Improving Understanding of the Global Hydrologic Cycle

Observation and Analysis of the Climate System: The Global Hydrological Cycle

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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 land-surface feedbacks help determine the planet's heat and water balances and distribution. Complex feedbacks and both linear and non-linear dynamics amplify and dampen effects of external forcings. Water on Earth in its three fundamental phases is integral to the functioning, dynamics, and variability of the global climatological and biological support systems. 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 problems of our time such as poverty, health, environmental sustainability, conflict, and economic prosperity.

Perhaps more than any other scientific discipline, the hydrological sciences traces its roots to efforts to tackle challenges of social and economic development, including the provision of safe and reliable drinking water, flood prediction 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), 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 et al. 2001, FC-GWSP 2004b, Oki, Valeo, and Heal, 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).

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 continental and global-scale impacts (Meybeck 2003, FC-GWSP 2004a,b, Oki and Kanae, 2006, Vörösmarty et al. 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 increasingly 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 paper 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 use of water, at enhanced 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, economical, 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), but also through the 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

[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.

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.

Within each core project there are common themes, including:
1) Observations and analysis
2) Model development, evaluation, and experiments
3) Processes and understanding;
4) Applications and services
5) Capacity building.

A few of the key questions for the future identified by GEWEX (Box 1 below) and CLIVAR (Box 2 below) 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]

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.

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

Processes: Develop approaches to improve process-level understanding of energy and water cycles in support of improved land and atmosphere models.
Modeling: Improve global and regional simulations and predictions of 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.

Box 2: CLIVAR

Overview

CLIVAR addresses Climate Variability and Predictability under the auspices of WCRP, with a focus on the role of ocean-atmosphere interactions in climate; the role of the land surface, snow and ice; and stratospheric processes in climate. Climate variability – both natural and human induced – pose threats to human and environmental health and economic well-being. CLIVAR works to improve understanding of climate variability, apply this understanding to improve forecasts of climate variability and change through the use of advanced climate models, and monitor and detect changes in our climate system. The specific objectives of CLIVAR are:

- To describe and understand the physical processes responsible for climate variability and predictability on seasonal, interannual, decadal, and centennial time-scales, through the collection and analysis of observations and the development and application of models of the coupled climate system, in cooperation with other relevant climate-research and observing programmes.
- To extend the record of climate variability over the time-scales of interest through the assembly of quality-controlled paleoclimatic and instrumental data sets.
- To extend the range and accuracy of seasonal to interannual climate prediction through the development of global coupled predictive models.
- To understand and predict the response of the climate system to increases of radiatively active gases and aerosols and to compare these predictions to the observed climate record in order to detect the anthropogenic modification of the natural climate signal.

In recent years CLIVAR has expanded research into the role of biogeochemical cycles and the application of CLIVAR science to societal applications and impacts. Among current partnerships are efforts with the International Biosphere-Geosphere Programme (IGBP), the International Human Dimensions Programme (IHDP), and the International Programme of Biodiversity Science (DIVERSITAS).
(Source: CLIVAR overview at http://www.clivar.org/)

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. Hydrologists (and scientists generally) always want more and better data. Without adequate data, understanding of existing conditions and dynamic processes will always be constrained. Without adequate data, the ability to develop more accurate models for forecasting and planning will be limited.

As Hornberger et al. (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-COHS 2011) 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 (Meehl et al. 2007, 2009, Zhang et al. 2007, Syed et al., 2010, Trenberth 2011b).

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 challenges are continuing to emerge, such as the role 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. 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 transformed observations of streamflow into gridded (or equivalent) spatial fields over 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 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.

