AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2015WR016892

Special Section:

The 50th Anniversary of Water Resources Research

Water security and the science agenda

Howard S. Wheater[1] and Patricia Gober[2]

[1]Global Institute for Water Security, National Hydrology Research Centre, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, [2]Johnson Shoyama Graduate School of Public Policy, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

Key Points:

- Global challenges of water security are unprecedented
- New trans-disciplinary water science is required for the Anthropocene
- Large basin-scale observatories can address the science-policy interface and large-scale science needs

Correspondence to:
H. S. Wheater,
howard.wheater@usask.ca

Citation:
Wheater, H. S., and P. Gober (2015), Water security and the science agenda, *Water Resour. Res.*, *51*, 5406–5424, doi:10.1002/2015WR016892.

Received 14 JAN 2015
Accepted 12 JUN 2015
Accepted article online 16 JUN 2015
Published online 14 JUL 2015

Abstract The freshwater environment is facing unprecedented global pressures. Unsustainable use of surface and groundwater is ubiquitous. Gross pollution is seen in developing economies, nutrient pollution is a global threat to aquatic ecosystems, and flood damage is increasing. Droughts have severe local consequences, but effects on food can be global. These current pressures are set in the context of rapid environmental change and socio-economic development, population growth, and weak and fragmented governance. We ask what should be the role of the water science community in addressing water security challenges. Deeper understanding of aquatic and terrestrial environments and their interactions with the climate system is needed, along with trans-disciplinary analysis of vulnerabilities to environmental and societal change. The human dimension must be fully integrated into water science research and viewed as an endogenous component of water system dynamics. Land and water management are inextricably linked, and thus more cross-sector coordination of research and policy is imperative. To solve real-world problems, the products of science must emerge from an iterative, collaborative, two-way exchange with management and policy communities. Science must produce knowledge that is deemed to be credible, legitimate, and salient by relevant stakeholders, and the social process of linking science to policy is thus vital to efforts to solve water problems. The paper shows how a large-scale catchment-based observatory can be used to practice trans-disciplinary science integration and address the Anthropocene's water problems.

1. Introduction: Global Pressures on the Freshwater Environment

The freshwater environment is facing unprecedented pressures in the "Anthropocene," the newest geological epoch, marked by profound human influence on natural systems [*Crutzen*, 2002]. With increasing global population and economic development, there are larger demands on water resources. Gross examples of over*use of water abound, with consequences that include reduced river flows, loss of lakes and wetlands, and falling groundwater levels. Loss of the Aral Sea due to upstream water withdrawals is an Anthropocene problem, widely quoted as a gross example of unsustainable use that has large-scale impacts [*Precoda*, 1991; *Small et al.*, 2001]. More generally, some of the world's major rivers, including the Nile and Colorado, now barely discharge to the sea, and recent applications of GRACE satellite imagery have revealed extensive regional depletion of groundwater resources [*Gleeson et al.*, 2012; *Rodell et al.*, 2009; *Voss et al.*, 2013]. While these are extreme, large-scale examples, overuse of water is widespread. Even in relatively well-regulated environments, such as the UK, water use is overlicenced [*Environment Agency of England and Wales*, 2009], and water-rich countries, such as Canada, experience stress at regional scales (e.g., water is fully allocated in Southern Alberta, which is facing unprecedented economic growth [*Wheater and Gober*, 2013]).

In addition to pressures on water quantity, degradation of water quality is a "use" of water [*Council of Canadian Academies*, 2013], with implications for other human uses, ecosystems, and human health [*UNESCO*, 2012]. Since the beginning of human civilization, the water environment has been widely used for disposal of human wastes and subject to accidental pollution. Gross pollution, due to untreated human sewage and unregulated industrial discharges, is still seen in developing economies [see "Rivers of blood: the dead pigs rotting in China's water supply," *The Guardian*, 2013]. While there have been notable success stories in developed economies in addressing these issues [e.g., "The clean-up of the River Thames," *The Telegraph*, 2010], nutrient pollution from human and animal wastes and arable agriculture has proved an intractable societal problem that is a threat to aquatic ecosystems globally [*National Academy of Engineering*, 2008].

Pharmaceutical products and other emerging contaminants are of additional concern to aquatic life [*Hecker and Hollert*, 2011].

Human influences on the land have profound impacts on the water environment through urbanization, deforestation, and agricultural development. Fifty-four percent of the global population now lives in urban areas [*United Nations, Department of Economic and Social Affairs, Population Division*, 2014]. Urbanization concentrates demand and has well-recognized implications for changing the nature of runoff and response to climatic extremes [*Wheater*, 2006]. Cumulative global loss of forest is estimated to be 1.8 billion ha, with annual loss over the last decade (to 2012) some 5.2 million ha [*Food and Agriculture Organization of the United Nations (FAO)*, 2012]. Hydrological impacts of deforestation (and afforestation) are significant and have been a driver for much hydrological research since the 1970s [e.g., *Marc and Robinson*, 2007]. Much less well understood are the implications of changes associated with other land clearance and agricultural land management in general [*Wheater and Evans*, 2009], despite the fact that cultivated land globally accounts for 1.5 billion ha [*FAO*, 2012].

Increasing pressures of human impacts on the land and water environment have increased vulnerability to extreme events. While the evidence for global increase in drought occurrence is mixed [*Seneviratne*, 2012], droughts can have severe local consequences and, in an increasingly interconnected world, these effects can be global. The international trade of food, goods, and services includes “embedded water” [*Allan*, 2003] with unintended consequences and hidden vulnerabilities. The 2010 Russian heat wave, for example, hurt wheat production, raised global food prices [*Oxfam*, 2011], and was arguably one aspect of the social unrest that led to the “Arab Spring” [*The Economist*, 2012]. At the time of writing (December 2014), the California drought is leading to widespread unsustainable exploitation of groundwater resources with a reported loss of 20 km^3 of freshwater [*University of California Center for Hydrologic Modeling*, 2014] and potentially long-term impacts on a critical agricultural industry (note a Bloomberg headline “California drought transforms global food market” [*Bloomberg*, 2014]). At the other extreme, increasing pressures of population and development have increased the risks to life, property, and infrastructure associated with flooding [*UNESCO*, 2012], due to the combined effects of human impacts on the natural environment (e.g., urbanization, agricultural intensification, and river management) and inappropriate location of people and assets in vulnerable areas [*Wheater and Gober*, 2013].

Vörösmarty et al. [2010] assessed the global impacts of multiple stressors, including land disturbance, water resources development, and pollution, and concluded that “nearly 80% of the world’s population lives in areas where either incident human water security or biodiversity threat exceeds the 75th percentile.” While global assessments are inevitably broad-brush and uncertain, it is clear that unsustainable use of surface and groundwater is ubiquitous, as is degradation of water quality. These pressures lead to increasing competition for human uses of water resources, locally, regionally, and across international boundaries, and increasing pressure on freshwater ecosystems. (*Vörösmarty et al*. [2010] estimate that 10,000–20,000 freshwater species are extinct or at risk.)

Pressure on the water environment will be exacerbated by the water-related human needs of a growing global population, including food (with increases of 70% in food production by 2050 required to meet projected demand [*FAO*, 2012]) and energy [*UNESCO*, 2012]. *Hanasaki et al*. [2013] estimate that approximately 50% of the world’s population will be living under severe water stress by 2071–2100, and similarly, *Gosling and Arnell* [2013] predict that by 2050 (under the A1B scenario), 0.5–3.1 billion people will be exposed to an increase in water scarcity due to climate change. *Arnell and Gosling* [2014] estimate the current 100 year flood will occur at least twice as frequently across 40% of the globe in 2050. This translates into a doubling of flood frequency for 450 million flood-prone people and 430 thousand km^2 of flood-prone cropland.

Given these unprecedented current and future pressures on global water systems, we now address the evolving role of the water science community in providing the basic understanding of these issues and in contributing to more effective public policy to relieve these pressures moving forward. We argue that business-as-usual, curiosity-driven, incremental science is not up to the task of tackling the unprecedented influences of the Anthropocene, the challenges of nonstationarity, and the potential unintended consequences stemming from water-land, water-energy, and water-food relationships. A new form of water science must emerge with a more holistic, agile, and strategic approach to meeting society’s most basic needs for water security.

2. Management of Water Security

"Water Security" is increasingly being used to conceptualize the multiple challenges associated with contemporary water management [*Cook and Bakker*, 2012]. Definitions of water security have moved from a more narrow focus on quantity, quality, access, and hazards (droughts and floods) to a more multidimensional sustainability-based, integrated systems perspective. The Global Water Partnership defines water security as the "sustainable use and protection of water resources, safeguarding access to water functions and services for humans and the environment, and protection against water-related hazards (flood and drought)" [*Global Water Partnership*, 2000]. This definition takes a long-term perspective, integrates human and natural systems, links to risk-based analyses and assessments, and explicitly includes environmental needs for water security.

The management of water security embodies a complex and interdependent set of issues. At a basic level, competing human needs for water resources include provision of drinking water, the use of water for irrigated agriculture (some 90% of global water consumption), water use for industry, and water to support power generation—either directly, for hydropower, or indirectly, for cooling thermal power stations. These demands are weighed in light of environmental water needs, but while an extensive body of research exists to quantify the benefits of ecosystem services [e.g., *Fisher et al*., 2009], the science to define these needs is in many senses in its infancy [*Poff and Zimmerman*, 2010]. Moreover, trade-offs between human and environmental needs depend on societal values which are subject to change and vary from one place to another. Water quality is another dimension of these management trade-offs. To take a simple example, policy and management decisions may involve choices between potential abstractions of surface water for supply and the need to maintain flows to dilute point-source effluents (such as treated sewage discharges) to minimize impacts downstream. Diffuse pollution, for example due to nutrients, presents a more complex set of issues with multiple sources (from human sewage, livestock, arable agriculture, industry, and wildlife) and multiple effects on downstream waters including aquatic ecosystem health, amenity, recreation, drinking water treatment, and animal and human health. Turning from surface water to groundwater, we note that overabstraction can lead to degradation of water quality, including salinization of coastal aquifers [*Simmons et al*., 2010], that nutrients in groundwater are increasingly exceeding drinking water limits [see e.g., *Council of Canadian Academies*, 2013] and that managed disposal of wastes (and of course accidental releases) can present threats to groundwater use [e.g., *Peach and Wheater*, 2014]. Pressures on water resources may lead to utilization of water of naturally poor quality, for example, groundwater in Bangladesh with high arsenic concentrations [*Nickson et al*., 2000] or prairie groundwater systems in North America with high concentrations of salts and metals [*Peach and Wheater*, 2014].

There are also important trade-offs inherent in flood risk management. Changing land management, for example, by urbanization, intensification of agricultural production, land drainage, and river training, has the potential to enhance flood risk, but equally, there is the potential to mitigate such risks, e.g., with appropriate urban infrastructure and agricultural management practices (commonly known as Beneficial Management Practices in Canada, Best Management Practices in the USA). Flood risk management can constrain water management when, for example, the operation of even a relatively simple single reservoir involves choices between the need for high storage (to meet future water needs), high discharge for hydropower generation, appropriate discharges and water levels to meet environmental needs, and a requirement to lower reservoir storage to provide temporary storage to minimize flood risk downstream.

