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Water in the anthropocene: New perspectives for global sustainability☆

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Humans are changing the global water system in a globally-significant way without adequate knowledge of the system and thus its response to change. So read the central tenet of the *Global Water System Project (GWSP)*, proposed by its founders back in 2004 [1,2]. It was hardly an accepted notion. Before year 2000, global-scale water studies based on modern data sets and modeling frameworks that explicitly combined the geophysics of water with its human dimensions were still in their infancy, and the scientific underpinnings for such a statement had yet to be articulated. The statement, at best, could reasonably be called an educated best-guess or some might argue more of a ''hunch''. At that time, world water assessments prepared by the U.N. [3] or as revealed in now-classic Russian monographs [4,5] relied on highly aggregated national if not regional indicators to define the state of the system and failed to appreciate many of its rich spatial and temporal details that were uncovered only over the last 10–15 years.

The turn of the century brought transformative developments as well as momentum to the global water research agenda. Among these, community-based exercises like the *World Water Vision* process dating to the 2nd *World Water Forum* in the Hague in 2000 [6], and amplified by key publications [*listed throughout this special issue*], began to forge a new path forward. Yet, even as late as 2001, when current *GWSP* co-Chair Claudia Pahl-Wostl organized a session on global water issues at the first *Open Science Conference* on *Challenges of a Changing Earth* (organized by the four *Global Environmental Change [GEC] Programmes*) in Amsterdam, the value of a fully global perspective within the water research or policy arena was highly contested and misconstrued. One discussion panel member went so far as to ridicule the idea of global governance by asking whether this simply meant shipping icebergs around the planet. In contrast, the many full-fledged global assessments presented at the May 2013 *GWSP*-organized *Bonn Conference* on *Water in the Anthropocene: Challenges for Science and Practice* shows a high level of comfort within the water sciences community for presenting a broad-scale frame of reference. The absence of global visions of water in year 2000 was rapidly filled by a large and rapidly expanding portfolio of data sets and models, and new ways of thinking — many catalyzed by GWSP itself, but certainly not exclusively, and collaboratively with many international partnership programs.

This special issue is only the second in *Current Opinion in Environmental Sustainability* that focuses more or less exclusively on fresh water (Vol. 3, #6 on aquatic systems), but is the first to take as its organizing principal the unique role that humans play in shaping the character of water systems, both today and into the future. In contrast, there have been many articles and special issues devoted to energy systems, terrestrial ecosystems, human settlement and industrialization, carbon and nitrogen cycling and, of course, climate change.

Given water's central role in linking these conceptual domains, one can observe a correspondingly large number of references to the importance of water in the mechanics of the modern Earth system. We see the papers presented here, however, to constitute a unique collection, as they explicitly embed and co-balance diverse interdisciplinary perspectives on water in the context of global change, from biogeophysics to socioeconomics to governance.

This special issue represents one of the chief products to emerge from the *Water in the Anthropocene Conference*, which brought together over 350 scientists, scholars, practitioners and policy makers, who for nearly a week presented the newest in interdisciplinary water research organized around more than 20 different themes. The associated in-depth discussions further helped to benchmark the current state-of-the-art in global water science, and provided foundational material for the *Bonn Declaration on Global Water Security*, which was adopted by consensus at the close of the *Conference*. The event, marking the 10-year anniversary of the *Project*, seemed a propitious moment to assemble the water research community, to take stock of progress over the decade, and to identify new arenas of research that could ultimately prove to be of practical value to the global development agenda.

Given the many rapid developments in research and new lines of thinking that led to a science of global water systems, the need for an organizing framework is apparent. To this end, we present this special issue as a collection of papers treating three major themes, the same as those used to structure the *Bonn Conference*. These themes also represent the elements of a conceptual reorganization of the *GWSP* that took place during its mid-phase (ca. 2007–08): first, *Global Water System — Current State and Future Challenges*; second, *Global Dimensions of Change in River Basins*; and, third, *Balancing Water Needs for Humans and Nature*.

The theme-based contributions are sandwiched between first a stage-setting and later a capstone paper. In the spirit of synthesizing the one-to-two decades of research leading to the current state-of-the-science, and immediately following this editorial, a lead-off paper by Vörösmarty, Pahl-Wostl and colleagues entitled *Global Water, the Anthropocene and the Transformation of a Science* charts some of the significant developments that helped to craft a global freshwater research agenda, tracing the role of the *GEC Programmes* in general and *GWSP* in particular in contributing to the paradigm shift. This provides a historical backdrop, of sorts, to the detailed thematic assessments that follow.