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, improving on 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.), and on social and economic factors that influence water demand and use (Vörösmarty et al. 2005). 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 has long been recognized as a critical priority for research by national science programs. In the late 1960s, the International Hydrological Decade promoted studies on world water balances, and pioneering estimates were published in the 1970s (L'vovitch, 1973; Korzun, 1978; Baumgartner and Reichel, 1975). Shiklomanov (1997) assembled country 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 United States, 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 through 2010). 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 perhaps most importantly, 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 remote-sensing data on soil moisture is poor; snow-water equivalent is inadequately monitored at high resolution, especially in mountainous terrain, variations in surface-water levels are not accurately captured by current sensors, and estimates of river discharge remains "an elusive goal" (NRC 2007). Four central data need remain paramount:[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 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.

- Improvements in a snow-ice observation network 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 global coverage of 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.

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, as well as improve our overall models and understanding of the global water cycle. Other data of interest include estimates of water vapor transport, wind fields, cloud structure, extent, and distribution, sea ice, groundwater balances, and a wide range of water-quality conditions.

[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 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 U.S. National Research Council in 2007 (NRC 2007a):

> "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 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).

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 United States, the total number of active streamgages maintained by the U.S. Geological Survey dropped from over 8250 in 1970 to 6759 in 1997 due to budget cuts (Figure xx). Some 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 pressures, cost-recovery strategies to finance the systems, and intellectual property issues conspire to discourage monitoring and contributed to the loss of both observational stations and important data sets. Figure xx shows the declining number of runoff monitoring stations worldwide in the GRDC database. Similar trends are occurring at the country level. The number of gages in South Africa dropped from a high of more than 4000 to around 1700 by the turn of the 21st century. Vast numbers of gages formerly in operation in the Soviet Union fell into disrepair or were dismantled (Stokstad 1999, Shiklomanov et al. 2002). Snow depth in Canada was recorded at over 2600 stations in 1981 and by fewer than 1600 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.

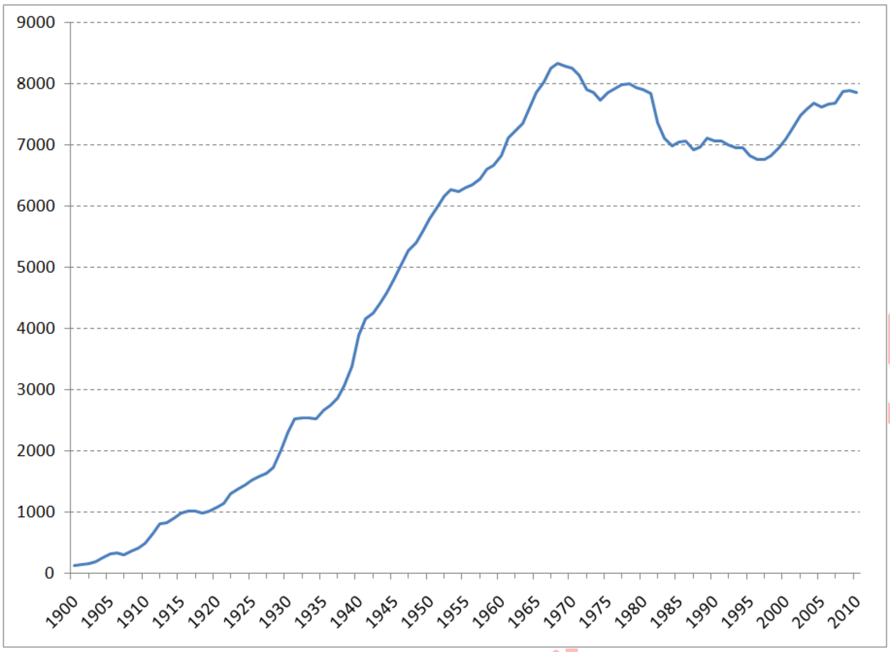


Figure xx. The number of active USGS streamgages from 1900 to 2010.
http://water.usgs.gov/nsip/history1.html

