Hydrol. Earth Syst. Sci. Discuss., 10, 6669–6693, 2013
www.hydrol-earth-syst-sci-discuss.net/10/6669/2013/
doi:10.5194/hessd-10-6669-2013

Hydrology and Earth System Sciences
Discussions
Open Access

Socio-hydrology and the science-policy interface: a case study of the Saskatchewan River Basin

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Received: 12 April 2013 – Accepted: 16 April 2013 – Published: 29 May 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

While there is popular perception that Canada is a water-rich country, the Saskatchewan River Basin (SRB) in Western Canada exemplifies the multiple threats to water security seen worldwide. It is Canada's major food-producing region and home to globally-significant natural resource development. The SRB faces current water challenges stemming from: (1) a series of extreme events, including major flood and drought events, since the turn of the 21st century, (2) full allocation of existing water resources in parts of the Basin, (3) rapid population growth and economic development, (4) increasing pollution, and (5) fragmented governance that includes the Provinces of Alberta, Saskatchewan, and Manitoba, various Federal and First Nations responsibilities, and international boundaries. The interplay of these factors has increased competition for increasingly scarce water resources across economic sectors and among provinces, between upstream and downstream users, between environmental flows and human needs, and among people who hold different values about the meaning, ownership, and use of water. These current challenges are set in a context of significant environmental and societal change, including widespread land modification, climate warming, and deep uncertainties about future water supplies. We outline the geographic setting of the SRB and its environmental history, and then discuss the major challenges to water security from: (1) environmental change, (2) rapid growth and economic development, and most importantly, (3) a governance model unsuited to managing complex and uncertain water systems. We conclude with a discussion of the emerging field of socio-hydrology and what it can contribute to knowledge translation, water management, policy, and governance in the SRB and worldwide.

1 Overview of the SRB

The SRB (Fig. 1) covers 336 000 km^2, encompassing a large portion of Western Canada, and is one of the world's larger river systems. The Canadian Rocky Mountains are the dominant sources of river flow, providing some 80 % of runoff (Pomeroy et al., 2005); the river's two major tributaries flow east from the continental divide. The South Saskatchewan River (SSR) passes through the Canadian Prairies, a major agricultural region with high natural climatic and hydrological variability (Fig. 2). The North Saskatchewan River (NSR) drains Prairie landscapes and Boreal Forest. The latter are an important global ecosystem; Canada contains approximately 30 % of the world's Boreal Forests (Natural Resources Canada, 2009). After the confluence of these two major tributaries, the river passes through one of the world's largest inland deltas, marking the downstream limit of the SRB catchment, and enters Lake Winnipeg, the world's 11th largest lake by surface area, ultimately discharging its waters into Hudson Bay via the Nelson River (Partners for the Saskatchewan River Basin, 2009; Toth et al., 2009).

The SRB is facing rapid environmental change. A warming climate is causing Rocky Mountain glaciers to retreat, changing the rain/snow balance and the processes of snow accumulation and melt, and hence influencing the magnitude and timing of river flows (Comeau et al., 2009; DeBeer and Sharp, 2009; Moore et al., 2009). Changing climate is also manifest in a mountain pine beetle infestation which has caused widespread devastation of forests in the province of British Columbia and is moving eastward into the SRB (Natural Resources Canada, 2012). In the Prairie portion of the SRB, spring snowmelt is now occurring two to three weeks earlier than it did in the 1950's (Bonsal and Prowse, 2003). The changing climate brings the prospect of new extreme conditions in the form of droughts and floods, though Bonsal et al. (2012) point to evidence of extreme drought in the region's paleorecord, noting that "observed twentieth century droughts were relatively mild when compared to pre-settlement on the Prairies, but these periods are likely to return (and even worsen) during this century". New patterns of extremes stress society's capacity to adapt quickly enough with new infrastructure, institutions, building codes, insurance rates, early warning systems, and emergency management procedures (Karl et al., 2008).

