# Improving Understanding of the Global Hydrologic Cycle

## Observation and Analysis of the Climate System: The Global Water Cycle

**Peter H. Gleick, Heather Cooley, James S. Famiglietti, Dennis P. Lettenmaier, Taikan Oki, Charles J. Vörösmarty, and Eric F. Wood**

**Abstract** Understanding the complexity of the hydrological cycle is central to understanding a wide range of other planetary geological, atmospheric, chemical, and physical processes. Water is also central to other core economic, social, and political issues such as poverty, health, hunger, environmental sustainability, conflict, and economic prosperity. As society seeks to meet demands for goods and services

P.H. Gleick (✉) • H. Cooley
Pacific Institute, 654 13th Street, Preservation Park, Oakland, CA 94612, USA
e-mail: pgleick@pacinst.org; hcooley@pacinst.org

J.S. Famiglietti
Department of Earth System Science, University of California
Center for Hydrologic Modeling (UCCHM), University of California, Irvine,
240K Rowland Hall, Mail Code 4690, Irvine, CA 92697, USA
e-mail: jfamigli@uci.edu

D.P. Lettenmaier
Department of Civil and Environmental Engineering, University of Washington,
164 Wilcox Hall, Seattle, Box 352700, WA 98195-2700, USA
e-mail: dennisl@uw.edu

T. Oki
Institute of Industrial Science, The University of Tokyo,
4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
e-mail: taikan@iis.u-tokyo.ac.jp

C.J. Vörösmarty
Department of Civil Engineering, City University of New York,
365 Fifth Avenue, New York, NY 10016, USA
e-mail: cvorosmarty@ccny.cuny.edu

E.F. Wood
Department of Civil and Environmental Engineering,
Princeton University, E-208 E-Quad, Princeton, NJ 08544, USA
e-mail: efwood@princeton.edu

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for a growing population, we must improve our understanding of the fundamental science of the hydrological cycle, its links with related global processes, and the role it plays in ecological and societal well-being. At the same time, human influences on the character and dynamics of the water cycle are growing rapidly. Central to solving these challenges is the need to improve our systems for managing, sharing, and analyzing all kinds of water data, and our ability to model and forecast aspects of both the hydrological cycle and the systems we put in place to manage human demands for water. We need to improve our understanding of each of the components of the hydrological water balance at all scales, and to understand the spatial and temporal variability in the components of the water cycle. This chapter provides a short summary of current WCRP efforts and addresses four primary research challenges:

1. The collection of more comprehensive data and information on all aspects of the hydrologic cycle and human uses of water, at enhanced spatial and temporal resolution and increased precision;
2. Improved management and distribution of these data;
3. Improved representation of the anthropogenic manipulations of the water cycle in the coupled land-atmosphere-ocean models used to forecast climate variations and change at both seasonal to interannual, and decade to century, time scales; and
4. Expanded research at the intersection of hydrological sciences and the technical, social, economic, and political aspects of freshwater management and use.

**Keywords** Hydrologic cycle • Water • Water systems • Climate • Modeling • Water balance • Data • GEWEX • GRACE • Water-energy nexus

## 1 Introduction: The Challenge

Water, energy, and climate are physically, spatially, and temporally linked. Energy from the sun and from internal geological processes drives the hydrological cycle. Atmospheric composition, climate system characteristics, and complex feedbacks help determine the planet's energy and water balances and distribution (Oki 1999). Both linear and non-linear dynamics amplify and dampen effects of external forcings. Water on Earth in its three phases is integral to the functioning, dynamics, and variability of the global climatological and biological support systems (Oki et al. 2004). From a purely scientific and academic point of view, understanding the complexity of the hydrological cycle is of paramount interest and central to our understanding of other planetary geological, atmospheric, chemical, and physical processes. But water is more than that: water is key to some of the core economic, social, and political issues of our time such as poverty, health, hunger, environmental sustainability, conflict, and economic prosperity (Gleick 2003).

Perhaps more than any other scientific discipline, hydrological science traces its roots to efforts to tackle challenges of social and economic development, including the provision of safe and reliable drinking water, flood forecasting and protection, wastewater treatment, irrigation development and food production, hydropower generation, and more (Loucks 2007; Wood et al. 2011). As society seeks to meet demands for goods and services for a growing population, the more apparent it becomes that we must improve our understanding of the fundamental science of the hydrological cycle, its links with related global processes, and the role it plays in ecological and societal well-being. At the same time, human influences on the character and dynamics of the water cycle are growing (FC-GWSP 2004a; Vörösmarty et al. 2010; Pokhrel et al. 2011), often faster than our understanding of these influences and their ultimate consequences.

Central to solving these challenges is the need to improve our systems for managing, sharing, and analyzing all kinds of water data, and our ability to model and forecast aspects of both the hydrological cycle and the systems we put in place to manage human demands for water. These improvements would help lead to a far better understanding of the local, regional, and global details of the water balance on timescales from minutes to millennia. In short, we need to improve our understanding of each of the components of the hydrological water balance at all scales, and to understand the spatial and temporal variability in the components of the water cycle. Extensive efforts in some of these areas are ongoing under the auspices of national research centers, universities, and international scientific collaborations, including the World Climate Research Program (WCRP). Recent reviews summarize the current state of understanding and future research priorities in the direct science-related aspects of these problems (for example, Hornberger 2001; FC-GWSP 2004b; Oki et al. 2006; NRC 2007, 2008b; Shapiro et al. 2010; Wood et al. 2011). This assessment expands on those efforts by integrating key scientific research needs with a broader perspective. There is also overlap between the recommendations here and in other reviews of geophysical components of the broad climate system, prepared for the October 2011 WCRP meeting (see, for example, the discussion on satellite observing systems and needs in Trenberth et al. 2011 and Oki et al. 2012).

The hydrological sciences community is faced with a complex moving target in three ways: First, very long-term climatological and hydrological balances are influenced by both cyclical and non-cyclical solar, orbital, and geophysical forcings. Second, climatological and hydrological balances are subject to substantial variability on widely varying timescales of seconds to millennia, and our limited instrumental and paleo observations give us an incomplete understanding of the statistics of extremes and natural variability. Thirdly, humans are now driving changes in atmospheric processes and have also substantially modified the natural hydrological cycle and altered hydrological processes across the land branch of the cycle, with growing evidence of oceanic, continental, and global-scale impacts and resource constraints (Meybeck 2003; FC-GWSP 2004a, b; Oki and Kanae 2006; Vörösmarty et al. 2010; Gleick and Palaniappan 2010).

While our understanding of the role that humans play in altering planetary systems has improved enormously in recent decades, uncertainties in both the science and in our knowledge of future societal factors such as population, economic conditions, technology trends, and energy choices make modeling efforts and future forecasts inherently imperfect. Any effort to summarize future needs must therefore note the important distinctions among the urgent need to improve our basic understanding of the hydrological cycle, the equally urgent need to improve our understanding of how humans are influencing and changing it, and the ultimate consequences of those changes for societal well-being. Perhaps in part as a result of these complexities, few if any of the current generation of land surface models used in coupled land-atmosphere-ocean climate models represent anthropogenic effects on the water cycle, a deficiency that is especially limiting as the demand for climate change information at regional and local scales increases.

This chapter provides a short summary of current WCRP efforts[1] and addresses four primary research challenges:

1. The collection of more comprehensive data and information on all aspects of the hydrologic cycle and human uses of water, at enhanced spatial and temporal resolution and increased precision;
2. Improved management and distribution of these data;
3. Improved representation of the anthropogenic manipulations of the water cycle in the coupled land-atmosphere-ocean models used to forecast climate variations and change at both seasonal to interannual, and decade to century, time scales; and
4. Expanded research at the intersection of hydrological sciences and the technical, social, economic, and political aspects of freshwater management and use.

