Catchment Classification and Services—Toward a New Paradigm for Catchment Hydrology Driven by Societal Needs

THORSTEN WAGENER1, MURUGESU SIVAPALAN2 AND BRIAN McGLYNN3

1Department of Civil and Environmental Engineering, Pennsylvania State University, University Park, PA, US
2Departments of Geography and Civil and Environmental Engineering, University of Illinois Urbana-Champaign, Urbana, IL, US
3Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT, US

Hydrologists do not yet possess a generally accepted catchment classification system. This article presents a review of work done so far, and discusses a general framework for a catchment classification system considering variability in relevant characteristics, increasing human impacts on catchments, and the assumption that our climate is changing. We stress that any classification system should explicitly account for uncertainty and have predictive power, rather than just being descriptive. We also propose an extension to catchment classification with the inclusion of catchment services and disservices, which would explicitly link hydrology to current and future societal issues. We discuss a framework that describes catchment climate and form and maps these on catchment function (include partition, storage and release of water, energy and matter). Climate, form, and function can be described using indices, distributions, or even conceptual models; and uncertainty needs to be preserved in individual descriptors as well as in their mapping onto each other. Descriptors of catchment function are discussed as signatures of catchment behavior, which in turn are related to catchment services and disservices. This mapping ultimately provides predictive skill by constraining the expected function at ungauged locations, even under potential nonstationarity, through knowledge of form and/or climate. Establishing this framework would provide an organizing principle, create a common language, guide modeling and measurement efforts, provide constraints on predictions in ungauged basins, and allow estimates of environmental change impacts.

INTRODUCTION

Webster’s English dictionary defines classification as a “systematic arrangement in groups or categories according to established criteria”. Classification of the central entity of interest lies at the heart of many sciences. The classifications of organisms in biology or of elements in chemistry are well-known examples. An important task of science in any field lies in perpetually organizing the body of knowledge gained by scientific inquiry. The science of hydrology, with the catchment being its main entity of interest, has not yet achieved a generally agreed upon classification system. A catchment can be defined as “all of the upstream area, which contributes to the open channel flow at a given point along a river” (see Table 1 for terminology used). Catchments “are delineated naturally by the land surface topography, and topographic ridges are usually taken as their boundaries; they can be considered as the natural conveyance systems for mass and energy on the land surface of the Earth” (Brutsaert, 2005). The catchment forms a landscape element (at various scales) that integrates all aspects of the hydrological cycle within a defined area that can be studied, quantified, and acted upon (Wagener et al., 2007).
Table 1  Terminology used in this article

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Catchment</td>
<td>A catchment can be defined as “all of the upstream area, which contributes to the open channel flow at a given point along a river. … Catchments are delineated naturally by the land surface topography, and topographic ridges are usually taken as their boundaries; they can be considered as the natural conveyance systems for mass and energy on the land surface of the Earth” (Brutsaert, 2005) (The term basin was used in the original text, but has been replaced with the term catchment here. The terms basin, catchment, watershed, and drainage area are often used simultaneously.)</td>
</tr>
<tr>
<td>Catchment form</td>
<td>The physical characteristics of the catchment such as soils, topography or land use. These elements of form do not have to be static, but can be changing in time</td>
</tr>
<tr>
<td>Catchment climate</td>
<td>The climatic regime the catchment is embedded in, mainly represented by the long-term precipitation and temperature of a region</td>
</tr>
<tr>
<td>Catchment function</td>
<td>The actions of the catchment on the water, matter or energy in its control volume</td>
</tr>
<tr>
<td>Catchment signature</td>
<td>Behavior of the watershed related to the catchment functions, and based on hydrologic theory</td>
</tr>
<tr>
<td>Catchment services</td>
<td>The benefits received by nature (ecosystems) and humans from resources and processes supplied by catchments</td>
</tr>
<tr>
<td>Catchment disturbance</td>
<td>Negative impacts received by nature (ecosystems) and humans due to actions (functions) of the catchment</td>
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</table>

Catchments are (usually) open and complex environmental systems (Dooge, 2005), which are characterized by enormous variability (Beven, 2000), but exhibit some degree of organization (Sivapalan, 2005).