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Residents of the Canadian Prairies have always lived with extremes; they are in fact a defining feature of Prairie life, history, and culture. The Palliser expedition of 1857–1860 observed drought conditions in the "Palliser Triangle" and declared it unsuitable for agricultural development (Marchildon, 2009; Toth et al., 2009) though later developments saw the Palliser Triangle become a major Canadian agricultural zone. The region experienced devastating drought conditions during the Dust Bowl years of the 1930s; wheat farmers flocked to cities for work; and images of large dust storms, rolling mounds of Russian thistles, and destitute Prairie farmers filled newspapers across Canada (Encyclopedia of Saskatchewan, 2012). Recent examples of natural extremes included a major drought in 1999–2004 which has been described 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) (see e.g., Wheaton et al., 2008). Extensive flooding in 2011 caused widespread damage across the Prairies; many communities experienced flooding, with some 40 roads under water in Saskatchewan alone, and costs in Manitoba reported to exceed $800 million (CBC News, 14 December 2011).

Groundwater use in the SRB is curbed by the limited extent of large aquifers and low rates of recharge (Toth et al., 2009). Total groundwater use is less than 1 mm per year, averaged over the area of the Basin. Nevertheless, groundwater resources are sufficient to provide water supplies for numerous individual houses and many small towns, where reliable surface water supplies are not available. The groundwater supplies represent a critical degree of water security, however, because they are insensitive to even long-lasting droughts. Much of the Prairies would be uninhabitable if it were not for water from wells. However, the potential of using groundwater for large-scale irrigation is minimal due to the low yields of wells and the unsuitable chemistry of groundwater.

The Prairies are Canada's major food-growing region. Dryland agriculture, depending on precipitation to supply moisture to crops and pastures, is the dominant food production method in the SRB. However, early European settlement recognized that irrigation could enhance productivity, and major waterworks were developed in

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southern Alberta. Today, the SRB (and more specifically the provinces of Alberta and Saskatchewan) is responsible for approximately 75 % of Canada's irrigated agriculture (Agriculture and Agri-Food Canada, 2011). Diversions for irrigated agriculture account for 82 % of consumptive water use in the SRB (Martz et al., 2007).

In addition to irrigation use, the large-scale development of the river includes dams for hydropower, water supply for industry and urban centers, 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 (Saskatchewan Watershed Authority, accessed on 20 March 2012). Lake Diefenbaker's Gardiner Dam has heavily modified conditions downstream (Fig. 3), with additional effects due to peak power generation at the E. B. Campbell Dam and Electrical Power Station further north. This infrastructure affects flow regimes downstream in the Cumberland Delta, one of Canada's richest regions for its abundant and diverse wildlife. In addition to the upstream water withdrawals and river regulation, removal of sediment outflow by impoundment has enlarged channels downstream and reduced sediment-borne nutrients to the Delta's ecosystem. Suppression of annual discharge peaks has reduced the frequency of overbank flooding and, consequently, the frequency at which water and nutrients are replenished in the Delta wetlands. Changes in the ecosystem are of profound concern to First Nations and Métis communities who depend on the Delta for fishing, hunting, trapping, and subsistence agriculture for their livelihoods.

Inter-provincial flows on the Saskatchewan River (SR) are governed by the Prairie Provinces Water Board Master Agreement on Apportionment, approved in 1969. In simple terms, the Master Agreement requires that the Province of Alberta pass 50 % of the annual natural flow in the SSR to the Province of Saskatchewan, which is in turn required to pass 50 % of that flow to Manitoba plus 50 % of flow arising in Saskatchewan (Prairie Provinces Water Board, 2011). While concerns have been expressed that under extreme drought Alberta may have difficulty maintaining its responsibilities to senior license holders (some of which predate the Agreement), the Agreement has so far

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proved a robust framework for water management that encourages cooperative water management and sharing of information.

2 Challenges to water security

2.1 Environmental change

Increasing evidence indicates that the environmental systems that support large-scale urbanization and commercial agriculture (grains and livestock), and produce oil and gas to power the USA and China are being altered by anthropocentric climate change. Nowhere is this process more apparent than in the Canadian Rockies and foothills region in Alberta which provides about 77 % of the SR flows (Toth et al., 2009) (Fig. 1). In a typical year, the accumulation of winter snow leads to snowmelt in spring and early summer which generates a characteristic early summer peak in the annual hydrograph, and later in the year, low flows are maintained by glacier melt, rainfall, and slow subsurface drainage processes (Toth et al., 2009). In recent years, these processes have been changing in a manner typical of a warming climate. Glaciers still provide important low flow contributions to the North Saskatchewan River Basin (NSRB), but the southern glaciers have retreated to the point of insignificant runoff generation. Data from the Marmot Creek Experimental Basin in the Rocky Mountains have shown that over the last 50 yr, winter minimum temperatures have increased by 5 °C, and that these changes are associated with changing patterns of distribution between snowfall and rainfall, smaller snowpacks, and earlier spring snowmelt (Harder and Pomeroy, 2013).