## 2 Current WCRP Efforts

WCRP's efforts in the area of hydrology, atmospheric dynamics, thermodynamics, and the interaction between surface-land-ocean-atmosphere processes and the hydrological cycle are addressed mostly by the Global Energy and Water Cycle Experiment (GEWEX), Climate Variability and Predictability (CLIVAR), and Climate and Cryosphere (CLIC) projects.[2] WCRP efforts are linked to the Global Water System Project (GWSP; a partnership with three other global environmental change programs) and the WMO Global Framework for Climate Services (GFCS) efforts. The latter is developing a new working group on climate information and services that is expected to deal with aspects of climate service delivery relative to the water management community. One area that would benefit from better integration of changes in terrestrial systems with oceanic and cryospheric ones is the

[1] Good and more comprehensive summaries of WCRP programs can be found online.

[2] GEWEX was formerly "Global Water and Energy Cycle Experiment" and is now "Global and Regional Energy and Water Exchanges." CLIVAR is the "Climate Variability and Predictability" program.

issue of understanding the dynamics and components of sea-level rise. An example is the effect of reservoir filling globally during the second half of the twentieth century on sea level rise (discussed by Lettenmaier and Milly 2009). Another is the 2010–2011 reduction in the rate of sea-level rise (see http://sealevel.colorado.edu/frontpage). One argument is that this anomaly can be traced to extreme rainfall over several major land areas associated with a strong La Niña event, which had the effect of storing unusually large amounts of water on the global land areas (e.g., Australia and northern South America). GRACE observations have generally confirmed this hypothesis (Behera and Yamagata 2010).

Within each core project there are common themes, including:

1. Making observations and performing analyses
2. Developing, conducting, and evaluating experiments
3. Understanding and evaluating processes
4. Developing applications and services
5. Building technical and management capacity.

A few of the key questions for the future identified by GEWEX (Box 1 below) and CLIVAR include:

- How are the Earth's energy budget and water cycle changing?
- Can we quantify feedback processes in the Earth system and determine how these processes are linked to natural variability?
- Can we accurately model climate variability on the seasonal to interannual timescale?
- What are the impacts of climate variability at different space and time scales on water resources?
- How does and will anthropogenic climate change interact with natural climate variability to alter both the means and extremes of regional water and energy budgets?
- Can we track the flow of energy through the atmospheric and oceanic system and understand the nature of global warming?
- Can we understand the forcings and feedbacks among the different climate system components?[3]

## 3 Improve Collection of Hydrological and Water System Data

The first recommendation in almost all past reviews of the state of the hydrological sciences is to substantially expand collection of a wide range of geophysical, climatological, and hydrological data. Without adequate data, understanding of existing conditions and dynamic processes will always be constrained. Without adequate

[3] From the WCRP website: http://www.wcrp-climate.org/waterclim.shtml

**Box 1 GEWEX Plans for 2013 and Beyond**

*Mission Statement*
To measure and predict global and regional energy and water variations, trends, and extremes (such as heat waves, floods and droughts), through improved observations and modeling of land, atmosphere, and their interactions; thereby providing the scientific underpinnings of climate services.

*Vision Statement*
Water and energy are fundamental for life on Earth. Fresh water is a major pressure point for society owing to increasing demand and vagaries of climate. Extremes of droughts, heat waves and wild fires as well as floods, heavy rains and intense storms increasingly threaten to cause havoc as the climate changes. Other challenges exist on how clouds affect energy and climate. Better observations and analysis of these phenomena, and improving our ability to model and predict them will contribute to increasing information needed by society and decision makers for future planning.

*GEWEX Imperatives*
**Datasets**: Foster development of climate data records of atmosphere, water, land, and energy-related quantities, including metadata and uncertainty estimates.
**Analysis**: Describe and analyze observed variations, trends and extremes (such as heat waves, floods, and droughts) in water and energy-related quantities.
**Processes**: Develop approaches to improve process-level understanding of energy and water cycles in support of improved land, ocean, and atmosphere models.
**Modeling**: Improve global and regional simulations and predictions of ocean evaporation, overall precipitation, clouds, and land hydrology, and thus the entire climate system, through accelerated development of models of the land and atmosphere.
**Applications**: Attribute causes of variability, trends, and extremes, and determine the predictability of energy and water cycles on global and regional bases in collaboration with the wider WCRP community.
**Technology transfer**: Develop new observations, models, diagnostic tools, and methods, data management, and other research products for multiple uses and transition to operational applications in partnership with climate and hydro-meteorological service providers.
**Capacity building**: Promote and foster capacity building through training of scientists and outreach to the user community.

(Source: WCRP 2010)

data, the ability to develop more accurate models for forecasting and planning will be limited. As Hornberger (2001) noted, most major advances in the environmental sciences have resulted from new observations and the acquisition of new, better, or more comprehensive data, not just from the creation of new analytical models. Recent analysis of hydrologic extremes in a changing climate (Trenberth 2011a; NRC 2011a) yet again highlights this issue, in particular the essential need for investments in coherent and long-term observations in light of the "death" of stationarity (Milly et al. 2008) and the growing evidence that changes in the hydrological and climatological cycle due to climate change are already occurring, on land, over the oceans, and in the atmosphere (Meehl et al. 2007, 2009; Zhang et al. 2007; Syed et al. 2010; Trenberth 2011b; Durack et al. 2012).

For example, new analyses of ocean salinity trends and atmospheric water content and fluxes provide evidence for such changes. Syed et al. (2010) used multiple remotely-sensed datasets to analyze the global ocean water balance for changes in water cycle strength. Over the 13-year (1994–2006) study period, they observed significant increases in the rate of oceanic precipitation (240 $km^3/year^2$), oceanic evaporation (768 $km^3/year^2$), and continental discharge (540 $km^3/year^2$), which included ice sheet melting. Durack et al. (2012) noted an increase in ocean salinity, which suggests an accelerating global water cycle. Other studies also support an intensification of the water cycle, including:

1. An increase in atmospheric water content (precipitable water). While not directly indicative of fluxes, these data suggest that the humidity of the atmosphere has been increasing at close to the Clausius–Clapeyron rate, especially over the oceans (Trenberth et al. 2005; Wentz et al. 2007). More work is needed to resolve differences in changes of both absolute and relative humidity.
2. An increase in oceanic evaporation rates. Yu and Weller (2007) find evaporation increasing over the global ocean at 1.3 %/decade since the mid-1970s, due to both warming and intensifying winds. This is above model predictions and close to expectations from Clausius–Clapeyron theory (see also Weimerskirch et al. 2012).
3. Changes in precipitation rates. Wentz et al. (2007) report that global precipitation rates observed from satellites have been increasing with sea-surface temperatures at a rate of about 9 %/°C in the last two decades, though other observations (such as estimates from the Global Precipitation Climatology Project) offer different regional patterns and rates (see, for example, Zhou et al. 2011). At this point, the satellite-based precipitation estimates comprise a short record, and given high natural variability and routine concerns about satellite calibration, additional observations and analysis are warranted.
4. An increase in sea-surface salinity trends. Sea-surface salinity differences have increased by ~8 % over the five decades from 1950 to 2000 (Durack and Wijffels 2010; Durack et al. 2012). The oceanographic data also support these observations, with a consistent pattern found in both the mean salinity and the long term salinity trends (Boyer et al. 2005). Since the oceans have no internal sources or sinks of salinity, the variations are introduced at the surface by changes in

evaporation, precipitation, and runoff. Additional observations and modeling work is needed to improve our understanding of the sensitivity of salinity to temperature and hydrologic changes.

While differences between modeled and observed evaporation and precipitation may be due in part to inadequate data (Allan and Soden 2007) and short observational time series, the trends noted above seem consistent with a strong response of the water cycle to warming. Additional studies should help improve our understanding of these changes.