Making choices between competing uses raises a complex set of issues around governance (who makes decisions and the social processes surrounding these decisions) that can be exacerbated by interjurisdictional issues, in particular, the competing needs and values of upstream and downstream users [*Gober et al*., 2015]. In the Saskatchewan River Basin, downstream users in the Province of Saskatchewan are significantly more concerned about climate change impacts and drought than those in highly developed upstream Province of Alberta because they worry that Alberta will be unable or unwilling to deliver mandated minimum flows under drought conditions. Upstream concerns are more about land use and developmental pressure in the immediate area.

Competing demands and difficult trade-offs are especially relevant to Canada's First Nations' communities, many of whom lie downstream of developments to the South, including oil sands, pipelines, and hydropower. Such developments are subject to complex and conflicting needs and values, which include economic development and the physical and spiritual well-being of downstream users who depend upon subsistence fishing, farming, and hunting and whose definition of water security is grounded in spiritual values. They are also complicated by legal demands from indigenous peoples with respect to land, water, and natural resources stemming from the 2007 United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP). UNDRIP asserts the right to self-determination and self-government to indigenous peoples worldwide [*von der Porten and de Loë*, 2013, 2014]. This implies a change from traditional collaborative approaches in which indigenous peoples are regarded as stakeholders along with the usual groups who have interest in water decision making. The rights associated with self-determination are quite different from those conveyed by the traditional collaborative process (e.g., the willingness to consider the views of others, decision making by consensus, representation, and inclusiveness). Efforts to integrate the perspectives of indigenous people in water policy reform therefore will require more than addressing the problems of outdated water policies and including First Nations as stakeholders. They will involve changing the very essence of social processes surrounding water policy reform to acknowledge First Nations peoples as exercising their rights of self-determination on preexisting lands and resources.

The previous discussion about competing demands and the need to make value-based trade-offs in water resources management implies that it will not be possible to fulfill all needs, of all people, at all times, given prevailing practices. Moreover, traditional water management has focused on solving clearly defined problems with science-based solutions. Increasingly, however, there are profound disagreements about the problem definition itself [*Head*, 2010]. Altering downstream flows to produce hydropower may or may not be a problem, depending upon whether you care about the need for electricity or the value of downstream aquatic habitats and First Nations livelihoods. Ambiguous problems present significant challenges for science because scientific results are highly dependent upon how the question is posed, data are gathered, and results are interpreted. For ambiguous problems, emphasis is less on the science itself and more on the social processes associated with the conduct of scientific activity. *Cash et al*. [2003] emphasize the importance of producing knowledge that is salient (useful to decision makers), credible (authoritative, trusted, and believable), and legitimate (how fair is the process and does it reflect the values and concerns of a variety of actors) in problems that involve translating knowledge into action. This means that scientists working in their own laboratories and field sites, applying the generally accepted rules of scientific practice, may not be producing scientific results with uptake to decision making. So-called “boundary science” or science for action requires a broader set of participants and brings conflicting values and nontraditional players into the process of defining the research problem, collecting data, and interpreting results. Social scientists are interested in the social processes that surround the conduct of scientific activity in addition to the human dimensions of water system dynamics [*Sarewitz and Pielke*, 2007; *White et al*., 2010; *Dilling and Lemos*, 2011].

The traditional practice of water science is also challenged by the profound uncertainties associated with both the physical and human aspects of complex and dynamic water systems [*Gober et al*., 2010]. *Milly et al*.’s [2008] call to arms that “stationarity is dead: whither water management” implies a need for new modeling methods that incorporate uncertainties associated with climate change, population growth, economic development, technological innovation, public attitudes, and policy decisions. Decision making under uncertainty (DMUU) embraces uncertainty and stresses the need for “robust” solutions that work well under a wide range of future environmental and societal conditions [*Lempert et al*., 2003; *Wilby and Dessai*, 2010]. The search for these robust solutions and building public support for them requires input from a wide range of actors who have not previously been central to water system science and management. Science is but one partner with farmers, the industrial sector, municipal water managers, environmental advocates, energy producers, and recreationists in defining the decision space and critical trade-offs inherent in today’s water system governance.

Policy scientists have coined the term “anticipatory governance” to frame a decision-making context that is alert to change, open to a range of potential future conditions, and flexible enough to change course should the need arise [*Brunner*, 2010; *Comacho*, 2009; *Quay*, 2010].

We conclude that management of water security involves complex decisions concerning multiple dimensions of environmental stressors and multiple human dimensions. The latter include human values and perceptions, problem framing, and the challenges of governance and policy in a contemporary context of deep uncertainty for the future. We turn next to the needs for science to support these management challenges.

3. Science Challenges of the Anthropocene

In the face of increasing pressures on the water environment, new disciplinary science is needed to contribute to a deeper understanding of the components of water system dynamics and their response to environmental change. Much remains to be known about the transport of water and solutes through landscapes, including surface water and groundwater interactions and response to climate variability and change, including extremes. And while much work has focused on humid temperate climates, other environments have their own scientific requirements and challenges, compounded by data limitations. The continuation of in-depth disciplinary research is absolutely needed, in particular with respect to environmental change.

It is however clear from the above discussion that many, if not most, of the applied water problems faced by society cross-disciplinary boundaries, that disciplinary boundaries limit the capacity to interrogate complex systems, and that broader research questions are required if we are to better understand and manage the complex, dynamic, and ambiguous problems of the Anthropocene. We assert that these problems will require a new paradigm for water resources research. This paradigm is predicated on the following assertions:

a. *The effects of the Anthropocene on the water environment are pervasive and poorly understood*. It remains the case that much research on hydrological processes and modeling is focused on natural systems. The challenges of understanding human impacts on the water environment have been relatively neglected; for example, regional and global climate models have until very recently treated the earth as a fictitious natural system [*Nazemi and Wheater*, 2014]. And while much has been written about the hydrological effects of nonstationarity due to climate, following *Milly et al*. [2008], much less attention has been given to changing land and water management. Such human-induced nonstationarity of environmental systems is widespread, with major implications for contemporary hydrology and water management, as well as climate feedbacks. Many of the effects are poorly understood and poorly modeled due to lack of knowledge and/or relevant data. For example, while forestry has been well studied, hydrological effects of agricultural intensification remain quite uncertain [*McIntyre et al*., 2013]. And while the dramatic hydrological effects of urbanization are well known in principle, characterization of impacts at basin scale remains challenging due to the important controls of local infrastructure [*Wheater*, 2006]. Similarly, water management systems are often highly complex and subject to multiple constraints and operational controls. While these may be known at a local level, their representation at regional and global scales is limited [*Nazemi and Wheater*, 2014, 2015a]. These are hydrological examples; similar if not greater needs apply to effects on water quality and aquatic ecosystems.

b. *Managing complex and dynamic systems requires new understanding of process interactions and feedbacks across multiple scales*. As water management must address a range of scales, from local sources to whole river basins and groundwater aquifers, sometimes involving multiple jurisdictions, so also does the underlying science need to cross multiple scales and disciplinary "jurisdictions." Two issues arise from this assertion:

   First, the effects of the Anthropocene are now sufficiently extensive that, in addition to direct impacts of anthropogenic emissions on climate, significant land-atmosphere feedbacks can arise from large-scale changes to land and water management and increasing evidence of feedbacks to local climate is being reported. Effects on climate of the regional-scale changes associated with large-scale irrigation and loss of flows to the Aral Sea have been reported by *Destouni et al*. [2010]. More subtle effects of irrigation and vegetation change on precipitation generation occur, see for example applications in California by *Lo and Famiglietti* [2013] and *Sorooshian et al*. [2011]. This requires new understanding of feedbacks at the scales of influence for weather systems, based on observations and modeling at regional and/or continental scales.

   Second, there is a set of unanswered questions concerning the scale dependence of hydrological processes, and their modeling and parameterization across scales. In particular, with the resolution of weather and climate models rapidly increasing at regional and global scales (e.g., 2.5 km weather modeling was implemented nationally in Canada in 2014), there are significant unanswered challenges for hydrologists concerning the appropriate scale of parameterizations for large-scale application [see e.g., *Wood et al*., 2011; *Beven and Cloke*, 2012]. We noted above that effects of land management can be subtle and dependent on the local environmental context. For example, particular agricultural Beneficial (or Best) Management Practices (BMPs) may be advantageous in one environment and counterproductive in another, and as discussed above, impacts of urban land management often depend on local infrastructure. We therefore need to understand local effects and their larger-scale implications for management. But the need to address process representation across multiple scales is generic, both for natural environmental processes and anthropogenic effects. For example, mountain hydrology is determined by complex interactions between topography, radiation, temperature, and airflows that are strongly affected by local topographic detail [*Marsh et al*., 2012], yet emergent properties must be identified for large-scale application. Hence, new understanding of interactions and feedbacks is needed across multiple scales, and these include the large scales appropriate to the world's major river basins, and at which land and water management may have significant feedbacks to climate systems.

c. *Trans-disciplinary science is needed to capture the effects of human activities on the water environment*. Understanding the Anthropocene requires a holistic approach. This includes integration of knowledge across multiple disciplines. One North American example of a large-scale eco-hydrological interaction involves the death of forests due to bark beetle attack, reflecting warmer winter minimum temperatures and management practices [see e.g., *Bentz et al*., 2010]. A second example is the (large) effects of zebra mussels (an invasive species) on water quality of the Great Lakes [*USEPA*, 2014]. However, we argue that to represent the challenges of the Anthropocene, truly trans-disciplinary research is needed, i.e., research that goes beyond current disciplines [*Meeth*, 1978]. Given that the Anthropocene, by definition, reflects human impacts on the Earth system, this new trans-disciplinary integration must also include the social sciences. At a simple level, flows in a managed river system depend on operational decisions made upstream—to model the actual flows therefore requires a basic understanding of the decision framework. That may be relatively straightforward under normal operations, but less so under droughts when resources are insufficient to meet demands [see *Nazemi and Wheater*, 2015a], under flooding when emergency interventions may be required and under nonstationarity conditions when the idea of "normal" may be fundamentally different from what has been known as normal in the past. At a more complex level, water policy will increasingly require the balancing of competing interests, between sectors of the economy, between upstream and downstream users (perhaps between different national jurisdictions), between human and environmental needs, and between climate risks and the pace of future development. Water use is influenced by societal choice—either expressed through regulation (as in the case of increased domestic appliance water use efficiency), or perhaps by the failure of regulation (noting that rural groundwater abstractions are notoriously difficult to regulate). Hence, river flows and groundwater levels ultimately depend on human actions, human value systems, and their political expression. Key science questions for water security therefore include not only understanding and predicting the effects of environmental change on water quantity and quality and aquatic ecosystems, but also understanding the effects of social values and societal controls on land and water management across multiple scales.

