



# Catchment Classification and Hydrologic Similarity

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## Abstract

Hydrology does not yet possess a generally agreed upon catchment classification system. Such a classification framework should provide a mapping of landscape form and hydro-climatic conditions on catchment function (including partition, storage, and release of water), while explicitly accounting for uncertainty and for variability at multiple temporal and spatial scales. This framework would provide an organizing principle, create a common language, guide modeling and measurement efforts, and provide constraints on predictions in ungauged basins, as well as on estimates of environmental change impacts. In this article, we (i) review existing approaches to define hydrologic similarity and to catchment classification; (ii) discuss outstanding components or characteristics that should be included in a classification scheme; and (iii) provide a basic framework for catchment classification as a starting point for further analysis. Possible metrics to describe form, hydro-climate, and function are suggested and discussed. We close the discussion with a list of requirements for the classification framework and open questions that require addressing in order to fully implement it. Open questions include: How can we best represent characteristics of form and hydro-climatic conditions? How does this representation change with spatial and temporal scale? What functions (partition, storage, and release) are relevant at what spatial and temporal scale? At what scale do internal structure and heterogeneity become important and need to be considered?

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## 1 Introduction

*Kings Play Chess On Fine Class Stools* is one of many mnemonics used to help remember the hierarchical classification of organisms in biology: (Domain) Kingdom, Phylum, Class, Order, Family, Genus, Species. Biology has been at the forefront of the science of classification and the term

taxonomy (from Greek verb *tassein* = 'to classify' and *nomos* = law, science, cf. 'economy') had for long only been associated with classification of organisms, but has since been used more widely to refer to classification or the principles underlying classification in other fields as well. Classification schemes have become well established in fields beyond biology. Examples include chemistry (periodic table) where elements with the same valency are expected to behave similarly, or limnology where bodies of water are classified by mixing regime, or by nutrient status. Fields such as fluid mechanics use continuous dimensionless numbers to describe the character of flow (e.g. Froude and Reynolds numbers). For example, the Reynolds number is used to separate the flow into laminar or turbulent regimes, while the Froude number distinguishes between sub- and super-critical flow in open channels; see Table 1 for other examples. These similarity indices are a natural consequence of the governing equations for fluid flow, when applied to particular cases.

Fifty years from now, if we were to look back at the state of the science of hydrology, it is possible that we might describe its current situation in the following terms: *successful locally in its various subbranches, but there was no global unity to the proliferating research programs*. Indeed, it turns out that this was actually a statement that appeared in a review of biology dating back to 1830 (Woods 2004), showing that biology too had a preclassification phase similar to where hydrology stands today. An important task of science in any particular field is to perpetually organize the body of knowledge gained by scientific inquiry. While biology is now a well-established science and classification of *organisms*, its main entity of interest, has progressed far, other sciences are younger and therefore perhaps less advanced in understanding how their knowledge could be similarly organized or generalized. Hydrology is such a science, which has not yet achieved a globally agreed upon classification system for its main 'entity' of interest, the catchment (also called basin or watershed), and the mechanisms of movement and storage of water within it.

A catchment is defined as the drainage area that contributes water to a particular point along a channel network (or a depression), based on its surface topography. The catchment forms a landscape element (at various scales) that integrates all aspects of the hydrologic cycle within a defined area that can be studied, quantified, and acted upon (Wagener et al. 2004). Catchments are typically open systems with respect to both input and output of fluxes of water and other quantities (Dooge 2003), and can be termed complex environmental systems – although with some degree of organization (Dooge 1986; Sivapalan 2005). For most hydrologists, particularly those who undertake extensive field studies in diverse catchments around the world, it is easy to believe that *diversity is nature's principal theme* (Gould 1989, 97). Such statements yield support to the *uniqueness of place* argument put forward by Beven (2000a), in which he discusses how the uniqueness of a place with respect to the topography, soil, geology, vegetation,

**Table 1. Dimensionless numbers used in fluid mechanics (Modified from Munson et al. 2002).**

Dimensionless groups	Dimensionless number	Interpretation <sup>1</sup> (ratios)	Application
$\frac{\rho V l}{\mu}$	Reynolds number, Re	Inertia force to viscous force	Generally of importance in all types of fluid dynamics problems
$\frac{V}{\sqrt{gl}}$	Froude number, Fr	Inertia force to gravitational force	Flow with a free surface
$\frac{p}{\rho V^2}$	Euler number, Eu	Pressure force to inertia force	Problems in which pressure, or pressure differences, are of interest
$\frac{\rho V^2}{E_v}$	Cauchy number, Ca	Inertia force to compressibility force	Flows in which the compressibility of the fluid is important
$\frac{V}{c}$	Mach number, Ma	Inertia force to compressibility force	Flows in which the compressibility of the fluid is important
$\frac{\omega l}{V}$	Strouhal number, St	Inertia (local) force to inertia (convective) force	Unsteady flow with a characteristic frequency of oscillation
$\frac{\rho V^2 l}{\sigma}$	Weber number, We	Inertia force to surface tension force	Problems in which surface tension is important

<sup>1</sup>Index of force ratio indicated. Variables: acceleration of gravity,  $g$ ; bulk modulus,  $E_v$ ; characteristic length,  $l$ ; density,  $\rho$ ; frequency of oscillating flow,  $\omega$ ; pressure,  $p$  (or  $\Delta p$ ); speed of sound,  $c$ ; surface tension,  $\sigma$ ; velocity,  $V$ ; viscosity,  $\mu$ .

and anthropogenic modification associated with each catchment limits our ability to create generalizable (or regionalizable) hypotheses. We are particularly limited due to our inability to 'see' the subsurface of a catchment, in which much of the hydrologic response often remains hidden from our current measurement techniques. *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, and land-forming processes* (Sivapalan 2005). Therefore, while the complexity and the differences between catchments can often be overwhelming, patterns and connections might be discernible and lead to advancement in hydrologic science through the formulation of hypotheses or relationships that may have general applicability. Achieving such generalization has been particularly difficult in all sciences related to the natural world (see Harte 2002, for an example from ecology), not just hydrology. Our currently available small-scale theories are limited in their ability to explain hydrologic behavior at the catchment scale (Kirchner 2003), and a potentially robust as well as reproducible theory is most likely to come from quantitative and causal explanations of differences and similarities between catchments in different parts of the world (Sivapalan 2005).

Underlying the search for a new theory is the human mind's craving for order – one approach to create order and sense in an otherwise heterogeneous world is through the means of classification (Gould 1989, 98). We view classification not simply as a way of creating a filing system, but rather as a rigorous scientific inquiry into the causes of similarities and relationships between catchments. In this sense, *classifications are theories about the basis of natural order, not dull catalogues compiled to avoid chaos* (Gould 1989, 98). Any particular class of natural entities so chosen (organisms, catchments, flow regimes) is of course likely to still contain large internal complexity or heterogeneity, but in our view *classification groups together those systems that are similar, and thus limits the variability within classes* (McDonnell and Woods 2004). In hydrology, we of course already have some globally agreed upon concepts like the conservation of mass, even if measurement techniques to capture such integrated fluxes and storages at relevant scales are still limited (Beven 2006). We also have different types of classification (or at least different descriptive terms) already in use, including those based on climate (humid versus arid, semi-arid, etc.), based on land cover (forested versus agriculture, urban, etc.), based on catchment response (fast versus slow), based on storage (groundwater dominated versus surface water dominated catchments), etc. Although these groupings by themselves do not provide a comprehensive classification system in our view, and some of them (e.g. fast versus slow) are not well defined and therefore difficult to apply in a consistent manner, attempts at precise definitions have been made (see for example Robinson and Sivapalan 1997). These classifications also do not reach a higher goal that we have set ourselves (i.e. providing insight into causes of similarities and relationships

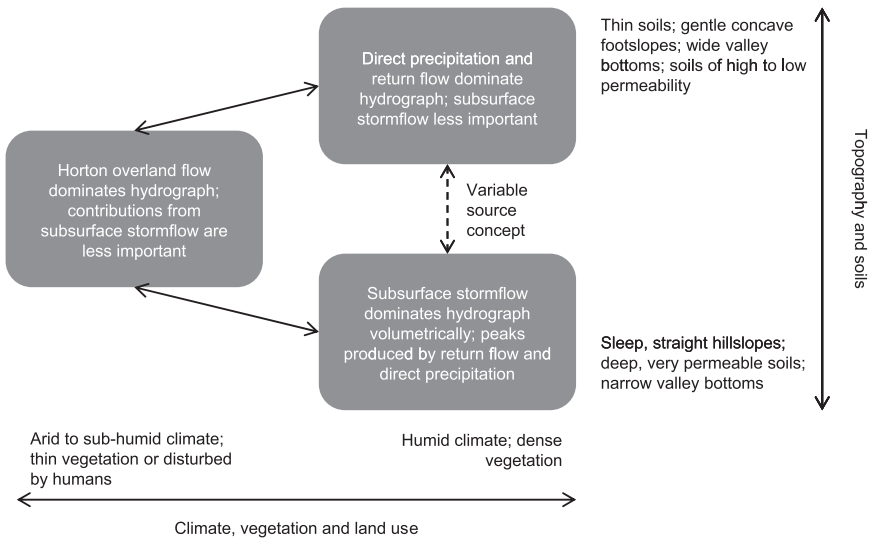


Fig. 1. Dominant processes of runoff generation mechanisms at the hillslope scale (after Dunne and Leopold, 1978; Dunne, 1983).

between catchments). The benefit of having a comprehensive and holistic classification system can be outlined by reference to the so-called Dunne diagram for runoff generation mechanisms (Dunne 1983; Dunne and Leopold 1978; Figure 1). Although not expressed in quantitative terms, this diagram shows likely dominant runoff generation processes in any catchment as a function of soils, topography, climate, vegetation, and land use (it is admitted that there is probably a strong correlation between some of these characteristics). In its essence, the Dunne diagram is able to relate certain aspects of catchment response or functioning in terms of a certain organization of climate and landscape properties, reflecting a distillation of our collective observational evidence. We are interested here in extending such a scheme to the overall catchment response through a rigorous classification system that is perhaps a generalization of the Dunne diagram.