While many core concepts in hydrological sciences have been largely understood for decades, important basic data on stocks and flows of water, water vapor, and ice are missing for vast regions of the planet – even regions with large populations and highly productive economies. And new opportunities are continuing to emerge, such as understanding the origins and roles of "atmospheric rivers" in long-distance transport of water vapor in the lower atmosphere (Dettinger et al. 2011; Ralph et al. 2011) which now appears to be the driving mechanism for most major floods along the U.S. West Coast and winter-time floods in the U.K. (Lavers et al. 2011). Rapid changes in Arctic sea ice conditions must now also be evaluated because of the likelihood that they will changes the dynamics of important circulation patterns and add a new source of moisture in high latitudes. New data sets focused on water-balance studies are needed because such dynamics and balances are central to the development of useful water models (addressed later). New continental and global hydrometeorological data sets will be required to support these activities. These data sets include observations of streamflow over watershed and continental domains (Fekete et al. 2002), gridded high-resolution precipitation data, and more work to integrate different efforts to improve evapotranspiration estimates at small and continental scales (Jin et al. 2011). Expanded budget studies covering the role of the oceans, snow accumulation, melt, runoff, and evaporation of snow in continental regions are also needed to better understand how snow contributes to the water cycle, and the role of diminishing snowpacks on climate and water availability. Four central data needs include[4]:

- Improvements in precipitation observations sufficient to resolve the diurnal cycle and at a spatial resolution capable of representing variations in precipitation that control runoff generation in small to medium sized watersheds. Precipitation observations should include boundary layer observations, aircraft observations, surface measurements, synoptic-scale information, and coordinated satellite observations.
- Expansion of surface water, ocean surface salinity and moisture flux, and ocean-topography observations are needed to provide data on water storage and flows, including variability, in oceans, rivers, lakes, reservoirs, and wetlands. Efforts should be made to strengthen ocean salinity measurements as an integral measure of water cycle changes through the new salinity satellites Aquarius and SMOS, the ARGO float program, and the Global Drifter program.

[4] Some of these needs will be addressed by planned satellite missions, notably the Surface Water and Ocean Topography mission (SWOT), a joint venture of NASA and CNES, the French space agency.

- Improvements in snow-ice observation networks capable of estimating water storage in snowpacks, especially in mountainous and polar regions, including volumetric measurements of glaciers. Enhanced ice sheet observations are needed, combining satellite remote sensing and deployment of ocean buoys and subsurface floats. Efforts should be made to expand observing systems such as the NRCS SNOTEL of automated snow-water equivalent observations network over the U.S. to provide a global in-situ observational basis for estimating snow water storage in mountainous headwater regions of major river basins.
- Development and deployment of a combination of remote sensing and in situ soil-moisture monitoring systems capable of filling gaps in key elements of the land-surface water balance and land-atmosphere fluxes of heat and water, again of sufficiently high spatial and temporal resolution. In this respect, NASA's planned (2014 launch) SMAP mission, coupled with the COSMOS and other in-situ soil moisture networks over the U.S., should be an important first step.

In addition to these data sets, however, there is a growing need for the collection of far more comprehensive data on human interactions with the hydrologic cycle, including water withdrawals, consumption, and reuse (for example, revising the comprehensive but dated work of Shiklomanov (1997) and the data currently available from UN datasets such as AQUASTAT). Data are also needed on redirection and transfers of water, information on disruptions of nutrient cycles and on contamination by human and industrial wastes (Galloway et al. 2004; He et al. 2011), and on social and economic factors that influence the size and efficiency of water use (Vörösmarty et al. 2005; Gleick et al. 2011). Some work has been done to estimate water withdrawals on a spatially distributed basis, using the distributions of population and irrigation area, for instance, as proxies (Vörösmarty et al. 2000; Oki et al. 2001; Alcamo et al. 2003) but these efforts are limited by data constraints and the strengths and relevance of the proxies chosen.

The global water cycle and related data needs have long been recognized as a top priority for national research programs. In the late 1960s, the International Hydrological Decade pursued studies of world water balances, and pioneering estimates on large-scale hydrologic processes were published in the 1970s (L'vovitch 1973; Korzun 1978; Baumgartner and Reichel 1975). Shiklomanov (1997) assembled country-level statistics on water withdrawals in the past and present and made future projections. These early efforts were expanded with recent advances in information technologies that permit some global water-balance estimates at finer spatial resolution (Alcamo et al. 2007; Shen et al. 2008).

In the U.S., the National Research Council has issued a series of reports addressing research priorities in the areas of global environmental change, the hydrologic sciences, water system management, and climate change (NRC 1998, 1999a, b, 2002a, b, 2005, 2007, 2008a, b, c, 2009, 2010a, b). In 1999, the NRC Committee on Hydrologic Science argued for a comprehensive program of research on the role of the hydrologic cycle in the context of the broader global climate system (NRC 1999a). That same year, the NRC issued another report calling for new strategies for addressing the challenges of watershed science and management (NRC 1999b).

The good news is that we have unprecedented new capabilities in the form of technologies for in-situ and remote sensing and data collection, new approaches for embedded network sensing (ENS), sophisticated computer models for analyzing complex hydrologic processes, techniques for visualization of data, and growing interest and concern on the part of the public and policy makers about a wide range of water challenges.

The bad news is that these tools are not adequately utilized and resources (and sometimes the political will) for collecting even basic data on human uses of water remain limited. For example, the quality of existing remote-sensing data on soil moisture is poor (the recently launched ESA SMOS and upcoming NASA SMAP missions will offer improvements); snow-water equivalent is inadequately monitored at high resolution, especially in mountainous terrain; remote sensing estimates of snow water equivalent are especially problematic in mountain and forested headwaters of major river basins, variations in surface-water levels are not accurately captured by current sensors, and estimates of river discharge remain "an elusive goal" (NRC 2007).

Having better real-time and long-term data on water-balance variables would substantially improve the ability to close the water balances in local and regional watersheds, and the ability to model and understand the global water cycle. Other data of interest include estimates of water vapor transport, wind fields, ocean salinity, cloud structure, extent, and distribution, sea ice, groundwater balances, and a wide range of water-quality conditions.

Improvements are also needed in the resolution and precision of data. These improvements will come about through the development and deployment of new technologies for data collection and observations, expansion of data collection networks, the preservation and broader distribution of existing data sets, and new approaches for identifying unused or underutilized sources of information. The global Earth Science imperative, acknowledged by both international scientific organizations and national academies includes strong recommendations for advances in ground and satellite observational capabilities and implementation of observational data collection and management programs. As stated by the National Research Council (NRC 2007):

> "The scientific challenge posed by the need to observe the global water cycle is to integrate *in situ and space-borne observations* to quantify the key water-cycle state variables and fluxes. The vision to address that challenge is a series of Earth observation missions that will measure the states, stocks, flows, and residence times of water on regional to global scales followed by a series of coordinated missions that will address the processes, on a global scale, that underlie variability and changes in water in all its three phases." (Emphasis added.)

The ultimate goal, not yet realized, is for scientists to be able to track surface, subsurface, and atmospheric water in real-time, over the entire planet, and at sufficiently fine spatial resolution to integrate a complete quantitative picture of the terrestrial water cycle and embed that knowledge into decision support tools for forecasting extreme events for reducing risks and improving the use of water for agriculture and economic development. While such tools will always have limitations because of social, political, and economic factors, it is expected that investments in research and improved models will produce substantial economic benefits. For example, the financial benefits in public-sector weather forecasting and warning systems have been large and positive, estimated at over $30 billion per year on an investment of $5 billion (Lazo et al. 2009).

### 3.1 Ground-Based, In-Situ Observations

Spatial and temporal observations from surface networks and sensors must be improved and expanded. Regional-scale networks of sites should be developed to record meteorological and surface hydrological variables, soil moisture and dynamics, and groundwater levels and quality. This includes ocean buoys, river gages, snow sampling, new approaches to "embedded network sensing" (ENS), and much more. Such expanded networks should include new inexpensive, linked sensors (e.g., Harmon et al. 2007), establishing monitoring stations near the deltas of major rivers to record water fluxes for dissolved and suspended material, in particular, to improve understanding of carbon and nitrogen cycles, and a wide range of other priorities (NRC 2008b), not the least of which is the protection of deltas from both upstream and ocean-derived threats (Syvitski et al. 2009; Vörösmarty et al. 2009).