The Prairie landscape portion of the South Saskatchewan River Basin (SSRB) has a different hydrological pattern and will be affected differently by climate change. This climate is semi-arid, and the topography is gently rolling or flat; the recently glaciated landscape is dominated by internal drainage basins and many hundreds of thousands of small lakes and wetlands which provide important habitats for wildlife (Fang et al., 2007). Flow contributions to the SSR are typically small; with average runoff per unit

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area from the prairie uplands only about 10 % of the runoff from the mountain slopes. Less than 50 % of the Prairie area normally connects to a major river system (Toth et al., 2009). The landscape is dominated by snow and ice for four to six months of the year. Future climate projections indicate a warming and wetting, with the greatest change in winter, though recent results show significant variability between models (Mearns et al., 2012). Some estimates project a decrease in summer precipitation for Alberta and Saskatchewan by 2081–2100. Projected changes to precipitation, and in particular hydrological extremes, remain highly uncertain (Wheater, 2002; Wheater, 2009). Also uncertain are effects on streamflow of increasing precipitation and increasing evaporation due to a warmer climate. Recent hydrological simulations for the SRB suggest changes in the annual streamflow in the SSR ranging from an 8 % increase to a 22 % decrease (Pomeroy et al., 2009). Small scale hydrological models for Prairie streams suggest a 24 % increase in spring runoff by 2050 followed by a 37 % decrease by 2080 as the winter snow cover becomes discontinuous (Pomeroy et al., 2009).

2.2 Population growth and economic development

Canada's Prairie Provinces, especially Alberta, are in the throes of large-scale population and economic growth and increased prosperity with profound consequences for land modification and water management. Alberta's historical development was based on agriculture and cattle production, but more recently, natural resource exploitation, including petroleum development and tourism, have been added to the mix. The Calgary-Edmonton Corridor is the most urbanized region in the Province and one of the densest and fastest growing areas in Canada. In 2012, Alberta's population was 2.5 million; more than double its size in 1980 (Canada Alberta, 2012). Growth in per capita gross domestic product in Alberta vastly outstripped the Canadian average after 1980, except for a temporary downturn during the global recession of 2007–2008 (Center for the Study of Living Standards, 2012) (Fig. 4). Alberta was Canada's fastest growing province between 2006 and 2011, with a remarkable five-year population growth rate of 10.6 % (Statistics Canada, 2013).

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Rapid growth, urbanization, agricultural intensification, oil and gas exploitation, and allocation of more than 100 % of the flow of some basins increased competition among licensed users, reduced water quality, and degraded riparian ecosystems. Schindler and Donahue (2006) warned of "an impending water crisis in Canada's western prairie provinces" involving the interaction of these effects. A severe drought in 2001–2002 revealed the vulnerabilities in Alberta's water system as farmers were required to cut back water use and cattle producers reduced their herds or hauled stock water (Wandal et al., 2009). The Province was unable to meet the requirements of all of its water licensees, and came close to being unable to deliver 50 % of the South Saskatchewan River's natural flow to Saskatchewan downstream, as stipulated in the Prairie Provinces Master Agreement. Acknowledging that the water system was tapped out, Alberta Environment temporarily closed three of the SSRB's sub-basins (Oldman, Bow, and South Saskatchewan) to new water licenses in 2003 (Alberta Environment, 2003a). Another symptom of vulnerability is the decline in water quality. Phosphorous loadings were above Alberta's official chronic guideline of 0.05 mg L^{-1} (Alberta Environment, 1999) for most of the SSR downstream from the Rockies (Fig. 5).