As we begin to compare and contrast catchments across places (e.g. across diverse climates and geologies), and across processes and functioning, we also recognize likely variations across scales (spatial and temporal). Thus, the general catchment classification scheme we seek to develop will likely require explicit consideration of both spatial and temporal scales. A study by Olden and Poff (2003) demonstrates that daily, monthly, and annual hydrologic indices are not always correlated, suggesting that different or independent information is present at these different temporal scales. Sivapalan and his colleagues (e.g. Atkinson et al. 2003; Farmer et al. 2003; Son and Sivapalan 2007) have shown that dominant climatic and landscape

controls on hydrologic behavior are time-scale dependent. Similarly, Poff et al. (2006) discuss our limited knowledge about how far hydrologic characteristics can be extrapolated up- or downstream along a river network away from a gauge location. This limited extrapolation potential could be caused by varying hydrologic characteristics with spatial scale (Dunne and Leopold 1978), particularly if the catchment under study covers different climatic or geologic regions. Additionally, it is likely that internal variability and connectivity of the catchment will play important roles at smaller spatial and temporal scales (Buttle 2006).

A globally agreed upon, broad-scale classification system for catchments is needed to advance the science of hydrology. Such a system would (modified and extended from McDonnell and Woods 2004):

- provide an important organizing principle in itself, complementing the concept of the hydrologic cycle and the principle of mass conservation,
- help with both modeling and experimental approaches to hydrology, by providing guidance on the similarities and differences between catchments,
- improve communication by providing a common language for discussions,
- allow the rational testing of hypotheses about the similarity of hydrologic systems from around the globe, as well as better design of experimental and monitoring networks by focusing on measuring the most important controls,
- provide better guidance for choosing appropriate models for poorly understood hydrologic systems,
- be a major advancement toward guidance for the applicability of various simulation methods for predictions in ungauged basins,
- provide constraints and diagnostic metrics that can be used for model evaluation/diagnostics and application and ungauged locations, and,
- provide, to first order, insights into the potential impacts of land use and climate changes on the catchment scale hydrologic response in different parts of the world.

*In particular, a rigorous catchment classification system would enable us to sort and group the tremendous variability in space, time, and process, which is present in natural hydrological systems all around the globe (McDonnell and Woods 2004), and to bring some harmony to the cacophony that is present in hydrology (Sivapalan et al. 2003b).* We might be called overconfident in claiming that we could produce a comprehensive classification system in a short article such as this one, whereas in other fields such as biology whole monographs have been required to achieve the same objective. The intention here is therefore to provide a basic discussion about what such a classification system should try to achieve and what the characteristics of a classification framework should be. This includes a discussion of what metrics should be used to judge similarity or dissimilarity between catchments, as well as advantages and disadvantages of metrics and schemes for

discrete classification (as in biology) or for continuous similarity variables (as in fluid mechanics). We start this discussion with three premises, namely, (i) the enormous complexity of environmental factors impacting the catchment response requires us to concentrate initially on dominant (or first-order) characteristics (controls) only, (ii) any classification system has to explicitly consider uncertainty in the variables underlying the classification metrics, and (iii) it should be based on data that is (relatively) uniformly available around the world – although the latter point is likely to change with advances in measurement techniques. The uncertainty present is mainly caused by our inability to observe or represent hydrologic variables/processes and catchment physical characteristics (Wagener and Gupta 2005). When the uncertainty of predictions of expected behavior is excessive, be it due to inadequate understanding of catchment behavior or due to the inability to know or estimate the salient catchment characteristics, the classification system loses its power or vitality. A discussion of mathematical techniques to discern clusters of similar metrics could be viewed as an essential component of a classification system but is viewed as beyond the scope of this article and can be found elsewhere (e.g. Arabie et al. 1996; Burn 1989, 1990, 1997; Burn and Goel 2000; Castellarin et al. 2001; Gordon 1999; Holmes et al. 2002; McIntyre et al. 2005; McKay 2003; Mirkin 1996; Nathan and McMahon 1990; Rao and Srinivas 2006a,b; Wagener et al. 2004; Yadav et al. 2007; etc.).

In this article, we (i) review existing approaches to define hydrologic similarity and to catchment classification; (ii) discuss outstanding components or characteristics that should be included in a classification scheme; and (iii) provide a basic framework for catchment classification as starting point for further analysis.

## *2 A Perceptual Model of Catchment Function*

We believe that a classification system, to be widely adopted, must be underpinned by a perceptual model of catchment function, as a common or unifying theme. A perceptual model of a catchment is based on the subjective understanding of hydrologic processes occurring and is not constrained by our ability (or inability) to represent these processes in mathematical form (Beven 2000b). It is also certainly not based on process description at the point or small scales. In this article, the perceptual model that will guide our proposed classification system is based on the commonly agreed perceptions of at least four hydrologists (although strongly simplified due to the length constraints of this paper). Discussions of other (more detailed) perceptual models can be found elsewhere (e.g. Anderson and Burt 1990; Beven 2000b; Kirkby 1978; Ward and Robinson 2000).

The term *function* is defined here as the actions of the catchment on the water entering its control volume (i.e. catchment area extended into

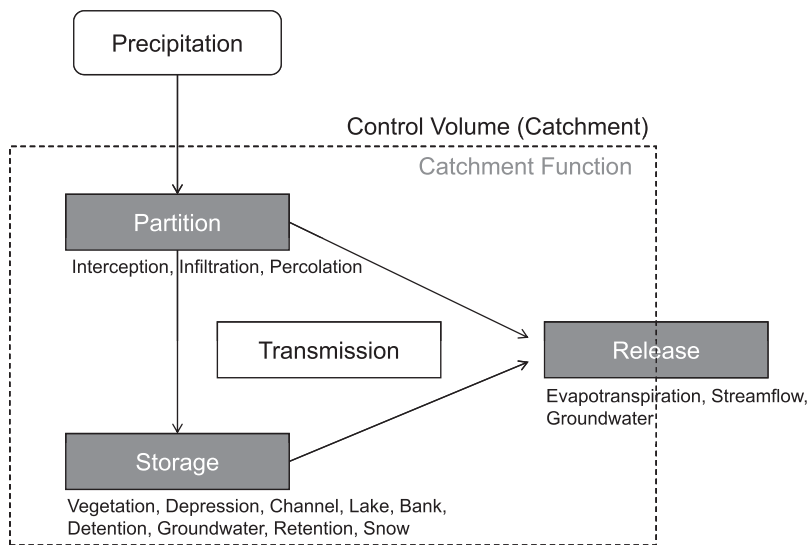


Fig. 2. Catchment function (partition, storage and release).

the near-surface atmosphere and down to the bedrock). What function a user of a catchment classification system will care about depends on user interest and sophistication (expert versus nonexpert). Here, we will distinguish three basic functions of a catchment (modified from Black 1997; Figure 2):

- *partition* of collected water into different flowpaths (interception, infiltration, percolation, runoff, etc.)
- *storage* of water in different parts of the catchment (snow, saturated zone storage, soil moisture storage, lakes, etc.)
- *release* of water from the catchment (evapotranspiration, channel flow, groundwater flow, etc.).

In addition to these functions, there will be transmission of water within the catchment. The starting point of the perceptual model is the formation of water input to the control volume. Precipitation occurs when water condenses around aerosols in the atmospheres and drops grow sufficiently large to fall to the earth. At temperatures below 32 °F, ice crystals are formed rather than water drops (Black 1997). The precipitation then falls as rain, snow, hail, freezing rain, fog drip, etc. and enters the control volume considered here, where the different functions of the catchment will act on it.

*Partitioning* occurs close to the surface when part of the incoming precipitation is intercepted by vegetation, while the remaining part reaches the ground as throughfall or stemflow. Leaf litter covering the soil may form another intercepting layer. Further partitioning happens when water

not retained by vegetation or litter infiltrates. This will occur unless the precipitation rate exceeds the actual infiltration rate of the soil. The water that does not infiltrate will run off over the land surface, although it might still infiltrate further downhill. The infiltrated water will either increase the soil moisture storage, or will percolate deeper to eventually recharge the groundwater or saturated zone storage. Lateral transmission of the infiltrated water in the unsaturated zone or in the saturated zone might move the water to other parts of the catchment.

*Storage* of water takes place throughout the watershed and mainly includes storage in vegetation, soil (retention/capillary water or detention/non-capillary water), channel network, and groundwater. Lakes, floodplains, and wetlands might sometimes provide significant storage in the system as well. At air temperatures below about 4 °C, the probability of precipitation falling as snow increases sharply and water might also be stored in frozen form as snow or ice (Dingman 2002). Type, size, and distribution of storage will vary widely between catchments. In this respect, one could see storage as the connecting element between partitioning and release, although the storage of some of the precipitation might be very temporary only. The largest storage is usually the soil profile, which in humid areas will often fill up during wet periods. The resulting saturated areas will occur in particular close to the stream network and in converging areas such as the bottom of hillslope or in hollows (Kirkby 1978). In dry or semi-arid areas much of the storage is held in the unsaturated zone as capillary water and then evaporated during the interstorm or dry periods of the year.

*Release* from the catchment is the ultimate fate of water. Here, we distinguish this function from the transmission of water within the catchment (i.e. within the control volume). How the release from different storages in the catchment is triggered is not always clear, particularly if this storage is in the subsurface, and estimates of and control on water residence time are a currently very active areas of research (e.g. Kirchner 2003; McGuire et al. 2005). Kirchner (2003) summarizes these unsolved issues, which might limit our ability to classify, in two questions: (i) *How do these catchments store water for weeks or months, but then release it in minutes or hours in response to rainfall inputs?* (ii) *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?* McGuire and McDonnell (2006) review the use of lumped mathematical models to simulate the related transit time of water through complex catchment systems, and discuss the limitations of currently available tools for this purpose. The release characteristics will also be strongly impacted by physical characteristics of the river network (Rodriguez-Iturbe and Valdes 1979), and by the connectivity between hillslopes and the river network (McGlynn and McDonnell 2003). Another release pathway is the one due to evaporation and transpiration into the atmosphere. This aspect of the hydrologic cycle gained

more attention in recent year due to its link to food production (e.g. the green and blue water concept, see Falkenmark et al. 2004). All the above processes take place in the context of temporal and spatial variability occurring at a wide range of scales for both atmospheric forcing and catchment form (e.g. Woods 2005).

Black (1997) also discusses chemical and habitat (ecological) catchment functions in addition to the three functions mentioned above. We will focus on the three functions discussed here in the remaining paper. Note that the descriptions of the broad functions defined by Black (1997) echo descriptions of similar broad-scale processes provided by L'vovich (1979), such as wetting, drying, storage, discharge, and drainage. L'vovich (1979), and later Ponce and Shetty (1995a,b), viewed the overall function of the catchment as consisting of a competition between these processes, mediated by climatic and landscape properties, perhaps following some as yet undetermined rules of behavior. The classification system that we hope to develop must provide insight into this competition, as a way of comparing and contrasting catchments in different hydro-climatic regions.

With respect to the specific characteristics of a hydrologic classification framework, one has to keep in mind that some of the functions that one might wish to address are not, or at least not directly, observable. It is likely that our ability in this regard will remain limited for some time, despite significant advances in observational technology.