Yet even maintaining existing collection networks is difficult. In the U.S., the total number of active streamgages maintained by the U.S. Geological Survey dropped from over 8,250 in 1970 to 6,759 in 1997 due to budget cuts (Fig. 1). Some

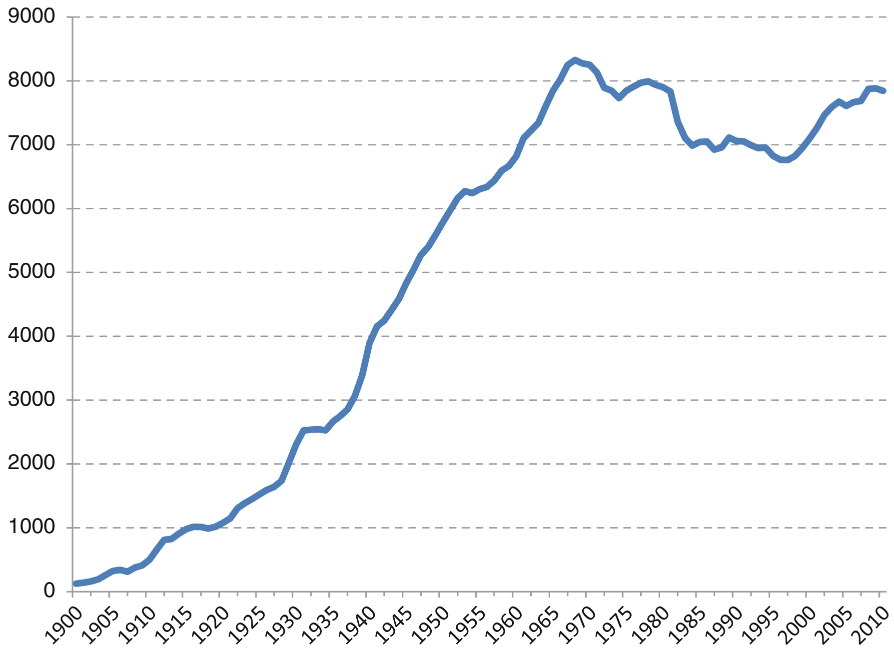


**Fig. 1** The number of active USGS streamgages from 1900 to 2010. http://water.usgs.gov/nsip/history1.html

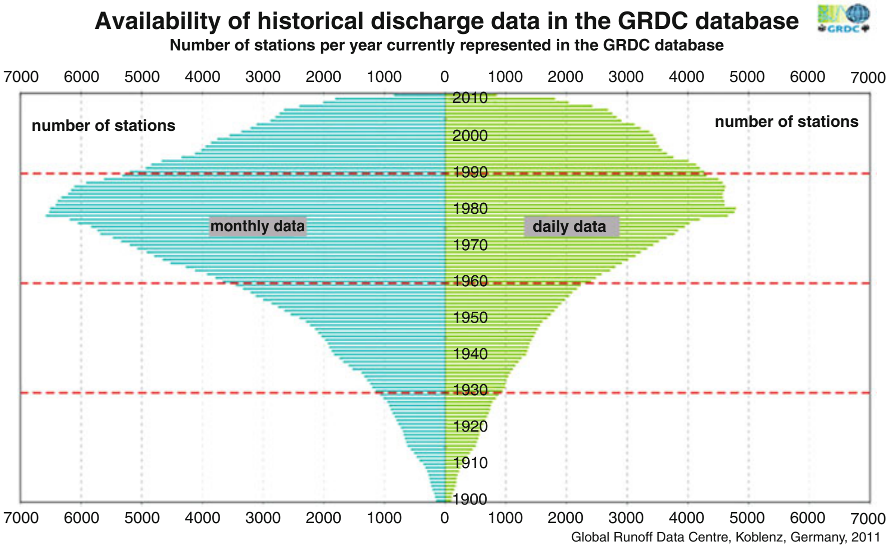


**Fig. 2** Availability of historical discharge data in the GRDC database by year (number of stations per year represented in the GRDC database) http://www.bafg.de/cln_031/nn_266918/GRDC/EN/02__Services/services__node.html?__nnn=true

stations have been restored in recent years, but the total number of observing stations is still below the levels of the 1970s and early 1980s. This is a global problem as well, where budget and financing pressures, intellectual property issues, and conflicting policy priorities conspire to discourage monitoring and contribute to the loss of both observational stations and important data sets. Figure 2 shows the declining number of discharge monitoring stations worldwide in the Global Runoff Data Centre (GRDC) archives. Similar trends can be seen at the national level. The number of gages in South Africa dropped from a high of more than 4,000 to around 1,700 by the turn of the twenty-first century. Vast numbers of gages fell into disrepair or were dismantled following the collapse of the former Soviet Union (Stokstad 1999; Shiklomanov et al. 2002). Snow depth in Canada was recorded at over 2,600 stations in 1981 and at fewer than 1,600 in 1999. New methods of data collection and network design may permit more and better data to be collected with fewer stations (Mishra and Coulibaly 2009), but even with these improvements, the current scale of hydrologic data collection is not adequate to satisfy information needs for either science or policy.

### *3.2 Remotely Sensed Observations*

Even with a significant expansion of ground-based monitoring, improved short-term event data collection from aircraft, and additional boundary layer observations, there are concerns that such monitoring is inadequate without increased reliance on satellite systems. There is some limited good news. The synoptic view afforded by satellites is uniquely poised to fill spatial and temporal gaps in ground-based data collection. For instance, improvements in global weather forecasting over the last several decades are largely attributable to better information from satellite retrievals about the distribution of atmospheric water vapor in the Southern Hemisphere. The Tropical Rainfall Monitoring Mission launched in 1997 improved our understanding of mid- and low-latitude precipitation. The GRACE satellites, despite the coarse resolution of their observations, have led to advances in the understanding of water storage changes in ice sheets and groundwater (Box 2).

Unfortunately, few countries and international consortia have the financial and technological resources to commit to comprehensive Earth Observing programs, and growing financial pressures are weakening the budgets allocated to such programs. This results in challenges to agencies, such as NASA in the U.S. and ESA in Europe, that wish to transition research satellites and sensors to other entities. Another aspect of the transition to operations problem (termed the "Valley of Death" by NRC 2000) is resistance by operational agencies to integrating data streams that may have a limited duration. While the authors appreciate this dilemma, we assert that it is in part a matter of culture and motivation. In this respect, a bright spot has been the European Center for Medium-Range Weather Forecasts (ECMWF), which has been working to evaluate the effect of new sensors and data on global weather forecast accuracy. ECMWF is now a global leader in weather forecasting, attributable at least in part to its willingness to evaluate and assimilate new data streams, especially satellite data. We will not review here the diverse and rapidly changing nature of these programs – by the time a final version of this paper is published, details will have changed again. But a general observation is that too little money has been made available to support building and maintaining adequate observing platforms with appropriate instruments, and even those few in development are at high risk of delay or cancellation. One example of a long-term remote observing program is the Global Precipitation Measurement effort, described in Box 3, which began in the late 1990s and is continuing to evolve, with expected launch of the core satellite in early 2014.