From a management perspective, these needs have long been recognized. The concept of Integrated Water Resources Management (IWRM) evolved from the 1950s and by the 1990s the need for integration within and between the "natural system" (land and water management, surface and groundwater, water quantity and quality, ecosystems) and the "human system" (institutional and policy/economic dimensions, as well as stakeholder engagement) had been articulated [*Cohen and Davidson*, 2011; *Jønch-Clausen and Fugl*, 2001]. However, a significant effort to support IWRM through integration of science and trans-sectoral policy has only recently begun to develop, for example with support from US and EU funding agencies. Recent discussion of socio-hydrology has continued to articulate these issues [*Sivapalan et al*., 2012], while recognizing that a much fuller integration of the social sciences with the natural sciences and engineering is required. In particular, human activities should be regarding as endogenous to, rather than external forcing conditions in, water resource systems.

d. *The social process of stakeholder engagement with water science is at least as important as the knowledge yielded by the science*. There is an abundance of evidence to support the notion that much of the science produced for climate impact assessment has not been incorporated into long-term water planning or climate adaptation efforts [*National Research Council*, 2007]. It has not addressed the problems deemed relevant to decision makers, been packaged or delivered to users in a timely or useful format, or produced with adequate user input, and therefore is lacking the credibility, salience, and legitimacy needed for it to resolve politically contentious and socially significant issues surrounding today's water resources management. *Dilling and Lemos* [2011] emphasize the importance of two-way iterative engagement between

> producers and users of scientific information to build trust and better understand the needs of policy and what scientists can provide to assist policy making. The new research paradigm for science includes a deeper understanding of the social processes that accompany effective science-policy engagement, including social learning, social capital, social memory, and social networks [*Cash et al*., 2003; *Folke*, 2006; *Clark and Clarke*, 2011]. While scientific understanding is critical to evidence-based decision making, local stakeholders are an important source of different types of knowledge; for example, indigenous and other rural communities have a wealth of traditional knowledge, and farmers have deep understanding of their land that is often multigenerational and intimately tuned to natural forces. Ultimately, a wide range of people and organizations have a "stake" in how water is managed, who makes decisions and how the difficult trade-offs discussed earlier are resolved. Essentially, the major challenges of water security lie with governance (who has the power to make decisions and how decisions are made).

These general issues of engagement, communication, and governance are particularly relevant to decision making, in light of the high degree of uncertainty attached to current water decisions. Managing uncertainty will require far more adaptive and flexible strategies than those that pertained in the past, especially given the high level of complexity of water systems and their interdependence with land, energy, and food systems at multiple scales: local to regional and global. Positive feedbacks raise the risk that systems will become unstable and transition to new states that we do not yet know how to manage. *Huitema and Meijerink* [2010] argue that a new paradigm will be required to manage these transitions and build long-term community support needed to sustain long-term goals (as politicians leave public office and water managers retire). Also key to managing these systems in periods of rapid change and high uncertainty is to reduce vulnerability and search for policy solutions that will work well under a range of future conditions [*Nazemi and Wheater*, 2015b].

These new approaches can however draw on a substantial body of research that already exists concerning the needs for integrated assessment and modeling (IAM) in the context of participatory processes. For example, *Hamilton et al*. [2015] provide a recent review of the development of IAM from its inception in the 1990s, through various phases of methodological development, to case study applications in the late 2000s. This work has recognized: (a) the need to frame modeling in the context of the issues of concern (noting that stakeholders may have different perspectives on these), the governance setting, and the human and natural systems to be addressed, (b) the importance of stakeholder participation in the modeling process, including issues definition and problem formulation, and (c) the associated benefits of mutual learning (including conflict resolution). Further, *Guillaume et al*. [2012] propose that uncertainty is an issue to be managed and prioritized in the context of the modeling task.

We conclude from the above discussion that the Anthropocene poses a set of key challenges for the scientific community, and that these provide an agenda to address the critical set of societal challenges identified in section 1.

To implement this agenda, we argue that place-based trans-disciplinary integration is needed, at spatial (and temporal) scales that (a) are meaningful for management and (b) are practical for addressing the complex and multiscalar science challenges defined above. As noted by *Cohen and Davidson* [2011], watershed definition is a multiscale issue linked to governance, and "policy-sheds" can be distinct from watersheds. Nevertheless, in general the watershed is a natural hydrological unit for both water science and water management. Large watersheds provide a framework that can address multiscale governance issues, such as overlapping jurisdictions and potentially competing legislation, and at the same time provide a suitable basis for the large-scale water science needed to address large-scale management, the impacts of human and environmental change, and associated feedbacks. Watershed-based science can offer the focus to address the policy, governance, and management challenges of the Anthropocene.

Elements of this type of infrastructure have been put in place by national programs, although in general these have been primarily focused on the natural science dimensions and informed by scientists' perceptions of science needs. For example, to address the hydro-ecological science needs of the EU Water Framework Directive, the Lowland Catchment Research program (LOCAR) [*Wheater et al*., 2007] moved the UK's experimental basin research agenda from small scale (<10 km^2) to mesoscale (100s of km^2). Modeling at larger scales, but with limited supporting investment in observational infrastructure, was supported by the UK's Terrestrial Initiative in Global Environmental Research (TIGER) [*Cummins et al*., 1995], and more recently,

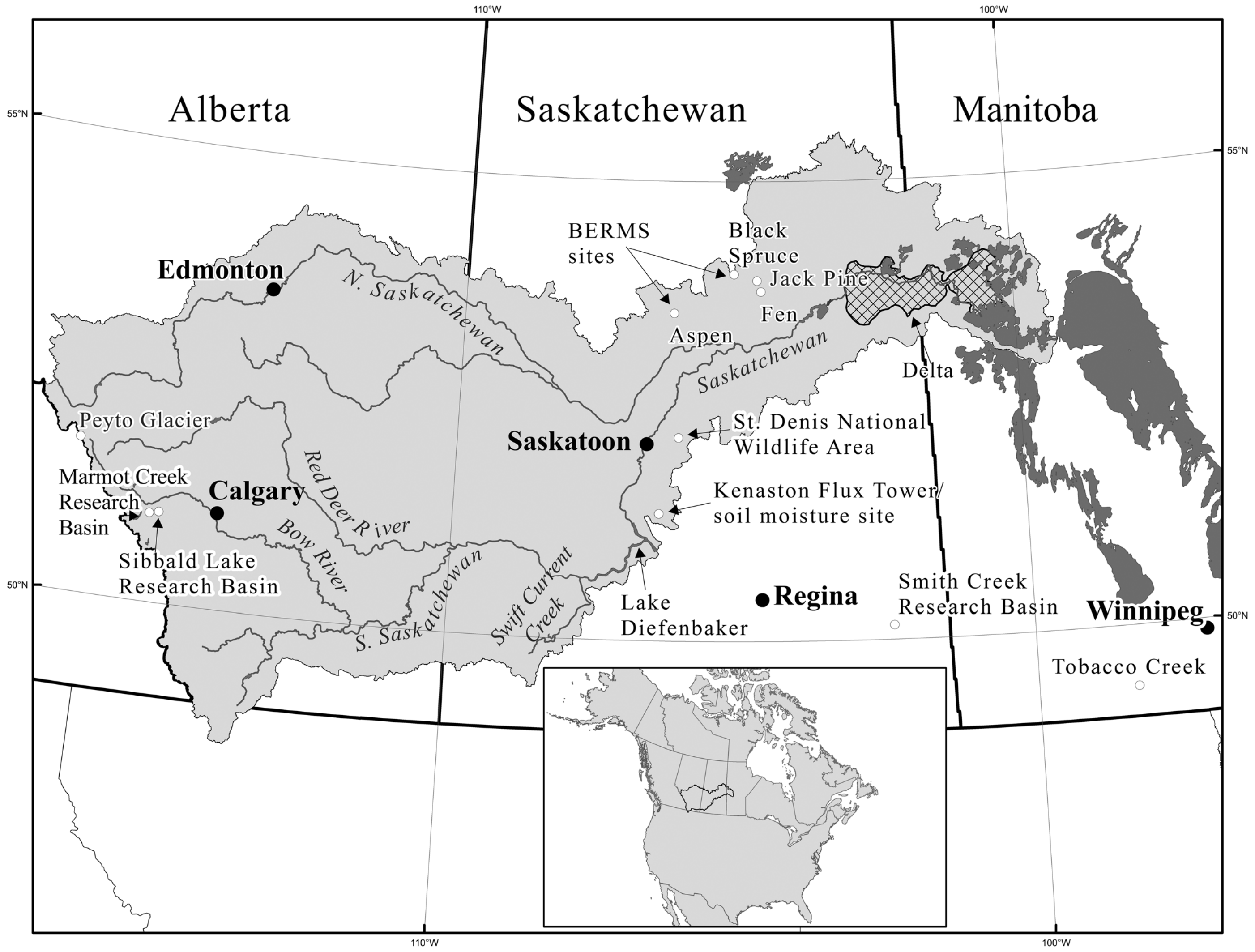

Figure 1. Saskatchewan River Basin (SaskRB) and research sites.

by the EU's WATCH program [*Warnaars et al*., 2009]. In the USA, there has been a strong focus on long-term monitoring and experimentation at small-basin scale with support from US Department of Agriculture (for basins such as Reynolds Creek and Walnut Gulch), the US Forestry Service (for Hubbard Brook, Coweeta, etc.) and most recently the Long Term Ecological Research Network (LTER) and Critical Zone Observatories (CZO) with National Science Foundation support. The Consortium of Universities for the Advancement of Hydrological Science, Inc. (CUAHSI) was formed to support just such an infrastructure investment, but while continuing to play a key role in facilitating research and infrastructure development, ultimately failed to win the necessary resources for a large basin-scale study.

The most significant developments in large basin-scale research are probably those of the World Climate Research Program's Global Energy and Water Exchanges (GEWEX) project. This includes a global network of Regional Hydroclimate Projects (RHPs) (http://www.gewex.org/projects-ghp.html) and historically these have included major basin-scale studies including the Mississippi, Mackenzie, Amazon, Plate, and Murray-Darling, as well as broader-scale studies such as the Baltic Sea Experiment (BALTEX), focused on Baltic Sea tributaries, the Northern Eurasia Science Partnership Initiative (NEESPI), the Monsoon Asian Hydro-Atmosphere Scientific Research and Prediction Initiative (MAHASRI), the African Monsoon Multidisciplinary Analysis project (AMMA) in west Africa, etc. These were designed to address GEWEX priorities related to large-scale science, data products, and modeling associated with global energy and water cycles, but draw on local and regional funding sources and hence commonly address, to a variable extent, linkage to stakeholder needs and concerns. Current projects include the Hydrological Cycle in the Mediterranean (HYMEX) experiment and the Saskatchewan River Basin (SaskRB) project. We argue that such initiatives are well conceived to address the large scales needed to deliver new physical science for the Anthropocene, but that much more remains to be done to develop the required human dimensions of research, and that this is an outstanding priority for the global community.

The SaskRB project was developed in 2010 under the Canada Excellence Research Chairs initiative, funded by Canada's Natural Sciences and Engineering Research Council (NSERC). It was thus defined, in classical manner, by scientists responding to a natural science and engineering funding stream, but a socio-hydrological theme was added to address the multifaceted human drivers of change in the region and to include a participatory process involving a wide range of regional stakeholders. It is described below, as an example of an evolving large basin-scale project which aims to (a) address a range of water security challenges, (b) meet the key requirements for Anthropocene science defined above, and (c) contribute in various ways to the development of the global science agenda.