Of course there are some existing classifications that have been used in hydrology to describe and group catchments. These classifications are based on climate (humid vs arid, semiarid, etc.), land cover (forested vs agriculture, urban etc.), catchment response (fast vs slow), storage (groundwater-dominated vs surface-water-dominated catchments), and so on. Although these groupings by themselves do not provide a comprehensive classification system in our view, and some of them (e.g. fast vs 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). However, currently available classifications have some crucial shortcomings. Some of these shortcomings of current classifications include the following:

- They lack consistency in definitions and many are qualitative in nature.
- They do not consider climate and catchment physical and catchment response characteristics simultaneously.
- They were developed with a specific use in mind, for example, water resources, rather than being more widely applicable.
- They assume stationarity of climate and land use.
- They rarely include both natural and human-impacted catchments.
- They lack explicit links to societal issues.
- And, probably most importantly, they do not provide insight into causes of similarities (or lack thereof) in the hydrologic response observed in different catchments.

Overcoming these shortcomings is crucial in order to achieve a generally accepted classification system. A widely accepted catchment classification system for hydrology would (see McDonnell and Woods, 2004; Wagener et al., 2007)

- provide an important organizing principle in itself, complementing the concept of the hydrological 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/dissimilarity of hydrological 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 hydrological systems;
- be a major advancement toward guidance for the applicability of various simulation methods for predictions in ungaged basins;
- provide constraints and diagnostic metrics that can be used for model evaluation/diagnostics and application and ungaged 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.

Therefore, while the complexity and the differences between catchments can often be overwhelming, patterns and connections might be discernible and lead to advancement in hydrological science through the formulation of hypotheses or relationships that may have general applicability.

In this article we provide a discussion of the basics of a catchment classification framework, and complement the discussion of Wagener et al. (2007) by introducing the concept of catchment services while differentiating between natural and human-impacted catchments. This discussion is based on three premises: namely, (i) the enormous complexity of environmental factors impacting 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 and relationships underlying the classification; and (iii) it should be based on data that is (relatively) uniformly available around the world.

A CLASSIFICATION FRAMEWORK INCLUDING UNCERTAINTY

A Perceptual Model of Catchment Function

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 or even directly measure them (Beven, 2000). In-depth discussions of possible perceptual models of catchments can be found elsewhere (e.g. Kirkby, 1978; Anderson and Burt, 1990; Beven, 2000; Ward and Robinson, 2000). Here, we simply list and define some the main functions of catchments that underlie a more complete perceptual catchment model (Figure 1; see for further discussion, Black, 1997; Wagener et al., 2007):

• Partition: This corresponds to the separation of water, energy, and matter into different pathways at the land surface through processes including interception, infiltration, percolation, and so on.

• Storage: Storage concerns storage of water, energy, and matter in different parts of the catchment and over
very different timescales. Storages include snow and ice, interception, soil moisture, aquifers, water bodies, and so on.

- **Transmission:** Transmission describes the fluxes of water and energy within the control volume (catchment). These fluxes are strongly dependent on the connectivity between different stores in the catchment and will significantly vary throughout time in many cases.

- **Transport:** Strongly linked to transmission, but not identical to it, this is the transport of matter through the catchment. Transport processes include erosion and sediment transport, solute transport in the channel and in the subsurface, and so on.

- **Release:** Water, energy, and matter are released from the control volume through atmospheric, surface, and subsurface fluxes. Fluxes of water, energy, and matter include evaporation, transpiration, channel flow, sediment transport, groundwater exchange, and so on.

Black (1997) also discusses chemical and habitat (ecological) catchment functions in addition to the functions mentioned above. 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.

While the integrated catchment behavior at larger scales often shows relatively simple characteristics that can be reproduced by simple nonlinear/linear models, it seems necessary to view catchments as nonlinear space–time filters if a catchment classification system that enables detailed analysis is the objective. A nonlinear space–time filter view will allow us to explicitly recognize event-driven, nonlinear and threshold dynamics, including a network of activity centers (hot moments and hot spots), on top of the continuum representation that is equally valuable and more often the focus.