New and near-future satellite missions brighten this picture somewhat, but a comprehensive global water cycle platform is desperately needed. The current ESA SMOS (Soil Moisture and Ocean Salinity Mission) and the future NASA SMAP (Soil Moisture Active Passive) missions are positioned to map the water content of the thin veneer of soil near the land surface. The planned joint NASA-CNES SWOT (Surface Water and Ocean Topography) mission will routinely map the heights and inundation extent of inland surface waters. However, current plans for earth observing systems remain inadequate for deliberately moving the science forward in the direction recommended by scientific reviews (Group on Earth Observations 2007; NRC 2007). Worse, the planet is in grave danger of losing a substantial part of the current observing network because replacement systems, including both ground- and ocean-based instruments and satellites, are not being built quickly enough to fill inevitable gaps caused by expected instrument aging and by satellite orbital decay and failure. As one example, the recent budget crisis in the United

**Box 2 Gravity Recovery and Climate Experiment (GRACE)**

The **G**ravity **R**ecovery **A**nd **C**limate **E**xperiment (GRACE) is a joint mission of NASA and the German Space Agency DLR. Launched in 2002, the twin GRACE satellites are now making extremely accurate measurements of changes in Earth's gravity field caused by mass redistribution over the planet. The major driver of these mass variations on the monthly time scales of GRACE observations is water movement. Hence the gravity maps generated by GRACE provide new detail on how the storage of water is changing in Earth's major land, ocean, and ice reservoirs. When combined with additional ground-based or satellite observations, GRACE data have helped improve the tracking of water flows through river basins, withdrawals of groundwater, rates of ice-sheet melting, and other important hydrologic, oceanographic, and geologic phenomenon (Neumeyer et al. 2006; Ramillien et al. 2004). The data collected by GRACE are also helping to reconcile regional and global terrestrial water budgets (Syed et al. 2008; Sahoo et al. 2011) and allow for water balance estimates of unknown fluxes, including evapotranspiration (Rodell et al. 2004a) and continental discharge (Syed et al. 2009). GRACE-based estimates of groundwater depletion are already influencing the discussion of regional water policies as new data on water withdrawal and storage are made available (Rodell et al. 2010; Famiglietti et al. 2011a).

A follow-on GRACE mission (GRACE-FO) is currently planned for launch in 2017. The GRACE-FO will be essentially identical to the current mission, providing near-continuous measurements of water storage variations from March 2002 through the end of its lifetime. Coupled with the availability of more user-friendly GRACE data projects (Rodell et al. 2010; Landerer and Swenson 2011), the water community will have far-greater access to GRACE data than previously possible. Future, improved versions of the GRACE mission, that would achieve greater spatial and temporal resolution than the current 200,000 km$^2$, monthly data with 1.5 cm accuracy, are not slated for launch until the next decade (NRC 2007). This so-called GRACE-II (see Table 1) mission will enhance capabilities for monitoring water storage changes at the smaller scales at which water management decisions are made. Moreover, when data from GRACE (or its successor missions) are combined with the remotely-sensed soil moisture and surface water data described here, and integrated into data-assimilating models, an unprecedented picture of global distribution of water, both laterally and vertically, will emerge (Famiglietti 2004).

States and instrument design issues have delayed the Joint Polar Satellite System (JPSS) program and launch to the point where there is now expected to be a major and risky gap in coverage for vital hydrometeorological data (Box 4).

In this context, and while the entries in Table 1 offer hope to estimate a variety of water-cycle variables using remote sensing, a coherent strategy will be necessary to

**Box 3 Global Precipitation Measurement (GPM)**

The Global Precipitation Measurement (GPM) mission started as an international mission and follow-on and expansion of the Tropical Rainfall Measuring Mission (TRMM) satellite. TRMM, which hosts the first precipitation radar as well as a passive microwave sensor, was launched in November 1997 and continues to make observations almost 16 years later. Its major objective is to measure the global distribution of precipitation accurately with sufficient frequency so that the information provided can improve weather predictions, climate modeling, and understanding of water cycles. An important goal for the GPM mission is the frequent measurement of global precipitation to produce rainfall maps using a TRMM-like core satellite, jointly developed by the U.S. and Japan, and a constellation of multiple satellites that will carry passive microwave radiometers and/or sounders intended to enhance precipitation estimates during the time when the radar is not overhead.

GPM is composed of core system and multiple satellites carrying microwave radiometers and/or sounders (Constellation satellites). The GPM Core Observatory is now schedule to be launched in 2014, and will carry the sensors from multiple countries and agencies designed to collect as much microphysical information as possible for accurate rain estimation, and to provide reference standards for the instruments on the constellation satellites.

Constellation satellites will carry a microwave imager and/or sounder, and are planned to be launched around 2013 by each partner agency for its own purpose. They will contribute to extending coverage and increasing frequency of global rainfall observations. Currently, several satellite missions are planning to contribute to GPM as a part of constellation satellites, including JAXA's Global Change Observation Mission – Water (GCOM-W) series; CNES/ISRO's Megha-Tropiques; EUMETSAT's MetOp series; NOAA's Polar Operational Environmental Satellites (POES) Joint Polar Satellite System (JPSS); and DoD's Defense Meteorological Satellite Program (DMSP) and Defense Weather Satellite System (DWSS).

link these data sources with the dynamics of water-management systems and regional watersheds. One example is need to understand the hydraulics of stream and river systems as well as the statistical time-space domains that different monitoring strategies would have to confront. For example, the technical requirements for developing short-term flood forecast and monitoring are quite different from those needed for long-term water resource assessment, agricultural water efficiency efforts, or integrated management among the energy, water, and food sectors.

A related and often overlooked issue is the need to link remote sensing with in-situ measurements. There is the misperception that satellites measure geophysical parameters. Rather, almost all (GRACE is a notable exception) measure radiation (such as brightness temperatures) and radar backscatter, which are then used to infer

**Box 4 Joint Polar Satellite System (JPSS)**

NOAA maintains both geostationary weather satellites and polar satellites. Their polar systems provide observations of land, ocean, and atmosphere over the entire Earth. There are only two polar research satellites systems that provide this kind of hydroclimatological data: NOAA's and Europe's EUMETSAT. These two systems provide the primary data for developing National Weather Service (NWS) weather prediction models at high confidence forecasts 2–7 days in advance and they are the backbone of all weather forecasts beyond 48 h. These polar satellites, however, also play other critical roles. They aid in hurricane forecasting and rapid coastal evacuation, provide continuity of the 40+ years of space-based earth observations to monitor and predict climate variability, produce drought forecasts worth $6–8 billion to the farming, transportation, tourism, and energy sectors, support troop deployment operations, and pick up rescue beacon signals. NOAA estimates that satellite observing systems saved 295 lives in the U.S. alone in 2010 and over 28,000 lives worldwide since 1982.

NOAA's current polar satellites are reaching the end of their useful lives. A research satellite known as NPP (NPOESS Preparatory Project) launched in October 2011 to serve as a bridge between from the current polar-orbiting satellites and the next-generation of polar-orbiting satellites, known as the Joint Polar Satellite System (JPSS). NOAA planned to launch the first two JPSS satellites in 2014 but the current budget crisis in the US led Congress to cut NOAA funding forcing a delay in JPSS launch to at least 2017 and possibly beyond. While the President's FY 2012 budget restores full funding, it will not prevent a gap in observation coverage. According to NOAA, it is now a "near-certainty that an unprecedented observational data gap of 15–21 months will occur between the anticipated end of the NPP spacecraft's operational life in 2016 and the date when the first JPSS mission is planned to begin".

Loss of coverage would set back weather observations and forecasting almost a decade to when forecasts were of lesser quality. This problem may reduce forecast accuracy, especially for major weather events such as winter snow storms over the East Coast and hurricane tracks and intensity, by as much as 50 %. Errors in track and intensity forecasts could delay hurricane warnings and evacuations or result in unnecessary evacuations.

geophysical variables. Harmonizing remote sensing data with past ground/in-situ measurements can help to greatly extend spatial and temporal data records. While these harmonization efforts are part of ongoing NASA, NOAA, ESA, JAXA, and EUMETSAT programs, more are needed.