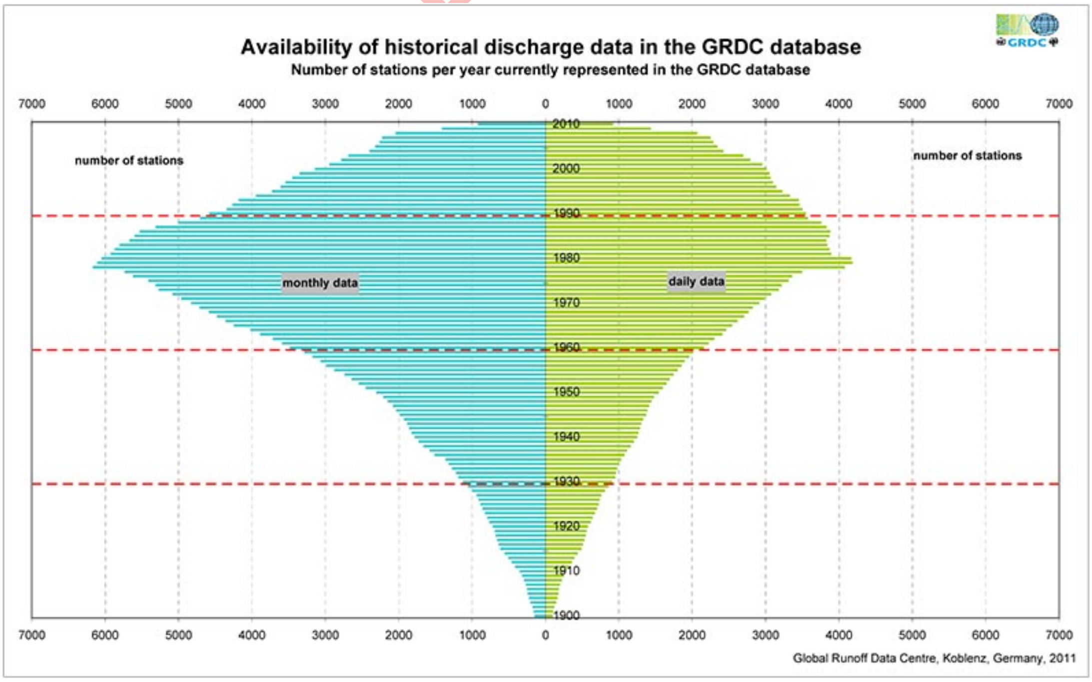


Figure xx. Availability of historical discharge data in the GRDC database by year (number of stations per year represented in the GRDC database). http://www.bafg.de/cln_031/nn_266918/GRDC/EN/02__Services/services__node.html?__nnn=true.

Remote Sensing and Data Collection

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 not going to be sufficient 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. Improvements in some observing systems and associated data archives have advanced scientific understanding. Emerging results from satellite missions over the last two decades are already providing important new insights into water-cycle dynamics. For example, 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 3).

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 paper will not review 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 4, which began in the late 1990s and is continuing to evolve, with expected launch of the core satellite in the next few years.

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 (GEO 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 States has 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 5).

Box 3. 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 the flows of water through aquifers, withdrawals of groundwater, ice-sheet thickness, and other important hydrological, oceanographic, and geological phenomenon (Neumeyer et al. 2006, Ramillien et al. 2004,). The data collected by GRACE are 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., 2004) and continental discharge (Syed et al., 2009). GRACE-based estimates of groundwater depletion are already influencing the discussion on regional water policies as new data on water withdrawal and storage are made available (Rodell et al., 2009; Famiglietti et al. 2011).

A follow-on GRACE mission (GRACE-FO) is currently planned for launch in 2016. The GRACE-FO will be identical to the current mission, and will ensure near-continuous measurements of water storage variations from March, 2002 through the end if 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 km3, 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).