The interaction between climate inputs with the landscape involves various transformations as represented by the functions listed above. These arise from the multiplicity of pathways that water takes from where it falls as precipitation towards a common outlet (of the catchment). There are different kinds of transformations that occur through interactions of space–time fields of climate inputs and space–time fields of landscape structure: (i) filtering in the time domain – linear filtering, storage in different parts of the landscape (surface, subsurface, rivers, lakes etc.), release (transport or movement), and dispersion leading to smoothing and time delay; (ii) nonlinear or threshold filtering in the time domain (partitioning at the land surface and at other key places below the subsurface) leading to removal and intermittency of processes; (iii) convergence in the space domain due to the funneling action of the watershed shape – from volume to area to line to point (watershed outlet), leading to scaling behavior; and (iv) spatial connectivity and diversity, leading to threshold patterns of landscape response and functioning.

The net result of these interactions between climate and landscape are space–time fields of runoff and storage (surface water, groundwater, soil moisture, depression storage, river flow, and storage) that embed within them aspects of the space–time structure of both climate (or weather) and landscape features, along with the transformations that arise from hydraulics (movement), transport, and reactions (biological and chemical). Characteristics of these runoff and storage fields can be viewed as signatures of catchment functions.

**Signatures of Catchment Function**

The different functions of catchments are reflected in their hydrologic response behavior. Characteristics of this behavior can be described using signatures, that is, specific characteristics of the catchment response behavior, which can be linked to any of the functions through hydrological theory (Sivapalan, 2005; Gupta et al., 2008). For example, the term runoff ratio (long-term ratio of runoff over precipitation) describes how the catchment releases water through different pathways, evaporative processes versus streamflow. Runoff ratio also provides an indication of how water is partitioned at the land surface, which is the basis of the blue and green water distinction introduced by Falkenmark (2007). Falkenmark and Rockström (2006) distinguish blue and green water for water management purposes. Blue water refers to water stored in aquifers, lakes, and dams, while green water refers to water stored as soil moisture. The separation is useful since blue water can generally be utilized in water resources engineering, while green water will largely return to the atmosphere through evaporation and transpiration, but might make up most of the water fluxes. The green water flux is mainly driven by the consumptive use of vegetation; however, in some dry regions of the world this flux can be largely driven by evaporation from bare soil or from vegetation cover following interception (Savenije, 2000). Considering the increasing urbanization occurring in many regions (e.g. Grimm et al., 2008), hydrological theory also needs to be extended from natural systems to human-impacted ones if the signatures are to represent anthropogenic alterations to the terrestrial water cycle, for example, through dams or land use change.

**Catchment Services and Disservices**

While signatures describe hydrologically relevant characteristics of the catchment response, it is crucial to include the implication of the values of different signatures for humans and ecosystems. This inclusion creates a classification
framework that explicitly defines the societal relevance of catchment behavior and that is directly significant for water resource management. Here we distinguish positive and negative implications of catchment functions (as reflected by the signatures) for humans and ecosystems. Benefits received by humans from resources and processes of natural ecosystems have become known as *ecosystem services* (e.g. Daily, 1997). Here, we are concerned with the positive impacts or benefits received by nature (ecosystems) and humans from resources and processes supplied by catchments, and will therefore refer to these as *catchment services*. Negative impacts are referred to as *disservices*. An example of a catchment service is the collection and supply of water to sustain aquatic ecosystems in rivers. This service will – depending on the species under investigation – for example, include aspects of water quality, water quantity, and water temperature. A specific service would, for example, be the provision of sufficient water to sustain a certain water level, or the occurrence of short-term flooding to allow access to the floodplain. Examples of catchment disservices for humans include floods and droughts and their impact on water resources, or the occurrence of persistent low-flow periods limiting the abstraction of water for the cooling of power plants. Ecosystems in this context might include both aquatic (invertebrates and fish) and terrestrial (vegetation) ecosystems. An example of a change in catchment service to terrestrial ecosystems lies in the reduction of groundwater storage due to excessive pumping, and therefore the drop of water tables, which has, for example, significant impacts on the terrestrial ecosystem characteristics in the southwestern US. Understanding the relationship between catchment services/disservices and signatures, with catchment climate and form, would create a classification framework with predictive power and the ability to provide information needed to address societal issues.