Alberta used simulation experiments with its Water Resources Management Model (WRRM) to assess the state of its water supplies, asking whether it would be possible for current resources to support agricultural expansion and assure ecosystem health under different environmental flow conditions. The model considered 10 % and 20 % increases in agricultural acreage over current allocations and used Instream Objectives (IOs) attached to current licenses and Instream Flow Needs (IFNs) to represent flows adequate to protect water quality, fish habitat, riparian ecosystems, and channel maintenance. Model runs produced sobering results. The IOs were very low compared to INFs in most years. Although it would be possible to expand irrigated acreage and improve environmental flows under average conditions, it would not be possible to support future growth and protect the environment in dry years. Governance and policy thus would need to be dictated by conditions in dry, rather than normal, years. Ideal IFNs could sometimes be achieved, but infrequently. Agricultural expansion would result in

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deficits for junior licensees under drought conditions, and environmental flows could be augmented, but only at the expense of junior licensees. As noted above, three sub-basins were permanently closed to new license applications. In 2003, Alberta authorized a water planning process with goals to: improve management and administration of allocations, develop markets to transfer water to higher-value development, and encourage water conservation (Alberta Environment, 2003b). From that planning process there emerged an evolving strategy for sustainability called *Water for Life* that acknowledged that new development would occur through conservation, reuse, and transfer (Alberta Environment, 2012). The Alberta Water Exchange, Inc. was established to acquire licenses from those who have excess capacity and bring licenses into good standing through reconstruction and proper operation of water works. The Exchange enables the transfer of licenses to new users and allows new development to occur despite full allocation (Alberta Water Exchange, 2012). In a recent survey of stakeholders in the SRB, land management issues were listed by 40 % of Alberta respondents as the single highest priority for water management, reflecting the inherent trade-offs and demand-side issues that accompany rapid development in a fully allocated system (Gober et al., 2013). Many stakeholders in Alberta take a pragmatic approach to water security, defining it as a process of sustainable development.

Saskatchewan's economic growth spurt was more recent (Fig. 5), but followed Alberta's trajectory – rapid growth and economic development, pressure for more water licenses, water quality issues, and emphasis on supply- over demand-side management. Saskatchewan's development was also rooted in resource development including food production (livestock and wheat), potash and uranium mining, and oil and gas extraction. The Province (approximately the size of France) had slightly more than one million residents in 2011, and in most years, uses only a small portion of SR flows; the assumption has been that adequate water supplies are available to support future growth. In 2012, the Saskatchewan Ministry of Agriculture published a report called "Lake Diefenbaker's Unfinished Business" outlining the potential to irrigate up to 500 000 additional acres (from today's 109 000), using only 17 % of current flows

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under normal conditions (Saskatchewan Ministry of Agriculture, 2012). The pressure to expand irrigated agricultural production, however, raises questions about whether there will be enough water during drought years; whether climate change will alter streamflows and future water supplies; what agricultural expansion means for dam management, river and lake levels for recreational uses, and hydroelectric power generation; and what other opportunities will be foregone as full allocation is approached. Also disquieting is the possibility that Alberta has come very close to being unable to deliver its mandated 50 % of the SR's natural flows under sustained drought conditions. In the survey of stakeholder concerns about water security, Saskatchewan representatives expressed significantly more concern about drought and climate change and less concern about land use management and competing demands, as compared to those in Alberta (Gober et al., 2013).

The Government of Saskatchewan recently formed a Water Security Agency and released a 25 yr Water Security Plan (Saskatchewan Water Security Agency, 2012) to address the need for sustainable supplies, water quality, ecosystem protection, hazards mitigation, improved governance, and increased public engagement. Sustainable development is to be achieved through more efficient water use, new water supply infrastructure, and reassessment of current allocations. Unlike Alberta, where the legal framework adheres to first in time, first in right, Saskatchewan's water framework provides the Water Security Agency with greater flexibility to adjust future allocations to adapt to changing environmental and societal conditions.

2.3 Governance

In a prosperous and highly educated country like Canada, the problems of climate change and rapid development should be manageable through foresight and coordination of water resource systems. Public attitudes in Canada acknowledge the reality of climate change and the vital role of governmental institutions in addressing it. In 2011, 80 % of Canadians (compared to 58 % of Americans) believed that there is solid evidence that Earth's temperatures have been warming (LaChapelle and Borick, 2011).

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A similarly higher proportion of the Canadian population believed that governments at all levels: federal (65 % versus 43 %), provincial and state (53 % versus 35 %) and local (42 % versus 29 %) have a role to play in taking actions to reduce climate warming. Even then, however, many parts of Canada, including the SRB, are ill prepared to anticipate and manage the effects of environmental change and face two significant management challenges: (1) fragmentation and (2) uncertainty.

