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Humans Transforming the Global Water System

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Fresh water figures prominently in the machinery of the Earth system and is key to understanding the full scope of global change. Greenhouse warming with a potentially accelerated hydrologic cycle is already a well-articulated science issue, with strong policy implications. A broad array of other anthropogenic factors—widespread land cover change, engineering of river channels, irrigation and other consumptive losses, aquatic habitat disappearance, and pollution—also influences the water system in direct and important ways. A rich history of site-specific research demonstrates the clear impact of such factors on local environments. Evidence now shows that humans are rapidly intervening in the basic character of the water cycle over much broader domains. The collective significance of these many transformations on both the Earth system and human society remains fundamentally unknown [*Framing Committee of the GWSP*, 2004].

The Notion of a Global Water System

Diminutive by ocean standards and representing but a small fraction of the planet's hydrosphere (< 3% of total volume [*Shiklomanov and Rodda*, 2003]), fresh water nonetheless serves as an essential building block of the Earth system. Fresh water is intertwined with energy exchange, atmospheric teleconnections, and feedbacks linking the climate system. Water movement constitutes the largest flow of any material through the biosphere, and serves as the primary vehicle for erosion and dissolution of the continents. The importance of fresh water, which strongly regulates productivity and supports ecosystems and biodiversity, is evident throughout the biosphere.

Fresh water is also critical to human society. It underpins global food production by providing the fundamental resource upon which irrigation, livestock production, fisheries, and aquaculture depend. Domestic, industrial, hydropower, and recreational water use is crucial to a large and growing population that aspires to long-term improvements in well-being. Providing basic sanitation and clean drinking water services remains a major public health challenge. More than 1 billion people are without access to clean drinking water, 2.5 billion are without sanitation, and over 5,000 people, mostly children, die each day from water-related diarrheal diseases [*World Water Assessment Programme*, 2003].

Key manifestations of variability in the terrestrial water cycle continue to shape human history and are a costly source of vulnerability. In the United States, annual drought damage averages $6 billion, with the 1988 drought alone costing over $60 billion in 2002 dollars [*Ross and Lott*, 2003]. Annual damages from flooding and other extreme weather involving the global water cycle are even more costly. Initial estimates in press reports put losses from the 2004 hurricane season in the tens of billions of dollars.

In the context of water's many roles in the Earth system, the concept of a Global Water System (GWS) provides a useful organizing framework. The GWS is defined by a series of interacting components (Figure 1): (1) water in all its forms, as part of the physical hydrologic cycle; (2) biological systems, as integral transformers of water and constituent fluxes that determine biogeochemical cycling and water quality; and (3) human beings and their institutions, as agents of environmental change, and as entities that experience and respond to ongoing transformations of the GWS.

A systematic assessment of how each of these components and their interactions define the evolving state of the GWS is a fundamental challenge confronting the Earth and human-dimensions science communities.

The Global Water System Project

A new international research effort constituted as an Earth System Science Partnership (ESSP) project of the Global Environmental Change Programmes (DIVERSITAS, International Geosphere-Biosphere Programme [IGBP], International Human Dimensions Programme on Global Environmental Change [IHDP], and World Climate Research Programme [WCRP]) has been launched to study these complex issues. The primary aim of the Global Water System Project (GWSP) is to promote improved understanding of fresh water in the Earth system through integrated study of its interactions, feedbacks, and thresholds. The GWSP science agenda emerged from a broad consensus of the water science and assessment community, with more than 200 contributors to interdisciplinary planning meetings starting in 2002, science planning documents, and a recent Open Science Conference (October 2003; Portsmouth, New Hampshire). A peer-reviewed framework and implementation plan consolidates these deliberations [*Framing Committee of the GWSP*, 2004]. This article presents the scientific rationale for the GWSP, the project's key research questions, and an emerging agenda for the decade-long effort.

In the crowded landscape of acronyms representing projects, programs, and institutions that deal with water, a strong justification must accompany any new international initiative. Several characteristics distinguish the GWSP from other international water-related programs. The GWSP is designed to be the following:

(1) *Science driven but policy-informing*. GWSP considers fundamental questions about water and global change. Owing to the central role of water in human society, the questions bear high relevance to environmental management and sustainable development.

(2) *Global in its perspective*. GWSP will help determine the importance of pandemic local changes to the hydrologic cycle on the behavior of the Global Water System as a whole. While new world water models and databases are envisioned, the project will draw heavily from a rich history of case studies and regional analysis.

(3) *Integrative and interdisciplinary*. From its inception, GWSP has sought to unite socio-economic, physical, and ecological perspectives.