### 3 Similarity and Classification Metrics

Chapman (1989) suggests that ecological classification would be an ideal starting point for a hydrologic classification system, because the ecological characteristics of an area effectively integrate features of the hydrologic regime. However, Chapman mentions large alterations of ecological regimes due to human activities as one of the main limitations of this idea. We will therefore take a different approach, but later discuss how ecology could (should?) still be part of a classification system.

What should the metrics be that define similarity or dissimilarity between catchments in a hydrologically relevant manner? *Hydrologists have always tried to relate structural features of catchments to their response characteristics* (Bras 1990, 589). If our underlying scientific curiosity is to understand this relationship, then our metrics should include static characteristics of a catchment's 'form' (e.g. geomorphologic and pedologic characteristics) and forcing (e.g. characteristics of precipitation and radiation), as well as dynamic catchment response characteristics (signatures, patterns) of 'function' (e.g. streamflow [runoff], groundwater [baseflow], soil moisture [evapotranspiration, recharge]), noting in passing that both the form and function of catchments reflect co-evolution of climate, soils, topography, and vegetation. Of course, static characteristics such as landscape topography are also changing (e.g. Collins et al. 2004), but at time-scales that are much larger

than the catchment behavior that is typically of interest. We can therefore consider them static in the context of this article, yet they provide a window into the long-term processes that created them while governing the short-term functional responses that we wish to predict. An early example of such of a relationship between form and function is described by the geomorphologic instantaneous unit hydrograph developed by Rodriguez-Iturbe and Valdes (1979), in which the authors relate event streamflow (runoff) characteristics to channel network geomorphology and geometry.

Some general suggestions about what relevant metrics might be could come from the increasing literature on regionalization of hydrologic models to achieve continuous streamflow predictions in ungauged basins (e.g. Abdulla and Lettenmaier 1997; Berger and Entekhabi 2001; Fernandez et al. 2000; Jakeman et al. 1992; McIntyre et al. 2005; Merz and Bloeschl 2004; Parajka et al. 2005; Wagener et al. 2004; Wagener and Wheeler 2006; etc.). These regionalization studies try to understand the controls on the continuous streamflow response, although many are relying on lumped catchment-scale models as vehicles to achieve this, which introduces potentially large uncertainty into this process due to problems of model structural error and our inability to appropriately formulate the calibration problem (Wagener and Wheeler 2006). A series of regionalization studies in the UK have shown a clear pattern of catchment characteristics that were most dominant in describing catchment similarity (Burn 1990; Burn and Boorman 1992; Calver et al. 2005; McIntyre et al. 2005; Robinson 1992; Yadav et al. 2006; 2007). These studies concluded that relevant static characteristics are related to surface and subsurface structure (form): such as drainage area, average basin slope, pedology, and geology; and related to hydro-climatology: long-term precipitation characteristics, or the annual precipitation to annual potential evapotranspiration index.

These results suggest that in a multidimensional space relating form (structure) and function (response), the axes describing the static characteristics of similarity should be labeled structure and hydro-climate. We can consider climate, the long-term average weather in a region, at least initially as static. This conclusion is in line with those of others including Winter (2001) who states that hydrologic landscape units should include descriptors of land-surface form (slope and area), geologic framework (hydraulic properties of geologic units), and climatic setting (in their case, precipitation minus evapotranspiration balance). Winter (2001) suggests that, *for example, areas having similar land slopes, surficial geology, and climate will result in similar hydrologic flow paths regardless of the geographic location of the site*. Yadav et al. (2007) additionally found land-use to be a hydrologically relevant descriptor of form (percentage grassland for 30 UK catchments), which makes these characteristics similar to those used in ecology related classifications (e.g. Detenbeck et al. 2000; Snelder and Biggs 2002; Snelder et al. 2004; Wardrop et al. 2005).

In addition, we will need an axis that describes the hydrologic variable of interest as a function of catchment form (structure) and hydro-climate (i.e. the dynamic characteristics describing the actual response behavior [subsequently called function] of the catchment). Function is for our immediate purposes our dependent variable. Understanding the connection between structure, hydro-climate and response behavior would advance hydrologic understanding and our predictive capability. McDonnell and Woods (2004) state that at its most fundamental level, a classification scheme will need to include descriptions of fluxes, storages, and response times as dependent variables, to achieve a meaningful distinctions between catchments. Example–dynamic metrics could include *the state in which water is predominantly stored: either frozen (snow and glaciers), or pore water (in soils and rocks), or open water (lakes, wetlands, river channels)*, and especially their magnitudes; and *the turnover time of the dominant catchment storage (volume of storage which has the largest flux, divided by the flux)* (McDonnell and Woods 2004).

As mentioned earlier, another important consideration is that emergent properties or behavioral characteristics will change with temporal scale (and maybe even spatial scale) of the analysis (e.g. Atkinson et al. 2003; Biggs et al. 2005; Farmer et al. 2003; Kirchner et al. 2004; Thoms and Parsons 2003). It is therefore also likely that the structural and hydro-climatic characteristics that control this behavior will change with scale. How the axes of function, structure and hydro-climate are therefore defined will be depend on the specific time and space scales chosen.

One difficulty of establishing such metrics lies in collapsing the vast complexity of environmental factors that define the hydrologic regime of natural catchments into a few parsimonious numbers, distributions or models. These difficulties arise in part from two major factors: the first is our as yet inadequate and slowly developing understanding of how climate, soils, topography, and vegetation interact and co-evolve to produce catchment responses and functioning, and the choice of the best or most appropriate metrics themselves. The second is our severely limited ability to measure structural characteristics (in particular those of the subsurface), hydro-climatic characteristics (e.g. precipitation in remote regions), and functional characteristics (e.g. residence time, soil moisture distributions) with currently available measurement technology (Beven 2000b). Work is required to achieve major advances to overcome both of these limitations, which feed back on our ability to improve and benefit from the proposed classification system.

#### 4 Classification Based on Catchment Structure

Classification and similarity as defined by structural catchment characteristics have a long tradition in hydrology. Characteristics of this type have been proposed in the form of (often dimensionless) numbers, of curves or distributions, and of conceptual and mathematical models.

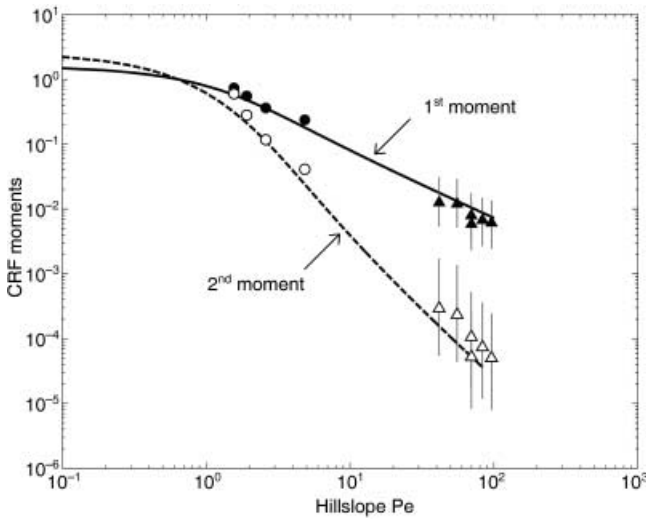


Fig. 3. Analytical relationship between 1st and 2nd CRF [Characteristic Response Function: the free drainage hydrograph from the hillslope, normalized by the total outflow volume, following an initial steady-state storage profile corresponding to a constant recharge rate] moments and hillslope  $Pe$  from Berne et al. (2005). Triangles (closed for 1st moment and open for 2nd moment) show optimized relations for Maimai hillslopes with error bars (vertical lines) defined using ranges for hydraulic conductivity from McGlynn et al. (2002). Circles (closed for 1st moment and open for 2nd moment) show the empirical results reported by Berne et al. (2005). (After Lyon and Troch, 2007).

#### 4.1 DIMENSIONLESS NUMBERS

Leopold et al. (1995), Bras (1990), and Rodriguez-Iturbe and Rinaldo (1997) provide good overviews of dimensionless numbers used to explain geomorphological or hydrogeomorphological characteristics of catchments. Leopold et al. (1995, Chapter 5) describe a range of dimensionless numbers describing geomorphological characteristics of catchments. Examples are stream order (an integer designation of a segment of a channel according to the number and order of tributaries, dimensionless) (Horton 1945; Strahler 1957), bifurcation ratio (average ratio of number of streams of a given order to number in next higher order, dimensionless), drainage density (ratio of cumulative length of stream and the total drainage area, unit is  $L/L^2$ ), and texture ratio (ratio of maximum number of channels crossed by contour to basin perimeter, unit is  $1/L$ ). Berne et al. (2005; see also Lyon and Troch 2007) show how hillslope form (slope, length, and convergence rate), hydraulic properties (conductivity and porosity), and climate (through the surrogate of average saturated storage along the hillslope reflecting an equilibrium state with recharge/discharge) can be related through a single dimensionless response (the hillslope Peclet number) to the hillslope hydrologic response (Figure 3). The hillslope  $Pe$  number can be interpreted as the ratio of the characteristic diffusive time-scale (*the time it takes,*

*on average, for water to travel down the hillslope driven by hydraulic diffusion alone*) and the characteristic advective time-scale (*the time it takes, on average, for water to travel down the hillslope driven by gravity alone*). Some additional dimensionless numbers relating climate to catchment function are discussed in the section on 'Classification based on hydro-climatic region'.

#### 4.2 CURVES OR DISTRIBUTIONS

One problem of using single numbers to describe complex patterns is the unavoidable loss of information that has to occur when complex system characteristics are collapsed into a single number. One approach to extract more information from available data is the use of curves or functions that describe distributions of characteristics, rather than just average or characteristic values as is the case with individual numbers. The nondimensional hypsometric curve introduced by Langbein et al. (1947) is one example of such a function. This curve shows the percent catchment area (area divided by total basin area) above a given percent elevation contour (Bras 1990). Another example is the well-known topographic index ( $\alpha/\tan\beta$ ) introduced by Kirkby (1975), which describes the propensity of a location in the catchment to become saturated. It is defined as the ratio of the upslope contributing area ( $\alpha$ ) and the local surface topographic slope ( $\tan\beta$ ). Distribution functions of this index for catchments form the basis of Topmodel (Beven and Kirkby 1979). Other examples of possible curves to describe catchment surface characteristics, as they can be derived from readily available digital elevation model data have, for example, been introduced by McGlynn and Seibert (2003). They calculated curves describing the distribution of riparian and hillslope inputs to the stream network, the variation of riparian-area percentage along the stream network, and subcatchment area distributions. They used this information to quantify local contributions of hillslope and riparian areas along a stream network.

