EDITORIAL

A grand challenge for freshwater research: understanding the global water system

Joseph M Alcamo
Charles J Vörösmarty
Robert J Naiman
Dennis P Lettenmaier
Claudia Pahl-Wostl

The authors make up the Executive Committee of the Global Water System Project (GWSP) of the Earth System Science Partnership and were members of the GWSP Framing Committee.

1. Introduction

A major shift in thinking about fresh water is taking place in science and policy circles, prompted by progress in arenas as disparate as earth science, climate policy, watershed management, and world economic integration [1]. Building on the legacy of more than a century of fundamentally local-scale hydrologic research, scientists and policy makers are poised to more clearly articulate the role of water in a broader earth system context [2]. Discovery of new pathways, thresholds and surprises in the character of the hydrosphere [2] shows that it is inadequate to focus solely on local processes, as there is a serious risk of overlooking important global dynamics with large and possibly irreversible impacts on society and nature.

Indeed, sustaining people and ecosystems requires a novel viewpoint of the earth’s water cycle—that of an interacting global water system—defined as a confederation of major players: physical processes in the traditional ‘water cycle’; biological and biogeochemical processes supported by biodiversity; and human-mediated processes associated with water management and governance with strong links to the global economy. Here we put forward the notion of a fully-integrated global water system. We present a rationale, opportunities for progress, and key strategic challenges for the next decade of interdisciplinary freshwater research.

2. Universal changes

There is a pandemic array of changes taking place in the terrestrial part of the water cycle. These changes are not isolated, but are part of universal transformations in the global water system. Among the changes are:

- Universal changes in the physical characteristics of freshwater systems including long-term changes in surface and subsurface moisture storage and runoff, and persistent changes in precipitation and hydrologic patterns. Researchers generally have a poor understanding of both the global scale manifestation of local mechanisms [2] and the intensity of changes in different regions [3, 4].

- Universal changes in the chemistry and biology of freshwater systems including long term alterations of the flux of nutrients and sediments to the oceans, and levels of key water quality and habitat parameters [5]. Freshwater systems have been physically modified and over-utilized to the extent that worldwide habitat for aquatic organisms has been greatly reduced [6, 7] with severe consequences for aquatic ecosystems [8, 9]. Conservatively, >20% of the world’s freshwater fishes have become extinct, endangered, or threatened in recent decades [7]. While surface water quality has improved in some
industrialized regions, it has and will continue to deteriorate in most developing regions and where industrialization is rapid [10]. For example, a range of scenarios points to a factor of four- to eight-fold increases in wastewater loadings within the next four decades over most of Africa [11]. One can easily imagine the effects of deteriorating water quality on aquatic ecosystems and freshwater fisheries which remain an important protein source for poor people. These and other trends will be difficult to track because of inadequate monitoring of the state of aquatic ecosystems throughout most of the world [12].

- Universal changes in anthropogenic water use and withdrawals including rapidly changing patterns of water use in different economic sectors and regions. Industrialized countries show a declining trend in water withdrawals, while developing countries show sharp increases [13, 14]. These trends are causing dramatic changes in patterns of water stress [3] with uncertain global implications. Only now have scientists begun to analyze the underlying causes of global changes in water use (e.g. changes in population, income, technology and consumption patterns) [14] and their implications for human health and economic growth [15]. Will lower withdrawals restore or sustain a good ecological state of aquatic ecosystems, or will climate change, physical modifications of waterways, and other factors confound these benefits? How will increasing water use in developing countries affect large scale patterns of water quality in these countries?

3. Large scale connectivities and systemic change

Apart from universal changes, a vast web of long-distance connectivities or ‘teleconnections’ (with spatial scales of hundreds to thousands of kilometres) plays an important role in water systems. These connectivities are physical, biogeochemical, ecological, economic and institutional in character, and are catalyzing systemic changes in the global water system.