The fragmentation problem begins with the fact that watershed boundaries rarely coincide with political boundaries. And then, myriad levels of government have overlapping, and sometimes conflicting, responsibilities for water management. The Constitution Act of 1930 between Canada and each of its western provinces passed responsibility for land and resources, including water, to the provinces (Partners for the Saskatchewan River Basin, 2009). As such, the provinces are responsible for infrastructure, flood forecasting, drinking water standards, water quality management, source water protection, water licenses, and fisheries regulation. The federal government has responsibility for trans-boundary issues, management of fish habitat, navigation and shipping, regulation of toxic substances, and First Nations lands. Obvious conflicts and gaps arise in the management of a multi-provincial water system that includes a large number of small, geographically dispersed First Nations reserves. Water quality on First Nations lands is the responsibility of the federal government, but protection of source waters lies at the provincial or local levels through groundwater/surface water interactions, land use management, community development, and collaborative watershed partnerships (Timmer et al., 2007). Boiled water advisories, an indicator of compromised water quality, are a common occurrence in many Aboriginal communities in Western Canada (Patrick, 2011). They reflect a lack of coordination between local and national water authorities and the unfortunate disconnection between land and water governance.

Growing evidence from the policy sciences suggests that dealing with fragmentation is not simply a matter of consolidating management into highly centralized systems, but rather better coordination of place-based, watershed-level governance. Brunner (2010) has warned of scientific bias in searching for the "one best way" to rationalize natural resources governance and preference for centralized decision making. He argues that adaptation efforts are most effective when they occur at the local level, incorporate a wider range of views in policy development, and find ways to use local knowledge to supplement scientific inquiry. In Western Canada, watershed advisory groups have been established to fill this vital governance role, but unfortunately, they are limited by the lack of legislative authority, uncertain budgets, and over-reliance on volunteers for planning and management (Hulbert et al., 2009). The 2001–2002 drought demonstrated the value of local and informal governance mechanisms as strong community spirit enforced compliance with water-saving strategies and social cohesion of rural communities persuaded senior water rights holders to share part of their allocations to maintain the viability of rural communities (Diaz et al., 2009; Marchildon, 2009).

Coordinated responses to new conditions in a decentralized governance system are difficult. These difficulties are magnified by the uncertainties associated with climate model results. Wilby and Dessai (2010) described a "cascade of uncertainty" accompanying regional impact assessment, beginning with different views of future society, climate model results, regional impacts, and potential adaptation resources and note the difficulty of accommodating this level of uncertainty in science-led adaptation efforts. The information systems of fragmented entities are ill prepared in terms of how to deal with uncertain climate model results, integrate data from varying spatial scales and technical sources, and mesh quantitative and qualitative results with the local knowledge and experiences of different operational and policy staffs. Prior research has demonstrated that policy makers view uncertainty as a constraint which may cause them to avoid solutions that employ uncertain information, exhibit bias toward initial solutions, undervalue negative or contrary evidence, and over-rely on results of prior outcomes (Cohen and Wallsten, 1992; Reece and Mathews, 1993). Decision making under uncertainty (DMUU) strategies are designed to manage, rather than reduce, uncertainty. They include exploratory modeling, scenario planning, robust decision making,

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and adaptive governance (Folke et al., 2005; Gober et al., 2010; Gober, 2013; Lempert et al., 2003; Quay, 2010).

Camacho (2009) has articulated a three-pronged approach for governing under uncertainty. First, invest in proactive strategies that reduce vulnerabilities in existing systems, thus allowing society more time to adapt should the need arise. Second, focus on procedural, over substantive, adaptation. In other words, give agencies more flexibility, allow decision makers to make mistakes and learn from them, and experiment through trial and error. And third, emphasize no-regret, co-benefit adaptation that will produce public benefit no matter the outcome of climate change.