#### 4.3 CONCEPTUAL MODELS

It would appear that subsurface characteristics are not easily described by individual numbers or even in the form of curves or distribution functions, but that more elaborate approaches are required. Pedological and geological characteristics that define some of the functional characteristics of catchments can occur in many combinations, which have to be captured in some parsimonious way. We define the term *conceptual model* here as a simplified (and usually generalized) schematic representation of more complex real-world processes. This definition of a conceptual model is similar to the one used in groundwater hydrology, but not to be confused with conceptual mathematical models as one class of models utilized in surface hydrology. A lot of attention has been given recently to the idea

of hydrologic landscapes, which are conceptual models developed for the United States (Winter 2001; Winter et al. 1998; Wolock et al. 2004). These landscapes are multiples of hydrologic landscape units, which are themselves defined based on land-surface form, geology, and climate (Winter 2001). A similar approach to develop a relatively small number of conceptual models describing subsurface characteristics by combining pedological and geological information from a hydrologic point of view has been put forward in the UK hydrology of soil types (HOST) system (Boorman et al. 1995). The basis of these conceptual models are three physical settings: (i) soil overlying permeable substrate with deep groundwater ( $>2$  m), (ii) soil overlying permeable substrate with shallow groundwater ( $\leq 2$  m), or (iii) no significant groundwater or aquifer but shallow impermeable substrate. These settings are further defined in sub-classes resulting in a 29-class system. This system has been used to regionalize a baseflow index ( $\text{BFI}_{\text{HOST}}$  = long-term average portion of flow that occurs as baseflow) throughout 575 UK catchments with a coefficient of determination of 0.79. Thus, suggesting that information regarding the slow catchment response is captured well in this class system.

#### 4.4 MATHEMATICAL MODELS

Of course, mathematical models of catchments also describe or incorporate aspects of the catchment structure. In addition, they provide a mechanism to generate relationships between catchment structure and response behavior. Development of these mathematical models can be based on different approaches, but catchment-hydrologic modeling is mainly based on an *a priori* definition of the model structure (equations) and a subsequent estimation of the model parameters either *a priori* using observable landscape characteristics or through a model calibration process.

One approach to developing model structures is commonly termed bottom-up, mechanistic, or reductionist. In this approach, one attempts to build a spatially explicit representation of the model structure based on our best knowledge of the underlying physics (e.g. Ebel and Loague 2006), landscape organization, and climatic inputs. Such a reductionist approach to model building can result in very complex model structures, making it potentially difficult to understand the meaning of the model output and to evaluate such models (Beven 1993; Wagener 2003; Wagener and Gupta 2005; Wood 2003).

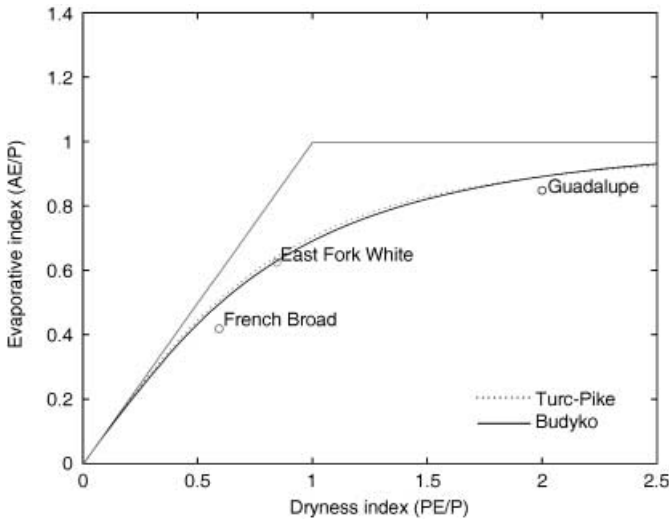
An alternative to the bottom-up approach has been suggested (Sivapalan et al. 2003a; Young 1998), based on ideas for a top-down analysis framework by Klemes (1986). The basic idea is to develop different working hypotheses (implemented as mathematical models) of the catchment structure and find the most parsimonious one that can preserve basic response behavior of the real system guided by observations of the output variable of interest. Sivapalan and his colleagues (Atkinson et al. 2003; Farmer

et al. 2003; Sivapalan 2005; Son and Sivapalan 2007) tested this approach in a series of articles using a hierarchical framework in which the minimum appropriate model complexity was found for behavioral characteristics at different time-scales. The parameters of the appropriate model structure should thus relate to the dominant structural characteristics of the catchment controlling its response.

Regardless of what approach has been chosen to arrive at a suitable model structure, mathematical models have the advantage that they provide a direct link between structure and response behavior, and can provide one approach to the development of a viable hydrologic classification system. Indeed, there have been a number of instances where catchment similarity has been explored, and a number of dimensionless variables proposed, based on mathematical models of various levels of complexity and physical realism (Aryal et al. 2002; Hebson and Wood 1982; Larsen et al. 1994; Milly 1994; Reggiani et al. 2000; Sivapalan et al. 1987; Woods 2003). However, high degrees of uncertainty in model parameterizations and parameter estimation problems can make it difficult to distinguish between sensible and insensible representations of catchments, thus limiting the usefulness of this approach (Uhlenbrook et al. 1999). As our understanding of catchment hydrology advances, we would expect to identify characteristics of form and function that are improved representations of emergent behavior at the time and space scales of interest, helping to reduce the degree of uncertainty in the classification scheme.

### *5 Classification Based on Hydro-Climatic Region*

Climate is another metric that has a strong impact on hydrologic catchment behavior (Budyko 1974; L'vovich 1979), as well as on ecology (Chapman 1989) and even on physical catchment characteristics (Abrahams 1984). The hydro-climatic region in which a catchment is located should play an important role in any classification system. Well-known climatological schemes include the one by Köppen (1936), which was initially derived from an ecological point of view. With respect to hydrology, it is the works by L'vovich (1979) and Budyko (1974), who used long-term average water and energy balance variables to develop climatic classification schemes, which are of relevance here. The main variables in this context are precipitation, potential evaporation, and runoff (Chapman 1989). A useful way of combining these variables is through the climatic dryness index, the ratio of average annual potential evaporation to average annual precipitation. The United Nations Educational, Scientific, and Cultural Organization (UNESCO) published two global maps of this ratio, one derived using the Budyko method (UNESCO 1978) and another derived using the Penman method (UNESCO 1979). Sankarasubramanian and Vogel (2002) and Yadav et al. (2007) found strong links between annual climatic and runoff characteristics for catchments in the United States and the UK,



**Fig. 4.** Budyko curve including the Turc-Pike relationship. Three US catchments represent wet (French Broad), medium (East Fork White), and dry (Guadalupe) regions (see Demaria et al. 2007). Line A defines the energy-limit to evapotranspiration, while Line B defines the water limit.

respectively. Figure 4 shows an example of application of Budyko's climatic classification scheme to compare and contrast three catchments representing wet, medium, and dry areas of the United States. This is achieved by presenting the specific response of each of these catchments on the *Budyko curve*, which is a plot that expresses  $E/P$ , the ratio of average annual actual evapotranspiration ( $E$ ) to average annual precipitation ( $P$ ) as a function of  $PE/P$ , the ratio of average annual potential evapotranspiration ( $PE$ ) to average annual precipitation ( $P$ ). Actual evapotranspiration ( $E$ ) for each catchment was derived as the long-term difference between  $P$  and  $R$  (runoff) for the three catchments. The lines on the Budyko curve represent globally averaged results obtained by Turc and Pike (Pike 1964) and Budyko (1974). Limitations of such a classification scheme that is based on long-term climatic average data are that it ignores seasonal variations of these variables, as well as year to year variability (Chapman 1989), although these characteristics are deemed to be relevant for the hydrologic regime at a subannual time-scale.

A refinement of the climate-driven approach dealing with the effects of within-year or seasonal variability of climate has been presented by Milly (1994), who showed that combination index variables including both soil and climate properties (including seasonality and intermittency) were able to explain observed variability in hydrologic response using a small number of dimensionless similarity variables that characterize the seasonality of climate. This approach has since been expanded to cover other processes and environments (e.g. Potter et al. 2005; Woods 2003).

As one result, Woods (2006) proposed three families of similarity indices to characterize average annual and seasonal response of hydrologic systems where storage is predominantly as (i) frozen water, (ii) pore water, or (iii) open water. Table 2 illustrates the resulting dimensionless numbers for pore water (Woods 2003), which can be used to estimate the annual and/or seasonal characteristics of throughfall and canopy evaporation, infiltration excess runoff and saturation excess runoff, root-zone water balance, and shallow water table position. Such indices make numerous simplifying assumptions, and therefore need careful testing in an uncertainty framework to ensure that the predictions contain hydrologic information.

### *6 Classification Based on Functional Response*

The main differentiating metric between catchments, from a hydrologic point of view, must be the catchment's response behavior and storage characteristics. Such behavioral characteristics or signatures should include streamflow, but could also extend to evaporation, groundwater dynamics, soil moisture dynamics, snow cover, distributions of residence time and water age, isotopic composition, concentrations of chemicals such as chloride and nitrate (Sivapalan 2005). These signatures could even extend to vegetation patterns that often provide insight into the underlying water balance (e.g. Caylor et al. 2004; Scanlon et al. 2005), and can themselves be seen as part of catchment function, albeit typically at much longer time-scales and large spatial scales. In particular, we should seek signatures of catchment response that provide us a glimpse into the holistic functioning of the catchment, the detailed study of which could elucidate for us the mapping between landscape structure and catchment responses. From this viewpoint, they can be considered as emergent properties. Different signatures of catchment response may emerge at different temporal and spatial scales, for example, mean monthly variation of runoff (regime curve), the flow duration curve, etc. (Figure 5; Atkinson et al. 2003; Farmer et al. 2003; Kirchner et al. 2004; Sivapalan 2005). It is therefore necessary to define a classification of catchment function in terms of temporal and spatial scales. Any correlation between functional and structural or climatological characteristics will then help us to advance our understanding of dominant controls on catchment behavior at a particular scale.

McDonnell and Woods (2004) suggest two functional characteristics of relevance: (i) the state in which water is predominantly stored: either frozen (snow and glaciers), or pore water (in soils and rocks), or open water (lakes, wetlands, and river channels), and their magnitudes and distributions; (ii) the response time in the dominant catchment storage (volume of storage, divided by the flux). Here, we will extend the discussion to a third aspect (i.e. characteristics based on the streamflow response), because this is the most widely observed response variable.

