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Heterogeneity in Hydrologic Processes: A Terrestrial Hydrologic Modeling Perspective

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Abstract

Heterogeneity of land surface and atmospheric processes contributes to all aspects of the hydrologic cycle. Understanding the types and sources of this heterogeneity is a fundamental component of both theoretical and applied hydrology. Observations of heterogeneity occur at multiple scales ranging from within-canopy variation in water-holding capacity of a single leaf to spatial variation in precipitation at continental to global scales. Consequently, strategies for addressing heterogeneity in hydrologic modeling depend on the scale and type of process being modeled. Further, hydrologic models must address heterogeneity in both inputs and parameters as well as the representation of underlying physical processes. This paper provides an overview of heterogeneity and its implications for hydrologic modeling. Crucial examples of heterogeneity in inputs, parameters, and underlying physical processes are described, and approaches used to deal with heterogeneity within hydrologic modeling are discussed. In particular, the use of effective parameters, probabilistic approaches, and landscape tessellation are described as strategies to address heterogeneity in parameters and inputs. Explicit consideration of process heterogeneity is also considered from the perspective of physically based hydrologic modeling, and the implications for the coupling between hydrologic and ecological process models is discussed.

Introduction

Analysis of heterogeneity in hydrology, as in other sciences, seeks to characterize and ultimately to explain spatial and temporal patterns of water in all of its forms—solid, liquid, and gas—and the pathways by which water is transported and stored on the surface of the earth. Observation of heterogeneity depends both on the spatial-temporal scale of observation and the particular hydrologic phenomena that are being observed. Observations can include fluxes (e.g., evapotranspiration) and stores (e.g., snowpacks, regional groundwater) as well as measures of quantity, quality, and/or timing. Understanding and quantifying heterogeneity in these different variables across a range of scales and exploring how heterogeneity changes across scales and between measures can be viewed as one of the basic challenges in hydrologic science.

Many of the fundamental research areas as well as practical applications of hydrology must deal with heterogeneity. In theoretical studies, analysis of heterogeneity with respect to different components of the hydrologic cycle often provides insight into the underlying controlling mechanisms. In applied studies, prediction of system behavior and its sensitivity to change often depends on estimates of heterogeneity. In both these arenas, heterogeneity must be considered both as a cause and as an effect. Heterogeneity of variables of interest (i.e., streamflow, soil moisture, groundwater storage, etc.) is linked to heterogeneity in other related variables (soil hydraulic conductivity, land cover) that describe underlying controlling processes or characteristics of the system. Thus, hydrologic analysis must deal both with the characterization, explanation, and prediction of heterogeneity of hydrologic measures of interest and with assessing the role that heterogeneity in related measures plays in shaping these patterns. Hydrologic modeling attempts both to capture relevant heterogeneity in outputs and to represent crucial heterogeneity in inputs, parameters, and processes.

Hydrologic models are used to address a variety of basic and applied research questions. The extent to which heterogeneity matters depends on the research question being asked. This is true both in terms of the ability of models to represent heterogeneity of response and the extent to which models must incorporate information about heterogeneity in the underlying system in order to capture relevant dynamics. Models designed to estimate flood conditions in urban environments, for example, might not need to capture spatial-temporal heterogeneity in low flow volumes (response) nor incorporate heterogeneity in deeper soil hydraulic properties (parameters). Nonetheless, for many hydrologic models, there are commonalities both in terms of key inputs, parameters, and processes for which heterogeneity is often an issue and in terms of the techniques used to incorporate heterogeneity within a modeling framework. This paper will provide an overview of common sources of heterogeneity in hydrologic systems and then discuss some of the approaches used to account for heterogeneity at different scales within hydrologic models. It is important at this point to distinguish between heterogeneity and variability. Heterogeneity typically implies a difference in type or class (i.e., differences in soil texture classes). Variability can denote a difference in amount or degree, often within a type or class (i.e., differences in values for hydraulic conductivity within a soil class). How the type or class is defined can determine whether observed variation might be called heterogeneity. For example, if different soil structures result in variation in hydraulic conductivity, it might be reasonable to examine heterogeneity in hydraulic conductivity. Given this semantic problem, I will consider both heterogeneity and variability that likely arises from underlying structural differences of the property in question.

Observations of Heterogeneity in Hydrology

In hydrology, the basic unit of analysis can range from a block of soil or the surface of a leaf at small scales, to hillslopes and watersheds at local to regional scales, and to the full hydrologic cycle at global scales. All of these systems, however, can be examined from the perspective of inputs and outputs of water and the internal state variables/parameters and processes that transform inputs to outputs. Heterogeneity of outputs at any scale may reflect heterogeneity in inputs, internal system parameters, and/or the processes involved.