**Table 1** Water resources panel candidate missions

| Summary of mission focus | Variables | Type of sensors | Coverage | Spatial resolution | Frequency | Synergies with other panels | Related planned or integrated missions |
|---|---|---|---|---|---|---|---|
| Soil moisture, freeze-thaw state | Surface freeze-thaw state, soil moisture | L-band radar, radiometer | Global | 10 km (processed to 1–3 km) | 2- to 3-day revisit | Climate<br>Weather | SMAP<br>Aquarius |
| Surface water and ocean topography | River, lake elevation; ocean circulation | Radar altimeter, nadir SAR interferometer, microwave radiometer, GPS receiver | Global (to ~82° latitude) | Several centimeters (vertical) | 3–6 days | Climate<br>Ecosystems<br>Health<br>Weather | SWOT<br><br>SMAP<br>GPM<br>NPP/NPOESS |
| Snow, cold land processes | Snow-water equivalent, snow depth, snow wetness | SAR, passive microwave radiometry | Global | 100 m | 3–15 days | Climate<br>Ecosystems<br>Weather | SCLP |
| Water vapor transport | Water vapor profile; wind speed, direction | Microwave | Global | Vertical | | Weather<br>Climate | 3D-Winds<br><br>PATH<br>GACM<br>GPSRO |

(continued)

**Table 1** (continued)

| Summary of mission focus | Variables | Type of sensors | Coverage | Spatial resolution | Frequency | Synergies with other panels | Related planned or integrated missions |
|---|---|---|---|---|---|---|---|
| Sea ice thickness, glacier surface elevation, and glacier velocity | Sea ice thickness, glacier surface elevation; glacier velocity | Lidar, InSAR | Global | | | Climate<br>Solid Earth | DESDynI<br>ICESat-II |
| Groundwater storage, ice sheet mass balance, ocean mass | Groundwater storage, glacier mass balance, ocean mass distribution | Laser ranging | | 100 km | | Climate<br>Solid Earth | GRACE-II |
| Inland, coastal water quality | Inland, coastal water quality; land-use, land-cover change | Hyperspectral imager, multi-spectral thermal sensor | Global or regional | 45 m (global), 250–1,500 km (regional) | About days (global), subhourly (regional) | Climate<br>Ecosystems<br>Health | GEO-CAPE |

Source: NRC (2007). Because launch dates change so quickly, we have not provided expected dates here

### 3.3 Managing Data

Climate data, including in-situ and satellite observations and model output (such as re-analyses) are not as widely available or readily accessible as they should be. This lack of access is a threat to GEWEX's ability to meet its imperatives (see Box 1) and more broadly, constrains all regional water planning, analysis, and management efforts. The applications goals for GEOSS (Global Earth Observation System of Systems) similarly cannot be met without better access to data. As additional hydrologic data are collected, new systems are needed to manage and distribute those data. Wood et al. (2011) note the additional complications and costs associated with data support systems, but developing such systems is secondary to access and having interoperability across products.

New commitments to establishing and maintaining hydrological data networks are not enough. As articulated by Parson (2011), there is consensus in the science and application communities that open and free access to hydrological and meteorological data is critical for improved utilization of data resources and for transparency in data-based research results and derived data products. Many international bodies such as the World Meteorological Organization, International Science Union and the Group on Earth Observations (ICSU 2004; WMO 1995; Group on Earth Observations 2009) have passed resolutions, advocated for, or created central principles for more open access to data. A global open-access database is highly desirable, and systems must be put in place to ensure access to data and to maintain data in forms that are useful for different research and application needs. These data are crucial for assessing water resources at multiple scales and for verifying hydrological models and evaluating policy solutions.

Many organizations already collect hydrological data using different and often inconsistent platforms for both operational (e.g., National Water Information System (NWIS) of the US Geological Survey (USGS), US EPA, NOAA) and research purposes (NASA, Atmospheric Radiation Measurement (ARM) program, AQUASTAT of the UNFAO, and the Global Runoff Data Center (GRDC)). Data fragmentation and variation makes it difficult for scientists to use data from different sources, to evaluate data accuracy or bias, and to combine mixed data sets without extensive analysis. The lack of data access prevents the development of systems to integrate data from disparate sources like in-situ observations and satellite measurements. Earlier in this article we recognized that satellites are "uniquely poised to fill spatial-temporal gaps in ground-based data," but the development of systems that can integrate and merge such data is seriously hindered by data access barriers. One specific example is the desirability of using TRMM (and in the future GPM), derived precipitation in data sparse regions for flood prediction where both real-time ground observations and satellite-based estimates, when integrated and merged, can lead to improved heavy precipitation monitoring and flood forecasting. Some efforts are now being made to integrate and manage such datasets under the auspices of the Consortium of Universities for the Advancement of Hydrological Science, Inc. (CUAHSI) but these efforts are neither comprehensive nor global (Oki et al. 2006).

The management of global data also remains a challenge. One European-led effort, GRDI2020 (Global Research Data Infrastructures), has been formed to develop "technical recommendations to increase the ability of the research community, industry, and academia to influence the development of a competitive global ICT infrastructure." The International Groundwater Resources Assessment Centre (IGRAC; www.un-igrac.org) offers another example of a new, international hydrological data collection and distribution strategy. Under the IGRAC approach, the continents are discretized into one-degree grid cells. Each one-degree cell has an associated expert, designated by his or her home country, who is responsible for monthly submissions of a short list of key groundwater variables, for example, well levels. The local expert is responsible for determining a representative monthly, one-degree average value for the key variables, and for uploading the averaged and raw data in standardized formats through a user-friendly web-based interface. IGRAC is a new center and as such, its success and the viability of its approach will only become apparent in time. If successful however, the IGRAC approach is one that could conceivably be implemented for other hydrologic variables and organized by UNESCO or the WMO. Other efforts such as CUASHI or GRDI also need to be supported and fostered.

# 4 Modeling

Models are critical tools for the hydrological sciences. Models are used over a wide range of spatial and temporal scales to forecast future conditions and to reconstruct hydrologic conditions in the instrumental and pre-instrumental past. They are also used to simulate scenarios such as hydrologic stocks and flows or water-quality variations under different observed or hypothetical conditions, and to interpolate observational data, integrate point data over large areas, downscale large-scale data to regional areas, and estimate hydrological variables where no observational data are available. Models help identify water-system risks and test strategies for reducing those risks. Ironically, our ability to develop complex hydrological models has outstripped our ability to provide them with adequate data, hence the need for improving data collection noted above. Despite progress in both model development and data collection and assimilation, Wood et al. (2011) note that the current class of parameterizations used to represent the land surface in numerical weather prediction and climate models is unable to address a wide range of societal needs for water-related information. For example, current weather forecasts are carried out using land surface models with resolutions that are too coarse to represent key local processes (e.g., evapotranspiration along riparian corridors in semi-arid landscapes). Efforts to make the outputs of the current generation of global climate models of use to hydrologists and water resource planners and practitioners, while of growing value, have yet to be completely successful (NRC 2011b). We argue that this should be a priority for WCRP (and GWEX in particular), which previously has placed more emphasis on understanding variations and controls on the global water and energy cycles than on their manifestations over land, and in particular over the most populous parts of the global land area.

Recently, the hydrologic community has begun to call for an acceleration in the development of hydrological models that can be applied to a range of high-priority issues related to food, energy, climate, and economic security, and that represent the land surface hydrology of managed, rather than just natural systems. As one example, the Community Hydrologic Modeling Platform (CHyMP) under development in the U.S., is a broad-based effort that parallels the successful efforts in climate model development (Famiglietti et al. 2009, 2010, 2011a, b). CHyMP will enable fully integrated (snow, ice, surface water, soil moisture, groundwater) modeling of the natural and managed water cycles, across scales, and will provide access to continental-scale models and datasets for a broad swath of research and practicing water scientists and engineers.

Wood et al. (2011) issued a "grand challenge" to the hydrologic community to develop a new generation of "hyperresolution" hydrologic models that can exploit advances in computing power, the internet, and improved access to data. Such models would be capable of representing critical water cycle systems at a high spatial and temporal resolution and would require improved information about existing and projected human modifications such as dams and other artificial storage, groundwater withdrawals and recharge, alterations of nutrient flows, the impacts of urbanization, and much more. This is a core activity required for the development of Earth System models that include human drivers, as described in the next section.