**Table 2. Dimensionless numbers for pore-water dominated hydrology at long time-scales (see Woods (2003) for details).**

Dimensionless groups		Dimensionless number	Interpretation	Application
Climate	$E_p/P$	Aridity index, R	Ratio of average demand for moisture to average supply of moisture	Approximate water balance (e.g. using Budyko curve)
	$ \delta_p - R \delta_E $	Seasonality index, S	Amplitude of the seasonal cycle of precipitation minus potential evaporation	Seasonal pattern of atmospheric moisture surplus/deficit
Canopy and soil	$w_{cm}/(P_t/N)$	Canopy storage index, $W_c$	Ratio of canopy storage to characteristic rainfall event depth	Throughfall
	$K/(P/N)$	Relative infiltration, K	Ratio of characteristic infiltration rate to characteristic rainfall event rate	Infiltration excess
	$w_{rm}/P_t$	Rootzone storage index, $W_r$	Ratio of soil water storage capacity to annual rainfall	Seasonal filling of soil moisture deficit
Saturated flow	$DL/(T_0 \tan \beta_v)$	Advection response index, $t_0$	Ratio of travel time for advective signal to duration of seasonal forcing	Responsiveness of lateral subsurface flow
	$T_0 \tan \beta / LP$	Relative transmissivity, $T_0$	Ratio of maximum lateral outflow to characteristic water input rate	Depth to water table
	–	Slope of topographic index distribution, $\omega$	Rate at which saturated area expands	Saturation excess runoff

Climate variables: mean annual precipitation,  $P$ ; mean annual potential evaporation,  $E_p$ ; amplitudes of precipitation and potential evaporation,  $\delta_p$ ,  $\delta_E$ ; number of rain events per unit time,  $N$ ; duration of annual cycle,  $\tau$ .

Canopy and soil variables: average interception storage  $w_{cm}$ ; mean hydraulic conductivity at surface,  $K$ ; rootzone water holding capacity,  $w_{rm}$ .

Saturated flow variables: depth to bedrock (or aquifer thickness),  $D$ ; length of hillslope (or other relevant flowpath),  $L$ ; transmissivity,  $T_0$ ; slope of topography (or head gradient)  $\tan \beta$ .

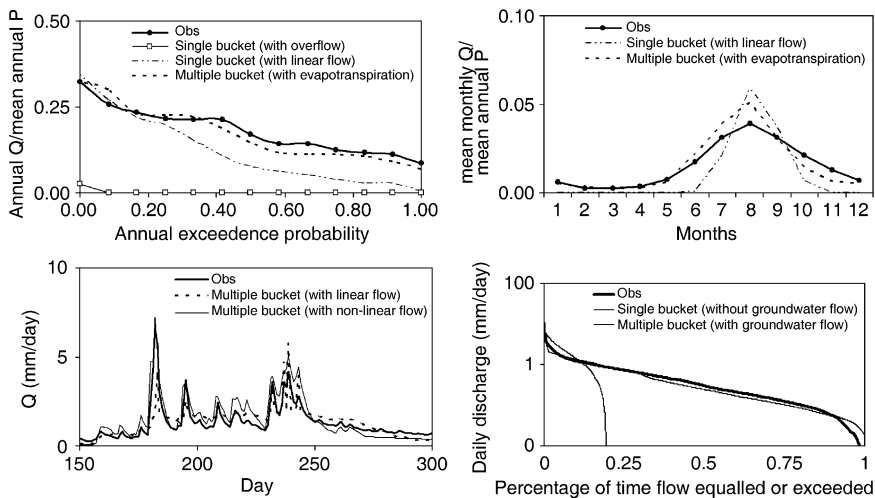


Fig. 5. Signatures of catchment runoff response at different time scales, and their sensitivity to model complexity: (a) inter-annual variability, (b) mean monthly variation of runoff, (c) runoff time series, (d) the flow duration curve (from Farmer et al. 2003).

Extensive work has been done in the field of ecology regarding stream-flow indices (i.e. single value numbers describing particular streamflow response characteristics), and their relationship to physical catchment characteristics (e.g. Clausen and Biggs 2000; Hannah et al. 2000; Olden and Poff 2003; Richter et al. 1996, 1997, 1998). The purpose of these classifications is typically to represent those hydrologic features most relevant to stream ecology (e.g. frequency, magnitude or persistence characteristics). A global classification study by Haines et al. (1988) examined measured monthly river flow regimes using cluster analysis, and produced a world map delineating 14 regions of distinctive seasonal streamflow regimes (see also Kresser 1981; McMahon et al. 1992). Stahl and Hisdal (2004) show typical flow regimes for different climatic regions classified using the Köppen system. Dynamic response characteristics of catchments have more recently been introduced in the context of hydrologic modeling (e.g. Atkinson et al. 2003; Morin et al. 2002; Shamir et al. 2005a,b; Yadav et al. 2006; Yu and Yang 2000). At different temporal and spatial scales different characteristics of the response will emerge (Kirchner et al. 2004), which can be captured in the form of signatures or indices (e.g. Farmer et al. 2003). The question is: what are the relevant characteristics or signatures at a particular temporal scale, and what compact landscape and climatic characteristics best reflect and could predict these signatures?

Another aspect is the issue of internal variability and connectivity of the catchment landscape elements. Buttle (2006) suggests a framework to consider the relative importance of drainage networks, of hydrologic partitioning into vertical and lateral pathways, and of hydraulic gradients

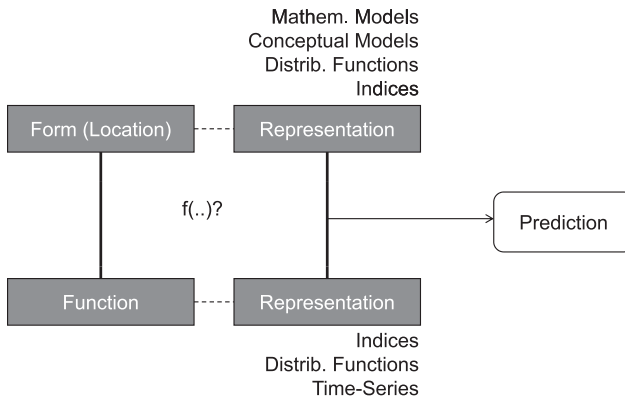


Fig. 6. Mapping of catchment form and function. Form can be represented as index, distribution function, conceptual model or mathematical model. Function can be represented as index, distribution function or time-series.

(defined by land-surface topography). This framework assumes that only catchments in similar hydro-climatic regions are compared, and so it might ultimately be nested within the broader hydro-climatic type of classification already discussed. The assumed hydrologic controls are the landscape's ability to produce runoff, the degree of linkage between landscape elements and the carrying capacity of the drainage network – thus reflecting partitioning, transmission, and release characteristics as discussed above. The question of which observable landscape characteristics, especially those relating to subsurface structure and patterns of heterogeneity, are able to describe or explain observed functional behavior remains to be answered.

### 7 Hydrologic Similarity: Mapping of Relationships between Metrics

The ultimate goal of classification is to understand the dominant controls of catchment structure and climate on the function of catchments (Figure 6) (i.e. to achieve a mapping between landscape form and the functional space). If we had a simple and physically meaningful classifications based on structural and climatic characteristics, and we would understand how these would map into the functional space (i.e. how they define catchment response behavior), then we would have a powerful tool to regionalize this understanding throughout the globe. This is a necessary step we will have to achieve to advance hydrologic science, although with our currently limited understanding regarding the working of hydrologic systems (Kirchner 2003; McDonnell 2003; Sivapalan 2005), it is not yet feasible to reliably predict the response characteristics of a catchment based on knowledge of structural characteristics alone.

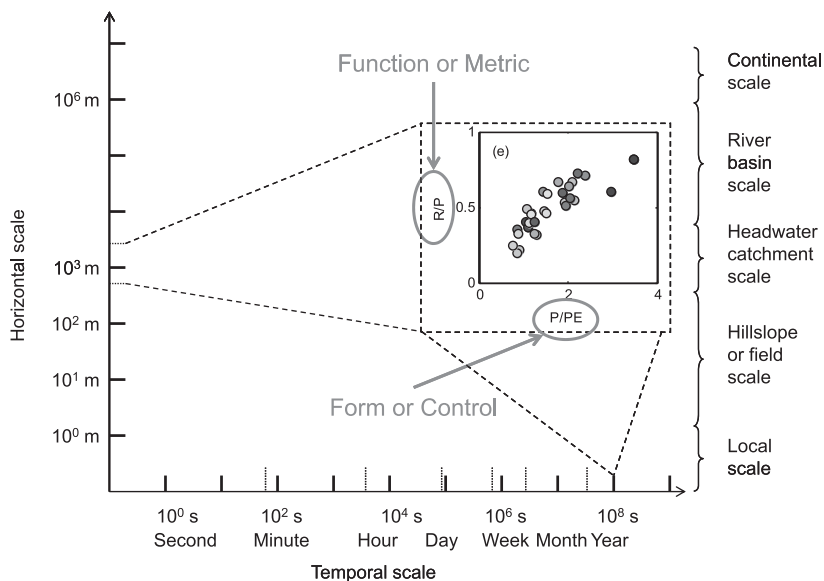


Fig. 7. The mapping of form (control) and function (metric) across spatial and temporal scales (P: Precipitation, R: Runoff, PE: Potential Evapotranspiration).

Linking these different classifications could be done in many forms including a fuzzy mapping approach (e.g. Beven 2000b), dimensional analysis guided by the governing dynamic equations linking form, climate and function (e.g. Berne et al. 2005; Lyon and Troch 2007; Woods 2003), simple overlay of classifications (Kovacs 1984), or through statistical analysis (e.g. Yadav et al. 2006, 2007). In this process, it will be important to limit the number of classes within the different metrics in order not to yield an excessive number of small geographical areas which relate to each other and which are highly sensitive to changes in the category limits of each classification (Chapman 1989).

One example of such a mapping at a particular temporal scale (annual) and at a range of spatial scales ( $\sim 50$ – $1000 \text{ km}^2$ ) is shown in Figure 7. Average annual wetness indices (P/PE) and the runoff ratios (R/P) for 30 catchments in the UK have been calculated and plotted against each other. The plot shows a strong correlation between the two, although with some scatter, suggesting that knowledge of the climate regime will provide a constraint on the expected runoff ratio of a catchment. The necessary simplicity of such a scheme and the limitations of our knowledge and measurement capabilities regarding the metrics will require such relationships to be developed in an uncertainty framework. In this manner, we achieve a probability or a membership of one class relating to another, rather than a crisp link of catchment function and static catchment characteristics. Beven (2000b, 298) discusses the modeling process in the *form of mapping a particular (unique) catchment or element of a catchment into a model space*.