(4) *Multitemporal*. GWSP focuses on a century time frame starting in the mid-20th century, a time of rapid change and growing human influence on many of the planet's physical and biogeochemical cycles. For broader context, it will draw on historical and paleo perspectives and scenario-based visions of the future.

Global Change and the Global Water System

The freshwater cycle is under rapid transformation (Figure 1). Climate change has clear ramifications for global hydrology, with major concerns surrounding the links of progressive

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greenhouse warming to extreme weather and reduced reliability of water resources.

But several other factors, until recently largely ignored, are proving to be globally significant as well (Table 1). These involve a great variety of direct anthropogenic activities, many operating at highly local scales. Tabulations made possible by improvements in remote sensing, GIS, data assimilation, and synthesis show that many impacts are now detectable over continental-to-global domains as well [*Framing Committee of the GWSP*, 2004].

A recent synthesis [*Meybeck and Vörösmarty*, 2004] goes further, suggesting that the global impact of direct human intervention in the terrestrial water cycle (through land cover change, urbanization, industrialization, and water resources development) is likely to surpass that of recent or anticipated climate change, at least over decadal time scales.

Water resource engineering provides a good example of the scope and rapid transformation of the GWS. Discharge in many rivers has been heavily altered (Figure 2), with the aim of stabilizing or redirecting flows to optimize water supply. Such hydraulic manipulation includes major surface water diversions and groundwater abstraction for irrigation (70% of global use [*Shiklomanov and Rodda*, 2003]), impoundment (45,000 large dams [*World Commission on Dams*, 2000]), channel dredging, river "training," and wetland drainage.

Many basins have been dramatically transformed, with some of the world's largest rivers showing a complete or nearly complete loss of perennial discharge to the ocean (e.g., the Colorado, Yellow, and Nile Rivers). Global manifestations include a doubling-to-tripling of the residence time of continental runoff in otherwise free-flowing rivers, a 600–700% increase in fresh water stored in channels, and a 30% decrease in global suspended sediment delivery to the oceans [*Vörösmarty et al.*, 2003]. Dam construction has resulted in a worldwide pattern of habitat fragmentation that threatens the biodiversity, structure, and function of aquatic ecosystems [*Revenga et al.*, 2000].

Given that the vast majority of such changes have occurred over the last half-century, by any measure of global change, these are arguably among the most rapid and substantial. Understanding the global consequence of this diverse array of changes will require coordinated, interdisciplinary study.