**DESCRIPTORS OF CATCHMENT CLIMATE**

Climate exerts a strong control on catchment function (Budyko, 1974; L’vovich, 1979; Sankarasubramanian and Vogel, 2002; Yadav et al., 2007); it strongly controls ecosystems (Chapman, 1989); and – over long timescales – it also controls physical catchment characteristics (Abrahams, 1984; Collins et al., 2004). Classification schemes such as those by Köppen (1936) and Thornthwaite (1931) define regions by their climatic characteristics. While these classification systems only considered evaporation (energy) and precipitation as descriptors, others have attempted to link these variables to functional catchment characteristics. Most important in this context are the works by L’vovich (1979) and Budyko (1974), both of which developed long-term average relationships between measures of water and energy availability in various regions. Typical indices used in this context include the dryness index (ratio of potential evaporation over precipitation) and the evaporative index (ratio of actual evaporation over precipitation). Budyko (1974) related both indices to each other through theoretical analysis. Figure 2 shows a plot of these variables for over 400 watersheds located across the US. Catchments with a dryness index below 1 are deemed energy limited: that is, there is insufficient energy to evaporate all the moisture available, while catchments with a dryness index above 1 are water limited. The Budyko curve shown ignores seasonal and year-to-year variability (Chapman, 1989). Others have derived indices that consider additional local characteristics of catchment form to be able to describe this variability (Milly, 1994; Potter et al., 2005; Woods, 2003).

**DESCRIPTORS OF CATCHMENT FORM**

Indices have also been used widely to describe geomorphological and other physical characteristics of catchments (see, for example, Leopold et al., 1955; Bras, 1990; Rodriguez-Iturbe and Rinaldo, 1997). Index formulations include both dimensionless and dimensional numbers. Popular examples of indices in this context 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⁻¹), texture ratio (ratio of maximum number of channels crossed by contour to basin perimeter, unit is l⁻¹), or the hillslope Peclet number (Berne et al., 2005).

An alternative approach to the use of single numbers is the use of (frequency) distributions of a catchment characteristic. This reduces the problem of expressing complex system characteristics in terms of a single number, which unavoidably results in a loss of information. Examples of frequency distributions used to describe physical characteristics at the catchment scale include the hypsometric curve (percent catchment area above a given percent elevation contour (Langbein et al., 1947)), the topographic index ln(a/atan β), (upslope contributing area divided by the local surface topographic slope (Kirkby, 1978; Beven and Kirkby, 1979; Seibert and McGlynn, 2007)), riparian to hillslope buffer ratios (McGlynn and Seibert, 2003), travel time surrogates (watershed flowpath lengths divided by gradients (McGuire et al., 2005)), connectivity duration curves (fractional hydrologic connectivity through time between uplands and streams (Jenco et al., in review)), and other metrics of watershed organization (McGlynn et al., 2003). Additional metrics and distributions are suggested by Seibert and McGlynn (2005). In Chapter 115, Landscape Element Contributions to Storm Runoff, Volume 3.
Even more information can be included when conceptual models are defined. The term conceptual model is used differently in different communities. Here we define it as a simplified (and usually generalized) schematic representation of a more complex real-world physical system. Popular examples are based on the concept of hydrologic landscapes (Winter, 2001) or the UK hydrology of soil types (HOST) system (Boorman et al., 1995). Hydrologic landscapes are multiples of hydrologic landscape units, which are themselves defined by land surface form, geology, and climate (Winter, 2001; Winter et al., 1998; Wolock et al., 2004). The HOST system combines pedological and geological information with assumptions about dominant groundwater characteristics to define conceptual models throughout the United Kingdom Boorman et al., 1995).

**SIGNATURES OF NATURAL CATCHMENT FUNCTION**

Signatures are representations of the underlying catchment function that can be observed (at least in theory). The notion of signatures has to be seen as a general way to describe characteristics of any catchment response variable, despite the fact that most studies have focused on the most widely available hydrologic variable, that is, streamflow. Other relevant characteristics that can be defined as signatures include those derived from residence time distributions (McGuire et al., 2005), soil moisture (e.g. Botter et al., 2007), groundwater, sediment transport, or water-quality characteristics.

Such emergent properties or behavioral characteristics will change with temporal and spatial scale at which they are observed or analyzed (e.g. Atkinson et al., 2003; Farmer et al., 2003; Thoms and Parsons, 2003; Kirchner et al., 2004; Biggs et al., 2005). Olden and Poff (2003) demonstrate 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 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 timescale dependent. With respect
to changes across spatial scales, 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, for example, 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 (McGlynn and McDonnell, 2003; Buttle, 2006).