After the collection of thematic papers, the special issue moves to a prospective stance, through a forward-looking synthesis by Pahl-Wostl, Vörösmarty and colleagues, who address water security from the dual perspective of human water security (conflict, economy, politics, health, habitability, resilience) and natural system security (ecosystem services, biodiversity protection). This paper also provides a synoptic blueprint for a *Sustainable Water Future* initiative, arguing for the necessity of a strong water programme during the next decade of global change research. The final paper proposes a global water research agenda focused not only on basic research but also on solutions through the co-production of knowledge. This partnership, of necessity, must involve scientists and stakeholders who together drive a reality-based, multi-perspective, and multi-scale knowledge-to action agenda on water. We propose a solutions-oriented research agenda, as an antidote to the otherwise sluggish flow of evidence-based knowledge from the water sciences to policy formulation to applications [7]. Without integrated paradigms to effectively bridge the science-policy divide, it is difficult to envision how highly interconnected and rapidly changing 21st century water systems could be managed sustainably.

A total of 19 thematic papers are presented. Emphasizing the cross-disciplinary nature of the issue at hand, each of the theme headings introduces a grouping of papers that cover not only the biogeophysical elements of water science but also new research into the human dimensions of water including its governance over the broadest of spatial domains. To maintain a coherency of purpose, contributing authors were asked to address three questions:

1. *What are the new knowledge and perspectives developed over the last decade with respect to the global state of water resources and water governance? What are the key new ideas and insights and how are these different than at the turn of the century?*
2. *How did the global water community contribute to this new thinking?*
3. *How well does the new thinking prepare us for future studies on water and its role in society and the Earth system?*

Armed with this guidance, the author teams went forward to produce their manuscripts. We believe that each thematic set of papers can stand on its own, and thought of as a smaller, more focused special issue. A brief synopsis of papers presented under each major theme follows.

Theme 1: ***Global Water System — Current State and Future Challenges***. A collection of six articles is offered. By their very nature they are focused on global-scale studies of the hydrologic components of the Earth system. They cast a wide net conceptually, working from the capabilities of state-of-the-art-models of the water system (Gerten *et al.*, Cosgrove *et al.*) to biogeochemistry (Kroeze *et al.*) to human decision-making (Gupta *et al.*). Two papers seek to enrich and clarify the planetary boundary debate [8], specifically linked to water (Bogardi *et al.*, Gerten *et al.*). A design for integrated world water scenarios (Cosgrove *et al.*) as part of a new visioning process to assess the

state of the global water resource base is also offered. A review article (Thorsteinsson *et al.*) explaining the linkages between the loss of ice and the critical importance of this phase-change to humankind rounds out this theme. Together, these papers discuss assessments of global water resource availability, the application of earth observations and the role of indicators, data and models, and multi-level governance of the global water system.

Theme 2. ***Global Dimensions of Change in River Basins.*** Seven articles are presented under this theme. These papers are motivated by new research on adaptive resource management for water security in river basins (Allan *et al.*), large-scale redistribution of water stress through international trade and minimizing water footprints (Yang *et al.*), and two papers on the water-energy-food (or land) nexus (Ringler *et al.*, Lawford *et al.*). Yang *et al.* provide an outlook and future prospects for *virtual water* and *water footprint* research in the context of globalization of the economy and greater inter-sectoral dependencies and connectedness. Lawford *et al.* summarize regional aspects of the water-energy-food nexus and explore how the approach is perceived in different river basins. Ringler *et al.* argue how nexus assessments can help to co-balance tradeoffs between human well-being and environmental outcomes, and how meeting the *Sustainable Development Goals (SDGs)* associated with the Rio+20 development agenda could become a litmus test for successful implementation of the nexus approach. The paper by Allan *et al.* demonstrates how achieving water security through a nexus approach can be addressed by adaptive, flexible and reflective approaches in light of socio-ecological complexity. While earth observation systems, including those broadly available from satellites, afford fully global perspectives, many such technical resources are also ideally suited for application at regional, basin, and subordinate scales. This subject is discussed in a paper by Lawford *et al.*, who review some of these capabilities and discuss the political ramifications of the resulting data transparency. A well-known concept in basin scale studies is the transfer of upstream impacts (e.g., from pollutant loading or poor land management) to downstream domains within the basin. In Renaud *et al.*, we find a review of work that has recently placed the vulnerability of coastal deltas on a much more comprehensive global change roadmap, not as solely a sea level rise or coastal storm surge question but also as a freshwater resource and land management challenge originating in upland contributing basins. Ngcobo *et al.* analyze vulnerabilities, responses and opportunities related to broader global change issues, but from a southern African perspective. They hold that global change reveals itself as impacts on water resources, but the nature of its influence is generated by multi-scale (i.e., global, regional and local) factors. The paper concludes with a strong plea for technical and institutional innovation to support integrated and adaptive water management.