Box 4. 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 14 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 global 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 a TRMM-like non-sun-synchronous orbit satellite (GPM Core Observatory) and multiple satellites carrying microwave radiometers and/or sounders (GPM constellation satellites). The GPM Core Observatory is scheduled to be launched in 2013, and will carry the Dual-frequency Precipitation Radar (DPR), which is being developed by Japan Aerospace Exploration Agency (JAXA) and

Japanese National Institute of Information and Communications Technology (NICT), and the GPM Microwave Imager (GMI), which is being developed by NASA. The roles of the GPM Core Observatory are to collect as much microphysical information as possible for accurate rain estimation by performing synchronous observation with the GMI and the DPR, and to provide reference standards for the other microwave radiometers 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 map. Currently, several satellite missions are planning to contribute to GPM as a part of constellation satellites; 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); DoD's Defense Meteorological Satellite Program (DMSP) and Defense Weather Satellite System (DWSS); and so on.

** [*update this – aside from jpss, what does the constellation consists of? Are there international partners other than Japan?]*

Box 5: 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 to 7 days in advance and they are the backbone of all weather forecasts beyond 48 hours. 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 to 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) is scheduled to be 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 2016, and most likely 2017 or 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" (NOAA 2011).

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. Moreover, the 2011 funding cut does not actually save money; rather it leads to additional out-year expenses. NOAA estimates that for every $1 not received in 2011, $3 to $5 extra will be required to cover inflation and additional expenses needed to rebid and award contracts, stop and restart work, and maintain instruments and launch systems for the additional time (NOAA 2011).

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 link these data sources with the dynamics of water-management systems and regional watershed. One example is from Bjerklie et al. (2003), who highlighted the 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 competition 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 than radiation (such as brightness temperatures) that are then used to infer 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, 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 Weather	SMAP 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 Ecosystems Health Weather	SWOT SMAP GPM NPP/NPOESS
Snow, cold land processes	Snow-water equivalent, snow depth, snow wetness	SAR, passive microwave radiometry	Global	100 m	3–15 days	Climate Ecosystems Weather	SCLP
Water vapor transport	Water vapor profile; wind speed, direction	Microwave	Global	Vertical		Weather Climate	3D-Winds PATH GACM GPSRO
Sea ice thickness, glacier surface elevation, and	Sea ice thickness, glacier surface elevation;	Lidar, InSAR	Global			Climate Solid Earth	DESDynI ICESat-II

glacier velocity	glacier velocity						
Groundwater storage, ice sheet mass balance, ocean mass	Groundwater storage, glacier mass balance, ocean mass distribution	Laser ranging		100 km		Climate Solid Earth	GRACE-II
Inland, coastal water quality	Inland, coastal water quality; land-use, land-cover change	Hyperspectral imager, multispectral thermal sensor	Global or regional	45 m (global), 250–1,500 km (regional)	About days (global), subhourly (regional)	Climate Ecosystems Health	GEO-CAPE

Source: NRC (2007).

Managing Data

Relevant climate data, information, products, and services are not widely available or readily accessible. This lack of access is a threat to GEWEX's ability to meet its Imperatives (see Box 1). 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 (Parsons, 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, GEO, 2009) have passed resolutions, advocated for, and/or created central principles for more open access to data. A global open-access database would be helpful if not critical, 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. The applications goals for GEOSS: Global Earth Observation System of Systems cannot be met without better access to data.

Several organizations already collect various hydrological data using different and often inconsistent platforms, such as the National Water Information System (NWIS) of the US Geological Survey (USGS), WMO, NASA, US EPA, NOAA, Atmospheric Radiation Measurement (ARM) programme, AQUASTAT of the UNFAO, and the Global Runoff Data Center (GRDC at BfG Germany). Data fragmentation and variation makes it difficult for scientists to use the 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 it is 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 being able to use 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 not comprehensive or global (Maidment et al., 2003, 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. Data are available as one-degree averages, or as the original, raw data, but both are in a common format. 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 by the hydrological sciences community for a wide range of purposes at a wide range of spatial and temporal scales from the local to the global, from seconds to centuries. They are used to forecast future conditions and recreate paleohydrological conditions. They are used to simulate scenarios such as hydrologic stocks and flows or water-quality variations under different observed or hypothetical conditions. They are used 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 approaches 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, and 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-COHS 2011).