3 Socio-hydrology and the science-policy interface

What then is the role of science in achieving effective governance of complex and uncertain water systems? Sivapalan et al. (2012) have called for the integration of human and natural forces for water science and planning and have used the term *socio-hydrology* to describe the study of the "co-evolution of human-natural coupled systems". They argue that it is not possible to predict water cycle dynamics over decadal or longer time periods without considering interactions and feedbacks among natural and human components of the water system. This is surely the case in Western Canada where it was the coincidence of rapid economic growth, drought, and rigid and outdated governance that triggered crisis conditions in 2001–2002 and opened the policy window in Alberta to *Water for Life*. Similar coincident conditions pertain in the Cumberland Delta where upstream development has changed the Delta's natural flows, and climate change threatens to further disrupt the balance of life for Aboriginal people and the biodiversity of the world's largest inland wetland ecosystem.

Effective governance of water systems will, however, entail more than the inclusion a human dimension in traditional hydrological modeling. Also required is a deeper understanding of the social processes that transfer this knowledge to decision makers in place-based contexts. There is growing evidence to suggest that this knowledge

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transfer process is not functioning well. A 2007 National Research Council report declared that "inadequate progress has been made in synthesizing research results assessing impacts on human systems or providing knowledge to support decision making and risk analysis"(National Research Council, 2007). These problems apply to natural resource management, in general, and to water governance, in particular. Pahl-Wostl and Borowski (2007) noted similar problems in implementing the requirement for participatory water management as outlined by the European Water Framework Directive. Despite claims of usability and problem solving by scientists and the European Commission, many of the tools designed for decision support did not meet user needs (Borowski and Hare, 2007).

Socio-hydrology challenges scientists to find a new role in evidence-based water decision making. This role is unlikely to follow the traditional, science-driven model of environmental management because, as Wilby and Dessai (2010) and Trenberth (2010) have pointed out, there is too much uncertainty about climate model results to plan water systems in the traditional way. Although new approaches to vulnerability analysis (Nazemi et al., 2013) provide an alternative strategy for risk management, there also is a need to move beyond purely science-driven assessment to consider community values and local knowledge. Socio-hydrologists can play a crucial role as partners in water governance across a range of scales (international, national, regional, and local). Dilling and Lemos (2011) have emphasized 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. Letcher et al. (2004) and Sharp and Curtis (2012) both illustrate the importance of stakeholder engagement in the development and application of integrated assessment modeling for water allocation.

In sum, we have provided an overview of the water challenges facing the SRB, noting that biophysical challenges cannot be separated from human ones. Effective management of water systems will require new forms of governance that can manage uncertainty, coordinate complexity, deliver benefits irrespective of the impacts of climate

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change, and engage stakeholders in value-based decisions. This governance also values social learning and place-based research disseminated through networks for voluntary adaptation elsewhere. Socio-hydrology provides new knowledge both about the nature of human-natural coupled water systems, but also about the social processes through which this knowledge is shared with decision makers and used for decision making. The pace and nature of change and its potential impacts for Earth's environment and society call for water scientists to both redefine the nature of their science and the relationship of that science to societal decision making and well-being.

Acknowledgements. This research was supported by the Global Institute for Water Security under funding from the Canada Excellence Research Chair for Water Security. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the University of Saskatchewan.

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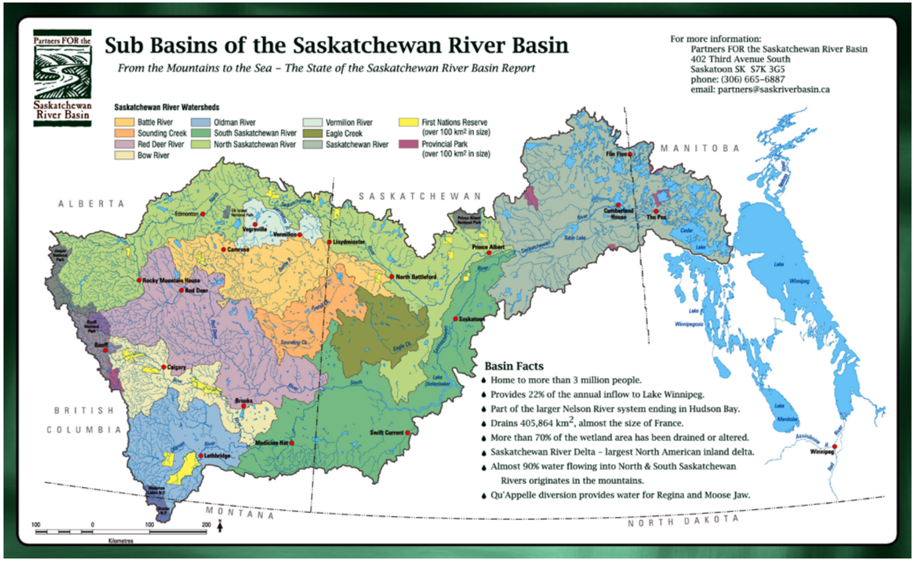

Fig. 1. Saskatchewan River Basin (Partners for the Saskatchewan River Basin).