SIGNATURES OF HUMAN-IMPACTED CATCHMENT FUNCTION

Human activities significantly alter catchment physical characteristics and (indirectly) climatic characteristics throughout the world, which in turn can severely change catchment signatures (Vörösmarty et al., 2004; Milly et al., 2008; IPCC, 2007). Any general catchment classification system therefore needs to acknowledge this impact and provide ways in which it can be quantified. Relative water demand ($R_{WD}$) is the most commonly used signature of human impacts on catchment water regimes (Vörösmarty et al., 2000; Weiskel et al., 2007). It is defined as

$$R_{WD} = \frac{W_{\text{human}}}{Q_{\text{natural}}}$$

the ratio of human withdrawals, $W_{\text{human}}$, to the natural catchment outflow, $Q_{\text{natural}}$. Weiskel et al. (2007) list other names under which $R_{WD}$ is known, including withdrawal ratio (Lane et al., 1999), water scarcity index (Falkenmark et al., 1989; Oki et al., 2001), criticality ratio (Alcamo et al., 2003), level of development (Hurd et al., 1999), and local water demand (Vörösmarty et al., 2005). Weiskel et al. (2007) stress that this signature is limited since it ignores return flows and interbasin water import, and they provide an extension that considers internal fluxes and interbasin exchange.

Human activities other than the abstraction of water can also have a significant impact on catchment function and behavior. The building of dams of various sizes has significantly altered the hydrology of many catchments around the world (Graf, 1999). Dams reduce high flows while increasing low flows, which subsequently has an impact on streamflow characteristics including water temperature, the amount of sediment transported, or the frequency of flooding, which would allow access to the floodplain for some species (Poff et al., 2007).

ASSESSING SIMILARITY AND MAPPING OF CONSTRAINTS

Similarity between catchments can be assessed once suitable metrics of form, function (signatures), and climate have been defined. In the case of indices (individual numbers), it is common to use some form of Euclidean distance measure between the locations occupied by different catchments in the multidimensional similarity-metric space. If characteristics are described through distributions, then tests of similarity between them can be applied to assign levels of significance with which they differ or are similar. The Kolmogorov–Smirnov test is a popular example of a test to assign levels of significance with which samples originate from the same underlying distribution. A discussion of mathematical techniques to discern clusters of similar metrics is an essential component of a classification system, but this discussion is beyond the scope of this article (further information can be found in the following papers: Burn, 1989, 1990, 1997; Nathan and McMahon, 1990; Arabie et al., 1996; Mirkin, 1996; Gordon, 1999; Burn and Goel, 2000; Castellarin et al., 2001; Holmes et al., 2002; Wagener et al., 2004; McIntyre et al., 2005; Rao and Srinivas, 2006a,b; Yadav et al., 2007, and others).

However, assessing similarity is only a first step toward reaching a hydrologically significant classification framework, since “hydrologists have always tried to relate structural features of catchments to their response characteristics” (Bras, 1990, p. 589). A catchment classification system ultimately has to map catchment form, function, and climate onto each other to provide insight into causal relationships between these three aspects and to achieve predictive power (Figure 3). This mapping should include the uncertainty in the individual metrics as well as the uncertainty in the mapping itself to acknowledge our lack of knowledge (i.e. gaps in hydrological theory) and our limited capability to observe hydrological processes (Yadav et al., 2007; Zhang et al., 2008). The mapping can be used to derive constraints on unknown aspects of the triangle shown in Figure 3. Yadav et al. (2007) demonstrated the use of such constraints on expected catchment function to ultimately derive continuous ensemble streamflow predictions in ungauged basins. Their approach mapped streamflow signatures onto climatic and form characteristics in an uncertainty framework. Beven (2000) suggested a mapping of the model space onto the landscape space

![Figure 3](image-url)
as an alternative to model calibration. If such a mapping would be performed using some form of fuzzy or probabilistic mapping, then the result would provide constraints on expected watershed behavior by constraining the number of feasible models.

THE NEED FOR A DYNAMIC CLASSIFICATION SYSTEM

Stationarity – the assumption that the variability of natural systems is limited to remain within an unchanging envelope – has become an unsuitable basis for science in a world that is changing at an increasing speed (Milly et al., 2008).