The concept of physical teleconnections has proven useful for better understanding the climate system [2] and can now be used to describe large-scale linkages in the global water system. These include: the impact of upstream storage on residence time of surface waters [16], the effect of water engineering and land use changes on river sediment characteristics/loading [17], and the coupling between changes in land use and regional climate [2]. Biogeochemical and ecological teleconnections include, for example, the role of water as a transport medium in the global cycling of carbon and nutrients. One consequence of these teleconnections is that rivers are effective carriers of excess nutrients to coastal zones, leading to disruption of coastal ecosystems and sometimes the formation of biological dead zones [18].

Economic factors also cause spatial connectivities. A new viewpoint is that water circulates in the global economic system as an embedded ingredient (‘virtual water’) of food and other internationally-traded products. The idea is that arid countries compensate for water deficits by importing water-intensive commodities rather than domestically producing them. This is significant because it implies that a large global flux of water is mediated exclusively by society [19] and that important international water dependencies are being overlooked [1].

Institutions can also play a role in producing connectivities. For instance, social scientists are beginning to document the far-reaching impact of decisions made by

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1 A teleconnection is a cause-and-effect chain that operates through several intermediate steps and leads to a linkage between two parts of a system that—to researchers at least—is unexpected or surprising.

2 A well known example of a physical teleconnection is the impact of deforestation in the Loess Plateau of China on the discharge of the Huang Ho River hundreds of kilometres downstream (increasing sediment load, elevated riverbed, and more frequent downstream flooding).
a few major organizations on world water resources. Centralized decisions about water pricing or trading of water technology can set off a chain of actions having significant worldwide effects on water withdrawals and the state of water resources [20, 21].

While these connectivities are beginning to be recognized, science has hardly begun to evaluate their implications. Furthermore, new connectivities are expected to emerge from growing worldwide economic integration. A grand challenge for science is to develop a means to identify large scale linkages in advance so that their negative impacts can be avoided, mitigated, or contained.

4. Vulnerability in the global water system

A likely consequence of universal changes and global connectivities in the freshwater system is increasing vulnerability of ecosystems and society. While major efforts have been devoted to evaluating these vulnerabilities on the local to river basin scale [22, 23, 24, 25] comparatively little effort has been invested in global scale vulnerability research, apart from studies of climate change impacts on water resources [1].

A major effort to assess vulnerability of aquatic ecosystems is embedded in the concept of ‘environmental flows’: the quality and quantity of water necessary to protect aquatic ecosystems and their dependent species and processes [26, 27, 28, 29]. It is essential to identify environmental flows in order to ensure ecologically sustainable development of water resources. However, water requirements of aquatic ecosystems have never been estimated globally. Since there are over 200 methods for assessing environmental water allocations [30], a major challenge is to evaluate their relative merits and provide regionally-relevant, hydro-ecological models [31, 32]. Likewise, these environmental requirements have not been globally compared to the water required to provide ‘goods and services’ to society such as water supply for municipalities, electrical production, manufacturing and irrigation [1]. A key task for researchers is to identify where hot spots of competition for water will occur and how they can be minimized.

While great effort has been devoted to studying local-to-regional scale vulnerabilities, hardly any attention has been given to new vulnerabilities arising from large scale changes and connectivities in the global water system. For example, a continuation or intensification of river transport of nutrients into the coastal zone could produce more coastal ‘dead zones’ and intensify risks to future fish production [33]. Another example stems from the strong economic connectivities in the global water system. Global water companies claim a steadily larger share of local water markets, and this may lead to a decrease in the variety of available products and services, thereby reducing the number of culturally-distinct management approaches [1]. Urgent questions include: in which regions, economic sectors and social groups worldwide will vulnerabilities arise? How will vulnerabilities be manifested in cultures and ecosystems?