Heterogeneity in Inputs

One of the most important factors contributing to spatial heterogeneity in hydrologic response variables, including soil moisture, evapotranspiration, and streamflow, is spatial-temporal variation in precipitation inputs. At the continental scale, heterogeneity in all hydrologic processes can be explained based on the annual amount and seasonal variation in precipitation. Thus, annual differences in the amount and timing of streamflow in the northeastern *versus* southwestern United States can clearly be attributed to differences in the amount and timing of precipitation.

Most hydrologic models are constrained by an energy or mass balance equation where (Inputs − Outputs = ΔStorage). For mass-balance models in hydrology, precipitation is a fundamental input; thus, heterogeneity in precipitation can be seen as the starting point for heterogeneity of all hydrologic processes within the system. Quantifying heterogeneity in precipitation and incorporation of this heterogeneity into models, particularly at more local scales, is often confounded by limited rain gauge density. Smith et al. (1996) found that even a high density of rainfall gauges resulted in a significant underestimation of storm event precipitation when compared to radar estimates. Advances in rainfall observations through radar have contributed to mapping the heterogeneity in precipitation; however, data availability and error assessment remain issues (Krajewski and Smith 2002).

Irrigation and interbasin transfers of water can confound analysis of heterogeneity where precipitation is assumed to be the only input. In areas where interbasin transfers of water are significant, monitoring of these additional inputs can be essential for accurate modeling of streamflow and evapotranspiration. In the South Platte Basin of Colorado, for example, it is estimated that almost 25% of flow is imported from outside basin with more than 15 interbasin diversions (Dennehy et al. 1993). Further, heterogeneity in baseflow and annual flow patterns of subbasins within the South Platte can often be attributed to differences in irrigation regimes (Strange et al. 1999).

At the watershed scale, the temporal scale of interest often determines the extent of relevant heterogeneity in precipitation. Spatial heterogeneity at the timescale of individual storm events is often, but not always, greater than that of longer term (seasonal-annual) patterns. The mechanisms that generate precipitation events are important controls on the associated spatial length scales and their relationship with temporal scale. For a given storm event, convective rainfall, for example, varies at length scales of < 1 km, whereas frontal cyclonic storms may be organized over hundreds of kilometers (Bloschl and Sivapalan 1995). Thus, modeling runoff for individual storms for a first-order watershed may need to account for spatial variability in precipitation inputs, particularly in regions dominated by convective rainfall. Modeling runoff response to a flood producing storm event in Fort Collins, Colorado, for example, would need to account for a doubling of precipitation input within less than a kilometer (Ogden et al. 2000). For storm-events modeling at larger space scales, such as the Colorado Front Range, interpolation of rain gauge data for input into hydrologic models must account for both typical length scales of storm events and the stochastic nature of individual events.

At longer-term (i.e., annual) timescales, heterogeneity in precipitation within a given climatic region may often show a consistent spatial pattern. Precipitation, for example, is often dominated by topographic controls such that there is a significant relationship between mean annual precipitation and elevation across climatic regions of North America (Dingman 1994). Human modifications to the land surface may also contribute to a consistent long-term spatial variation of precipitation at relatively local scales. Urban heat island contributions to the frequency and intensity of convective rainfall, for example, can generate heterogeneity at storm event to annual timescales (Changnon 1992). In these cases, where heterogeneity in precipitation is temporally consistent, these patterns must be considered in longer term models of continuous streamflow, evapotranspiration, and so forth. Inputs, in this case, are often derived from atmospheric climate models such as Regional Atmospheric Modeling System (RAMs) (Walko et al. 2000) or models such as Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al. 1994) that provide spatial estimates of precipitation by interpolating rain gauge data using topographic, wind direction, and other controls on spatial patterns.

Finally, in addition to precipitation inputs, energy balance approaches in hydrology must consider energy inputs or solar insolation as a key control on heterogeneity in response characteristics. Energy inputs often vary in structured predictable ways following topography (slope, aspect) and, at larger scales, latitude. As with precipitation, capturing this heterogeneity in input often requires going beyond available measured data and using models, such as Mtn-Clim (Running et al. 1987), to estimate spatial variation in radiation input.