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. As one example, the Community Hydrologic Modeling Platform (CHyMP; Famiglietti et al., 2008, 2009, 2011) under development in the United States, is a broad-based community modeling effort that parallels the successful efforts in climate modeling. 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.

Likewise, Wood et al. (2011) called for a "grand challenge" 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.

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., 2004) have grids scales around 25 km; 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. In addition, four dimensional data assimilation (4DDA) will be used for estimating forcing data. The spatial resolution of this model eventually will be as high as 100 m globally, corresponding to the horizontal resolution of most regional hydrological models or higher. If such a system becomes operational on a daily timestep, and if observational data of sufficient quality were 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).

Wood et al. (2011) lay out six specific challenges in development of the next generation of hydrologic models:

- Improve representation of surface-subsurface interactions due to fine-scale topography and vegetation;
- Improve representation of land-atmospheric interactions and resulting spatial information on soil moisture and evapotranspiration;
- Include water quality as part of the biogeochemical cycle;
- Represent human impacts from water management;
- Use massively parallel computer systems and recent computational advances in solving hyperresolution models that will have up to 10^9 unknowns; and
- Develop the required in-situ and remote-sensing global data sets.

In addition to these challenges, new modeling efforts will have to include the complex role of water in ecosystems and improvements in representing extreme events and dynamic variability.

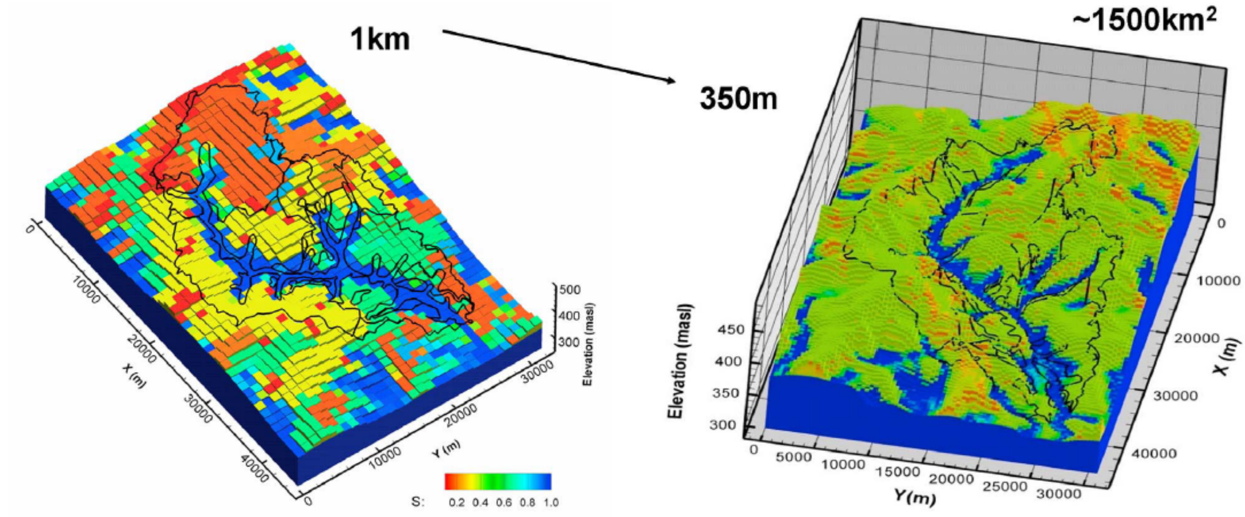
Modeling Human Influence on the Hydrologic Cycle

Human influences on the hydrological cycles of the Earth are now widespread and often large in magnitude. Yet many current hydrological models either exclude or poorly represent human influence on the terrestrial water cycle through activities such as agriculture, forestry, grazing, urbanization, or water diversions. Yet 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 et al. 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., 2006; Hanasaki et al., 2006). Hanasaki et al. 2008a describe an integrated water resources model that can simulate the timing and quantity of irrigation requirement and estimate environmental flow requirement. 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. 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 now sufficiently large that we now recognize that the redistribution of water mass stored behind the global network of reservoirs 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/yr, 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.