The reasons for this change in our current and future world are mainly (i) human changes to land cover and channels (include dams) in catchments driven by increasing population size, and subsequent needs for increased agriculture and urbanization; (ii) natural and human-induced climate change; and (iii) natural variability of the climate system. While human impacts on catchments and natural variability have been acting for a long time, it is only recently that science confidently concluded that anthropogenic impacts on climate would lead to significant changes with impacts on means and extremes of precipitation and evaporation and subsequently on the hydrological response (Oki and Kanae, 2006; Barnett et al., 2008). Combining this understanding with increasing population pressure in many parts of the world (Vörösmarty et al., 2000), and therefore increasing human consumption of water resources (for direct use, for agriculture or food production (Brown and Funk, 2008; Lobell et al., 2008), and for industry), leads to the need for a dynamic classification system in which these changes of catchment services can be continuously updated. Land use changes will also strongly alter the partitioning of water at the land surfaces and therefore will change subsequent flowpaths and storages. Gordon et al. (2005) analyzed the hydrologic impact of human modifications to the land surface on the basis of projections of widespread deforestation in sub-Saharan Africa and increasing agricultural production in the Asian monsoon region. Their study showed that impacts of irrigation and deforestation were similar in magnitude and increasing food production in one region might negatively impact another. Other changes can be introduced through major infrastructure, mainly dams. While the rate of building of new dams has decreased, at least in the developed world, the impacts of existing dams on flow and sediment regimes and their subsequent implication on ecosystems are not yet fully understood (e.g. Nilsson et al., 2005; Poff et al., 2007; Walter and Merritts, 2008). The nonstationarities introduced by these changes have significant implications for the earth sciences (Vörösmarty, 2002), and demand that a hydrologically relevant catchment classification system is dynamic enough to account for these alterations.

SUMMARY AND IMPLICATIONS

Hydrologists are and will increasingly be charged with providing the scientific basis to support, whenever possible, the search for sustainable water resource management strategies to achieve water security for humans and ecosystems in a world where the speed of hydrologically relevant changes is increasing. A main driver of this change is population increase, with its consequences to land use and water consumption, and climate change, with its change to moisture and energy availability. The world population has tripled in the twentieth century, while, over the same period, water use has increased sixfold. Currently, 1 billion people live in water-scarce or water-stressed regions, and in 2025, this number will have increased by a factor 3.5. In such water-stressed regions, mainly located in the poor countries of the world, water withdrawals to sustain irrigated agriculture for increased food production make up about 70% of total withdrawals. Globally, irrigated agriculture is the largest and fastest growing user of freshwater (Holdren, 2008). The land use changes associated with increasing population will have significant impacts on catchment function around the world (e.g. Gordon et al., 2005; Piao et al., 2007). Climate change is likely to add further insecurity to food availability in many regions (Brown and Funk, 2008). This will be a particular problem in poor regions of the world where monitoring networks are least available.

Understanding the potential impacts of these changes on catchment signatures and thereby catchment services and their relationship with ecosystem services (Palmer et al., 2004) and human services (Milly et al., 2008) will require improved understanding of natural processes and of the integrated complex human–environment system. Closely linked with this new understanding is the need for new modeling capabilities that are transferable to thus far unobserved systems, which will remain valid under nonstationary conditions and which will provide probabilistic estimates of the uncertainty associated with their predictions. Focusing on catchment function and related services will provide one adaptation to change in such a way that catchment services are maintained at a desired level wherever possible. It also offers avenues for economical analysis (Smith et al., 2006).

Developing a catchment classification system across relevant spatial and temporal scales with a focus on catchment function would help provide structure to our science. Mapping catchment form and climate onto catchment function as observed in catchment signatures (or indicators) would provide predictive power, enabling transfer of understanding to currently ungauged regions. And finally, linking such a classification framework to catchment services would provide a new way to advance scientific understanding of the benefits for humans and ecosystems derived from catchments, and how these benefits will change in a nonstationary world. Such a catchment classification framework
could underpin integrated water resources management and even enable direct economic analysis of catchment services. It would take a community effort to achieve implementing such a framework across the globe and across scales (Figure 4). Our vision is that of a dynamic web-based map of the world’s catchments where users would define the signatures related to their catchment service/disservice of interest. A mapping between form, climate, and function originating from the studies of many hydrologists around the world would provide a global view on changes to signatures and services/disservices based on climatic and land use scenarios.

FURTHER READING


REFERENCES