Heterogeneity in System Characteristics or Parameters

Distinctions between heterogeneity of system characteristics or parameters (i.e., variation in soil hydraulic conductivity) and heterogeneity of processes (i.e., saturation excess *vs* infiltration excess as runoff production mechanisms) depend on both the scale and the model being employed. Coefficient-based models in hydrology estimate runoff volumes as a function of precipitation using parameters related to land surface characteristics. The curve number approach developed by the U.S. Soil Conservation Service, for example, compiled data to determine standardized precipitation-runoff relationships for a variety soil (i.e., sandy loam, clay, silt) and land-use characteristics (i.e., high density urban, commercial, forest). In these models, spatial heterogeneity in runoff coefficients can represent both a change in parameters or in the strength of relationships (i.e., an increase/decrease in infiltration capacity) and/or a mechanistic shift between dominant runoff production mechanisms (i.e., from subsurface to surface overland flow). In more process-based models, processes are explicitly represented, and parameters tend to reflect measurable characteristics that control the rates of these processes. In both types of models, however, several commonly used, physically based parameters are often the main drivers of heterogeneity in hydrologic responses. Key parameters include various measures that describe soil, vegetation/land cover, and topography as well as several measures of channel characteristics including channel geometry and surface roughness.

Soil parameters such as depth, texture, hydraulic conductivity, and porosity are often key inputs into hydrologic models. Significant efforts have been made in recent years to develop national databases (e.g., SSURGO; http://www.ncgc.nrcs.usda.gov/branch/ssb/products/ssurgo) that provide data on soil properties at scales ranging from 1:12,000 to 1:63,360. Nonetheless, significant uncertainty around the impact of soil properties on hydrologic behavior often remains, particularly at smaller (first order) watershed scales. For example, heterogeneity in soil characteristics is often represented by aggregate measures of hydraulic conductivity and has been shown to vary across multiple scales. Variation in hydraulic conductivity is often tied to soil type (i.e., fraction of sand, silt and clay; (e.g., Clapp and Hornberger 1978); however, site-specific variation within soil types can be significant. In particular, macropores—generated by roots, soil structure, and so forth—can result in significantly higher effective hydraulic conductivities than implied by the soil matrix (McDonnell 1990). Similarly, the role played by bedrock fractures, soil crusting, and so forth, can confound attempts to map heterogeneity in soil hydraulic characteristics based on typically available soil classification information. Given these uncertainties, soil hydraulic conductivity is often left as a calibrated parameter in hydrologic modeling (Beven and Binley 1992).

Heterogeneity in land cover characteristics often drives spatial heterogeneity in hydrologic processes, particularly infiltration, interception, and evapotranspiration. Mapping of this type of heterogeneity, and subsequent incorporation into hydrologic models has greatly been improved by remote sensing and, in particular, remote sensing estimates of leaf area index, which is a key parameter in many physically based hydrologic models (Waring and Running 1998). In more urban environments, land cover characteristics are typically derived from land use maps (i.e., Moglen and Casey 1998; Rose et al. 2001), although there is a potential for incorporating much finer and potentially more hydrologically relevant characteristics (i.e., impervious/pervious area) using remote sensing data. In both of these applications, scale becomes a crucial issue and is tied to the resolution of available sensors and/or mapping information.

It is important to consider that human activities, both agriculture and urbanization, can have a significant impact on heterogeneity of not only land cover but of other hydrologic parameters as well. Agricultural practices (such as tile drainage and plowing) can alter effective soil properties (i.e., infiltration rates, hydraulic conductivity) and even topography. More than 20.6 million acres within the U.S. Midwest can be classified as under agricultural drainage. The hydrologic impact of these agricultural drainage practices typically include both impacts on streamflow (i.e., increases peak runoff rates) and soil hydrologic conditions (i.e., reduction of swamp and wetland area) (Fausey et al. 1995). In these watersheds, human design often overwhelms natural controls on heterogeneity, and differences in agricultural practices can play a crucial role in defining hydrologic properties across a range of scales (Skaggs et al. 1994). Similarly, urbanization can increase watershed scale drainage efficiency through the development of storm sewer networks and impervious surfaces (Chester and Gibbons 1996). As discussed in Chapter 13 (Band et al. this volume), the net impact of urban design can alter heterogeneity in parameters and ultimately hydrologic behavior, although there is evidence of both increases and decreases in heterogeneity of response depending on the scale, location, and specific process of interest.