Figure 3. Higher-resolution modeling leads to 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 impact that the resolution has on its estimation [Kollet and Maxwell, 2008].



5. New Interdisciplinary Hydrological Sciences Needs for the 21st Century

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 are not going to be resolved solely through improvements in scientific understanding. Many of these challenges lie at the intersection between pure and applied science, or by 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, and coastal disruptions (NRC-COHS 2011). We must improve our understanding of the role of extreme events and thresholds, the extent to which the water cycle is accelerating (Huntington 2006, Trenberth 2011), how much of the acceleration is due to human activities, and the social implications of -- and possible responses to -- such an acceleration.

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 Subcommittee to broaden the issues addressed by AGU members and to develop new approaches to addressing a wide range of water-related challenges. While such efforts are not traditionally addressed in the context of efforts by organizations such as the World Climate Research Programme, it would be worth a serious discussion about the advantages and disadvantages of doing so.

Three examples highlight the importance of such integration: the growing importance of adaptation as a response to the impacts of climate change on hydrology and water resources, the increased interest in 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. Each of these topics demands both high-quality science and innovative cross-disciplinary thinking.

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 (NRC 2011). 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 (AWWA 1997, Gleick 2000, CDWR 2009, USGCRP 2009, Stakhiv 2011). 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.

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, efforts in the energy policies of some industrialized countries to greatly expand 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 ao. 2009). Similarly, efforts to expand natural gas and oil production from unconventional fields, especially shale oil and gas, has led to unanticipated 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. 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 generation land models simulate the most critical variable, water temperature. That is beginning to change – recent work by XXX (pavel's group) and Cooley et al. (2012) illustrates the sensitivity of electric power generation in the Rhine River system and the Intermountain West of the United States (respectively) to hydrological conditions, assumptions about energy futures, and technology choices. This is an area that is deserving of much greater attention by both the scientific and applications communities.

Water quality and ecosystems

There are serious limitations to our understanding of water quality, including both natural variability in quality 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 (Amiotte-Suchet et al. (2003) will also change these land-to-ocean linkages. Frameworks are necessary, and today being constructed, to handle the component hydrologic, sediment, and biogeochemical dynamics (Wollheim et al. 2008) but much more needs to be done.

6. The Need for a Grand Challenge in Hydrologic and Water-Resources Modeling

Existing vulnerabilities and new threats to water posed by climatic changes, increased exposure to extreme events, and growing populations and economic demands for water and water services are driving urgent needs for improvements in our understanding of the world's hydrological resources and systems (Kundzewicz et al., 2007, Hirschboeck 2009, Shapiro et al. 2010). We are not going 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 also progress 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 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: changes in land use and water management and storage may now be influencing sea level (Milly et al., 2010). At regional scales, human effects have, in many cases, been large for a longer time – for instance, six 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 are strong on the regional level include groundwater mining, net increases in soil moisture in irrigated areas, urbanization, and permafrost melt, but more research is needed. These effects nonetheless generally are not represented at all in regional or global climate models, and regional hydrology models often focus on runoff generation areas, which are 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, and global scales. This enterprise will involve the development of new parameterizations of 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 in promoting the development of these new parameterizations by fostering activities such as model intercomparison projects. Furthermore, and perhaps more importantly, 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 water 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, the contemporary water system has emerged from an increasingly tight coupling of 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 basic observational networks, our basic understanding, 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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