In this paper, we discuss the multiple dimensions of water security and define a set of thematic challenges for science, policy and governance, based around cross-scale dynamics, complexity and uncertainty. A case study of the Saskatchewan River basin (SRB) in western Canada is presented, which encompasses many of the water-security challenges faced worldwide. A science agenda is defined based on the development of the SRB as a large-scale observatory to develop the underpinning science and social science needed to improve our understanding of water futures under societal and environmental change. We argue that non-stationarity poses profound challenges for existing science and that new integration of the natural sciences, engineering and social sciences is needed to address decision making under deep uncertainty. We suggest that vulnerability analysis can be combined with scenario-based modelling to address issues of water security and that knowledge translation should be coupled with place-based modelling, adaptive governance and social learning to address the complexity uncertainty and scale dynamics of contemporary water problems.

1. Introduction

Water resources are under pressure worldwide, through population growth and movement, economic development, climate and land-use changes and pollution [1,2]. Recent Intergovernmental Panel on Climate Change (IPCC) estimates [3] are that between 1.4 and 2.1 billion people live in areas of water stress. Unsustainable use of water is widespread, with consequences that include significant environmental degradation, the Aral Sea being one of many well-known examples. Even in the
highly regulated UK, the majority of England and Wales has been designated as either over-licensed, over-abstracted or with no water available [4].

Around the world, tensions are rising over scarce water resources, as societies increasingly face difficult choices arising from increasing competition between sectors, human use and environmental flows, and quality and quantity. The need to balance upstream and downstream water uses is particularly problematic for transboundary water resources, especially where they cross international borders. The potential for population migration in the face of water stress has been identified [4] and there is growing awareness of the role of ‘embedded water’ in the international trade of food, goods and services [5], and the realization that food security in some areas undermines water security in others [6].

In addition, some 90% of natural hazards are water-related. As populations increase and development unfolds, with more people and assets at risk, the frequency and intensity of water-related disasters is rising. UNESCO [2] noted that, in 2010, water-related natural disasters killed nearly 300,000 people, affected some 208 million others and cost nearly $110 billion. Such events are never far from the news—at the time of writing (November 2012), 20% of the USA is under extreme or exceptional drought [7], while New York City recovers from inundation due to Hurricane Sandy.

The term ‘water security’ is increasingly used to capture the wide-ranging global water challenges, from inadequate supply and poor quality, to hazards, unequal access, inept management and unsustainable use [8]. We summarize our definition of 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)’. It has been recognized as a strategic regional, national and international priority. The UK Government’s Chief Scientist has referred to the ‘perfect storm’ around water, food and energy futures [9], the Belmont Forum of 12 leading nations has identified freshwater security as a major area requiring research [10], and, at a regional level, the Canadian province of Saskatchewan has (in October 2012) launched a new Water Security Agency to develop and implement a 25-year plan for water [11].

The scientific, management, policy and governance challenges of water security are considerable. The pressures outlined above are set in a context of extensive and sometimes rapid environmental change, including climate change, widespread land modification and large-scale urbanization, and rapid economic development (for some segments of the world’s population). The nature of these changes and their implications for water systems raise significant challenges for water science and management as they have been traditionally practised. This paper will identify key features of contemporary water challenges— their scale dynamics, complexity and uncertainty—and discuss what they mean for the practice of water science in the Saskatchewan River basin (SRB) in western Canada. After a discussion of thematic challenges underlying science, policy and governance aspects of water security, we summarize water challenges as they are manifest in the SRB, describe how scientific research addresses issues of scale, complexity and uncertainty, and conclude with a plea for greater integration of hydrology, engineering and social science and more effective translation of scientific results into support tools using principles of decision making under uncertainty (DMUU). The SRB exemplifies many, if not most, of the water-security challenges faced worldwide and has been selected as a major focus of the $30 million Canada Excellence Research Chair in Water Security research programme at the University of Saskatchewan and a Regional Hydroclimate Project of the World Climate Research Programme’s GEWEX programme.