Heterogeneity in topography (slope, aspect, elevation) is probably the most accurate and readily available parameter used in hydrologic modeling. The geomorphic unit hydrograph (Rodrigues-Iturbe and Valdes 1979), for example, illustrates how topographic relationships readily derived from a digital elevation model (DEM) can account for spatial differences in stormflow behavior. Many simple coefficient-based rainfall-runoff models (i.e., Soil Conservation Service Curve number approach) use variation in slope to adjust or select coefficients that determine the relationship between rainfall and runoff for particular land-use types. Other models such as TOPMODEL (Beven and Kirkby 1979), which also consider within-watershed hydrologic conditions, use topographic indices to account for heterogeneity in soil moisture patterns as well as streamflow. Heterogeneity in topography occurs at multiple scales, and its impacts on hydrologic processes vary with these scales. At the plot scale, topographic heterogeneity might be expressed as surface irregularities that account for a surface detention storage capacity. At the hillslope scale, slope varies such that in particular regions, characteristic profiles emerge; for instance, Piedmont hillslopes are characterized by broad, gently sloping uplands, steep side slopes, and flat bottomlands, whereas the western Cascade mountains are characterized by steep slopes and narrow riparian zones. These characteristic profiles contribute to explanations for the rate that water moves through the landscape and within hillslope spatial variation in soil moisture. At these scales, differences in mean hillslope topographic characteristics (slope, aspect, elevation) account for heterogeneity in hydrologic responses.

In addition to topographic control on the rate of flow, topographic parameters can be used to indicate heterogeneity due to the magnitude and timing of latent and sensible heat fluxes. Variation in insolation follows both slope and aspect and contributes to spatial patterns of evapotranspiration and soil moisture, particularly in water-limited environments (Moore et al. 1988). Variation in air temperature associated with a change in elevation can explain heterogeneity in soil moisture due to differences in the timing and rate of snow melt. At larger, regional to continental scales, topographic variation reflects dominant geologic controls. However, at these large scales, the impact of topography on variation in hydrologic response is often secondary to differences in climatic regime.

Finally, it is worth noting that at all scales, the relationship between topographic parameters and processes and associated responses such as streamflow and spatial patterns of soil moisture can be complex. For example, Western et al. (1999) found topographic indices were highly correlated to measurements of soil moisture patterns during wetting and drying periods for the Tarrawarra catchment in Western Australia. During very dry periods, however, this relationship breaks down. The dynamic relationship between topography and soil moisture reflects a shift in the dominant control on heterogeneity—from topography, in a hydrologically connected landscape, to local soil properties in a drier, hydrologically disconnected landscape. Similar limitations to using topographic parameters as surrogates for other hydrologic properties occur in areas where the underlying bedrock topography does not follow surface topography and acts as the main control for the redistribution of soil moisture.

Heterogeneity in Process

Ultimately, heterogeneity in hydrologic systems behavior may reflect heterogeneity in process. From a modeling perspective, spatial or temporal heterogeneity cannot always be easily represented by variation in parameters such as hydraulic conductivity, surface slope, or inputs such as the amount of rainfall. In these cases, heterogeneity is best explained by variation in space and time in the type of underlying processes rather than the intensity of those processes. For example, heterogeneity associated with differences in climate often reflects a shift in underlying controlling processes. Variation in temperature, for example, can result in a shift from rain to snowmelt-dominated hydrology. Snowmelt dynamics can then become the dominant control on the shape of seasonal hydrographs. Similarly, a shift from a climate dominated by short duration, high-intensity convective rainfall to one dominated by lower intensity frontal systems is often associated with a shift in runoff generation mechanisms from overland flow to subsurface throughflow. Modeling climate change impacts on hydrology, therefore, must be sophisticated enough to incorporate not only changes in input but also potential change in dominant controlling processes.

Incorporating Heterogeneity in Hydrologic Modeling: Approaches

Given ample evidence of significant heterogeneity in parameters and inputs typically associated with hydrologic models, strategies for incorporating this heterogeneity into hydrologic models are needed and have been the subject of considerable research. The particular approach used depends on the specific modeling objective and the response to the following questions: (a)When and where does heterogeneity matter?(b)What data are available to characterize this heterogeneity? (c)What are the costs (in terms of complexity, computation efficiency, etc.) of including this heterogeneity in a given model?

There are a variety of ways in which heterogeneity of parameters and/or inputs can be incorporated into models. Models range from lumped to quasidistributed to fully explicit representations (Watts 1997) where the transition from lumped to distributed type models is often evoked specifically to account for spatial heterogeneity. For example, representation of the expansion and contraction of saturated areas (and hence spatial heterogeneity in soil moisture and runoff production) can explicitly be represented in a spatially distributed model. In contrast, a lumped bucket model (i.e., a model that produces runoff in proportion to rainfall only after a single finite hillslope scale volume/store has been filled) might underestimate flow during the runoff period following a storm (recession period) because it ignores this heterogeneity.

