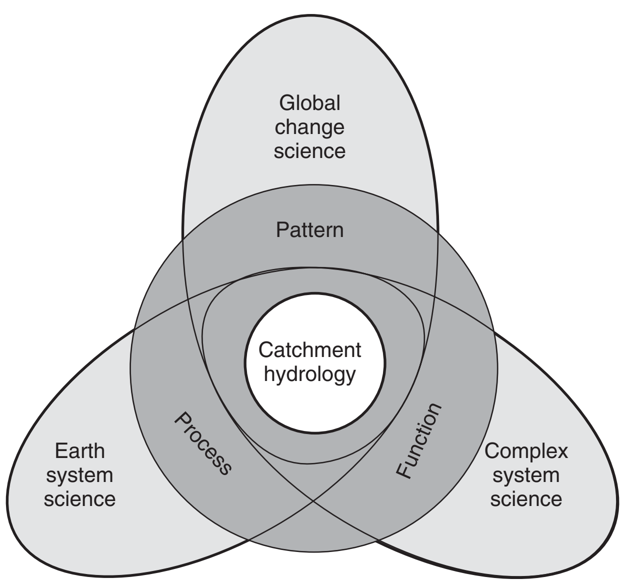


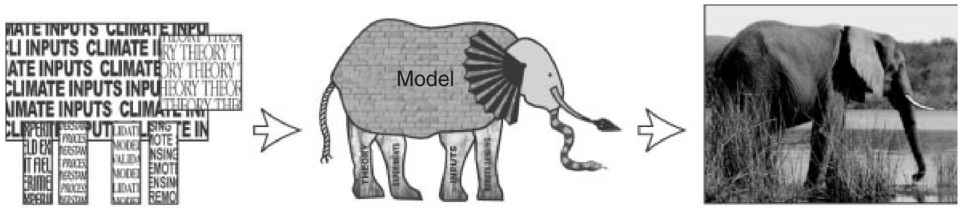
Figure 13 Current global scientific and intellectual environment providing a strong catalyst toward development of a new and holistic theory of hydrology at the catchment scale

Concluding Remarks

The urgency for a new, unified theory of catchment hydrology arises partly from the increasing frustration with the difficulties faced with existing hydrological models based on current theories, including the inability to satisfactorily resolve observed paradoxes. The urgent need to make satisfactory predictions of water quantity and water quality in ungauged basins, including the effects of climatic changes and human impacts requires a sound theory of hydrology that is solidly based on understanding and not calibration (Sivapalan *et al.*, 2003b). Therefore, the time is ripe for fundamental research that will set the stage for major advances in our predictive capabilities. Many national programs, and international initiatives such as PUB, are beginning to provide the necessary infrastructure, leadership, and coordination for groups of scientists to work together to address some of the most fundamental questions related to the development of a new theory. The increasing focus on earth system science, global change science, and complex system science is providing the necessary intellectual framework for a cross-fertilization of ideas across diverse disciplines, which can only benefit hydrology. For these reasons, there is real hope and excitement that catchment hydrology will leave behind the empiricism and fragmentation that has bedeviled it for so long, move forward toward a more unified and holistic theory that is fully accommodative of broad multidisciplinary perspectives, and will evolve from the "cacophony of noises to a harmonious melody" as anticipated in Figure 14. Hydrologists should rise up to these challenges and make use of the exciting opportunities that the pursuit of a new unified theory will generate.

Acknowledgments

Many of the ideas presented in this article are the result of discussions I have had with numerous colleagues and students over the past few years. As such, they are not just personal views and, to a large extent, they reflect the emerging views of many in the hydrology community. In particular, I am indebted to Günter Blöschl, Christoph Hinz,



From a cacophony of noises to a harmonious melody

Figure 14 From a fragmented to a holistic view of catchment hydrology, as an integral part of earth system science (Reproduced from Sivapalan *et al.*, 2003b by permission of IAHS. Illustration of elephant reproduced with permission from Jason Hunt © 1999)

Gavan McGrath, Jeff McDonnell, Hubert Savenije, Stan Schymanski, Ross Woods, Matthias Boer, Greg Hancock, and Patricia Saco, for freely sharing their ideas with me, and for offering advice and many constructive criticisms, which have helped to substantially improve the article.

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