4. The Saskatchewan River Basin as a Large Basin-Scale Trans-Disciplinary Project

4.1. Basin Selection, Description, and Management Context

The 406,000 km^2 Saskatchewan River Basin (SaskRB) in western Canada (Figure 1) embodies many of the challenges of water security faced worldwide, including fully allocated water resources, a high level of irrigated water use, pressures on water quality, and a recent history of damaging extreme events. It is experiencing rapid economic development and rapid climate warming. It is located in one of the world's more extreme climates and includes environments of global significance, including the Rocky Mountains (source of the major rivers in Western Canada), the Boreal Forest (representing 30% of Canada's land area), and the Prairies (home to 80% of Canada's agriculture).

In Canada, the primary responsibility for water management lies at the provincial level. In this trans-jurisdictional basin, the Canadian Rocky Mountains in Alberta are the dominant sources of river flow, providing some 80% of runoff. The Saskatchewan River's two major tributaries flow east from the continental divide, providing critically important water resources to the province of Saskatchewan, and then Manitoba. The South Saskatchewan River passes through the Canadian Prairies, home to 80% of Canada's agriculture. While most agriculture is based on natural precipitation (in which snow plays a major role), Alberta and Saskatchewan account for approximately 75% of Canada's irrigated agriculture, mostly located in the South Saskatchewan River Basin. Diversions for irrigated agriculture account for some 82% of SaskRB consumptive water use [*Martz et al*., 2007]. The North Saskatchewan River passes through Prairie landscapes and Boreal Forest—an important global ecosystem that represents 35% of Canada's total land area [*Natural Resources Canada*, 2009]. After the confluence of these two major tributaries, the river passes through the Saskatchewan Delta (one of the world's largest inland deltas and North America's largest freshwater wetland, home to First Nations communities), marking the downstream limit of the SaskRB catchment, and enters Lake Winnipeg, ultimately discharging its waters into Hudson Bay. In addition to irrigation, the large-scale development of the river includes dams used for hydropower, water supply (for municipal, agricultural, and industrial use), and flood relief. The largest of these is the 225 km long Lake Diefenbaker multipurpose reservoir in Saskatchewan which stores 9.4 billion cubic meters of water [*Martz et al*., 2007] (Figure 1) and has substantially changed the seasonality of the natural flow regime [*Wheater and Gober*, 2013; *Gober and Wheater*, 2014].

Selection of this watershed at this scale includes trans-boundary governance and overlapping jurisdictions. Each of Canada's three Prairie Provinces has primary responsibility for water management within its own territory, but subject to the Master Agreement on Apportionment [*Prairie Provinces Water Board*, 1969], overseen by the Prairie Provinces Water Board (PPWB) of which the Provinces and the Federal Government (through Environment Canada) are constituent members. Dating from 1969, this agreement determines water allocation; Alberta is required to pass 50% of the natural flows to Saskatchewan, which in turn is required to pass 50% of that inflow plus other natural flows to Manitoba. In a 1992 extension, water quality standards for various parameters were defined at the interprovincial borders (but with a notable exception, see below). Parallel Federal Government responsibilities include fisheries (through the Department for Fisheries and Oceans), which has led to legal disputes concerning aspects of drainage and water quality. There are also statutory duties to consult with First Nations. The basin thus represents a spatial scale that addresses issues of relevance to both governance and large-scale science.

Extremes are a defining feature of the Prairie's climate and culture. Recent examples include the major drought of 1999–2004, described at the time as Canada's most costly natural disaster, with a $3.6 billion drop in agricultural production in the years 2000–2001 and a $5.8 billion decline in Gross Domestic Product (GDP) [*Wheaton et al*., 2008]. Flooding has been a recurring problem in recent years. An extreme event in 2013 gave rise to severe flooding in Alberta that caused four deaths and more than $6 billion in direct damage [*CBC News*, 2013]. Changing patterns of runoff in the prairies have been apparent, with summer rainfall flood runoff exceeding spring snowmelt (J. Pomeroy, personal communication, 2015). Management and policy concerns include flood forecasting capability, reservoir management, the role and viability of publically funded flood insurance, policies for wetland protection, and the need for improved legislation (and its enforcement) to control drainage. Management concerns also include provision of water resources to three million inhabitants, including rural and indigenous communities. As noted above, the water resources of the South Saskatchewan are fully allocated in Alberta. In Saskatchewan the agriculture industry has ambitions to increase investment in irrigation; issues include balancing the needs for industrial and natural resource development with those of agriculture and hydropower. And while the Master Agreement provides simple rules for water sharing between the provinces, concerns have been expressed that the agreement might fail under extreme drought.

Environmental flows are an emerging issue. For example, regulation has changed the seasonality of flows, and impacts on the delta ecosystem are not well understood. Water quality issues include nutrient pollution from major cities and agricultural production. Water quality in Saskatchewan's major reservoir (Lake Diefenbaker) is deteriorating, with increasing concern over eutrophication and water supply [*Hecker et al*., 2012], and the SaskRB is a tributary of Lake Winnipeg, which in 2007 had an algal bloom of 15,000 km^2 [*Kling et al*., 2011], due to nutrient loads from both the US and Canada. As elsewhere, nutrient loads provide a major science and policy challenge [*National Academy of Engineering*, 2008]. It is noteworthy that under the interprovincial Master Agreement a limit value for total phosphorus is specified at the (downstream) Saskatchewan-Manitoba border, but not at the (upstream) Alberta-Saskatchewan border. One of the effects of high nutrient loads is to raise challenges for water treatment processes, and exceedances of trihalomethane standards in rural drinking water are common. We also note that prairie streams are typically ephemeral (dominated by spring snowmelt), so that for much of the year water quality reflects effluent discharges. Issues of concern include not only nutrients [*Waiser et al*., 2011a] but also exotic chemicals such as pharmaceutical products [*Waiser et al*., 2011b].

Groundwater is of some strategic importance, but has received relatively little detailed analysis [*Peach and Wheater*, 2014]. Groundwater resources currently provide essential domestic and municipal drinking water supplies to many communities outside the major cities, and the mining and oil and gas industries use groundwater in their extraction processes when surface waters are not readily available, for example due to distance from a main river. The pore space of geological formations beneath the Prairies is also used for the disposal of wastewaters from mining and oil and gas development, and the world's first operational Carbon Capture and Storage project. Additionally, the role of groundwater in the provision of base flow to the main rivers is currently thought to be small, but climate change may mean that it is of growing importance, for example, as glaciers retreat in the Rocky Mountain headwaters.

4.2. Science Strategy and Infrastructure

For this basin, a research strategy was (of necessity) adopted that involved prior definition of an initial set of science questions that were of relevance to key basin-scale water management challenges, and addressed a set of generic research questions. During the last 4 years, these have been progressively reviewed, refined, and expanded, based on a wide range of different types of engagement with stakeholder groups. Understanding of stakeholder needs has been developed through discussions (and with federal and provincial agencies, joint research) with the Prairie Provinces Water Board, provincial government ministers and agencies, federal agencies (Environment Canada, Agriculture and Agri-Food Canada, Natural Resources Canada, and Parks Canada), local watershed associations, First Nations communities, and local residents' associations. Refinement of the science needs has been supported by interdisciplinary place-focused working groups within the Global Institute for Water Security (faculty from 14 academic units and Federal scientists).

The initial research foci included the need to improve understanding and modeling of (i) climate variability and change over the basin, including, the key biomes of the Rocky Mountains, Boreal Forest and Prairies, and in particular, the extremes of floods and droughts, (ii) effects of land use/management change on water flows, water quality, and environments of regional and global importance, and (iii) societal controls on water management, including operational constraints, water management vulnerabilities, and policy and governance opportunities. Improved science is needed to support local issues of water management, basin-scale management of water quantity and quality, and more generally to address the diagnosis and prediction of changing interactions and feedbacks between the climate, land, and water components of the earth system.

4.2.1. Observatory Sites

The strategy adopted has been to develop the basin as a whole as a large-scale observatory, supported by multiscale observations of river flow (using a base network of 50 Environment Canada (EC) gauging stations), distributed precipitation and networks and climate stations, remote sensing data, and modeled data products. A series of major research sites has been developed to address the need for improved understanding of environmental and anthropogenic change in the key biomes (Figure 1). These include detailed observations, at local to small basin-scale, and build on legacy data to provide an historical context for the improved understanding and diagnosis of environmental change [e.g., *van der Kamp et al*., 2003; *DeBeer and Pomeroy*, 2009; *Barr et al*., 2012]. These sites provide the basis for the development of improved process understanding and fine-scale models and the application of those models in the analysis and prediction of environmental change at local scales. They also provide an important resource for the development and testing of improved large-scale models, which are needed for weather and climate models and for large basin-scale hydrological, water resource, and water quality modeling. In addition, key sites are attractors to related international research, as noted below.

A network of sites in the Canadian Rocky Mountains is centered on Marmot Creek, a research focus for 50 years that was near the epicenter of Alberta flooding in June 2013 [*Pomeroy et al*., 2012]. With intensive instrumentation to observe cryospheric and hydrological processes, the site provides a key test bed to understand and model effects of rapid warming on mountain hydrological processes. This has provided the stimulus for the International Network for Alpine Research Catchment Hydrology, a GEWEX crosscut theme that links global research to address the challenges of observing and modeling the alpine systems that provide water resources to 50% of the world's population. Sibbald Wetlands is the focus of hydro-ecological research into Rocky Mountain wetlands and the effects of current and legacy beaver activity on flows and water quality [*Janzen and Westbrook*, 2011].

Boreal Forest research derives from a set of globally important experimental sites developed under the international BOREAS (Boreal Ecosystem-Atmosphere Study) initiative to measure land-atmosphere exchanges of carbon, water, and energy [*Barr et al*., 2012]. Based on measurements of soil water, groundwater, surface water, and ecological processes, research objectives include assessment of the vulnerability of ecosystem response to climate variability and change, and the synthesis and upscaling of hydro-ecological understanding of stand-scale processes. The site has attracted collaboration with NASA's AirMOSS (Airborne Microwave Observatory of Subcanopy and Subsurface) and SMAP (Soil Moisture Active Passive) remote sensing soil moisture missions.

The Prairies present a wide range of science and management challenges; hence, multiple prairie research sites have been developed. St. Denis National Wildlife Area consists of numerous prairie pothole lakes of varying salinity. With a 60 year history, research at this site focuses on runoff processes and pothole lake connectivity, surface-subsurface interactions, and salinity dynamics [*Nachshon et al*., 2014]. Brightwater Creek, near Kenaston, Saskatchewan, a relatively typical flat agricultural area, provides a focus for multiple-scale monitoring of spatial soil moisture, groundwater, and land-atmosphere interactions. In collaboration with EC, Agriculture and Agri-Food Canada (AAFC) and the University of Guelph, this site is also a test bed for NASA's SMAP soil moisture remote sensing mission, launched in 2014, and has also provided local test data for GRACE evaluation [*Lambert et al*., 2013]. The site provides a focus for hydrological and land-surface multiscale modeling and study of the impacts of different agricultural land management practices on land-atmosphere feedbacks.

