The Hydrological Synthesis special section presents synthesis topics that have the potential to revolutionize hydrological sciences in a manner needed to meet critical water challenges that we now face. The special section also highlights topics that are important and exciting enough to compel researchers to engage in collaborative synthesis activities. This introductory paper provides a brief overview of nine papers that are included in this special section, which discuss the synthesis of tools, data, concepts, theories, or approaches across disciplines and scales. The wide range of topics that are explored include groundwater quality, river restoration, water management, nitrogen cycling, and Earth surface dynamics. Collectively, the special section papers illustrate that the challenge to deal effectively with complex water problems is not purely a scientific, technological, or socioeconomic one; it is instead a complex, 21st century problem that requires coordinated synthesis.

Meeting the water needs of humans and ecosystems is perhaps one of the greatest challenges of the 21st century. Over the last decade, it has become increasingly clear that if we are to face the water and environmental challenges of the future we must view the Earth as a single, though highly complex, system that includes the atmosphere, the hydrosphere, the geosphere and the biosphere. It has also become clear that these components are coupled and highly dynamic over various spatial and temporal scales; changes that occur in one component at one location often influence the environment elsewhere at later times. Understanding these coupled processes and complex feedbacks, with sufficient accuracy and in the face of anthropogenic and global changes, is a prerequisite to successful management of water resources and ecosystems.

Since the water cycle connects the atmosphere, land, and the oceans, and since biological and geochemical characteristics are inextricably linked to the flux of water, hydrologic problems are by nature multidisciplinary. Historically, hydrologic research has been conducted by disciplinary scientists or engineers working in a particular hydrological compartment (i.e., surface water, groundwater) using a particular approach to solve a specific problem. Hydrological sciences is now at a point in its evolution where many of the challenging problems exist at the interface of natural sciences disciplines [e.g., National Research Council, 2001, 2004; Hornberger et al., 2001; National Science Foundation, 2001; National Science and Technology Council, 2004; Consortium of Universities for the Advancement of Hydrological Science, Inc., 2003]. However, advancing these interface frontier topics requires prioritization of problems, coordination of efforts, and perhaps most importantly, it requires synthesis.

Although the calls for synthesis within hydrological sciences have been numerous over the past decades, defining synthesis is often challenging. Webster defines synthesis as “the combination of parts or elements into a whole.” Underlying the diversity of definitions of synthesis within the scientific community is a shared kernel of meaning that synthesis occurs when data, techniques, tools, concepts, or theories from two or more disciplines of specialized knowledge are integrated to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single research area and are more comprehensive than the constituent parts. It would be difficult, for example, to study the Earth's climate without considering the oceans, rivers, atmosphere, land surface, vegetation, and transport processes together with anthropogenic impacts and feedback mechanisms that link the climate system across space and time. Hydrological synthesis thus often requires integration (1) of knowledge from multiple, water-related disciplines, (2) across the molecular-to-process-to-basin scales of the hydrologic system, and (3) between theory, models, and observations. Such synthesis does not typically happen easily or spontaneously. It demands that researchers learn about related sciences, learn new methods, develop collaborations, and build consensus, and it often requires construction of new modes of organization, reward systems, and infrastructure [National Academy of Sciences, 2005].

This synthesis special section was developed to stimulate ideas about synthesis topics (across disciplines, across scales, and between models and observations) that have the potential to revolutionize hydrological sciences in the manner needed to meet the water challenges that we now face. The special section was also designed to highlight synthesis topics that are important and exciting enough to compel
a critical mass of researchers to move beyond their disciplinary comfort zone and participate in a collaborative synthesis effort. Nine contributors were asked to describe a synthesis topic that they believe offers significant opportunities for integrative research and major advances over the coming decade(s). The contributors come from a variety of disciplines and the papers cover a wide range of topics, including groundwater quality, river restoration, water management, nitrogen cycling, and Earth surface dynamics. In spite of the breadth of subjects, several themes resonate throughout many of the papers, including the need to better understand the coupled nature of hydrological-biogeochemical processes, the importance of incorporating structure or patterns into our investigations, the need to improve our characterization and analysis tools and predictive capabilities, the challenges associated with scaling and integration, and the importance of improving communication between scientists and decision makers. A brief description of the nine contributions is given below.