2. Thematic issues for water security

We begin our discussion by introducing a set of generic thematic issues that underpin the science and social needs of water security and are also reflected in the associated policy and governance challenges.
(a) Cross-scale dynamics

Although the challenges of water security are global in scale, it is increasingly clear that many solutions lie at regional and local levels where impacts are felt and decisions are made. Water insecurity stems in part from large-scale global processes such as CO2 emissions and a changing climate, modernization and economic development, growing social inequality, changing lifestyles and diets, and the international trade in food. They are, in turn, filtered through national and regional environmental and social systems to have real effects on people and the places where they live. IPCC assessments reflect these scale dimensions with large-scale modelling of the physical system and regional-scale assessments of climate impacts [3]. There is a critical need for both physical science and social science that connects these scales of analysis, an example of the former being the need to reconcile downscaled climate scenarios with regional observations, and of the latter to evaluate the impacts of international trade for the water security of regional farmers. In the SRB, for example, Hurlbert et al. [12] and Corkal et al. [13] observed that increasing use of water in the agricultural sector has enabled the south SRB to remain food-secure and maintain exports but at a cost of greater insecurity in the water sector.

Cross-scale linkages equally apply to the needs for upscaling, across the science, policy and governance areas. Climate change is affecting cryospheric, hydrological and ecological processes that in turn affect larger-scale climate change and its impacts, but so are the anthropogenic effects of land and water management. Important science challenges arise in understanding and modelling these effects at local scale, and upscaling to quantify the effects on land surface systems at regional and large basin scale and the associated feedbacks to the climate system, both from current practices and from prospective future adaptation and mitigation strategies. Similarly, governance must address the challenges of reconciling local initiatives and actions, for example as exemplified by the widespread emergence of local catchment-based non-governmental organizations, with catchment-scale management and policy applied at the scale of provincial and national governments. There is also the issue of source-water protection for First Nations lands in western Canada, where water quality on a patchwork of local reserves is the responsibility of federal authorities, but control over surrounding lands lies with provincial and local governments. Breakdown of jurisdictional and institutional responsibilities for source-water protection has led to chronic boiled water advisories in many rural First Nations communities [14].

Social scientists have noted the failure of top-down national and international efforts for climate adaptation. Brunner [15] has described science and management strategies to find ‘the one best way’ for achieving common interests, noting public resistance to the standardized, rationalized model of environmental management. He notes the success of locally based efforts designed around policies adapted to local needs and perspectives. This process has the effect of breaking down large intractable problems into smaller, more manageable ones that address on-the-ground concerns. Successful efforts can then be diffused through networks of similar communities and used to inform larger-scale decision making. Policies emerge from the bottom up; failures can be seen as a source of social learning; and local needs are used to inform national resource decisions. Decision making is informed by wider participation of actors in civil society, and work at varying scales is complementary rather than competing. This pattern surely describes climate adaptation efforts in North America and worldwide, where cities have taken a leading role in climate adaptation and mitigation and formed networks to share their stories and inform national and international policy [16].

(b) Complexity

Challenges of complexity arise in water science, policy and governance, and at their interface. For example, analysis of water futures requires an understanding of: the impacts of changing climate on hydrology and ecology at local scale and the resulting large-scale feedbacks to the atmosphere [17]; the local-scale impacts of land-use change, including field-scale management
interventions, and the cumulative effects at river basin scale [18]; and the effects of management of complex water resource systems on river flows, wetland and groundwater systems, and land–atmosphere feedbacks [19]. Anthropogenic changes are strongly influenced by water policy and governance, which in turn are intimately linked with other resources. Zeitoun [6] has noted the close coupling between agriculture and water, as more than 80% of the world’s consumptive use of water is from irrigated crop production. The connection of food and water has been intensively studied through the ideas of a ‘water footprint’ and ‘virtual water’. Energy and water are linked; the demand, management and waste generated by both resources are driving global change in a variety of ways [20]. Also significant are relationships between water and land use and the growing recognition that unsustainable land practices are compromising water security. In urban settings, water-hungry suburban developments are increasing per capita water use and generating ‘suburban drought’ in places that are experiencing little change in streamflow regimes [21]. There are considerable challenges for policy and governance in developing consistent policies across multiple sectors of the economy and multiple perspectives on the use and value of water. Changes in water quantity are, however, just one aspect of system complexity. As discussed in more detail below, changes to water quality and environmental needs for water raise science issues that also underpin important challenges for policy and governance.

(c) Uncertainties

Both cross-scale dynamics and complexity raise issues of understanding, representing and managing uncertainties. In particular, the global transition from a stationary to a non-stationary world has profound implications for uncertainty and hence for water science and practice. While non-stationary hydrological variables can in principle be modelled stochastically to describe temporal changes in their probability distributions (see [22] for a treatment of extremes), in practice, generation of non-stationary hydrological variables is subject to major difficulties: detection of change in observational records is challenging [23], and methods for estimating model parameters under future states are limited by predictive capability. Scenario analysis is increasingly popular as a means of investigating the sensitivities of water systems to a wide range of future conditions—both climatic and societal—but Wilby & Dessai [24], for example, have noted the ‘cascading uncertainties’ associated with the translation of greenhouse gas (GHG) concentrations to local impacts on human and natural systems. In essence, they say that the dominant method of first downscaling climate projections from the global climate models (GCMs) under a range of GHG scenarios into local scenarios that are then fed into impact models to estimate future stream flows is fraught with uncertainties, and therefore unable to effectively inform decision making.