Three additional prairie sites provide relevant data and address different aspects of prairie hydrology and agricultural management. Hydrological connectivity and the effects of agricultural drainage on flows and water quality is the research focus at Smith Creek, Saskatchewan. The site has demonstrated the dramatic effects of interannual climate variability on water quality and a complex response of flood generation and transmission to agricultural drainage [*Shook and Pomeroy*, 2011]. In collaboration with local community organizations, EC, AAFC, and the University of Manitoba, the effects of agricultural Beneficial Management Practices (BMPs) on flows and water quality, particularly those associated with changing tillage practices and on-farm reservoirs, are explored at Tobacco Creek, Manitoba (T. H. Mahmood et al., Hydrological responses to dry and wet conditions in an agricultural cold region, submitted to *Hydrological Processes*, 2014). A principal goal of this research is to develop improved local and regional modeling capability for BMPs. Finally, Swift Current, Saskatchewan is home to AAFC agricultural research runoff plots with high-frequency, long-term data to support experimental monitoring of the surface hydrology and hydrological model building and testing to improve understanding of the fundamental drivers of threshold-like hydrological runoff responses to snowmelt and rainfall events in a semiarid, prairie landscape.

4.2.2. Surface Water Systems and Surface Water Quality

The research observatories described above focus on land-atmosphere processes, and the delivery of water (and solutes) to the aquatic environment. A dominant issue for the region (and a global grand challenge as noted earlier) is the management of nutrients. The first major study of pollutant loads and their ecological impacts for the South Saskatchewan River, Lake Diefenbaker and its tributary, Swift Current Creek (SCC), is under way [*North et al*., 2014]. Lake Diefenbaker is 225 km long and plays a major role in economic and social development of a large proportion of the province. However, the capability of the reservoir to continue to provide water of reasonable quality under rapid economic development and under a changing climate is unknown, given nutrient loads and increasing evidence of eutrophication. A comprehensive evaluation of the sensitivity of the reservoir to current and future nutrient inputs includes limnology, paleolimnology, toxicology, and hydrodynamic water quality modeling (A. Sadeghian et al., Water quality modelling of Lake Diefenbaker, submitted to *Journal of Great Lakes Research*, 2015). A similar study has been initiated for Buffalo Pound Lake, including real-time water quality monitoring to support treatment of this major source of drinking water for the cities of Regina and Moose Jaw, Saskatchewan. Research to explore other water quality issues in the basin ranges from the study of the winter biogeochemistry of lakes to the monitoring of pharmaceutical products and heavy metals in urban wastewater and storm water.

4.2.3. Wetland Habitats: The Saskatchewan Delta

Located near the Saskatchewan/Manitoba border, the Saskatchewan River Delta is a complex series of abandoned and active river channels, lakes, and wetlands. Home to Cumberland Marshes which has been designated as an Important Bird Area, this region experiences the accumulated effects of upstream water use, including abstractions and power generation. Since the beginning of the last century, annual discharge has been reduced by approximately 30%. In addition, winter base flow is now higher and spring freshets have been dampened due to capture and storage in the dams. Interdisciplinary expertise in climate, hydrology, ecology, and social science is being integrated to address the cumulative responses of these changes in flow for the production of fish, water-birds, and mammals, and for the associated impacts on the activities and livelihoods of local communities. One aim of this research is to develop scenarios and an operational plan to provide for sustainable hydropower output from upstream dams without endangering the Delta habitat in the long term.

4.2.4. Groundwater

Groundwater is of importance to the economic development and well-being of the SaskRB, but has received relatively little detailed analysis [*Peach and Wheater*, 2014]. St. Denis, discussed above, has provided a focus for research into near-surface groundwater and groundwater surface water interactions, but additional research sites need to be developed. A major project is currently under development to evaluate the hydrogeology associated with the Bakken shale oil play in the south of the Prairies, including the sustainable yield from the Quaternary and (lower quality) Tertiary and Upper Cretaceous aquifers, the role of aquitards and buried valleys and cumulative impacts of deep waste disposals.

4.3. Modeling Under Current and Future Climate

High-quality hydrological and water quality data from the research sites and their small-scale basins are essential to provide new process insights and to develop improved models to support management and hydro-ecological and climate modeling. For example, a focus for process modeling is the Cold Region

Hydrological Modeling (CHRM) system [*Pomeroy et al*., 2007] which represents key cold region hydrological processes (e.g., frozen soils and blowing snow) and has been used worldwide. Local applications include exploration of effects of changing mountain hydrology and agricultural practices. Observatory data have led to improved algorithms for (i) soil freezing-thawing, (ii) frost table impacts on soil moisture storage and hydraulic conductivity, (iii) flow through organic materials, (iv) snow dynamics on glaciers, (v) snow redistribution by avalanche, and (vi) wetland fill and spill. New multiscale algorithms have been developed for fine-scale modeling of radiative transfer to snow under forests and in forest gaps; research from Tobacco Creek is being used to introduce agricultural water quality into CRHM. Other platforms are being used to explore the movement of water in frozen soil and coupled runoff-dissolved organic carbon algorithms to improve our understanding of coupling between the carbon and water balance. The sites also provide data to support the testing, intercomparison and refinement of land-surface schemes for weather, climate, and large-scale hydrological models, including the Canadian Land Surface Scheme (CLASS) and its hydrological extension (MESH), NCAR's WRF system, including CLM and NOAH-MP, and the UK's JULES modeling system. Preliminary work is under way on coupled hydro-ecological models, in particular using the Canadian CTEM model (linked to CLASS). One outcome thus far is an improved large-scale prairie model [*Mekonnen et al*., 2014]. Modeling research is also providing new insights into the connectivity of prairie lakes and wetlands, in particular showing complex cycles of hysteresis as wetlands fill, spill, and empty under cycles of wet and dry years [*Shook and Pomeroy*, 2011, 2012; *Shook et al*., 2013].

The SaskRB embodies many of the management pressures experienced worldwide, and an important objective of the SaskRB is to provide improved modeling tools and methodologies to address water management at the river basin scale, as well as the need to support improved weather prediction and global and regional climate modeling.

Large-scale hydrological model capability is needed for a range of applications, including flood forecasting, flood risk management, water resource operational management and planning as well as the analysis of land atmosphere feedbacks under changing land management and climate. Work is under way to develop improved capability to address these needs. Preliminary analysis (using MESH) has identified key issues to be addressed. These include, for example, uncertainty in inputs (particularly precipitation), the representation of key biomes (in particular upscaling of mountain hydrological processes and representation of variable contributing areas in the prairies), the representation of water management (e.g., reservoirs and irrigation [see *Nazemi and Wheater*, 2015a,b]), the utility of remote sensing products such as GPM, SMAP, and GRACE and regionalization of model parameters.

A critical need is to understand better climate variability and change and to provide improved tools to evaluate scenarios of future climate. Research is therefore under way into climate processes and modeling, including Rocky Mountain precipitation and convective precipitation over the Prairies. This includes detailed analysis of the 2013 Calgary flood event using high-resolution atmospheric modeling. Concerning future climate, improved statistical downscaling methods have been developed for the Prairie Provinces, providing improved capability to generate time series of precipitation and evaporation for future climate scenarios [*Chun et al*., 2013], and detailed multimodel analyses have been made of the North American Regional Climate Change Assessment Program [*Khaliq et al*., 2014], providing new insights into the current skill levels of regional climate models and the model uncertainty associated with future projections. Current work on extreme precipitation and drought is building on the IPCC AR5 (Intergovernmental panel on climate change—Fifth assessment report) climate model results [*Asong et al*., 2014].

The development of new water resources modeling and decision support tools is required, given the challenges of decision making under uncertainty [*Lempert et al*., 2003; *Gober and Wheater*, 2014]. Traditional approaches to assess effects of future climate involve a cascade of uncertainty; uncertain future emissions and socio-economic scenarios are used to generate uncertain outputs from global or regional climate models, which are downscaled and input to hydrological models, introducing further uncertainty [*Wilby and Dessai*, 2010]. While such modeling remains important for the prediction of change, the large associated uncertainties have inhibited usefulness for decision making. Through collaboration with Alberta in simulating the response of the complex South SaskRB water resource system in Southern Alberta (11,000 license holders), a new approach has been developed to assess water resource vulnerability to climate change [*Nazemi et al*., 2013; *Nazemi and Wheater*, 2014]. A major focus has also been on the development of user-focused decision support modeling tools, with which stakeholders can be engaged in a dialog. A new systems dynamic modeling capability has been developed for the province of Saskatchewan that is capable of interactive exploration of scenarios of changing inflows from Alberta and changing agricultural, domestic, and industrial water use in the province. This includes capability for dynamic (climate-dependent) irrigation demand and economic valuation [*Hassanzadeh et al*., 2014]. The project is working toward a basin-wide (multiprovince) simulation capability that can be used for risk-based assessment of future water scenarios. To support this, paleoclimate evidence provides important insights into historical drought on a time scale of many centuries. Hence, research is developing improved reconstructions of paleoclimate, based on multivariate tree ring analysis [*Razavi et al*., 2015].

Water quality modeling includes development of a nutrient model for the SaskRB, a tributary of Lake Winnipeg, based on the U.S. Geological Survey SPARROW (SPAtially Referenced Regressions ON Watershed attributes) modeling platform, to provide the first basin-wide modeling capability with which nutrient management issues can be explored and to assist the work of the Canada-US International Joint Commission.

The range of modeling outlined above is not exhaustive, but illustrates the capability of a large basin-scale observatory to address (a) a wide range of science issues, including diagnosis and prediction of environmental change, and the interactions and feedbacks within changing earth system processes, including human activities, and (b) a range of local to large basin-scale management issues associated with water quantity, water quality, extreme events, and water futures, including user-focused models and analysis of vulnerabilities to change.

4.4. Socio-Hydrology and the Science-Policy Interface

The Anthropocene's science problems as articulated in section 3 are, by definition, social science problems because they involve the human drivers and impacts of environmental change, feedbacks between human and biophysical processes in complex and dynamic environmental systems, the practice of science as a social institution, and the social processes of stakeholder engagement. The SaskRB Project has used the term "socio-hydrology" to capture a range of activities designed to bring out the human dimensions of water science. *Sivapalan et al*. [2012] reintroduced the term "socio-hydrology" to describe the study of the "coevolution of human-natural coupled systems," arguing that it is not possible to predict water cycle dynamics over decadal or longer time periods without considering the interactions and feedbacks among natural and human components of the water system. These feedbacks have potential to move systems beyond critical tipping points into new, previously unobserved states [*Scheffer*, 2009]. There has been a good deal of discussion in the policy community about how to manage these transitional periods when the paradigms of traditional water management are designed for stationary conditions [*Folke et al*., 2005; *Huitema and Meijerink*, 2010]. To these science and management issues, we have added the need for greater collaboration between the science and policy communities [*Gober and Wheater*, 2014], noting that science-based water planning requires not only knowledge about human-natural coupled systems but also about the social processes by which knowledge is transferred through social systems embedded in place-based contexts.

