Hydrologic systems as complex networks: structure, connections, and dynamics

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Abstract: Driven by sheer necessity or pure curiosity and facilitated by advances in technology, hydrology has witnessed an unprecedented growth during the last century. Invention of powerful computers, remote sensors, geographic information systems, and worldwide web and networking tools have enabled collection and sharing of extensive hydrologic data, formulation of sophisticated mathematical techniques, and development of complex hydrologic models.

There is no question that we today possess a far greater ability to represent real hydrologic systems, understand their past and present functions, and project their future trajectories. However, there still remain numerous challenges, not only in developing models to accurately represent hydrologic systems but also in applying them for practical purposes. Among the issues dominating debates and discussions are: (1) models being developed are often far more complex than that may actually be needed; (2) more and more data are collected, without adequate scrutiny of their relevance and significance; and (3) models are often developed for specific situations, and so their extensions to other situations are generally difficult. Although these issues are addressed in many different forms, they all seem to emphasize the need for a generic theory or framework for hydrologic modeling.

A key requirement for developing a generic theory in hydrology is an adequate knowledge of the nature and extent of connections among the different hydrologic system components at various (space and time) scales. This is because, connections are ubiquitous and vital in hydrology. This is abundantly clear from the hydrologic cycle or water cycle itself, as every component in the hydrologic cycle is connected, either directly or indirectly and strongly or weakly, to every other component. Despite our efforts and progress through numerous scientific concepts and mathematical models, our understanding of connections in hydrologic systems remains largely inadequate. The present study proposes that the science of complex networks, a recent development in the field of complex systems science, offers a generic theory for studying all types of connections associated with hydrologic systems.

First, the basic concepts of complex networks and a number of associated measures for identifying network properties are described. Then, the relevance of complex networks for hydrology is explained through several examples, including the hydrologic cycle, rainfall and streamflow monitoring networks, river networks, global climate model outputs and their downscaling, and water distribution systems. Finally, the usefulness of the science of complex networks for studying connections in hydrology is tested through application of several network-based measures (e.g. clustering coefficient, degree centrality, degree distribution) to rainfall and streamflow data. For this purpose, monthly rainfall data monitored over a network of 230 stations in Australia and monthly streamflow data from a network of 639 stations in the United States are analyzed. Different threshold values, which are based on correlations (of rainfall and streamflow), are used in the analysis to obtain and compare some important information about the network properties. The results are discussed in terms of the type and nature of rainfall and streamflow monitoring networks, spatial and temporal connections in rainfall and streamflow, interpolation/extrapolation of rainfall and streamflow data, and catchment classification and regionalization.

The results generally suggest that the above rainfall and streamflow monitoring networks are not random networks, but networks of some other nature. Such results have important implications for rainfall and streamflow modeling theories, model complexities, data collection, and predictability, among others. Efforts to verify, and possibly confirm, the present results are currently underway. The broader implications of the outcomes of the present study for water resources planning and management are also highlighted.

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