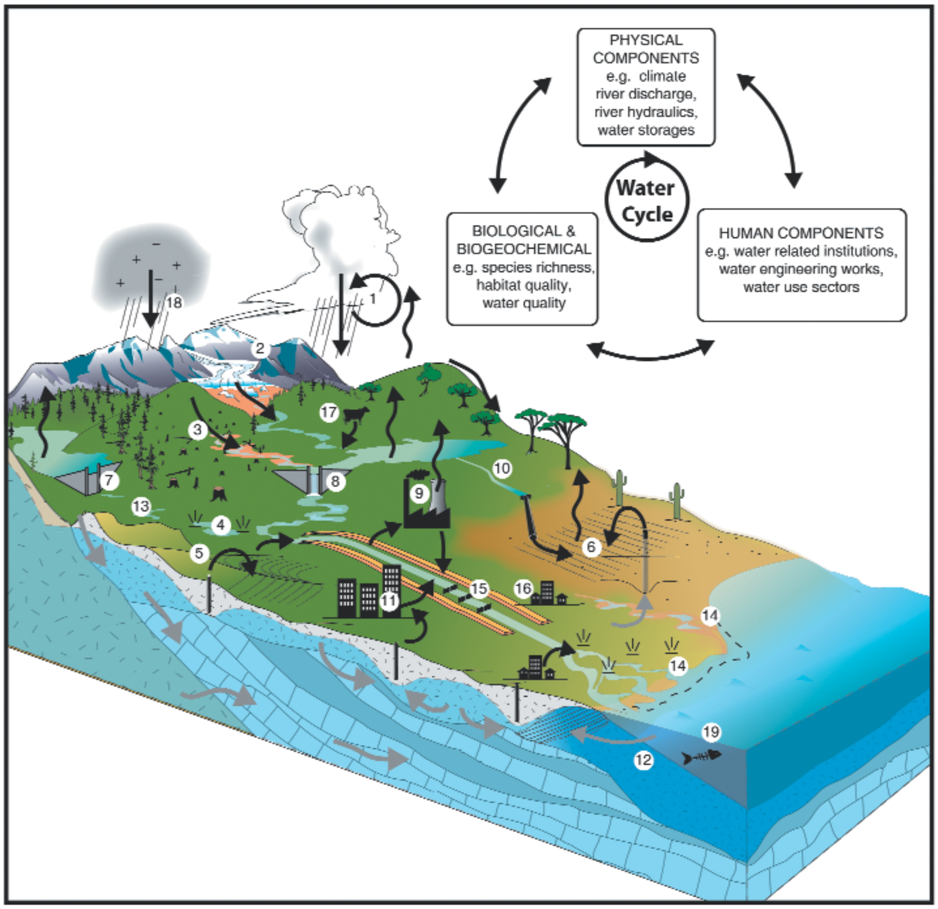

Fig. 1. The Global Water System under natural conditions is a complex amalgam of pools and dynamics, linked through complex interactions defined by the physics, biogeochemistry, and biology of the planet. In populated regions of the world, these systems have been transformed dramatically through direct and indirect human interventions in the water cycle. Understanding these complex transformations requires an integrated, interdisciplinary perspective that considers humans as an important and interactive part of the Global Water System. See Table 1 for description of numerical entries.

GWSP Science Questions

With continuing population growth and rising standards of living, transformations to the GWS will be inevitable. An important issue surrounds whether these now-worldwide changes are simply a collection of many local alterations or if they elicit synergisms that modify overall behavior of the GWS. The issue is central to our understanding of global change and water resources, as humans are likely to expand their control of this important resource well into the future [*Shiklomanov and Rodda*, 2003].

The central tenet of the GWSP is that human-induced changes to the water system are now global in extent, yet we lack an adequate understanding of how the overall system works, how it responds to change, and how society can best adapt to rapidly-evolving and potentially new system states. The GWSP is organized to address this assertion in a systematic and unified manner. A special issue of *Aquatic Sciences* [*Pahl-Wostl et al.*, 2002] highlights our collective capacity for pursuing this broad objective, which must unite social science, water resource management, and biogeophysical perspectives in order to achieve success.

From this vantage point, the GWS can be viewed as a unified system, with equal attention needing to be paid to its physical, chemical, biological, and anthropogenic components.

The GWSP also needs to define how humans are transforming this water system beyond greenhouse warming alone, and to determine if the accumulated impact of a much broader set of human-derived changes has moved the GWS outside the range of natural variability to a nonanalogue state. Like other components of the Earth system, the GWS could also have significant linkages, feedbacks, and thresholds that are yet to be discovered. A modified hydrologic cycle could lead to abrupt change and surprises, such as a potential shutdown of North Atlantic deep water formation and ocean circulation arising from changes in Eurasian river discharge, or the emergence of anoxic dead zones near the mouths of rivers heavily polluted by upstream agriculture and urbanization [*Framing Committee of the GWSP*, 2004].

The GWSP is supported by three framing questions, which form its thematic structure:

Question 1: What are the magnitudes of anthropogenic and environmental changes in the GWS, and what are the key mechanisms by which they are induced? This question is dedicated to first quantifying the principal indicators of change to the global hydrologic cycle and then assigning causality. In general, the mechanisms by which changes have occurred in the physical components of the GWS are better understood than in its biogeochemical and biological dimensions. A major challenge is to identify the unique role of human versus natural sources of variability and change.

Question 2: What are the main linkages and feedbacks within the Earth system arising from a changing GWS? Knowledge from Question 1 will formally be linked to synthesis studies aimed at uncovering interactions among GWS components, their sensitivities, and responses to change. A major goal of the GWSP is to improve our understanding of the co-evolution of human-technology-environment systems across scales, and to identify major teleconnections, nonlinearities, and thresholds.

Question 3: How resilient and adaptable is the GWS to change, and what are sustainable management strategies? If the hypothesized importance of humans on the global water stage is confirmed, water resource management, which traditionally has been cast at more local or regional scales, will move into the domain of global climate change, chlorofluorocarbon (CFC) regulation, and other pressing international policy concerns. The GWSP will catalyze a dialogue around this issue by focusing on (1) the capacity of the GWS to maintain its important services to humans in the face of global change (resilience) and (2) its propensity to evolve (adaptability). The allied issue of societal and ecosystem vulnerability will also be addressed.