Socio-hydrology in the SaskRB Project has included studies of the values, attitudes, concerns, and decision context for regional water stakeholders. If, in fact, it will not be possible to meet the needs of all users for all purposes at all times in the Anthropocene, then it is critical to understand what people are most concerned about and why. Online interviews and a series of workshops with water managers, irrigators, scientists, representatives of environmental groups, and members of First Nations communities revealed that regional water stakeholders place higher priority on the human components of water security, such as governance, land use, and competing demands, than on physical problems such as climate change, drought, and flooding [*Gober et al*., 2015]. Results imply that framing water security in terms of its social and human dimensions offers more potential to unite actors under a common umbrella of water security than a physical-hazard-based approach. Multiple competing definitions for water security offer an opportunity for actors with quite different perspectives on water security to move forward in policy debate and look for common ground and ways to live with their differences. Political scientists argue that ambiguity allows actors to blur or hide their differences and assists them in avoiding barriers that would otherwise block consensus [*Stone*, 2002; *Fisher*, 2003]. Data from the same workshops and interviews, subjected to Q-Sort analysis, differentiated between two different conceptualizations of sustainability in the context of water security [*Strickert et al*., 2015]. So-called "weak sustainability" defines sustainability in strictly human terms as a nondeclining stock of economic capital and allows substitution between human and natural capital. "Strong sustainability" supports the position that there are limits on substitution based on the intrinsic value of natural assets and that humans need to consume less to support earth's long-term natural capital. Respondents who hold the former position typically support sustainable economic development; while those with the latter are concerned with trade-offs between natural and human capital.

SaskRB socio-hydrology has also followed *Sivapalan et al.*'s [2012] modeling agenda [*Hassanzadeh et al.*, 2014]. *The* so-called SWAMP model has been used for futures analysis to evaluate trade-offs between investments in irrigated agriculture vis a vis hydropower generation. It has also been used to assess system vulnerability to a range of climate change conditions [*Nazemi et al.*, 2013] and stochastic reconstructions of historical conditions. Results show that water availability is sensitive to both the level of irrigation development and to climate change-induced variation in the volume and peak timing of flows. Large irrigation expansion is feasible, but would exacerbate drought stress on the current water resource system, produce unstable economic revenues, and decrease flood frequency in the Saskatchewan River Delta, a region of high biodiversity and environmental significance and home to First Nations people who subsist on the Delta for hunting, fishing, and farming [*Hassanzadeh et al.*, 2014].

In addition, socio-hydrology includes activities that connect research outputs to decision makers and the general public. For example, the Invitational Drought Tournament (IDT) is a 1 day workshop designed to enhance discussions among interdisciplinary groups about how to manage the immediate and longer-term effects of droughts—how to anticipate drought and plan for it [*Hill et al.*, 2014]. The IDT presents teams with scientifically derived drought scenarios [*Lapp*, 2012] and then asks them to select from a list of adaptation options for drought mitigation, differentiating impacts on society, economy, and environment. The IDT allows participants to consider trade-offs associated with different mitigation options, for instance, whether to improve the efficiency of irrigation networks by 25% or to promote stocking rate reductions.

Another experiment in socio-hydrology involved the production and showing of "downstream," a forum-theater production which was derived from SRB stakeholder perspectives (G. E. H. Strickert and L. E. A. Bradford, Of research pings and ping-pong balls: A protocol for the use of forum theatre as engaged water security research, submitted to *International Journal of Qualitative Methods*, 2015). The narrative involved the downstream consequences of a flood from an irrigated farm upstream, via fish in the river, a First Nation's owned golf course, municipal water treatment plant, prairie town, and a midstream oil field to a SR Delta village downstream. At each point along the way, relevant characters plead with the audience for the resources needed for flood management, and deflect insults from other stakeholders. The audience allocated resources in response to the theatrical performance [*Bradford et al.*, 2014]. The interactive play, downstream, conveyed the complex context for flood management decision making, used science-based flood scenarios, and called upon the audience's values, emotions, and attitudes about flood risk for mitigation strategies, policy reform, and adjudicating among competing interests. It combined emotions about water with water science via a structured activity and the social process of theater.

4.5. Discussion

After 4 years, the SaskRB project continues to evolve to address the science agenda as defined in section 3, including partnerships with stakeholders and policy makers. An example of trans-disciplinary research is the Delta project, which deals with an increasing human-driven system, complex in its governance and social challenges, and includes climatology, hydrology, ecology, toxicology, and social science. There has been intensive stakeholder engagement from the beginning and active First Nations participation. The research questions are ambiguous and defy traditional science questions, uncertainty is high, and the system is complex.

These are early steps, and much more remains to be done to respond to the socio-hydrology mandate, both with respect to modeling complex systems [*Sivapalan et al.*, 2012] and developing social processes to surround scientific activities [*Gober and Wheater*, 2014]. However, we present the SaskRB, with its current strengths and limitations, as an example of the potential of a large-scale observatory as a focus for science integration, and a program that has been developing in the light of the discussion above of societal needs and the associated science agenda.

5. Conclusions

As we celebrate the 50th anniversary of *Water Resources Research*, the water environment worldwide faces daunting problems of unsustainable water demand, degraded water quality, groundwater drawdown, loss of aquatic habitats and species, and increasing vulnerability to extreme events. While water management has been seen as a local and regional issue, we now live in an era where drought can affect global food supplies and political systems. The challenges of water management are complex, uncertain, and ambiguous. As we increase stress on water systems, there are urgent science needs to improve our understanding of these natural systems. However, in an era now named the Anthropocene, to reflect the dominant impact of human activities on the earth system, the water sciences must address the challenges of better understanding the human dimensions of water systems and integrate the biophysical and societal drivers and impacts of complex water systems.

We have asserted above that the effects of the Anthropocene on the water environment are pervasive and poorly understood, that managing complex and dynamic systems requires new understanding of process interactions and feedbacks across multiple scales, that trans-disciplinary science is needed to capture the effects of human activities on the water environment, and that the social process of stakeholder engagement with water science is at least as important as the knowledge yielded by the science.

We thus argue for new trans-disciplinary water science that (i) engages and integrates the natural sciences, engineering and the social sciences, (ii) focuses on system dynamics in which human and natural components interrelate, (iii) incorporates local and regional scales where water decision making for the most part occurs, (iv) addresses decision making under uncertainty which seeks to manage, not control, the uncertainties that underlie both biophysical and human systems, and (v) supports the observational networks that link research results across sites and across scales. In this view, water scientists and communities are partners in understanding and managing change. Our conclusion is that these represent both an unprecedented challenge and unprecedented opportunity for the water sciences.

Research activities from the SaskRB represent one effort to focus on in-depth local processes, link them to larger-regional scale change and function within a larger global network seeking to implement a new science model linked to decision making for the Anthropocene. This imperfect example will perhaps stimulate the next generation of large-scale research initiatives, which are in our opinion urgently needed as we look at the current and future water challenges facing North America and the world.

Acknowledgments

We thank the Editor for the invitation to contribute this article at a defining point in the history of *Water Resources Research*. The SaskRB is a Regional Hydroclimate Project of the World Climate Research Program's Global Energy and Water Exchanges Project, and the support and endorsement of the GEWEX Hydroclimate Panel is much appreciated. The SaskRB project receives financial support from the Canada Excellence Research Chair in Water Security, with funding from Canada's Federal Government National Science and Engineering Council (NSERC), the Province of Saskatchewan, and the University of Saskatchewan. Additional infrastructure support has been provided by the Canadian Foundation for Innovation, and additional research is funded by the Province of Saskatchewan, numerous grants to Global Institute for Water Security members from NSERC, the Social Sciences and Humanities Research Council (SSHRC) and from industry, not least SaskPower. Further information on research related to the Saskatchewan River Basin and access to relevant data can be found at www.usask.ca/water.

References

Allan, J. A. (2003), Virtual water: The water, food, and trade nexus: Useful concept or misleading metaphor?, *Water Int.*, *28*, 106–113, doi:10.1080/02508060.2003.9724812.

Arnell, N. W., and S. N. Gosling (2014), The impacts of climate change on river flood risk at the global scale, *Clim. Change*, 1–15, doi:10.1007/s10584-014-1084-5.

Asong, Z. E., N. Khaliq, and H. S. Wheater (2014), Regionalization of precipitation characteristics in the Canadian Prairie Provinces using large-scale atmospheric covariates and geophysical attributes, *Stochastic Environ. Res. Risk Assess.*, *29*(3), 875–892, doi:10.1007/s00477-014-0918-z.

Barr, A. G., G. van der Kamp, T. A. Black, J. H. McCaughey, and Z. Nesic (2012), Energy balance closure at the BERMS flux towers in relation to the water balance of the White Gull Creek watershed 1999–2009, *Agric. For. Meteorol.*, *153*, 3–13, doi:10.1016/j.agrformet.2011.05.017.

Bentz, B. J., J. Regniere, C. J. Fettig, E. M. Hansen, J. L. Hayes, J. A. Hicke, R. G. Kelsey, J. F. Negron, and S. J. Seybold (2010), Climate change and bark beetles of the western United States and Canada: Direct and indirect effects, *BioScience*, *60*(8), 602–613.

Beven, K. J., and H. L. Cloke (2012), Comment on: "Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water" by Eric F. Wood et al., *Water Resour. Res.*, *48*, W01801, doi:10.1029/2011WR010982.

Bloomberg (2014), California drought transforms global food market. [Available at http://www.bloomberg.com/news/2014-08-11/california-drought-transforms-global-food-market.html, last accessed 16 Dec. 2014.]

Bradford, L. E. A., G. E. H. Strickert, D. A. Clark, N. Koechl, G. Marion, I. Rose, B. Kobelsky, C. Orosz, and K. T. Williams (2014), Downstream: A performance-based knowledge mobilization project for water security, internal report, 30 pp., *Global Inst. for Water Security*, Saskatoon, Saskatchewan, Canada.

Brunner, R. D. (2010), Adaptive governance as a reform strategy, *Policy Sci.*, *43*(4), 301–341.

Cash, D. W., W. C. Clark, F. Alcock, N. M. Dickson, N. Eckley, D. Guston, J. Jäger, and R. Mitchell (2003), Knowledge systems for sustainable development, *Proc. Natl. Acad. Sci. U. S. A.*, *100*, 8086–8091.

CBC News (2013), Calgary floods to cost economy billions, 25 Jun. [Available at http://www.cbc.ca/news/canada/calgary/calgary-floods-to-cost-economy-billions-1.1365207, last accessed 16 Dec. 2014.]

Chun, K. P., H. S. Wheater, A. Nazemi, and M. N. Khaliq (2013), Precipitation downscaling in Canadian Prairie Provinces using the LARS-WG and GLM approaches, *Can. Water Resour. J.*, *38*(4), 311–332, doi:10.1080/07011784.2013.830368.

Clark, J. R. A., and R. Clarke (2011), Local sustainability initiatives in English National Parks: What role for adaptive governance?, *Land Use Policy*, *28*(1), 314–324, doi:10.1016/j.landusepol.2010.06.012.