GEWEX's scientific strategy also includes improved prediction. To better represent improved land-surface interactions that include human activities, resolution must increase, and the schemes need to be tested off-line before they are coupled. Steps are being taken in this direction, and the spatial resolution of global hydrological simulations is improving. Current global land-surface hydrologic simulations, such as the Global Land Data Assimilation System (GLDAS) (Rodell et al. 2004b) have grids scales around 25 km and approximately 50 km for offline global simulations (e.g., Dirmeyer et al. 2006; Haddeland et al. 2011); however, a land information system is under development that will have a spatial resolution of 1 km$^2$ (Oki et al. 2006). This model is designed to be an operational tool that will provide estimates of all major surface hydrological quantities (including evaporation, transpiration, soil moisture, snow depth and melt, and more), using a daily timestep. Forcing data and surface characteristics, including precipitation, radiation, surface winds, and vegetation cover will be provided by both surface (in situ) observations and remote sensing and will be tied into a modeling framework using four dimensional data assimilation (4DDA). The spatial resolution of the resulting model analysis fields eventually will be as high as 100 m globally, which is at least as high as the spatial resolution of most current generation regional hydrological models. If such a system becomes operational on a daily or even hourly timestep, and if observational data of sufficient quality are available to populate and test the model, then it could form an early warning system for hydrological disasters, such as floods and droughts, anywhere in the world (Oki et al. 2006).

Human influences on the hydrological cycles of the Earth are now widespread and often large in magnitude. Yet many current hydrological and land-surface models either exclude or poorly represent human influence on the terrestrial water cycle through activities such as agriculture, forestry, grazing, urbanization, or water diversions. These are critical elements of the contemporary water cycle to understand, with a perhaps more immediate impact than future effects of climate change (which, of course, will be felt in addition to these other anthropogenic influences) (Vörösmarty and Meybeck 2004). Many of these impacts appear to be an inescapable byproduct of economic development, (Vörösmarty et al. 2010), but that does not mean they cannot be mitigated through changes in policies, incentives, behaviors, and technology. An important feature of these influences is that they are, by their nature, interdisciplinary. Another is that they are often local, but with growing regional and even global influence.

Global hydrological models should now consider the effects of human intervention on hydrological cycles. Some efforts in this direction are underway. Several recently developed macro-scale models for water-resources assessment now include reservoir operation schemes (e.g., Haddeland et al. 2006a, b; Hanasaki et al. 2006). Hanasaki et al. (2008a) describe an integrated water-resources model that can simulate the timing and quantity of irrigation requirements and estimate environmental flow requirements. Such an approach can help assess water demand and supply on a daily timescale, and the gaps between water availability and water use on a seasonal basis in the Sahel, the Asian monsoon region, and southern Africa, where conventional water-scarcity indices such as the ratio of annual water withdrawal to water availability and available annual water resources per capita (Falkenmark and Rockström 2004) are not adequate (Hanasaki et al. 2008b). Wisser et al. (2008), Fekete et al. (2010), and Lehner et al. (2011) have worked to assess the implications of large infrastructure projects on water balances. Further improvements in models that couple natural hydrological systems with anthropogenic activities can improve our understanding of key challenges in water management, including the sustainability of water use, ecosystem health, and food production (Hanasaki et al. 2010; Pokhrel et al. 2011).

The effects of anthropogenic alterations in the land surface hydrologic cycle can go far beyond the river basin scale. The scale of human intervention is large enough that we now recognize that the water stored behind reservoirs globally has influenced Earth rotational variations and orbital dynamics, including length of day and polar motion (Chao 1995; Chao and O'Connor 1988). Similarly, Lettenmaier and Milly (2009) estimate that sea level rise, which over the last 50 years has averaged about 3 mm/year, would have been 15–20 % larger in the middle of the last century were it not for the reduction in freshwater flux to the oceans associated with filling of manmade reservoirs (they also note that the rate of filling has since decreased substantially, perhaps to a global net less than zero due to infilling of reservoirs with sediment and slowing of reservoir construction. Recently, Pokhrel et al. (2012) estimated on the basis of an integrated modeling framework that artificial reservoir water impoundment caused a sea level change (SLC) of −0.39 mm/year, while unsustainable groundwater use (groundwater depletion), climate-driven terrestrial

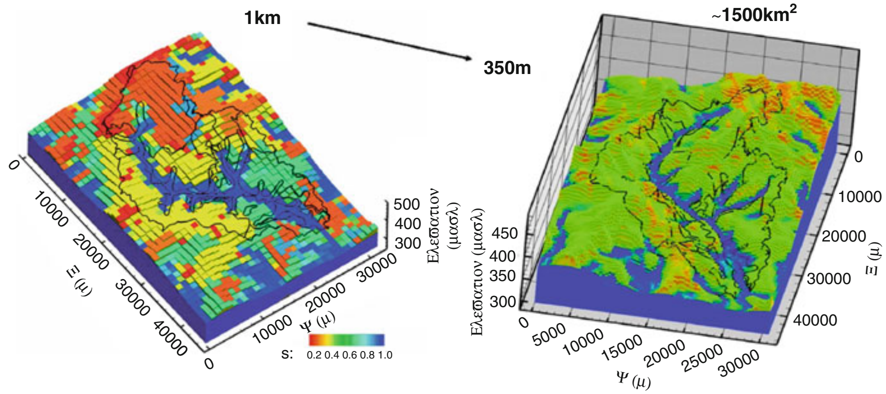


**Fig. 3** Higher-resolution models allow better spatial representation of saturated and nonsaturated areas, with implications for runoff generation, biogeochemical cycling, and land-atmosphere interactions. Soil moisture simulations on the Little Washita showing the effect of resolution on its estimation of variables (Kollet and Maxwell 2008)

water storage (TWS) change, and the net loss of water from endorheic basins contributed +1.05, +0.09, and +0.03 mm/year of the SLC, respectively. Therefore, the net TWS contribution to SLC during 1961–2003 is +0.77 mm/year. Their result for the anthropogenic TWS contribution to global SLC partially fills the gap in the global sea level budget reported by the Fourth Assessment Report (AR4) of IPCC (2007) (Fig. 3).

## 5 Hydrological Sciences Needs for the Twenty-First Century in the Earth System Context

As described above, extensive efforts are underway by the global hydrological sciences community to identify and prioritize needs for data collection, modeling, and analysis. But it is also becoming increasingly apparent that many of the current water-related challenges facing society will not be resolved solely through improvements in scientific understanding. Many of these challenges lie at the intersection between pure and applied science, or require interactions among the sciences, economics, and policy. For example, we must improve our understanding of the societal and economic risks associated with extreme events such as droughts, floods (e.g., Okazawa et al. 2011), and coastal disruptions (NRC 2011a). We must improve our understanding of the role of extreme events and thresholds, the extent to which the water cycle is being modified or intensified (Huntington 2006; Trenberth 2011b), how much of the change is due to human activities, and the social implications of – and possible responses to – such changes. We must improve our understanding of "peak" constraints on water withdrawals from renewable and non-renewable hydrologic systems (Gleick and Palaniappan 2010). IPCC (2012), in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), noted that while risks cannot be fully eliminated, the character and severity of impacts from climate extremes depend not only on the extremes themselves but also on exposure and vulnerability, and emphasized the value of disaster risk management and adaptation strategies that focus on reducing exposure and vulnerability and on enhancing resilience to climate extremes.

As a result, there are new efforts underway to improve our understanding of the complex social, economic, and structural challenges facing water managers and users. These efforts would be greatly enhanced by interdisciplinary research efforts involving the scientific community and a broader range of engineers, economists, utility managers, irrigators, and local communities. Through these efforts, scientists may better understand the data needs of practitioners and some of the constraints they face, thereby helping to ensure that the products produced are actually applied. For example, as one measure of the recognition of these challenges, the Hydrology Section of the American Geophysical Union has just constituted a new Water and Society Technical Committee to heighten the visibility of water policy issues among AGU members and to develop new approaches to addressing a wide range of water-related challenges at the interface of science and policy. While such efforts are not traditionally addressed in the context of efforts by organizations such as the WCRP, it would be worth a serious discussion about the advantages and disadvantages of doing so.