An alternative approach is to allow potential adaptation decisions to lead the science and modelling processes. The idea is to look for ‘low regret’ interventions that yield benefits regardless of climate change. Protecting water sources from contamination or salinization would yield positive benefits under any climate conditions. Monitoring of environmental quality is necessary for benchmarking changing conditions, warning of approaching tipping points and measuring impacts of management decisions. Sensitivity analyses enable decision makers to sort through a range of management options to find strategies that will work, irrespective of future climate conditions.

DMUU stresses the need to tackle difficult problems despite profound uncertainties about the future [25–28]. Lempert et al. [29] have warned of paralysis in the face of uncertainty and the need to reframe science and policy questions from ‘what is the optimum future’ to: what kind of future do we want and what policy decisions need to be made to get there, what is the price of delay, what is the range of how the future may look and how do we avoid regrettable outcomes, and what is the cost of delay relative to the cost of making expenditures now that prove unnecessary in the future? The emphasis is on robust decision making—choosing strategies that are insensitive to uncertainty about the future [30]. Robust strategies include hedging actions that reduce vulnerabilities in case unfavourable future conditions come to pass,
shaping actions intended to influence the future and marking signposts that monitor change and alert decision makers of the need for action. DMUU approaches are being used to tackle a wide range of complex and uncertain environmental problems, including water resources management [25,26,31], agricultural adaptation [32] and bridging the knowledge gap between environmental science and decision making [33].

Having introduced the thematic challenges of cross-scale dynamics, complexity and uncertainties, we next introduce the multiple dimensions of water security, to establish the full context of what is often treated as an issue of reduced dimensionality. We then present a case study based on the SRB, Canada, for which we outline the associated science, policy and governance challenges.

3. The multiple dimensions of water security

Water security embodies a complex and interdependent set of issues. The competing societal uses for water have led to much discussion of the water–food–energy nexus, but this is to oversimplify the challenges faced in addressing water security. For example, water quantity (and its temporal variability) is also of critical importance for ecosystem function; changes to the hydrological functioning of the natural environment will have important consequences for ecosystem resilience and survival. Environmental water needs are therefore an important aspect of water security. Societal values with respect to environmental flows are, however, highly subjective and likely to change with time as societies develop. For example, development of the western USA treated water as a commodity whereas the 2000 European Union’s Water Framework Directive placed highest priority for water management on the protection of ecological quality [34].

Water quality is a further important dimension of water security. Human society has typically turned to its rivers to receive, transport and dilute wastes, and intensification of human activities is putting increasing pressure on the quality of both surface waters and groundwater. Impacts of human activities on water quality are therefore a ‘use’ of water resources, affecting subsequent human uses and environmental quality [35]. While point-source pollution remains a major issue for developing countries, most developed economies have effective controls on such discharges with respect to nutrients and major pollutants; current concerns relate more to the fate of ‘exotic chemicals’, for example pharmaceutical products in sewage effluents and their impacts on the receiving aquatic systems [36].

A more difficult set of issues arises where pollutant sources are diverse and spatially distributed. One example is acid deposition from air pollution, with associated impacts on terrestrial and aquatic ecosystems [37]. A second concerns nutrient pollution. The pressures of increasing population and their wastes, together with intensification of agricultural production, are leading to significant increases in nutrient concentrations (nitrogen and phosphorus) in surface waters and groundwater. Adverse effects include impacts on drinking water supplies, health of aquatic ecosystems, animal and human health, and amenity. In many parts of the world, local concentrations of nitrate in surface waters and groundwater exceed drinking water standards (precluding water use without blending or expensive treatment) [35]. Algal blooms can arise from excess phosphorus, with effects on ecosystems, drinking water treatment and amenity; toxic algal species can cause death to animals and potentially to humans [35]. A notable transboundary example is Lake Winnipeg, Canada, the world’s eleventh largest freshwater lake, which experienced an algal bloom of 15 000 km² in extent in 2007 [38].