Cohen, A., and S. Davidson (2011), The watershed approach: Challenges, antecedents, and the transition from technical tool to governance unit, *Water Alternatives*, *4*(1), 1–14.

Comacho, A. E. (2009), Adapting governance to climate change: Managing uncertainty through a learning infrastructure, *Emory Law J.*, *59*(1), 1–77.

Cook, C., and K. Bakker (2012), Water security: Debating an emerging paradigm, *Global Environ. Change*, *22*, 94–102.

Council of Canadian Academies (2013), *Water and Agriculture in Canada: Towards Sustainable Management of Water Resources*, 259 pp., The Expert Panel on Sustainable Manage. of Water in the Agric. Landscapes of Canada, Ottawa, Ont.

Crutzen, P. J. (2002), Geology of mankind: The Anthropocene, *Nature*, *415*, 23, doi:10.1038/415023a.

Cummins, C. P., M. A. Beran, B. G. Bell, and H. R. Oliver (1995), The TIGER programme, *J. Biogeogr.*, *22*, 897–905.

DeBeer, C. M., and J. W. Pomeroy (2009), Modelling snowmelt and snowcover depletion in a small alpine cirque, Canadian Rocky Mountains, *Hydrol. Processes*, *23*, 2584–2599.

Destouni, G., S. M. Asokan, and J. Jarsjö (2010), Inland hydro-climatic interaction: Effects of human water use on regional climate, *Geophys. Res. Lett.*, *37*, L18402, doi:10.1029/2010GL044153.

Dilling, L., and M. Lemos (2011), Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy, *Global Environ. Change*, *21*, 690–689.

Environment Agency of England and Wales (2009), Water for people and the environment: Water resources strategy for England and Wales, Environment Agency, Bristol, U. K. [Available at www.environment-agency.gov.uk, last accessed 23 Dec. 2014.]

Fisher, B., K. R. Turner, and P. Morling (2009), Defining and classifying ecosystems services for decision making, *Ecol. Econ.*, *63*(3), 643–653.

Fisher, F. (2003), *Reframing Public Policy: Discursive Politics and Deliberative Practices*, Oxford Univ. Press, N. Y.

Folke, C. (2006), Resilience: The emergence of a perspective for social-ecological systems analyses, *Global Environ. Change*, *16*(3), 253–267, doi:10.1016/j.gloenvcha.2006.04.002.

Folke, C., T. Hahn, P. Olsson, and J. Norberg (2005), Adaptive governance of socio-ecological systems, *Annu. Rev. Environ. Resour.*, *30*, 441–473, doi:10.1146/annurev.energy.30.050504.144511.

Food and Agriculture Organization of the United Nations (FAO) (2012), *State of the World's Forests 2012*, 46 pp., Rome.

Gleeson, T., Y. Wada, M. F. Bierkens, and L. P. van Beek (2012), Water balance of global aquifers revealed by groundwater footprint, *Nature*, *488*, 197–200.

Global Water Partnership (2000), *Towards Water Security: A Framework for Action*, Stockholm.

Gober, P., and H. S. Wheater (2014), Socio-hydrology and the science-policy interface: A case study of the Saskatchewan River Basin, *Hydrol. Earth Syst. Sci.*, *18*, 1413–1422.

Gober, P., C. Kirkwood, R. C. Balling Jr., A. W. Ellis, and S. Detrick (2010), Water planning under climatic uncertainty in Phoenix: Why we need a new paradigm, *Ann. Assoc. Am. Geogr.*, *100*(2), 357–372.

Gober, P. A., G. E. Strickert, D. A. Clark, K. P. Chun, D. Payton, and K. Bruce (2015), Divergent perspective on water security: Bridging the policy debate, *Prof. Geogr.*, *67*(1), 62–71, doi:10.1080/00330124.2014.883960.

Gosling, S. N., and N. W. Arnell (2013), A global assessment of the impact of climate change on water security, *Clim. Change*, 1-15, doi:10.1007/s10584-013-0853-x.

Guillaume, J. H. A., M. E. Qureshi, and A. J. Jakeman (2012), A structured analysis of uncertainty surrounding modelled impacts of groundwater-extraction rules, *Hydrogeol. J.*, *20*, 915–932.

Hamilton, S. H., S. ElSawah, J. H. A. Guillaume, A. J. Jakeman, and S. A. Pierce (2015), Integrated assessment and modelling: Overview and synthesis of salient dimensions, *Environ. Modell. Software*, *64*, 215–229.

Hanasaki, N., et al. (2013), A global water scarcity assessment under shared socio-economic pathways—Part 1: Water use, *Hydrol. Earth Syst. Sci.*, *17*, 2375–2391.

Hassanzadeh, E., A. Elshorbagy, H. S. Wheater, and P. Gober (2014), Managing water and food in complex systems: Developing a dynamic agro-hydro-economy simulator for the Saskatchewan River Basin, Canada, *Environ. Modell. Software*, *58*, 12–26.

Head, B. (2010), Wicked problems in water governance: Paradigm changes to promote water sustainability and address planning uncertainty, in *Urban Water Security Research Alliance, Tech. Rep. 38*, Urban Water Security Res. Alliance, City East, Queensland, Australia. [Available at http://www.urbanwateralliance.org.au/publications/UWSRA-tr38.pdf.]

Hecker, M., and H. Hollert (2011), Endocrine disruptor screening: Regulatory perspectives and needs, *Environ. Sci. Eur.*, *23*, 1–14.

Hecker, M., J. S. Khim, J. P. Giesy, S.-Q. Li, and J.-H. Ryu (2012), Seasonal dynamics of nutrient loading and chlorophyll A in a Northern Prairies Reservoir, Saskatchewan, Canada, *J. Water Resour. Prot.*, *4*, 180–202.

Hill, H., M. Hadarits, R. Rieger, G. Strickert, E. G. Davies, and K. M. Strobbe (2014), The invitational drought tournament: What it is and why it is a useful tool for drought preparedness and adaptation?, *Weather Clim. Extremes*, *3*, 107–116.

Huitema, D., and S. Meijerink (2010), Realizing water transitions: The role of policy entrepreneurs in water policy change, *Ecol. Soc.*, *15*(2), 26.

Janzen, K., and C. Westbrook (2011), Hyporheic flows along a channeled peatland: Influence of beaver dams, *Can. Water Resour. J.*, *36*(4), 331–347.

Jønch-Clausen, T., and J. Fugl (2001), Firming up the conceptual basis of integrated water resources management, *Int. J. Water Resour. Dev.*, *17*(4), 501–510.

Khaliq, M. N., L. Sushama, A. Monette, and H. Wheater (2014), Seasonal and extreme precipitation characteristics for the watersheds of the Canadian Prairie Provinces as simulated by the NARCCAP multi-RCM ensemble, *Clim. Dyn.*, *44*, 255–277, doi:10.1007/s00382-014-2235-0.

Kling, H. J., S. B. Watson, G. K. McCullough, and M. P. Stainton (2011), Bloom development and phytoplankton succession in Lake Winnipeg: A comparison of historical records with recent data, *Aquat. Ecosyst. Health*, *14*, 219–224.

Lambert, A., J. Huang, G. van der Kamp, J. Henton, S. Mazzotti, T. S. James, N. Courtier, and A. G. Barr (2013), Measuring water accumulation rates using GRACE data in areas experiencing glacial isostatic adjustment: The Nelson River Basin, *Geophys. Res. Lett.*, *40*, 6118–6122, doi:10.1002/2013GLO57973.

Lapp, S. (2012), Okanagan invitation drought tournament, *J. Ecosyst. Manage.*, *13*(3), 13–15.

Lempert, R. J., S. W. Popper, and S. C. Bankes (2003), *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis*, RAND Corp., Santa Monica, Calif.

Lo, M.-H., and J. S. Famiglietti (2013), Irrigation in California's Central Valley strengthens the southwestern U.S. water cycle, *Geophys. Res. Lett.*, *40*, 301–306, doi:10.1002/grl.20108.

Marc, V., and M. Robinson (2007), The long-term water balance (1972–2004) of upland forestry and grassland at Plynlimon, mid-Wales, *Hydrol. Earth Syst. Sci.*, *11*, 44–60, doi:10.5194/hess-11-44-207.

Marsh, C. B., J. W. Pomeroy, and R. J. Spiteri (2012), Implications of mountain shading on calculating energy for snowmelt using unstructured triangular meshes, *Hydrol. Processes*, *26*(12), 1767–1778, doi:10.1002/hyp.9329.

Martz, L., R. Armstrong, and E. Pietroniro (2007), The South Saskatchewan River Basin: Physical geography, in *Climate Change and Water*, SSRB final technical report, edited by L. Martz, J. Bruneau, and J. T. Rolfe, Univ. of Sask., Saskatoon, Canada.

McIntyre, N., et al. (2013), Modelling the hydrological impacts of rural land use change, *Hydrol. Res.*, *46*(6), 737–754, doi:10.2166/nh.2013.145.

Meeth, L. R. (1978), Interdisciplinary studies: A matter of definition, *Change*, *10*(7), 10, doi:10.1080/00091383.1978.10569474.

Mekonnen, M. A., H. S. Wheater, A. M. Ireson, C. Spence, B. Davison, and A. Pietroniro (2014), Towards an improved land surface scheme for prairie landscapes, *J. Hydrol.*, *511*, 105–116, doi:10.1016/j.jhydrol.2014.01.020.

Milly, P. C. D., J. J. Betancourt, M. Falkenmark, R. M. Hirsh, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer (2008), Stationarity is dead: Whither water management?, *Science*, *319*, 573–57.

Nachshon, U., A. M. Ireson, G. van der Kamp, S. R. Davies, and H. S. Wheater (2014), Impacts of climate variability on wetland salinization in the North American Prairies, *Hydrol. Earth Syst. Sci.*, *18*, 1251–1263, doi:10.5194/hess-18-1251-2014.

National Academy of Engineering (2008), *Grand Challenges for Engineering*, Natl. Acad. of Sci., Washington, D. C. [Available at http://www.engineeringchallenges.org/File.aspx?id=11574&v=ba24e2ed, last accessed on 23 Jun 2015.]

National Research Council (2007), *Evaluating Progress of the U.S. Climate Change Science Program: Methods and Preliminary Results*, The Natl. Acad. Press, Washington, D. C.

Natural Resources Canada (2009), *The Atlas of Canada: Boreal Forest*, Ottawa, Ont. [Available at http://atlas.nrcan.gc.ca/site/english/learningresources/theme_modules/borealforest/index.html, last accessed 16 Dec. 2014.]

Nazemi, A., and H. S. Wheater (2014), How can the uncertainty in the natural inflow regime propagate into the assessment of water resources system?, *Adv. Water Resour.*, *63*, 131–142, doi:10.1016/j.advwatres.2013.11.009.

Nazemi, A., and H. S. Wheater (2015a), On inclusion of water resource management in Earth System models—Part 1: Problem definition and representation on water demand, *Hydrol. Earth Syst. Sci.*, *19*, 33–61, doi:10.5194/hess-19-33-2015.