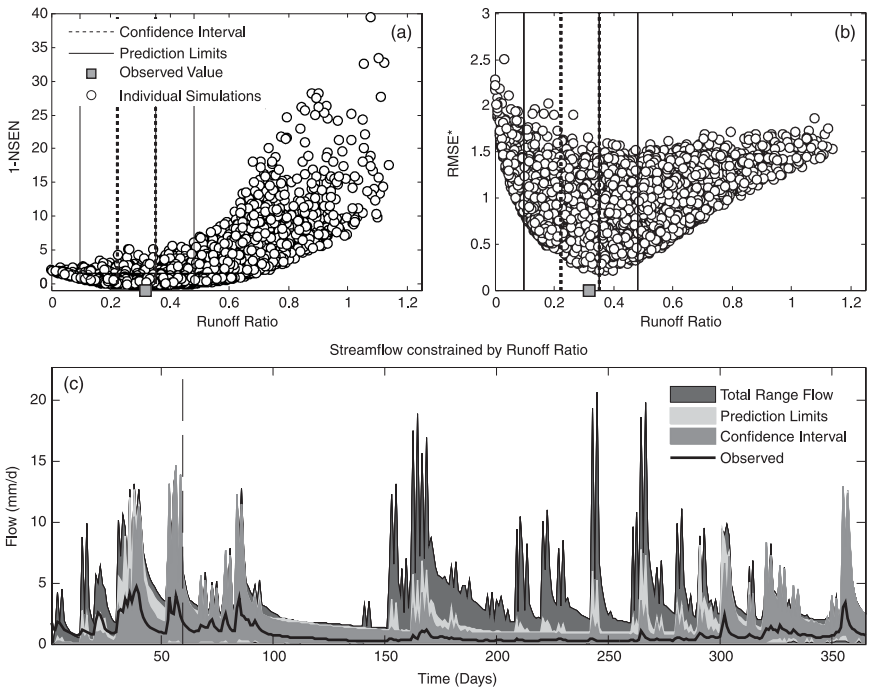


Fig. 8. Dotted plots of simulated runoff ratio versus (a) 1-NSE (Nash-Sutcliffe Efficiency) and (b) RMSE\* (Root Mean Squared Error). (c) Observed and (constraint) predicted streamflow ranges. (From Yadav et al. 2006)

One advantage of such a mapping is that it could be done in an uncertainty framework (e.g. set-theoretic or statistical). Similarly, we could see the linkages between structure, hydro-climate and function as an uncertain mapping from one space to the other. Using an uncertainty framework would enable us to learn, for example, which structural or hydro-climatic characteristic maps into a small area in the structural space – and thus constrain possible catchment behavior (Yadav et al. 2007). Examples of this sort have been provided by McIntyre et al. (2005) exploring the issue of similarity in a Generalized Likelihood Uncertainty Estimation (GLUE) framework (Beven and Freer 2001); and Yadav et al. (2007) in a statistical regression framework, including uncertainty. McIntyre et al. (2005) developed pooling groups of the most similar catchments in the three-dimensional Euclidean space, which could then be used to extrapolate knowledge to similar ungauged catchments.

Yadav et al. (2006; 2007) show how an uncertainty framework for classification can be used for predictions in ungauged basins. Figure 8 shows the result of Monte Carlo sampling of the feasible parameter range of a simple lumped hydrologic model in an ungauged catchment in the UK. The runoff ratio simulated by all the 10,000 sampled parameter sets is then

calculated. A regression equation with runoff ratio as dependent variable and few climate/form characteristics has been derived, including estimates of prediction and confidence limits using 25 gauged catchments. Only predictions with runoff ratios falling within the regionalized range are kept and used for an ensemble forecast at the ungauged site, yielding reliable forecasts (Figure 8c).

While the uncertainty framework quantifies a combination of our lack of understanding and inadequate measurement capabilities, the measure of uncertainty should motivate us to advance both understanding and measurement capabilities. A refinement of our perceptual models, an understanding of the catchment function in all its complexity and evolution, and a representation of the function in terms of a competition between different processes (wetting, drying, storage, drainage along the lines of L'vovich 1979) should gradually nudge us toward better understanding, and eventually more targeted measurements, that will together also advance the cause of classification. The use of more physically and biologically based models, and the search for possible underlying organizing principles (e.g. ecological optimality) should also move us inexorably toward better understanding.

## 8 Discussion and Outlook

In this article, we discussed the need for a catchment classification system, a possible framework for classification based upon a unifying perceptual model of the catchment system and its function, and possible metrics to be included in such a classification framework. This first discussion will hopefully provide the foundation and starting point to advance hydrologic sciences in this regard, and result in a new universal framework to organize all aspects of the science: theory, observations, and modeling. A global effort by the entire hydrologic community in which we would build and continuously populate a database of catchments, sorted by the classification framework and metrics put forward in this article, could be part of such an effort. Individuals would take charge in maintaining certain classes. Each added catchment would be another data point and would increase our understanding about how catchment structure and climatic region define catchment function. A parallel effort would focus on developing improved understanding of the interactions between hydroclimate and catchment form that result in different signatures of catchment function at various time and space scales of interest; this could lead to more refined descriptions of catchment form and function that closely reflect the co-evolution of climate, soils, topography, and vegetation, and in this way help reduce further the uncertainty or fuzziness in the catchment classifications we develop initially.

The following requirements for a classification framework were identified:

1. The framework has to map catchment form/hydro-climatic conditions on catchment function across spatial and temporal scales.

2. Catchment functions should include: partition, storage, and release of water. With transmission within the catchment as a connecting process.
3. It needs to explicitly consider uncertainty in the metrics/variables used and mappings established.
4. It should initially be based on functions characterized by streamflow in order to be widely applicable, and graduate to other more complex functions subsequently. Although available remote sensing data might already allow for the consideration of snow and ice cover, and open water bodies.

The following questions remain to be answered to obtain such a framework:

1. How can we best represent characteristics of form and hydro-climatic conditions? What characteristics can be collapsed into single numbers, or require representation as distribution function or model?
2. How does this representation change with spatial and temporal scale?
3. What functions (partition, storage and release) are relevant at what spatial and temporal scale?
4. At what scale do internal structure and heterogeneity become important and need to be considered?

Establishing such a framework requires a community effort. The tree of life project in biology is an excellent example of a global scientific effort to create a database of all organisms and their evolution maintained by a community (<http://tolweb.org/tree/phylogeny.html>), and could provide a blueprint for what we are proposing for hydrology.

### *Acknowledgements*

Thanks to Yaoling Bay for creating Figure 4.

### *Short Biographies*

Thorsten Wagener is an Assistant Professor of Hydrology in the Department of Civil and Environmental Engineering of the Pennsylvania State University, University Park, PA, USA. He received civil engineering degrees from the University of Siegen (BS, 1995), Delft University of Technology (MS, 1998), and Imperial College London (PhD, 2002). He was a DAAD (Deutscher Akademischer Austauschdienst) postdoctoral fellow at the National Science Foundation Science and Technology Center for Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA) and the University of Arizona before joining Penn State in 2004. His main research interests are predictions in ungauged basins, hydrologic/environmental model identification and evaluation under uncertainty, and scenario analysis for sustainable water management.

Murugesu Sivapalan specializes in Watershed Hydrology. Trained as a Civil Engineer, he obtained his PhD from Princeton University in 1986. Dr. Sivapalan is Professor of Geography and Civil and Environmental Engineering at the University of Illinois, Urbana-Champaign where he is an affiliate member of the Center for Water as a Complex Environmental System. Prior to 2005, he was at the Centre for Water Research, University of Western Australia for over 17 years, finishing as Professor of Environmental Engineering. The principal focus of his research interests is prediction of ungauged catchments. He is a Fellow of the American Geophysical Union, Fellow of the Australian Academy of Technological Sciences and Engineering, a recipient of the John Dalton Medal of the European Geophysical Society, and was awarded a Centenary Medal by the Australian Government in 2003. Professor Sivapalan was founding chair of an International Task Force for the International Association of Hydrological Sciences Decade on Prediction in Ungauged Basins (PUB) initiative.

Peter Troch is a Professor of Hydrology in the Department of Hydrology and Water Resources at the University of Arizona. He holds MSc diplomas in Agricultural Engineering (1985) and Systems Control Engineering (1989) and received his PhD from the University of Ghent, Belgium, in 1993. He was assistant and associate professor in the Forest and Water Management Department at the University of Ghent from 1993 to 1999. He was professor and chair of the Hydrology and Quantitative Water Management group at Wageningen University, the Netherlands, from 1999 to 2005. His main research interests are measuring and modeling flow and transport processes at hillslope to catchment scales, and developing remote sensing and data assimilation methods to improve water resources management.

Ross Woods is a Hydrologist from Christchurch, New Zealand. He is a Principal Scientist and Group Manager with NIWA, New Zealand's National Institute of Water and Atmospheric Research, where he works on hydrologic research and consulting, and leads a team of nine hydrologists. He obtained his Bsc(Hons) in Mathematics (1984) and MComm(Hons) in Operations Research (1986) from the University of Canterbury, before joining the Hydrology Centre of the Ministry of Works and Development. Ross obtained his PhD in Environmental Engineering from the University of Western Australia (1997), investigating the representative elementary concept. His current research interests include spatially distributed modeling and measurement of catchment response, and the development of new hydrologic theory. His applied interests include the development of a national hydrologic model for New Zealand, for use in flood forecasting and for examining the effect of changes in land use and climate on water resources.