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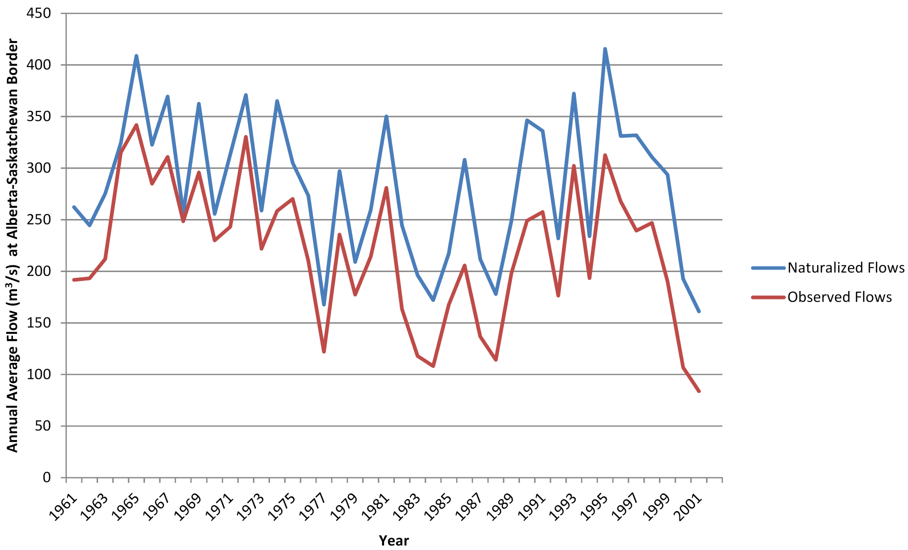

Fig. 2. Naturalized and observed annual average flows at the Alberta-Saskatchewan Border (Alberta Environment and Environment Canada).

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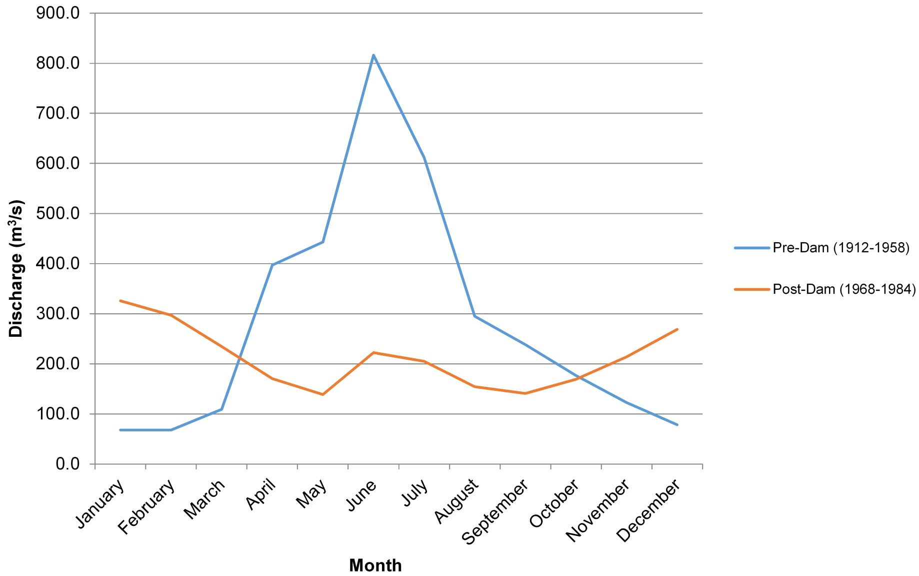

Fig. 3. Annual hydrograph of the South Saskatchewan River at Saskatoon pre- and post-construction of the Lake Diefenbaker Reservoir (Water Survey of Canada).