## 5.1 *Climate, Water, and Social Adaptation*

As large-scale climate models have improved in their parameterizations of hydrologic processes and their spatial resolution, it has become increasingly clear that some of the most likely and unavoidable impacts to society of changes in climate will be changes in water availability, timing, quality, and demand (Kundzewicz et al. 2007; NRC 2011b). For more than a decade, the research community (and sometimes the water management community) has issued increasingly urgent calls for expanded efforts to integrate the findings from climate models with water management and planning efforts at regional levels because of the issues at the intersection of water, food, and energy (increasingly referred to as the "water-energy-agricultural nexus"), and the need to improve our integration of water quality and ecosystem needs into research efforts (AWWA 1997; Gleick 2000; Karl et al. 2009; CDWR 2009; Stakhiv 2011). Each of these topics demands both high-quality science and innovative interdisciplinary thinking. Such integration will require improvements in the quality and detail of information available from global and regional climate models, but will also require new approaches for integrating climate information into water-management institutional planning, improved economic and health risk assessment models, more robust engineering reviews of existing water-related infrastructure, and updated or improved operations rules for water supply, treatment, delivery, and wastewater systems.

## 5.2 Water, Energy, Agricultural Nexus

Connections between water, energy, and food have been recognized for centuries, but most of the focus of attention has been on ensuring the basic availability and reliability of supply of key resources for the production of other goods and services demanded by society. In the past decade or so, there has been new work to expand our understanding of these connections, in part because of adverse consequences caused by ignoring them. For example, changes in the energy policies of some industrialized countries to encourage greatly expanded production of domestic biofuels, such as corn-based ethanol programs, had unanticipated impacts on global food markets and prices and on conflicts over water resources (NRC 2008c, 2010b), with little reflection of biogeophysical realities (Melillo et al. 2009). Similarly, efforts to expand natural gas and oil production from unconventional fields, especially shale oil and gas, has led to unanticipated and poorly studied impacts on water quality, the generation of large volumes of "produced water" with high concentrations of pollutants, and new water demands in some water-scarce regions (Cooley and Donnelly 2012). Growing demands for electricity and for water to cool these systems are also intensifying competition for water in water-short regions and new efforts are underway to pursue alternative water sources and cooling technologies as well as less water-intensive generating systems.

Most current generation land-surface models are not well suited to address these issues. For instance, while climate change will almost certainly affect the availability of cooling water – a key constraint on energy production in many parts of the world – few current models simulate the most critical variable, water temperature. That is beginning to change – recent work by Van Vliet et al. (2012) and Cooley et al. (2011) illustrates the sensitivity of electric power generation to both the hydrological and surface climatic conditions, as well as to assumptions about energy futures and technology choices. This is an area that is deserving of greater attention by both the scientific and applications communities.

## 5.3 Water Quality and Ecosystems

There are serious limitations to our understanding of water quality, including both natural variability and human-induced changes in quality, and the role that water plays in ecosystem dynamics and health. Representations of these complex factors in regional and global models are inadequate and unsophisticated, though some small-scale catchment models have been developed that include physical and biochemical dynamics for some water-quality constituents such as carbon, nitrogen and phosphorus, and sediment (Vörösmarty and Meybeck 2004). Very little work has been done on other chemical components, heavy metals, or new contaminants such as pharmaceuticals (Palaniappan et al. 2010), and the challenge of articulating the additive, and possibly synergistic, interactions of multiple stressors from a variety of sources (broad array of chemicals, thermal pollution, sedimentary impacts) remains (Vörösmarty et al. 2010).

In this context, humans both accelerate and decelerate discharge and biogeochemical (BGC) fluxes through rivers (Meybeck and Vörösmarty 2005). For example, despite huge increases in local erosion from poor land management, around 30 % of global sediment flux is estimated to be trapped upstream behind dams and fails to enter the oceans (Syvitski et al. 2005), placing major coastal landforms like river deltas at risk and altering nutrients available to fisheries. Climate change and its attendant impacts on runoff, carbon and nutrient cycling, and weathering rates will also change these land-to-ocean linkages (Amiotte-Suchet et al. 2003). Frameworks are necessary to handle the component hydrologic, sediment, and biogeochemical dynamics, but notwithstanding ongoing work (e.g., Wollheim et al. 2008) much more needs to be done.

## 6 A Grand Challenge in Hydrologic and Water-Resources Modeling

Existing vulnerabilities and new threats to water posed by demographic changes, climatic changes, increased exposure to extreme events, and growing economic demands for water and water services are driving urgent needs for improvements in our understanding of the world's water resources and systems (Kundzewicz et al. 2007; Hirschboeck 2009; Shapiro et al. 2010). We will not go back to a time when hydrological sciences could only address pristine, unaltered systems. Humans now not only influence the water-cycle but are integral to it, and we must develop predictive models that represent human interactions with the water cycle at scales useful for water management. This implies that weather and seasonal climate models and land-surface parameterizations must improve in parallel. Without a strong understanding of the dynamics of global and regional water balances and the complex human interactions and influence on water quantity and quality, society risks making incorrect decisions about critical issues around energy, human health, transportation, food production, fisheries, ecosystem protection and management, biodiversity, and national security.

Until recently, anthropogenic effects on the global land water cycle were thought to be small (in part because the global land area is small compared with the oceans and because human populations were small). This is changing: it is now clear that anthropogenic activities such as land use and land cover change, irrigation, groundwater withdrawals, and reservoir storage have influenced sea level (Milly et al. 2010) and even orbital parameters; similarly we have an improved understanding of the role of the oceans in influencing land-surface hydrology. At regional scales, human effects have, in many cases, been large for a longer time – for instance, a number of major global rivers, including the Nile and the Colorado, no longer flow at their mouths as a result of consumptive water use (mostly for agriculture) and trans-basin diversions (Alcamo et al. 2005). In the case of the Colorado, about 1/3 of the river's natural discharge is diverted out of the basin and the rest is used consumptively. Other human influences that substantially affect regional hydrology include groundwater mining, increased soil moisture in irrigated areas, urbanization, and permafrost melt. These effects nonetheless are mostly not represented in regional or global climate models, and regional hydrology models often focus on runoff generation areas far upstream of the parts of the basin that have been most affected by anthropogenic activities. At continental scales, direct anthropogenic effects are probably more modest, but nonetheless can be substantial – especially the effects of land cover change, including irrigation, on moisture recycling and precipitation generation, mostly in the interior of the North America and Eurasia (Haddeland et al. 2007). These effects likewise are rarely represented in land-atmosphere models or their host climate global models.

We therefore argue that the "grand challenge" in the hydrology/water resources/climate arena is to model the role of humans on the water cycle at regional (e.g., large river basin), continental, oceanic, and global scales, including the feedbacks of these effects to the climate system, such as ocean/land interactions. This enterprise will involve the development of new understandings of the complex interactions of humans with the water cycle such as reservoir storage, diversions, and return flows, but even more importantly, of the decision process that will determine the nature of changes in water management as the climate warms. WCRP can serve an important role by fostering activities such as expanded data collection, model development, and intercomparison projects. Furthermore WCRP could and should promote the development of the global data sets that will be required to support the development and testing of these new models. Some of the required data sets have already been developed through activities like the Global Water System Project (GWSP), but effort will be required to assure that they are sufficient for the purposes of land models that ultimately must run within fully coupled Earth System models.

## 7 Conclusions

Over the last decade there has been a transformation in the way in which we view the continental water cycle. While freshwater systems of the planet are collectively an essential regulator of the non-living dynamics of the Earth System, they also play a central role in human existence and water security. At the same time, we now understand that our contemporary water system is increasingly tightly coupled to economic, social, technological and other factors like climate change. Along with this recognition of a globalized water system has come the awareness that human activities are themselves significantly and increasingly dominating the nature of this major cycle. This dominance takes the form of many "syndromes" that are at once both the causes as well as manifestations of rapid human-induced changes. Although we can increasingly detect and in many cases understand the sources, scope, and mechanisms associated with these changes, we urgently need to improve investments in our observational networks, our basic understanding of the water cycle and the ways it is integrated with energy, climatic, atmospheric, oceanic, and other complex geophysical characteristics of the planet, and our training of the next generation of researchers who increasingly will be called upon to study these larger-scale challenges, which are outside the traditional training perspectives of the hydrologic science community. Otherwise we will be unable to counteract the rising threats to public health, economic progress, and biodiversity caused by a global water system in transition.

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