Subunit Heterogeneity

Both lumped and spatially distributed models require estimation of parameters and inputs at the scale of the fundamental modeling unit. For a given modeling unit, the simplest approach is to use an estimate of the mean value of the parameter. Error associated with using a mean value will depend on the degree of nonlinearity of the process dependent on this parameter or input. Many hydrologic processes show significant nonlinearities. Numerous researchers have shown that nonlinearities in the relationship among soil properties, soil moisture, and evapotranspiration can result in under- or overestimation of evapotranspiration based on mean soil conditions (Kabat et al. 1997; Lammers et al. 1997). Runoff, particularly saturated overland flow, can also be highly nonlinear, given the threshold nature of the response. Many studies (reviewed by Giorgi and Avissar 1997) use soil-vegetation-atmospheric transfer (SVAT) models to estimate the coupling of land surface hydrology to the atmosphere for global climate models (GCMs) and have shown nonlinearities in the relationship between land surface characterizations and associated energy and moisture fluxes. Further, these studies show that these nonlinearities can result in significant errors in estimating these fluxes based on parameters averaged at the scales typically used in GCMs (e.g., Famiglietti and Wood 1994; Giorgi and Avissar 1997).

Spatial or temporal averaging of parameters to account for heterogeneity can also lead to errors when the scale at which the parameter is measured does not match the scale of application. For example, hydraulic conductivity is measured in the field at scales of the order centimeters to meters. Hillslope hydrology models, however, often include hydraulic conductivity as a parameter at scales of the order meters to kilometers. At this scale, heterogeneity in soil structure such as macro-pores, cracks, and so forth often increase effective conductivity (McDonnell 1990). Thus, mean soil hydraulic conductivity no longer controls the rate of flow. Instead, shallow subsurface resistance to flow is a complex function of soil matrix characteristics and the organization of flowpaths that produce an effective hydraulic conductivity. An alternative in this case is to use secondary field data, such as streamflow or lysimeter data, to infer effective parameter values through calibration. Even with calibration, however, the issue of using a single effective parameter to represent a distribution of conditions remains a problem when there is significant nonlinearity in the relationship between parameter values and response. Thus, a calibrated value for mean hillslope hydraulic conductivity may still result in error if distribution of actual values of hydraulic conductivity within the hillslope result in a nonlinear relationship between soil moisture and runoff production.

Parameter Distribution Approaches

One alternative to the use of a single averaged or effective parameter value is to run the model over a distribution of parameter values for each modeling unit. Avissar (1992) defined this approach as a statistical dynamical approach and has used it to incorporate heterogeneity in stomatal resistance, leaf area index, and albedo in SVAT models of land surface evapotranspiration (Avissar 1992; Avissar 1993). Hartman et al. (1999) illustrated an increase in correspondence between observed and predicted runoff when a distribution rather than mean value for snow accumulation was used. Use of a distribution in this case accounted for heterogeneity in within-grid cell snow cover due to significant wind-driven redistribution of snow in alpine regions.

The well-known TOPMODEL (Beven and Kirkby 1979) also uses probability distributions of a wetness index (7.1) to incorporate the effect of topography and soil characteristics on soil moisture and runoff production.

$$w_i = \ln\left(\frac{aT_{\mathrm{i}}}{T_o \tan \beta}\right), \tag{7.1}$$

where T_i and T_o are local and mean watershed saturated soil transmissivity, respectively, tan β is the tangent of the local slope, and a is upslope contributing area. Soil transmissivity is calculated as:

$$T = \int_{s_i}^{\infty} K_o e^{(-s/m)} ds, \tag{7.2}$$

where K_o is saturated hydraulic conductivity at surface, s is a saturation deficit (or depth from the surface to the water table), s_i is local saturation deficit, and m is a soil parameter that scales hydraulic conductivity with depth.

In TOPMODEL, the wetness index distribution is used to compute the distribution of local saturation deficits and runoff production. One of the strengths of TOPMODEL is that the topographic component of the wetness index distribution is easily derived from a DEM. Estimation of the distributions of K_o and m (which define local soil characteristics), however, presents a greater challenge and is often cited as explanation for differences between observed and predicted saturation deficits (Blazkova et al. 2002).

In most applications, TOPMODEL is calibrated by adjusting a mean m and K_o to achieve a best fit between observed and modeled streamflow. Calibration in this case reflects a method to deal with uncertainty in some of the underlying parameters—including the extent to which macropore flow and other heterogeneities in soil parameters impact the response. Calibration can also compensate for errors in estimating the distribution of the wetness index. In particular, the estimation of the TOPMODEL index has been shown to be sensitive to the resolution of the underlying DEM where too coarse a resolution will truncate the tails of the distribution and change the corresponding estimate of streamflow. Consequently, calibrated values for parameters based on DEMs of differing resolution tend to vary (Saulnier et al. 1997).