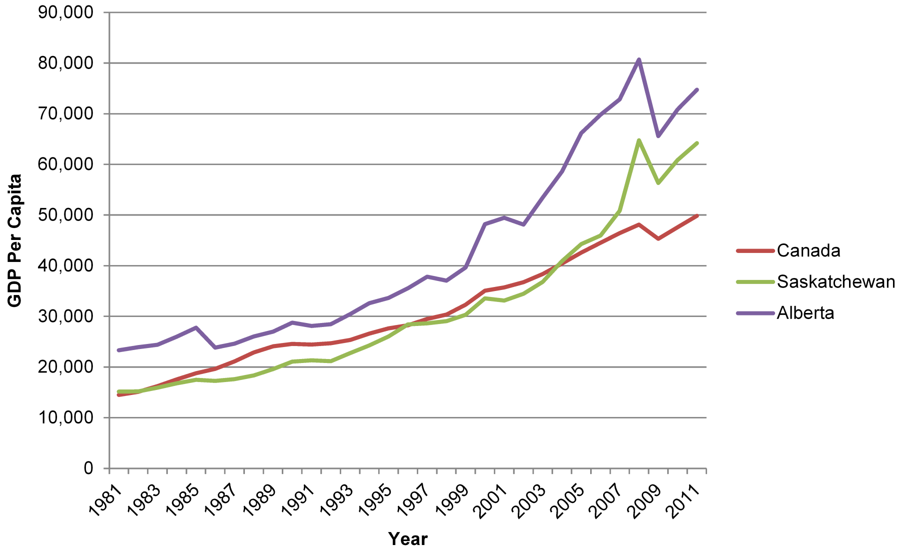

Fig. 4. Growth in Gross Domestic Product in Canada, Saskatchewan, and Alberta: 1990–2010 (Center for the Study of Living Standards, 2013.

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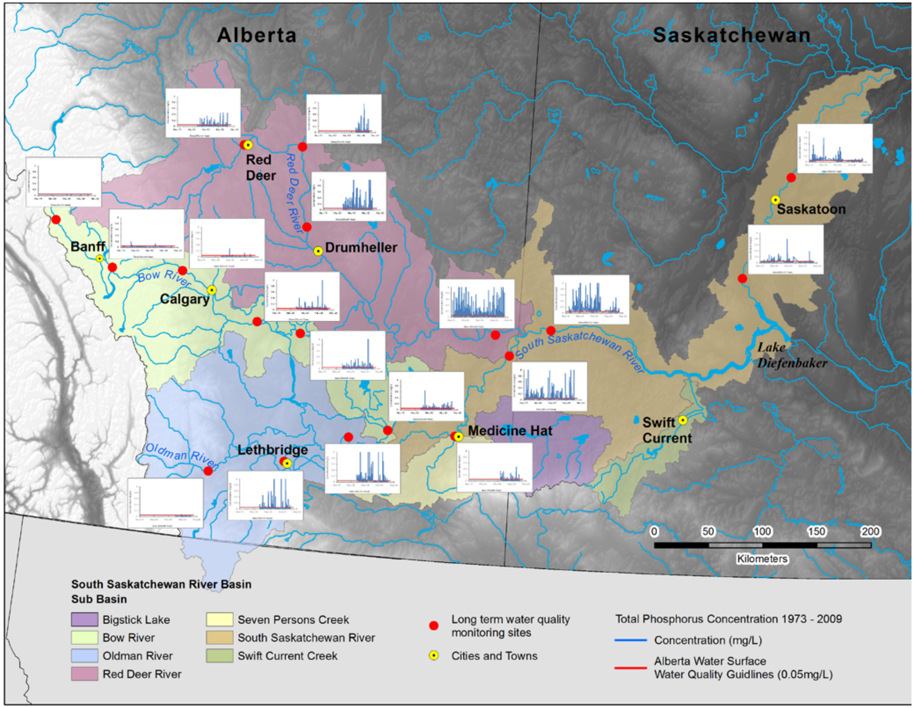

Fig. 5. Total Phosphorous concentration (1973–2009) in Alberta and Saskatchewan (Federal data through the Prairie Provinces Water Board, Alberta data from Alberta Environment – River network station water quality data, accessed online through http://environment.alberta.ca/01288.html, Saskatchewan data from Saskatchewan Ministry of Environment).

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