A common theme across several of the papers is the recognition that synthesis is needed to allow us to better understand and utilize patterns across scales, places, and time. Blöschl [2006] describes how each aquifer, catchment, and river reach is by its nature unique, and how that uniqueness poses a challenge for hydrogeologists who desire to generalize their findings beyond their areas of investigation. Blöschl discusses the challenges associated with scaling within natural systems, which often exhibit organized, nonrandom variability and where outliers (such as macropores or hydrological extremes) often dominate the system behavior. Blöschl suggests that investigation of patterns is an important synthesis topic and describes the need to develop complex models and advanced characterization methods that will allow us to detect, understand, and incorporate pattern information into hydrological analysis. As an alternative approach to process-based prediction, Blöschl describes how classification-based predictions can also be used to understand natural systems based on similarities and dissimilarities of aquifers, catchments, and river reaches. In a related paper, Schulz et al. [2006] also emphasize the importance to hydrological processes of organizational patterns of land and subsurface properties over a variety of scales. They discuss different approaches for representing spatial variability across scales, and describe advanced characterization approaches and structure-building processes that that hold promise for elucidating these spatiotemporal patterns, but which require synthesis for further development. Schultz et al. also discuss the need for incorporating spatial structure within hydrological models, and describe a variety of synthesis approaches that could be explored to facilitate this.

Kirchner [2006] challenges us to synthesize theory and measurements to develop the next generation of hydrological data analysis and modeling tools that can adequately represent hydrological processes at hillslope and catchment scales over a variety of conditions. This author suggests that many hydrological measurement approaches and analysis tools are inherently ill suited to investigate hydrological systems. Kirchner argues that although current tools or models may perform acceptably when calibrated and when used within certain “normal” system ranges, they are likely to be unreliable for use when the system is driven beyond normal conditions (by, for example, extreme events, shifts in land use, or global change). This author discusses the need to develop reduced form models that are governed by equations that may be different from those that describe small-scale physics (to which we are accustomed) and that have a minimal number of free parameters. As an example, Kirchner describes a modeling approach that incorporates the spatial character of hillslopes and catchments directly into effective governing equations. Kirchner argues that striving not only to get the right answers, but to get the right answers for the right reasons through development of such new tools, offers a challenging synthesis initiative.

Improving our understanding of water quality and the potential impact of degradation over large scales and long time frames is the theme of two contributions to this synthesis special section. Fogg and LaBolle [2006] describe how the groundwater that we drink is substantially older than many of the constituents that are now present in groundwater, such as MTBE, or nitrates and salinity associated with agricultural activities. Because reliable, multidecadal groundwater quality data sets and long-term, basin-scale, reactive transport modeling efforts are rare, little is known about the potential impact of these contaminants on groundwater, which is our largest reservoir of readily available water. Fogg and LaBolle argue that “creeping normalcy” or society's inability to perceive gradual trends, exacerbates the threat of declining groundwater quality. They argue that synthesis within hydrological sciences and between scientists, economists, and decision makers is urgently necessary to predict and ultimately sustain our groundwater quality, and they provide several suggestions of activities that could advance this synthesis.
area. Also exploring the impact of water quality, Schlesinger et al. [2006] describe the vast amounts of reactive nitrogen that are being introduced through human activity. They describe how humans roughly double the input of fixed nitrogen to the global land surface, and that there is only a limited understanding of where it all goes. Schlesinger et al. discuss the potential impact of fertilizer and other human sources of reactive nitrogen on the planet's biogeochemistry, and specifically on our water resources. They suggest that studies of subsurface storage, transport, and transformation of nitrogen and studies linking specific understanding of stream and river nitrogen cycling with catchment models of nitrogen export are needed to advance our understanding of nitrogen cycling. Such an understanding is a prerequisite to developing the watershed-based planning needed for optimal management of the nitrogen and other biogeochemical cycles of human interest.