Errors in TOPMODEL as well as the need for calibration illustrate the extent to which the estimation of the required probability density function can be problematic. For other parameters that are not easily measured, such as stomatal resistance or deeper groundwater conductivities, deriving a reasonable distribution may depend solely on ancillary data or another model. The use of probability density function can also be problematic in a more complex model, with multiple parameters, given that modeling over a distribution is considerably more computationally and mathematically intensive than the use of a single effective parameter.

Nonetheless, there are many cases where the probability distribution can readily be derived and may be important in terms of capturing significant nonlinearities in response. Representing land cover (particularly in urban environments, where the length scale of heterogeneity is small) by the use of a distribution may be very useful and help to avoid a situation where large areas (i.e., major drainage basins encompassed within urban areas) must be modeled at very fine scale resolutions (i.e., individual lawns, houses, streets). Even in cases where high resolution data may be available to delineate these objects, the associated computational and data storage costs would preclude spatially explicit modeling, except for small localized neighborhoods.

Aggregation or Partitioning Strategies

In spatially distributed models, an alternative to representing heterogeneity of inputs/parameters as either a probability density function (pdf) or an effective value is to explicitly represent heterogeneity through landscape tessellation. Defining the basic spatial modeling unit to minimize within-unit heterogeneity, however, again requires key issues of parsimony to be addressed including (a) When does heterogeneity matter? and (b) How simply can this heterogeneity be adequately described? Further, the use of effective or averaged parameters must be considered in conjunction with the strategy used to partition the landscape.

Numerous researchers have endeavored to derive optimal modeling units for representing landscape heterogeneity, given a specific hydrologic modeling task (e.g., Lammers et al. 1997). For many inputs/parameters/processes, aggregation often reduces heterogeneity. Wood et al. (1988) developed the concept of a representative elementary area to explore this effect with respect to runoff production. Evidence from both rainfall-runoff models and observed streamflow data illustrates that variability between different catchments within the same region tends to decrease as catchment size increases, such that a representative elementary area (REA) where variability between samples is minimized can be obtained (Woods et al. 1995). This effect is generally attributed to averaging of soil and topographic variability. At larger scales, of course, variability often increases again as regional scale climatic and geologic controls become important. For rainfall-runoff modeling at the regional scale, the concept of a REA provides a useful construct for dealing with heterogeneity. It illustrates that as the scale of the response variable (in this case runoff) changes, the scale of important heterogeneity also changes. The REA is a method to characterize this for topographic control of streamflow. The concept of a REA and associated scale analysis could also be applied to other hydrologic properties, such as effective hydraulic conductivity. In hydrologic modeling, however, response variables of interest may not necessarily be at the scale of a REA or, further, the response variable of interest or relevant inputs/parameters may not show this kind of scaling relationship. For example, a model designed to provide hydrologic information for the purposes of characterizing aquatic habitat must address streamflow defined at the scale of habitat sensitivity rather than scale (such as a REA) that simplifies analysis of streamflow behavior.

Theoretically, in situations where heterogeneity of the parameter produces nonlinear responses, the issue of heterogeneity in parameter values can be dealt with by partitioning the landscape into units with minimal within-unit parameter variation. RHESSys (Band et al. 2000), for example, allows patch size and shape to vary based on available input data and associated parameter variability. Proposed partitioning strategies based on topographic indices (slope, aspect, accumulated area) and land cover have been shown to reduce errors associated with averaging of observed nonlinear parameters/inputs (e.g., Lammers et al. 1997). In practice, however, the minimum modeling unit is often constrained by (a) resolution of available data and (b) computation memory/time. For example, distributed representation of land cover characteristics is often limited by the resolution of remote sensing data. On the other hand, as higher resolution data become available, computational limitations emerge.

Spatial Connectivity

Finally, it is important to recognize that even fully explicit representations aggregate or lump the landscape at the scale of the fundamental modeling unit (e.g., a 30-m grid cell). It is useful, therefore, to distinguish between a single lumped model that is replicated over an array of spatial units and a fully explicit representation. In the fully explicit representation, in addition to accounting for spatial variation in inputs and parameters, the connectivity between units and the spatial organization of the units is considered.