Nazemi, A., and H. S. Wheater (2015b), On inclusion of water resource management in Earth System models—Part 2: Representation of water supply and allocation and opportunities for improved modeling, *Hydrol. Earth Syst. Sci.*, *19*, 63–90, doi:10.5194/hess-19-63-2015.

Nazemi, A., H. S. Wheater, K. P. Chun, and A. Elshorbagy (2013), A stochastic reconstruction framework for analysis of water resource system vulnerability to climate-induced changes in river flow regime, *Water Resour. Res.*, *49*, 291–305, doi:10.1029/2012WR012755.

Nickson, R. T., J. M. McArthur, P. Ravenscroft, W. G. Burgess, and K. M. Ahmed (2000), Mechanism of arsenic release to groundwater, Bangladesh and West Bengal, *Appl. Geochem.*, *15*, 403–413.

North, R. L., N. H. Khan, M. Ahsan, C. Prestie, D. R. Korber, J. R. Lawrence, and J. J. Hudson (2014), Relationship between water quality parameters and bacterial indicators in a large prairie reservoir: Lake Diefenbaker, SK, Canada, *Can. J. Microbiol.*, *60*(4), 243–249, doi:10.1139/cjm-2013-0694.

Oxfam (2011), The impacts of Russia's 2010 grain export ban, Oxfam Res. Rep., 32 pp., Oxford, U. K. [Available at https://www.oxfam.org/sites/www.oxfam.org/files/file_attachments/rr-impact-russias-grain-export-ban-280611-en_3.pdf.]

Peach, D., and H. S. Wheater (2014), *Groundwater, Hydrogeology and Sustainability in Saskatchewan: A Review of Groundwater and Hydrogeological Issues for Saskatchewan and the Development of a Research Strategy*, Global Inst. for Water Security, Saskatoon, Sask., Canada. [Available at http://www.usask.ca/water/documents/GIWS%20Goundwater%20Report%20and%20Appendices%2028%20Feb%202014.pdf, last accessed *16 Dec*. 2014.]

Poff, N. L., and J. K. H. Zimmerman (2010), Ecological responses to altered flow regimes: A literature review to inform the science and management of environmental flows, *Freshwater Biol.*, *55*(1), 194–205, doi:10.1111/j.1365-2427.2009.02272.x.

Pomeroy, J., X. Fang, and C. Ellis (2012), Sensitivity of snowmelt hydrology in Marmot Creek, Alberta, to forest cover disturbance, *Hydrol. Processes*, *26*, 1891–1904, doi:10.1002/hyp.9248.

Pomeroy, J. W., D. M. Gray, T. Brown, N. R. Hedstrom, W. L. Quinton, R. J. Granger, and S. K. Carey (2007), The cold regions hydrological model: A platform for basing representation and model structure on physical evidence, *Hydrol. Processes*, *21*, 2650–2667, doi:10.1002/hyp.6787.

Prairie Provinces Water Board (1969), *Master Agreement on Apportionment*, Regina, Sask., Canada. [Available at http://www.ppwb.ca/gsDisplayGeneral/show/menu_id/79/id/11.html, last accessed 8 May 2015.]

Precoda, N. (1991), Requiem for the Aral Sea, *Ambio*, *20*, 109–114.

Quay, R. (2010), Anticipatory governance: A tool for climate change adaptation, *J. Am. Plann. Assoc.*, *76*(4), 496–511.

Razavi, S., A. Elshorbagy, H. Wheater, and D. Sauchyn (2015), Toward understanding nonstationarity in climate and hydrology through tree ring proxy records, *Water Resour. Res.*, *51*, 1813–1830, doi:10.1002/2014WR015696.

Rodell, M., I. Velicogna, and J. Famiglietti (2009), Satellite-based estimates of groundwater depletion in India, *Nature*, *460*, 999–1002, doi:10.1038/nature08238.

Sarewitz, D., and R. A. Pielke Jr. (2007), The neglected heart of science policy: Reconciling supply of and demand for science, *Environ. Sci. Policy*, *10*, 5–16.

Scheffer, M. (2009), Critical transitions in nature and society, in *Princeton Studies in Complexity*, edited by S. A. Levin and S. H. Strogatz, pp. 1–379, Princeton Univ. Press, Princeton, N. J.

Seneviratne, S. I. (2012), Historical drought trends revisited, *Nature*, *491*, 338–339.

Shook, K. R., and J. W. Pomeroy (2011), Memory effects of depressional storage in Northern Prairie hydrology, *Hydrol. Processes*, *26*, 1752–1766, doi:10.1002/hyp.8381.

Shook, K. R., and J. W. Pomeroy (2012), Changes in the hydrological character of rainfall on the Canadian prairies, *Hydrol. Processes*, *26*, 1752–1766.

Shook, K. R., J. W. Pomeroy, C. Spence, and L. Boychuk (2013), Storage dynamics simulations in prairie wetland hydrology models: Evaluation and parameterization, *Hydrol. Processes*, *27*(13), 1875–1889, doi:10.1002/hyp.9867.

Simmons, C. T., et al. (2010), Variable density groundwater flow: From modelling to applications, in *Groundwater Modelling in Arid and Semi-Arid Areas*, edited by H. S. Wheater, S. A. Mathias, and X. Li, pp. 87–117, Cambridge Univ. Press, Cambridge, U. K.

Sivapalan, M., H. H. G. Savenije, and G. Blöschl (2012), Socio-hydrology: A new science of people and water, *Hydrol. Processes*, *26*, 1270–1276.

Small, I., J. Van der Meer, and R. E. Upshur (2001), Acting on an environmental health disaster: The case of the Aral Sea, *Environ. Health Perspect.*, *109*, 547–549.

Sorooshian, S., J. Li, K. Hsu, and X. Gao (2011), How significant is the impact of irrigation on the local hydroclimate in California's Central Valley? Comparison of model results with ground and remote-sensing data, *J. Geophys. Res.*, *116*, D06102, doi:10.1029/2010JD014775.

Stone, D. (2002), *Policy Paradox: The Art of Political Decision Making*, Norton, N. Y.

Strickert, G. E., K. P. Chun, L. Bradford, D. Clark, P. Gober, M. Reed, and D. Payton (2015), Unpacking viewpoints on water security: Lessons from the South Saskatchewan River Basin, *Water Policy*, in press.

The Economist (2012), Food and the Arab spring. Let them eat baklava, 17 Mar. [Available at www.economist.com/node/21550328.]

The Guardian (2013), Rivers of blood: The dead pigs rotting in China's water supply, 29 Mar. [Available at http://www.theguardian.com/world/2013/mar/29/dead-pigs-china-water-supply, last accessed 16 Dec. 2014.]

The Telegraph (2010), The clean up of the River Thames, 13 Oct. [Available at http://www.telegraph.co.uk/earth/wildlife/8059970/The-clean-up-of-the-River-Thames.html, last accessed 16 Dec. 2014.]

UNESCO (2012), *The 4th edition of the UN World Water Development Report*, Paris. [Available at http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/wwdr/wwdr4–2012/, last accessed 16 Dec. 2014.]

United Nations, Department of Economic and Social Affairs, Population Division (2014), *World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352)*.

University of California Center for Hydrologic Modeling (2014), *UCCHM Water Advisory #1, Water Storage Changes in California's Sacramento and San Joaquin River Basins from GRACE: Preliminary Updated Results for 2003–2013*, Univ. of Calif., Irvine. [Available at http://www.ucchm.org/publications, last accessed 23 Dec. 2014.]

USEPA (2014), *The Great Lakes Water Quality Agreement: United States Great Lakes Program Report on the Great Lakes Water Quality Agreement: Exotic Species*, Washington, D. C. [Available at http://www.epa.gov/grtlakes/glwqa/usreport/part5.html, last accessed 23 Dec. 2014.]

van der Kamp, G., M. Hayashi, and D. Gallen (2003), Comparing the hydrology of grassed and cultivated catchments in the semi-arid Canadian prairies, *Hydrol. Processes*, *17*, 559–575.

von der Porten, S., and R. C. de Loë (2013), Collaborative approaches to governance for water and indigenous peoples: A case study from British Columbia, Canada, *Geoforum*, *50*, 149–160.

von der Porten, S., and R. C. de Loë (2014), Water policy reform and Indigenous governance, *Water Policy*, *16*(2), 222–243.

Vörösmarty, C. J., et al. (2010), Global threats to human water security and river biodiversity, *Nature*, *467*, 555–561, doi:10.1038/nature09440.

Voss, K. A., J. S. Famiglietti, M. Lo, C. de Linage, M. Rodell, and S. C. Swenson (2013), Groundwater depletion in the Middle East from GRACE with implications for transboundary water management in the Tigris-Euphrates-Western Iran region, *Water Resour. Res.*, *49*, 904–914, doi:10.1002/wrcr.20078.

Waiser, M. J., V. Tumber, and J. Holm (2011a), Effluent dominated streams. Part 1: Presence and effects of excess nitrogen and phosphorus in Wascana Creek, Saskatchewan, Canada, *Environ. Toxicol. Chem.*, *30*(2), 496–507.

Waiser, M. J., D. Humphries, V. Tumber, and J. Holm (2011b), Effluent dominated streams. Part 2: Presence and possible effects of pharmaceuticals and personal care products in Wascana Creek, Saskatchewan, Canada, *Environ. Toxicol. Chem.*, *30*(2), 508–519.

Warnaars, T., R. Harding, E. Blyth, F. Ludwig, S. Hagemann, M. Best, L. Tallaksen, and H. van Lanen (2009), WATCH IP. Water and global change. Second year activity report to the European Commission, *CEH Proj. C03276*, NERC/Cent. for Ecol. and Hydrol., Wallingford, U. K.

Wheater, H. S. (2006), Flood hazard and management: A UK perspective, *Philos. Trans. R. Soc. A*, *364*, 2135–2145, doi:10.1098/rsta.2006.1817.

Wheater, H. S., and E. P. Evans (2009), Land use, water management and future flood risk, *Land Use Policy*, *26*(S1), 1–21, doi:10.1016/j.landusepol.2009.08.019.

Wheater, H. S., and P. Gober (2013), Water security in the Canadian prairies: Science and management challenges, *Philos. Trans. R. Soc. A*, *371*, doi:10.1098/rsta.2012.0409.

Wheater, H. S., D. Peach, and A. Binley (2007), Characterising groundwater-dominated lowland catchments—The UK lowland catchment research programme (LOCAR), *Hydrol. Earth Syst. Sci.*, *11*, 108–124.

Wheaton, E., S. Kulshreshtha, V. Wittrock, and G. Koshida (2008), Dry times: Hard lessons from the Canadian drought of 2001 and 2002, *Can. Geogr.*, *52*, 241–262.

White, D. D., A. Wutich, K. L. Larson, P. Gober, T. Lant, and C. Senneville (2010), Credibility, salience and legitimacy of boundary objects: Water managers' assessment of a simulation model in an immersive decision theater, *Sci. Public Policy*, *37*(3), 219–232.

Wilby, R. L., and S. Dessai (2010), Robust adaptation to climate change, *Weather*, *65*(7), 180–185, doi:10.1002/wea.543.

Wood, E. F., et al. (2011), Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water, *Water Resour. Res.*, *47*, W05301, doi:10.1029/2010WR010090.