### *Note*

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## References

- Abdulla, F. A., and Lettenmaier, D. P. (1997). Development of regional parameter estimation equations for a macroscale hydrologic model. *Journal of Hydrology* 197, pp. 230–257.
- Abrahams, A. D. (1984). Channel networks: a geomorphological perspective. *Water Resources Research* 20 (2), pp. 161–188.
- Anderson, M. G., and Burt, T. P. (eds) (1990). *Process studies in hillslope hydrology*. Chichester, UK: John Wiley.
- Arabie, P., Hubert, L. J., and De Soete, G. (eds) (1996). *Clustering and classification*. River Edge, NJ: World Scientific Publishing.
- Aryal, S., O'Loughlin, E., and Mein, R. (2002). A similarity approach to predict landscape saturation in catchments. *Water Resources Research* 38 (10), p. 1208.
- Atkinson, S., et al. (2003). Physical controls of space-time variability of hourly streamflows and the role of climate seasonality: mahurangi catchment, New Zealand. *Hydrological Processes* 17, pp. 2171–2193.
- Berger, K. P., and Entekhabi, D. (2001). Basin hydrologic response relations to distributed physiographic descriptors and climate. *Journal of Hydrology* 247 (3–4), pp. 169–182.
- Berne, A., Uijlenhoet, R., and Troch, P. A. (2005). Similarity analysis of subsurface flow response of hillslopes with complex geometry. *Water Resources Research* 41, W09410; doi:10.1029/2004WR003629.
- Beven, K. J. (1993). Prophecy, reality and uncertainty in distributed hydrological modeling. *Advances in Water Resources* 6, pp. 41–51.
- . (2000a). On the uniqueness of place and process representations in hydrological modeling. *Hydrology and Earth System Science* 4 (2), pp. 203–212.
- . (2000b). *Rainfall-runoff modelling: the Primer*. Chichester, UK: John Wiley.
- . (2006). Searching for the Holy Grail of scientific hydrology:  $Q_t = (S, R, \Delta t)A$  as closure. *Hydrology and Earth System Sciences* 10, pp. 609–618.
- Beven, K. J., and Freer, J. (2001). Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology. *Journal of Hydrology* 249 (1–4), pp. 11–29.
- Beven, K. J., and Kirkby, M. J. (1979). A physically based, variable contributing model of basin hydrology. *Hydrological Sciences Bulletin* 24, pp. 43–69.
- Biggs, B. J. F., Nikora, V. I., and Snelder, T. H. (2005). Linking scales of flow variability in rivers to lotic ecosystem structure and function. *River Research and Applications* 21, pp. 283–298.
- Black, P. E. (1997). Watershed functions. *Journal of the American Water Resources Association* 33 (10), pp. 1–11.
- Boorman, D. B., Hollis, J. M., and Lilly, A. (1995). *Hydrology of soil types: a hydrologically based classification of soils in the United Kingdom*. Institute of Hydrology Report No. 126, Wallingford, UK.
- Bras, R. (1990). *Hydrology: an introduction to hydrologic science*. Reading, MA: Addison-Wesley Publishing Company.
- Budyko, M. I. (1974). *Climate and life*. New York: Academic Press.
- Burn, D. H. (1989). Cluster analysis as applied to regional flood frequency. *Journal of Water Resources Planning and Management* 115 (5), pp. 567–582.
- . (1990). Evaluation of regional flood frequency analysis with a region of influence approach. *Water Resources Research* 26 (10), pp. 2257–2265.
- . (1997). Catchment similarity for regional flood frequency analysis using seasonality measures. *Journal of Hydrology* 202, pp. 212–230.
- Burn, D. H., and Boorman, D. B. (1992). *Catchment classification applied to the estimation of hydrological parameters at ungauged catchments*. Institute of Hydrology Report No. 118, Wallingford, UK.
- Burn, D. H., and Goel, N. K. (2000). The formation of groups for regional flood frequency analysis. *Hydrological Sciences Journal* 45 (1), pp. 97–112.
- Buttle, J. (2006). Mapping first-order controls on streamflow from drainage basins: the T3 template. *Hydrological Processes* 20, pp. 3415–3422.
- Calver, A., et al. (2005). *National river catchment flood frequency method using continuous simulation*. R&D Technical Report FD2106/TR, Unpublished. [online]. Retrieved on August 2006

- from [http://www.defra.gov.uk/science/project\\_data/DocumentLibrary/FD2106/FD2106\\_3125\\_TRP.pdf](http://www.defra.gov.uk/science/project_data/DocumentLibrary/FD2106/FD2106_3125_TRP.pdf)
- Castellarin, A., Burn, D. H., and Brath, A. (2001). Assessing the effectiveness of hydrological similarity measures for flood frequency analysis. *Journal of Hydrology* 241, pp. 270–285.
- Caylor, K. K., Scanlon, T. M., and Rodriguez-Iturbe, I. (2004). Feasible optimality of vegetation patterns in river basins. *Geophysical Research Letters* 31, L13502; doi:10.1029/2004GL020260.
- Chapman, T. (1989). Classification of regions. In: Falkenmark, M. and Chapman, T. (eds) *Comparative hydrology: an ecological approach to land and water resources*. Paris: UNESCO, pp. 67–74.
- Clausen, B., and Biggs, B. J. F. (2000). Flow variables for ecological studies in temperate streams: grouping based on covariance. *Journal of Hydrology* 237, pp. 184–197.
- Collins, D., Bras, R., and Tucker, G. E. (2004). Modeling the effects of vegetation-erosion coupling on landscape evolution. *Journal of Geophysical Research-Earth Surface* 109 (F3), F03004; doi:10.1029/2003JF(0000)28.
- Demaria, E., Nijssen, B., and Wagener, T. (2007). Monte Carlo sensitivity analysis of land surface parameters using the variable infiltration capacity model. *Journal of Geophysical Research – Atmosphere* forthcoming.
- Detenbeck, N. E., et al. (2000). A test of watershed classification systems for ecological risk assessment. *Environmental Toxicology and Chemistry* 19 (4), pp. 1174–1181.
- Dingman, S. L. (2002). *Physical hydrology*. Engelwood Cliff, NJ: Prentice Hall.
- Dooge, J. C. I. (1986). Looking for hydrologic laws. *Water Resources Research* 22 (9), 46S–58S.
- . (2003). *Linear theory of hydrologic systems*. EGU Reprint Series (Originally published in 1965), Katlenburg-Lindau, Germany.
- Dunne, T. (1983). Relation of field studies and modeling in the prediction of storm runoff. *Journal of Hydrology* 65, pp. 25–48.
- Dunne, T., and Leopold, L. B. (1978). *Water in environmental planning*. New York: WH Freeman Company.
- Ebel, B. A., and Loague, K. (2006). Physics-based hydrologic-response simulation: seeing through the fog of equifinality. *Hydrological Processes* 20 (13), pp. 2887–2900.
- Falkenmark, M., Rockstrom, J., and Savenije, H. (2004). *Balancing water for humans and nature: the new approach in ecohydrology*. London: Earthscan.
- Farmer, D., Sivapalan, M., and Jothityangkoon, C. (2003). Climate, soil and vegetation controls upon the variability of water balance in temperate and semi-arid landscapes: downward approach to hydrological prediction. *Water Resources Research* 39 (2), pp. 1035–1055.
- Fernandez, W., Vogel, R. M., and Sankarasubramanian, A. (2000). Regional calibration of a watershed model. *Hydrological Sciences Journal* 45 (5), pp. 689–707.
- Gordon, A. D. (1999). *Classification*. Boca Raton, FL: Chapman and Hall/CRC.
- Gould, S. J. (1989). *Wonderful life: the Burgess Shale and the nature of history*. New York: Norton & Company.
- Haines, A. T., Finlayson, B. L., and McMahon, T. A. (1988). A global classification of river regimes. *Applied Geography* 8, pp. 255–272.
- Hannah, D. M., et al. (2000). An approach to hydrograph classification. *Hydrologic Processes* 14, pp. 317–338.
- Harte, J. (2002). Toward a synthesis of the Newtonian and Darwinian world views. *Physics Today* 9, pp. 29–34.
- Hebson, C., and Wood, E. F. (1982). A derived flood frequency distribution using Horton order ratios. *Water Resources Research* 18 (5), pp. 1509–1518.
- Holmes, M. G. R., et al. (2002). Region of influence approach to predicting flow duration curves in ungauged catchments. *Hydrology and Earth System Sciences* 6 (4), pp. 721–731.
- Horton, R. E. (1945). Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. *Bulletin of the Geological Society of America* 56, pp. 275–370.
- Jakeman, A. J., et al. (1992). A systematic approach to modeling the dynamic linkage of climate, physical catchment descriptors and hydrologic response components. *Mathematics and Computers in Simulation* 33, pp. 359–366.
- Kirchner, J. W. (2003). A double paradox in catchment hydrology and geochemistry. *Hydrological Processes* 17, pp. 871–874.
- Kirchner, J. W., et al. (2004). The fine structure of water-quality dynamics: the (high-frequency) wave of the future. *Hydrological Processes* 18, pp. 1353–1359.

- Kirkby, M. (1975). Hydrograph modeling strategies. In: Peel, R., Chisholm, M. and Haggett, P. (eds) *Processes in physical and human geography*. London: Heinemann, pp. 69–90.
- Kirkby, M. J. (ed.) (1978). *Hillslope hydrology*. Chichester, UK: John Wiley.
- Klemes, V. (1986). Operational testing of hydrological simulation models. *Hydrological Sciences Journal* 31 (1), pp. 13–24.
- Kovac, G. (1984). Proposal to construct a coordinating matrix for comparative hydrology. *Hydrological Sciences Journal* 29 (4), pp. 435–443.
- Köppen, W. (1936). Das geographische system der klimate. In: Köppen, W. and Geiger, R. (eds) *Handbuch der klimatologie*. Berlin, Germany: Gebrueder Borntraeger, pp. 1–46.
- Kresser, W. (1981). Die wasserwirtschaftlichen Verhältnisse in Österreich. *Schriften des Vereines zur Verbreitung naturwissenschaftlicher Kenntnisse in Wien*, pp. 69–97.
- L'vovich, M. I. (1979). *World water resources and their future*. Chelsea, UK: LithoCrafters Inc.
- Langbein, W. B., and others (1947). *Topographic characteristics of drainage basins*. United States Geological Survey, Water-Supply Paper 968-C, pp. 125–158.
- Larsen, J. E., et al. (1994). Similarity analysis of runoff generation processes in real-world catchments. *Water Resources Research* 30 (6), pp. 1641–1652.
- Leopold, L. B., Wolman, M. G., and Miller, J. P. (1995). *Fluvial processes in geomorphology* (Reprint from 1964). Mineola, NY: Dover Publications.
- Lyon, S. W., and Troch, P. A. (2007). Hillslope hydrologic similarity: real-world tests of the hillslope Peclet number. *Water Resources Research* forthcoming.
- MacKay, D. J. C. (2003). *Information theory, inference, and learning algorithms*. Cambridge, UK: Cambridge University Press. [online]. Retrieved on 22 June 2006 from <http://www.inference.phy.cam.ac.uk/mackay/itila/>
- McDonnell, J. J. (2003). Where does water go when it rains? Moving beyond the variable source area concept of rainfall-runoff response. *Hydrological Processes* 17 (9), pp. 1869–1875.
- McDonnell, J. J., and Woods, R. (2004). On the need for catchment classification. *Journal of Hydrology* 299, pp. 2–3.
- McGlynn, B. L., and McDonnell, J. J. (2003). Quantifying the relative contributions of riparian and hillslope zones to catchment runoff and composition. *Water Resources Research* 39 (11), doi:10.1029/2003WR(0020)91.
- McGlynn, B. L., and Seibert, J. (2003). Distributed assessment of contributing area and riparian buffering along stream networks. *Water Resources Research* 39 (4), doi:10.1029/2002WR(0015)21.
- McGuire, K. J., and McDonnell, J. J. (2006). A review and evaluation of catchment transit time modeling. *Journal of Hydrology* 330 (3–4), pp. 543–563.
- McGuire, K. J., et al. (2005). The role of topography on catchment-scale water residence time. *Water Resources Research* 41, W05002; doi:10.1029/2004WR(0036)57.
- McIntyre, N., et al. (2005). Ensemble prediction of runoff in ungauged watersheds. *Water Resources Research* 41, W12434; doi:10.1029/2005WR(0042)89.
- McMahon, T. A., et al. (1992). *Global runoff: continental comparisons of annual flows and peak discharges*. Cremlingen-Destedt, Germany: Catena Verlag.
- Merz, B., and Bloeschl, G. (2004). Regionalization of catchment model parameters. *Journal of Hydrology* 287, pp. 95–123.
- Milly, P. C. D. (1994). Climate, interseasonal storage of soil water, and the annual water balance. *Advances in Water Resources* 17, pp. 19–24.
- Mirkin, B. (1996). *Mathematical classification and clustering*. London: Kluwer Academic Publishers.
- Morin, E., et al. (2002). Objective, observational-based, automatic, estimation of the catchment response time scale. *Water Resources Research* 38 (10), pp. 1212–1227.
- Munson, B. R., Young, D. F., and Okiishi, T. H. (2002). *Fundamentals of fluid mechanics*, 4th ed. Hoboken, NJ: John Wiley & Sons.
- Nathan, R. J., and McMahon, T. A. (1990). Identification of homogeneous regions for the purpose of regionalization. *Journal of Hydrology* 121, pp. 217–238.
- Olden, J. D., and Poff, N. L. (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications* 19, pp. 101–121.
- Parajka, J., Merz, R., and Bloeschl, G. (2005). A comparison of regionalization methods for catchment model parameters. *Hydrology and Earth System Sciences* 9, pp. 157–171.
- Pike, J. G. (1964). The estimation of annual runoff from meteorological data in a tropical climate. *Journal of Hydrology* 2, pp. 116–123.

