7
Heterogeneity in Hydrologic Processes: A Terrestrial Hydrologic Modeling Perspective

Christina Tague

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