Theme 3. ***Balancing Water Needs for Humans and Nature.*** Contributions to this theme explicitly recognize developments in the knowledge base that have demonstrated the essential needs for water by aquatic ecosystems, and the life contained within them, viewed by many as a legitimate ''user'' of water, just like human society. Poff *et al.* present a history of conceptual developments in this realm, from predominantly the ecologist's standpoint. Its complement is a water security paper (Pahl-Wostl *et al.*), exploring this concept from a governance perspective, with discussion on the requirements for governance reform to best manage sustainable water uses to cover environmental as well as human water needs. Also included is a paper by Foster *et al.* on the unique interactions of groundwater with surface water dynamics, which in turn bear important implications on aquatic ecosystems. The ecosystem services concept itself is explored in terms of its capacity to frame and help solve global water problems, and to identify and mitigate tradeoffs between different management options. (Engel and Schäfer).

Taken together, the *Conference* program [9] and papers [10], *Bonn Declaration*, this *Special Issue* and a decade of *GWSP* activities show that, beyond any reasonable doubt, direct human actions involving the planet's water systems are increasingly debilitating the very environmental systems on which humankind must rely for an essential strategic resource — fresh water. Local-scale water management decisions accumulate as global syndromes and arguably will continue to predominate over climate change in defining future patterns of water scarcity, at least over the next several decades. This is both bad news and good news. Of course, continued impairment that adds to the mounting water crisis is bad news, but these problems also provide opportunity space for innovative solutions that can be applied directly to the problems at hand, quite a different story than if we had to manage water solely through the lens of climate change mitigation, which seems an increasingly remote possibility due to the absence of international consensus, entrenched contrarians and ferocious political battles. While advances have been made in the biogeophysical dimensions of emerging water system problems, knowledge-to-action has been far less well-articulated and we can reasonably ask the question: *Are the available scientific tools and knowledge base sufficient to address imminent water problems, simultaneously conveying water security and well-being to humankind while attenuating threats to biodiversity, both now and in the future?* Probably not, as pandemic impairment of water systems is *prima facie* evidence that we lack either the knowledge or political willpower to act. We also conclude, then, that a paradigm shift is urgently needed to move us from discourse and academic study to action.

Given its focus on change and the centrality of humankind to water sustainability, the intellectual niche

occupied by the *Global Water System Project* proved to be unique and as necessary as ever we struggle to keep up with the proliferation of changes associated with the anthropocene. Perceptions have now changed and the importance of a global response to global challenges in the water sector has increasingly been recognized as legitimate. A global response may embody elements ranging from U.N. conventions to international economic trade, but requires critical assessment and the design of creative solutions. In this context, water research becomes increasingly pivotal as we look toward producing a knowledge base that can tangibly support the policy-making process associated, for example, with the Rio+20 development agenda.

While it may be intellectually satisfying to recognize that an interdisciplinary focus on water is the correct way to approach assessments of the global resource state, its trajectories of change, and sensible management strategies, the many interwoven issues make it difficult to translate our findings into meaningful objectives for the sustainable development agenda. Our capacity to meaningfully influence the *Sustainable Development Goals* [11] for water, which we recognize must necessarily consider issues as diverse as water quantity, quality, ecosystem integrity, biodiversity protection, engineering technologies, social norms and dynamics, plus economics remains an open but critically important question. These broad strategic issues infuse themselves within the many papers of this *Special Issue*, and we view the contributions as a collective statement to the decision-making community. The cautionary message: *Humans are changing the global water system in a globally-significant way without adequate knowledge of the system and thus its response to change*.

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