- Poff, N., et al. (2006). Placing global stream flow variability in geographic and geomorphic contexts. *River Research and Applications* 22, pp. 149–166.
- Ponce, V. M., and Shetty, A. V. (1995a). A conceptual model of catchment water balance. 1. Formulation and calibration. *Journal of Hydrology* 173, pp. 27–40.
- . (1995b). A conceptual model of catchment water balance. 2. Application to runoff and baseflow modeling. *Journal of Hydrology* 173, pp. 41–50.
- Potter, N. J., et al. (2005). Effects of rainfall seasonality and soil moisture capacity on mean annual water balance for Australian catchments. *Water Resources Research* 41, W06007; doi:10.1029/2004WR(0036)97.
- Rao, A. R., and Srinivas, V. V. (2006a). Regionalization of watersheds by fuzzy cluster analysis. *Journal of Hydrology* 318, pp. 57–79.
- . (2006b). Regionalization of watersheds by hybrid-cluster analysis. *Journal of Hydrology* 318, pp. 37–56.
- Reggiani, P., Sivapalan, M., and Hassanizadeh, S. M. (2000). Conservation equations governing hillslope responses: exploring the physical basis of water balance. *Water Resources Research* 36 (7), pp. 1845–1863.
- Richer, B. D., et al. (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* 10, pp. 1163–1174.
- . (1997). How much water does a river need? *Freshwater Biology* 37, pp. 231–249.
- . (1998). A spatial assessment of hydrologic alteration within a river network. *Regulated Rivers* 14, pp. 329–340.
- Robinson, J. S., and Sivapalan, M. (1997). Temporal scales and hydrological regimes: implications for flood frequency scaling. *Water Resources Research* 33 (12), pp. 2981–2999.
- Robinson, M. (ed.) (1992). *Methods for hydrological basin comparison*. Institute of Hydrology Report No. 120 – Proceedings of the 4th Conference of the European Network of Experimental and Representative Basins University of Oxford, 29th September to 2nd October.
- Rodríguez-Iturbe, I., and Rinaldo, A. (1997). *Fractal river basins*. Cambridge, UK: Cambridge University Press.
- Rodríguez-Iturbe, I., and Valdés, J. B. (1979). The geomorphologic structure of hydrologic response. *Water Resources Research* 15 (6), pp. 1409–1420.
- Sankarasubramanian, A., and Vogel, R. M. (2002). Annual hydroclimatology of the United States. *Water Resources Research* 38 (6), doi:10.1029/2001WR(0006)19.
- Scanlon, T. M., et al. (2005). Dynamic response of grass cover to rainfall variability: implications for the function and persistence of savanna ecosystems. *Advances in Water Resources* 28, pp. 291–302.
- Shamir, E., et al. (2005a). Temporal streamflow descriptors in downward parameter estimation application. *Water Resources Research* 41 (6), doi:1029/2004WR(0034)09.
- Shamir, E., et al. (2005b). The role of hydrograph indices in parameter estimation of rainfall-runoff models. *Hydrological Processes* 19, pp. 2187–2207.
- Sivapalan, M. (2005). Pattern, processes and function: elements of a unified theory of hydrology at the catchment scale. In: Anderson, M. (ed.) *Encyclopedia of hydrological sciences*. London: John Wiley, pp. 193–219.
- Sivapalan, M., Beven, K., and Wood, E. F. (1987). On hydrologic similarity 2: a scaled model of storm runoff production. *Water Resources Research* 23 (12), pp. 2266–2278.
- Sivapalan, M., et al. (2003a). Downward approach to hydrological prediction. *Hydrological Processes* 17 (11), pp. 2101–2111.
- . (2003b). IAHS Decade on Predictions in Ungauged Basins (PUB), 2003–2012: shaping an exciting future for the hydrological sciences. *Hydrological Sciences Journal* 48 (6), pp. 857–880.
- Snelder, T. H., et al. (2004). Is the river environment classification an improved landscape-scale classification of rivers? *Journal of the North American Benthological Society* 23 (3), pp. 580–598.
- Son, K., and Sivapalan, M. (2007). Improving model structure and reducing parameter uncertainty in conceptual water balance models through the use of auxiliary data. *Water Resources Research* 43 (1), W01415; doi:10.1029/2006.WR(0050)32.
- Stahl, K., and Hisdal, H. (2004). Chapter 2: drought hydroclimatology. In: Tallaksen, L. M. and van Lanen, H. (eds) *Hydrological drought: processes and estimation methods for streamflow and groundwater*, Development in Water Sciences (48). Amsterdam, The Netherlands: Elsevier.
- Strahler, A. N. (1957). Quantitative analysis of watershed geomorphology. *Transactions of the American Geophysical Union* 38 (6), pp. 913–920.

- Thoms, M. C., and Parsons, M. (2003). Identifying spatial and temporal patterns in the hydrological character of the Condamine-Balonne River, Australia, using multivariate statistics. *River Research and Applications* 19, pp. 443–457.
- Uhlenbrook, S., et al. (1999). Prediction uncertainty of conceptual rainfall-runoff models caused by problems in identifying model parameters and structures. *Hydrological Sciences Journal* 44 (5), pp. 779–797.
- UNESCO. (1978). *Atlas of world water balance*. Paris, France: UNESCO.
- . (1979). *Map of the world distribution of arid regions*, MAB Technical Note 7. Paris, France: UNESCO.
- Wagener, T. (2003). Evaluation of catchment models. *Hydrological Processes* 17, pp. 3375–3378.
- Wagener, T., and Gupta, H. V. (2005). Model identification for hydrological forecasting under uncertainty. *Stochastic Environmental Research and Risk Assessment* 19 (6), pp. 378–387.
- Wagener, T., and Wheeler, H. S. (2006). Parameter estimation and regionalization for continuous rainfall-runoff models including uncertainty. *Journal of Hydrology* 320, pp. 132–154.
- Wagener, T., Wheeler, H. S., and Gupta, H. V. (2004). *Rainfall-runoff modelling in gauged and ungauged catchments*. London, UK: Imperial College Press.
- Ward, R. C., and Robinson, M. (2000). *Principles of hydrology*, 4th ed. London: McGraw-Hill.
- Wardrop, D. H., et al. (2005). Use of landscape and land use parameters for classification of watersheds in the mid-Atlantic across five physiographic provinces. *Environmental and Ecological Statistics* 12, pp. 209–223.
- Winter, T. C. (2001). The concept of hydrologic landscapes. *Journal of the American Water Resources Association* 37, pp. 335–349.
- Winter, T. C., et al. (1998). *Ground water and surface water a single resource*. US Geological Survey Circular 1139. [online]. Retrieved on 23 June 2006 from <http://pubs.usgs.gov/circ/circ1139/index.html>
- Wolock, D. M., Winter, T. C., and McMahon, G. (2004). Delineation and evaluation of hydrologic-landscape regions in the United States using geographic information system tools and multivariate statistical analyses. *Environmental Management* 34, pp. S71–S88.
- Woods, R. A. (2003). The relative roles of climate, soil, vegetation and topography in determining seasonal and long-term catchment dynamics. *Advances in Water Resources* 26 (3), pp. 295–309.
- . (2004). *Role of catchment classification in PUB*. Presented at the IAHS PUB Workshop 2004, Perth, Western Australia, 2–5 February 2004.
- . (2005). Hydrologic concepts of variability and scale. In: Anderson, M. (ed.) *Encyclopedia of hydrological sciences*. London: John Wiley.
- . (2006). *Global similarity indices for mean and seasonal hydrology of ungauged basins*. Presentation at USA PUB Workshop 16–19 October (<http://www.hydrologicscience.org/pub/talks.html>).
- Yadav, M., Wagener, T., and Gupta, H. V. (2006). Regionalization of dynamic watershed behavior. In: Andréassian, V., et al. (eds) *Large sample basin experiments for hydrological model parameterization Results of the Model Parameter Estimation Experiment (MOPEX) Paris (2004) and Foz de Iguaçu (2005) workshops*. Wallingford, UK: IAHS Redbook Publication No. 307.
- . (2007). Regionalization of constraints on expected watershed response. *Advances in Water Resources* forthcoming.
- Young, P. (1998). Data-based mechanistic modelling of environmental, ecological, economic and engineering systems. *Environmental Modelling and Software* 13 (2), pp. 105–122.
- Yu, P. S., and Yang, T. C. (2000). Fuzzy multi-objective function for rainfall-runoff model calibration. *Journal of Hydrology* 238, pp. 1–14.