In SVAT modeling to support atmospheric modeling, Giorgio and Avissar (1997) note that spatial heterogeneity can in fact generate meteorological behavior due to gradients created by heterogeneity in land surface characteristics. In this case, the organization of heterogeneous patches and fluxes between them must be considered in addition to the distribution of different patch characteristics. Similarly, in hydrologic models of biogeochemical cycling, the potential for uptake of nutrients along hydrologic flowpaths means that spatial organization of heterogeneity cannot be ignored. Further, connectivity between heterogeneous areas and the potential for that connectivity to change must then be represented in accounting for the impact of heterogeneity on water quality.

TOPMODEL is an approach that represents connectivity between heterogeneous landscape units implicitly, rather than explicitly. The higher wetness afforded to units with higher upslope contributing areas [*a* in Eq. (7.1)] implies a movement of water to lower areas. TOPMODEL, however, does not actually move the water from one cell to another; thus, it does not necessarily account for processes where explicit connection is important. For example, in an urbanizing watershed, some upslope cells may have higher water loads due to lawn watering, and downslope cells that are hydrologically connected to these upper cells should be wetter than those in similar topographic positions but whose upland areas have not yet been developed.

In addition to ignoring specific upslope/downslope linkage, implicit approaches such as TOPMODEL typically assume a constant connectivity. With respect to subsurface flow, field evidence has shown that under dry conditions, upland areas within a watershed may be disconnected from lower regions (Western et al. 1999). Similarly, in urban environments, sewers and roads may act to alter topographically based hydrologic connectivity and result in the bypass of lowland areas (Djokic and Maidment 1991; Tague and Band 2001). These examples serve to illustrate (a) the need in some cases to account for explicit connections between heterogeneous areas and (b) the potential for those connections to vary with time. Models such as DHSVM (Wigmosta et al. 1994), RHESSys (Tague and Band 2001), Topog (Vertessy et al. 1996), and EPA's SWIMM account for explicit connections, although the adequacy of submodels and parameters used to define the strength of connectivity is an area of continued research.

Physically Based versus *Empirical Coefficient Models*

Classification of hydrologic models also distinguishes between empirical-coefficient driven and physically based or process-based models (Watts 1997). This distinction, however, is a loose one because, as argued by Beven (1992), all physically based models include parameters derived from empirical relationships. Nonetheless, physically based models are more explicit in their representation of process heterogeneity. For example, observed differences in evapotranspiration and snowmelt between north- and south-facing slopes can be estimated in a physically based model that drives submodels of snowmelt and evapotranspiration with solar radiation inputs across spatially variable terrain (e.g., Band et al. 1993; Wigmosta et al. 1994) The increasing complexity of a physically based model, however, also increases the sources for potential error.

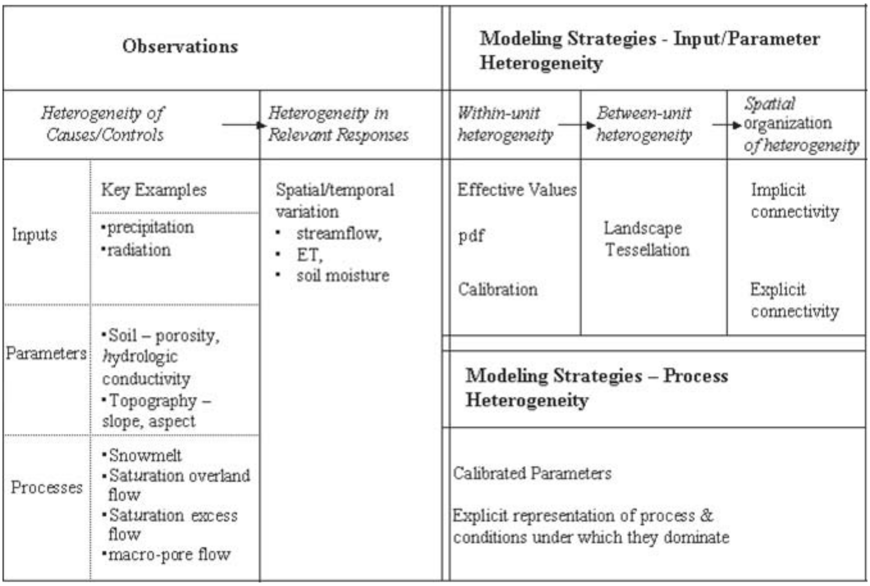
Physically based models are generally sensitive to interactions between specific inputs and/or processes. Soil moisture at any given point will be a function of rainfall, parameters controlling drainage such as hydraulic conductivity, and the representation of processes such as subsurface throughflow and evapotranspiration, which are both in turn dependent on current soil moisture conditions. The ability of process-based models to account for spatial/temporal heterogeneity assumes that the significant controls on variability, as well as covariation between different controls, inputs, and parameters, have been incorporated into the model structure (Beven 2002). In spite of these potential sources of error, physically based models do provide an important heuristic tool by explicitly representing the impact of dominant processes and landscape features on hydrologic response. In this sense, they are distinct from coefficient-based approaches to the extent to which they can be used as tools to assess the implications of different explanations for causes and consequences of heterogeneity.