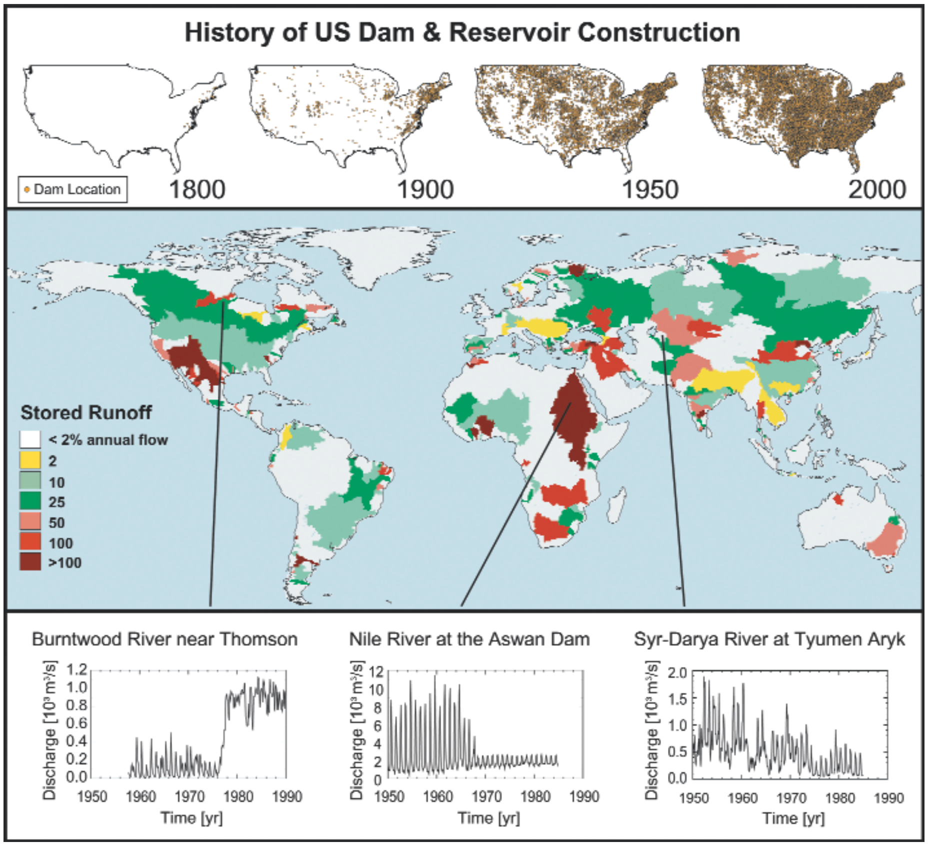

Fig. 2. Hydraulic engineering to ensure reliable water supply is now a worldwide phenomenon and central feature of the Global Water System. (top) In the United States and industrialized parts of the world, river regulation expanded rapidly during the 20th century, with much of the developing world awaiting such growth. (middle) Globally, engineered impoundments store on the order of 20–25% of continental runoff. (bottom) Water management has greatly modified natural flow regimes in many rivers, and such transformations have been nearly instantaneous from a global change perspective. While water engineering conveys important benefits, there are many unintended consequences that cascade through the physics, biology, chemistry, and socioeconomics of the Global Water System. Sources: (top) National Inventory of Dams; (middle) modified from Vörösmarty et al. *[2003]; (bottom) data from UNESCO and Global Runoff Data Center (Koblenz, Germany) archives.*

New Opportunities, New Challenges

With the advent of high-resolution Earth systems science models and data sets, the GWSP community is poised to assemble a fully global view of the GWS, or at least of its major components. High technology observing systems, global and regional simulations, numerical weather prediction models, and assimilation schemes produce digital products that are often global in domain and near-real time, are spatially and temporally consistent, and provide a consistent, political "boundary-free" view of the terrestrial water cycle. Compiling relevant subsets of these data into an integrated compendium constitutes a major opportunity as well as a challenge. In this context, continued threats to the wide availability of field-based hydrographic records necessary for global model development and validation will limit progress [*Framing Committee of the GWSP*, 2004].

A coherent view of global water resources will be impossible without a common framework to bridge the conceptual and practical gaps separating the social and natural sciences. Such gaps arise from differences in nomenclature, quantitative and descriptive approaches, and the scope and scale of typical disciplinary studies. The global scale is also a major challenge for ecologists and social scientists, whose studies are typically executed at the local scale. A systematic assessment of required data sets, a shared lexicon, and a formal program to harmonize this information are critically needed. Entraining the engineering community to identify and assess major trends in water technology is another important goal.

While the state of water resources at local and even national scales is often a highly visible policy concern, the international scope of the issue is only now being conveyed to decision-makers. Recent milestones like the three World Water Forums, the U.N. World Summit on Sustainable Development and its emphasis on water, and the World Water Development Report [*World Water Assessment Programme*, 2003] have elevated the profile of the global water situation. Ambitious United Nations Millennium Development Goals to halve by 2015 the proportion of people lacking clean drinking water and sanitation require sound scientific information upon which to monitor progress and reformulate policy interventions, as does the challenge of feeding several billion more people over the coming decades, keeping peace across the more than 250 international river basins, and protecting aquatic biodiversity [*World Water Assessment Programme*, 2003]. GWSP science therefore has an important role to play in helping to maintain momentum on these and other important policy fronts.