An important issue is society’s capacity to adapt to undesirable changes in the water system. Although good water governance is known to increase society’s adaptive capacity [34], research on global-scale governance issues is almost entirely lacking [1]. There are many open questions in this area: is it feasible or desirable to manage water on the global scale? What is the practicability of applying institutional models such as river basin compacts to the global scale? What could be the role of new institutional models such as ‘global dialogues’? What will lead to greater resilience in the global water system—a worldwide, uniform approach to water governance, or a diversity of regional approaches?

3 As examples of new institutions see the discussion of institutionalizing groundwater resources in [35] and the results of a ‘global dialogue on water and climate’ in [36].
5. Making the global water system relevant

A major remobilization of the water sciences and policy communities is indeed gaining ground. But the direction forward in the study of global water is unclear, at least compared to the global climate change issue, with its dedicated international ‘Conference of Parties’ and supporting machinery of the Intergovernmental Panel on Climate Change (IPCC). Furthermore, as evident from the numerous and sometimes conflicting interests involved in the World Water Forum process\(^4\) it will not be easy to find a common agenda for global water research and policy.

One way forward is suggested by the Millennium Development Goals (MDGs) which have successfully mobilized the global development community\(^5\). Freshwater issues are embedded in nearly all of the MDGs and good water stewardship will be fundamental to their success. One well-publicized interim target is to halve the proportion of people without sustainable access to safe drinking water by 2015 relative to the mid-1990’s. We also believe it is valuable to set concrete, time-anchored targets for water research and policy engagement. The following grand challenges can contribute to this end:

1. Identify the role of humans in the continental water cycle through new interdisciplinary perspectives. **Target:** Develop global assessment capabilities (integrated data sets, models, and information technology) on a par with current IPCC assessment activities by 2015.
2. Provide strategic information to monitor progress towards water-related MDG’s. **Target:** Create a repository of free and universally available earth system science data sets and modeling products for spatially and temporally contiguous global water resource assessment by 2010.
3. Substantially reduce the vulnerability of the world’s population to hazardous floods and droughts. **Target:** Set in place by 2015 a global early warning system for floods and droughts covering 90% of the earth’s population that consolidates environmental monitoring, climate prediction, and watershed modeling efforts.
4. Undertake a comprehensive freshwater biodiversity initiative to benchmark loss of species and associated goods and services. **Target:** Categorically survey freshwaters in 50% of the terrestrial area of the earth by 2015.
5. Provide the technical tools needed for reconciling competing water uses (household, municipal, food production, industry, aquatic ecosystems) in watersheds world-wide. **Target:** Provide by 2015 a world-wide, accessible, usable and affordable data base and technical tool kit for integrated water management applicable to 90% of the watersheds throughout the world.
6. Cut the rapid loss of local knowledge about water resource systems. **Target:** Establish by 2010 a Global Water Heritage Library to preserve disappearing indigenous knowledge about world water resources.
7. Educate a new generation of water scientists with integrated perspectives on water science and management. **Target:** Triple the number of water system scientists in the developing world by 2015 through nationally- and internationally-supported training programs.

Pursuing these challenges will establish a rich domain for scientific studies exploring new teleconnections and system-relevant changes, improving forecasting of human and ecosystem vulnerabilities, and helping to make clear the tradeoffs between different uses of the global water system. At the same time,

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\(^4\) The Forum encompasses numerous water-related organizations, including national and international governmental agencies and scientific organizations, non-governmental advocacy groups and private firms and corporations. For a description of World Water Forum 4 2006 in Mexico City see: [http://www.worldwaterforum4.org.mx/home/home.asp](http://www.worldwaterforum4.org.mx/home/home.asp).

\(^5\) Descriptions of the UN Millennium Development Goals are available at: [http://www.un.org/millenniumgoals/](http://www.un.org/millenniumgoals/).
water policy and management experts—accustomed to knowledge generated at local scales—will soon have a new context to judge the effectiveness of their decisions. Now is the right moment, for both research and management, to embrace a global perspective on water.

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