Two contributions suggest that river restoration and water management offer exciting topics for synthesis. Palmer and Bernhardt [2006] describe the evolution of river restoration from a purely hydraulic engineering approach to a hydroecological approach, which considers aspects such as biodiversity and ecological process restoration as key objectives in the restoration process. These authors call for integration across geomorphology, ecology, engineering, and hydrology to address science questions associated with river restoration. Palmer and Bernhardt identify seven compelling research topics that they believe are most critical for river restoration, including evaluating the ecological effectiveness of past restoration efforts, urban stream restoration, designing or developing ecosystems that can optimize services such as denitrification and sediment removal, and the intersection of restoration science and social science for improving restoration process and decision making. In a paper that focuses on flood control and urban water management examples, Potter [2006] explains how smaller-scale, spatially distributed management practices can be designed to exploit or enhance natural systems. This author argues that small-scale, spatially distributed water management practices, such as treatment wetlands or infiltration practices, can be more efficient and can result in less environmental impact than conventional, centralized systems. Potter urges the scientific community to develop better methods for collecting data and better operational hydrological models for evaluating scenarios over a range of conditions and scales. Both Palmer and Bernhardt's and Potter's papers describe how critical improved communication between scientists, practitioners, and decision makers is for guiding river restoration or water management.

Knopman [2006] expands on this theme by describing how critical it is to develop a scientific basis for interactions between scientists and decision makers. This author argues that, where appropriate, scientists should engage in decision-making activities during the research process, rather than first focusing on understanding or predicting processes and subsequently informing decision makers after completion of the research. Knopman suggests that the synthesis of scientific studies with the psychology of decision making (known as "judgment and decision making") will ultimately increase the impact of scientific investigations for guiding complex, long-term environmental problems (such as climate change, nuclear waste storage, or water management). Knopman further suggests that with early inclusion, scientific experiments and decision-making tools can be designed that will optimally guide the choices about the level of complexity that is required for the decision-making process.

Paola et al. [2006] call for the scientific community to work together toward the grand goal of developing a unified surface process science that synthesizes insights from hydrology, geomorphology, ocean and atmospheric sciences, biology, geology, and ecology to enable the understanding and ultimately the prediction of Earth surface processes. They describe several potential synthesis topics that would require a comprehensive understanding of coupled processes, including stream restoration, the impact of climate change on streamflow and sediment flux, and the linkages between surface dynamics and subsurface stratigraphy in active depositional systems. They propose that investigation of channel networks offers a logical starting point for surface process sciences, because these networks drain most of the continental surface, organize how water and sediment are transported and how vegetation grows, and have similar patterns across a variety of environments and spatial scales. Paola et al. discuss four areas that are ripe for integrative research, including improving our understanding of channel networks across environments and scales, relating channel morphology to the spatial organization and scaling of floods and vegetation, developing improved predictive capabilities, and advancing new observational techniques for studying
Earth surface processes. Paola et al. suggest that a fully realized science of Earth surface dynamics would facilitate the synthesis of many disciplines and problems.

These contributions illustrate that the challenge to deal effectively with complex water problems is not purely a scientific problem, a political problem, a technological problem, a computer science problem, nor a socioeconomic problem. It is a complex, 21st century problem that demands collaborative coordination between many disciplines via focused and coordinated synthesis. These papers further suggest that the scientific community has a very important role to play in the synthesis of tools, data, concepts, theories, and approaches that are needed to advance our understanding of our natural system and to effectively guide management of water resources and ecosystems. Through this special section, we hope to open a dialogue with the community about synthesis and to stimulate the community to provide their own perspectives and opinions about compelling synthesis topics as well as to provide feedback to the synthesis topics suggested here via Water Resources Research “Opinion” articles.

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