The GWSP is seen as the first step in establishing a new understanding of humans and their place in a changing hydrosphere. The consolidation of otherwise independent studies of water, a move toward a fully global perspective, and interdisciplinarity are the project's central features. Studies of linkages, including the nonlinearities and feedbacks that resonate through the biogeophysical and social dimensions of the water system represent a new challenge.

The GWSP implementation plan [*Framing Committee of the GWSP*, 2004] describes an array of supporting activities and practical outputs, including workshops, science meetings, an integrated database, modeling strategies, a policy dialogue, capacity building, and outreach. Inputs from the water sciences, management, and policy communities are welcome. Contacts and additional background information can be obtained from the GWSP International Project Office in Bonn, Germany (www.gwsp.org).

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Table 1. Examples of major anthropogenic forces and their impacts transforming the contemporary Global Water System. An abundant literature documents effects at the local scale. Below is an initial assessment of the global importance of these changes, highlighted by key examples. Numbers refer to those in Figure 1. Early GWSP activities aim at producing a more definitive ranking of the importance of each factor, in order to focus future research activities. See *Framing Committee of the GWSP* [2004] for additional documentation.

Issue	Agents of Change	Impacts and Potential Global Significance
Climate Change	Emissions of greenhouse gases lead to sustained rise in surface air temperature and other atmospheric changes through the instrumental record.	Possible accelerated hydrologic cycle (1), increased frequency of extreme events; loss of snow cover/mountain ice (2); more frequent, intense ENSO-like events; unknown threshold linking increased Eurasian runoff to potential shutdown of ocean circulation with rapid northern hemisphere cooling; sea level rise impacts sensitive coastal areas (14), such as deltas, that depend on a balance of river basin and ocean processes.
Basin-scale Water Balance Changes	Climate change and variability (1, 2); deforestation (3); wetland drainage (4); irrigation (5, 6); evaporation in reservoirs (7, 8); cooling water loss (9); interbasin transfers (10).	In heavily populated (11) and irrigated (5, 6) basins, withdrawal can exceed river flow and water is reused many times, yielding public health and pollution problems; groundwater mining in arid regions (6) and coastal salinity intrusion (12); water use/diversions create artificially dry river systems with severed connections to ocean (13, 14), with global contributing basin area under threat of ≈10M km^2.
River Flow Regulation	Dams (7, 8); interbasin transfers (10); locks, stream channelization, leveeing, human settlement of floodplains (15, 16)	Pandemic waterworks reconfigure natural hydrographs; impoundment (7, 8, 13) stabilizes flows for human use, but changes habitat and migration paths of aquatic organisms; globally 45,000 large and 800,000 small dams; area of basins heavily regulated rivals free-flowing systems; global 2- to 3-fold increase in residence time of continental runoff in river corridors.
Sediment Fluxes	Elevated erosion from deforestation (3), grazing (17), agriculture (5, 6), mining, construction (11); reduced flux via reservoir siltation (7, 8) and reduced river discharge (13).	Local-scale order-of-magnitude increases in erosion, depending on management and globally a factor 3-4 increase over natural state; loss of agricultural fertility upstream; habitat destruction, loss of reservoir investments through siltation; erosion of deltas and shorelines (14); artificial sediment retention ≥ 30% of natural global flux.
Chemical Pollution	Industrialization (9), mining, urbanization (11) without adequate treatment; industrial agriculture (5, 6); atmospheric transport and deposition (acid rain) (18).	Impacts across full land-to-ocean continuum; nutrient loads accelerate eutrophication; stoichiometric shifts yield coastal zone anoxia, harmful algal blooms, fisheries loss (19); xenobiotic distribution now global; worldwide river nitrogen transport to ocean increased 2- to 3-fold over pristine condition, with 10x increases in some industrialized regions.
Microbial Pollution	Increases in fecal contamination from uncontrolled urbanization (11) and animal husbandry (17).	Waterway pollution followed by downstream use yields major global public health threat; under control in most advanced countries; increasing faster than population in most regions particularly around megacities (11).
Bio-diversity Changes	Pollution from agriculture (5, 6), cities (11), mining; fragmentation of waterways (7, 8, 13, 15), thermal pollution (9); introduction of exotics from globalization.	Threats to habitat and pollution have caused widespread species loss (e.g. >120 North American freshwater fish species since 1900); introduction of exotics changes local plant and animal communities; invasions by exotic species now widespread.

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