For example, Pauwels and Wood (1999) illustrate that incorporation of freeze/thaw cycles and distinct overstory (forest) and understory (moss) layers into a physically based model has a significant impact on the estimation of evaporative fluxes in a high-latitude boreal forest landscape. These results suggest that spatial and temporal patterns of these processes may play a significant role in boreal forest hydrology. Similarly, Bonan (1995) showed that including a distinct lake surface submodel in a SVAT approach significantly altered estimates of evaporative fluxes. By altering model structure rather than parameters, adaptive physically based models can be used where the research focus is understanding rather than prediction. However, using models to address process heterogeneity requires that model design be flexible enough that alternative models and/or additional processes can easily be implemented (Leavesley et al. 2002).

Conclusions

Figure 7.1 presents a framework that summarizes the multiple avenues through which heterogeneity becomes an important consideration in hydrologic modeling. From one perspective, hydrologic models can be used to predict heterogeneity in variables of interest. Characterizing heterogeneity in hydrology responses such as streamflow is often a prerequisite for environmental planning directed at managing water resources. Simply quantifying heterogeneity in space and time of hydrologic fluxes (streamflow, evaporation, precipitation, and so forth.) remains a challenge that is currently being addressed both by extension of monitoring networks and by hydrologic modeling. Limited spatial-temporal coverage of monitoring networks and the potential for error in inputs, parameters, and the structure of hydrologic models, however, must be recognized and evaluated as sources of uncertainty in this information.

Both resource managers and scientists need a more complete understanding of the controls on heterogeneity in hydrologic responses. At the same time, the complementary issue of how heterogeneity in particular land surface characteristics impacts the way in which water moves through the landscape must also be recognized and evaluated. Hydrologic models are key tools that explore and illustrate both of these scenarios. The testing of hydrologic models against empirical data, therefore, improves the understanding of the role that heterogeneity of inputs, parameters, and processes plays in hydrology. By exploring the conditions under which different representations of heterogeneity (i.e., through effective parameters,



Observations

Heterogeneity of Causes/Controls →		*Heterogeneity in Relevant Responses*
Inputs	Key Examples •precipitation •radiation	Spatial/temporal variation • streamflow, • ET, • soil moisture
Parameters	•Soil – porosity, hydrologic conductivity •Topography – slope, aspect	
Processes	•Snowmelt •Saturation overland flow •Saturation excess flow •macro-pore flow	

Modeling Strategies - Input/Parameter Heterogeneity

Within-unit heterogeneity →	*Between-unit heterogeneity* →	*Spatial organization of heterogeneity*
Effective Values pdf Calibration	Landscape Tessellation	Implicit connectivity Explicit connectivity

Modeling Strategies – Process Heterogeneity

Calibrated Parameters

Explicit representation of process & conditions under which they dominate

FIGURE 7.1. A framework for considering the role of heterogeneity in hydrologic modeling. The framework acknowledges the distinction between heterogeneity in inputs, parameters, and processes and summarizes different approaches commonly used in hydrologic modeling to account for effect on model predictions.

probability density functions, or process algorithms) can adequately capture observed responses, hydrologic models are improved along with a basic understanding of key landscape controls on relevant hydrologic processes.

Linking hydrology with ecology broadens the context in which hydrologic models are used. Coupled hydro-ecological models employ many of the same techniques used in more classic hydrologic approaches. In these models, additional controls and feedbacks can become important drivers of heterogeneity. For example, models that couple vegetation carbon and nutrient cycling with hydrology must consider feedbacks between soil moisture and vegetation productivity and thus consider heterogeneity in both. The added complexity of considering interactions between hydrology and ecology means that parsimony becomes a crucial issue in model design. Ecological considerations, however, also help to bound the precision over which heterogeneity is relevant. For instance, for many ecological predictions, a 10% difference in streamflow or soil moisture may not be important. Further work that extends both the technical advances in addressing heterogeneity in hydrologic modeling and provides an ecological context for interpreting and evaluating model results, will, likely make valuable contributions to both disciplines.

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