Diffuse pollution often raises complex science and governance questions, the former related to the identification of cause and effect, and potential for mitigation, and the latter to effective policy and governance in a situation with high scientific uncertainty, multiple actors and potentially multiple jurisdictions. Thus, nutrient pollution concerns air pollution, urban wastewaters, agriculture (with respect to both the impacts of agriculture on the environment and the role of agriculture in environmental protection) and the levels of nutrients that are acceptable in the aquatic environment. The primary source of nutrients to Lake Winnipeg is the Red River, which
flows north into Canada from the USA [39]. Thus, governance is distributed between the USA and Canada, involving multiple states and provinces, federal government agencies, local communities and farmers. The US Academy of Engineering recently identified nitrogen management as one of the major societal challenges of the twenty-first century [40].

The interdependences embedded within water security include the interaction of water quality with water quantity. For example, while agricultural activities can affect water quality, the quality of irrigation water is important to meet food safety requirements [35], and in managed surface water systems there is often a need under low flow conditions to maintain flows to dilute effluents and meet environmental water quality standards.

Water security is often dramatically compromised by extreme events—rare natural events that stress the human capacity to adapt to environmental conditions [41]. Flooding remains one of the world’s most dangerous and damaging natural hazards. Human habitation has always tended to develop around water, and, with increasing pressures of population and development, the risks to life, property and infrastructure associated with flooding are increasing worldwide [2]. At a basic level, flooding can be seen simply as the response of a natural system to an extreme weather event (or sequence of events), but the reality is more complex. Human activity changes the environment in multiple ways, with implications for flood risk and flood risk management. For example, run-off from the land can be radically altered by human activities. The effects of urbanization on increasing flood run-off are well known, and commonly mitigated by specially designed urban infrastructure [42]; the effects of widespread changes to the landscape due to agricultural development and intensification are less understood, but can be significant [43]. Major floods will inevitably exceed river channel capacity, and the floodplain provides an important function of temporary storage and attenuation of the flood. The pattern of human development for much of the twentieth century has been to disconnect floodplains from river channels, to provide protection for riparian urban development or agriculture, with a consequent increase in flood hazard downstream; attempts are now being made, in cases such as the Rhine, to reconnect the two [42]. Thus, flood risk results from complex interactions between extreme events, human changes to the natural environment, human perceptions and responses to risk, and the capacity of human institutions to reduce and manage risk.

The opposite extreme is drought. Clearly, a lack of precipitation will lead to pressures on water resources and agriculture, and effects can be severe, depending on the resilience of the local society and population; in less developed areas, such as the Sahel and the Horn of Africa, drought can lead to mass starvation. We recall the discussion of the multiple societal uses of water, above. Under low flow conditions, tensions between competing water uses will be exacerbated, not least between human uses and environmental flows [43]; under extreme conditions, basic functions, for instance power generation, may need to be shut down. Agricultural drought can have wide-ranging repercussions. For example, events such as the 2010 Russian heat wave affected global food production and food prices [44,45], arguably one aspect of the social unrest that led to the ‘Arab Spring’ [46].

Water security has significant human dimensions and, during the past two decades, the social science community has gained a deeper understanding of the social dimensions of environmental management under uncertainty, including organizational and institutional flexibility for handling uncertainty and change [47,48], social capital [49–52] and adaptive governance [15]. Social sources of resilience, such as social capital and social memory, are essential for building capacity to manage risk and shape governance practices. The development of social networks between researchers and decision makers increases the likelihood that decision makers will use scientific information to govern water resources [53]. Pahl-Wostl & Borowski [54] and Dilling & Lemos [55] 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.

Social scientists also have explored the meaning of the term ‘water security’ for science and decision making. Cook & Bakker [8] reviewed the emerging academic and policy literature and identified four water security themes around which policy discussion and research are based:
(i) quality and quantity, (ii) hazards and vulnerability, (iii) human needs including affordability and access, and (iv) sustainable development. Gober et al. [56] argued that ambiguity over the meaning of the term ‘water security’ for policy debate allows stakeholders with very different viewpoints to look for consensus and a path forward for conflict resolution. Their case study of stakeholders in the SRB revealed widely varying definitions of water security and characterizations of the barriers for achieving water security. Significant, however, was the tendency for people to link climate change to rapid population growth and weak governance as barriers to security, suggesting that a multi-dimensional view of water security is the way to bridge diverse values, motivations and expectations to reach consensus and move forward with collective action to solve local water problems.

We conclude that water security does indeed have multiple and highly interconnected dimensions, that each of these involves complex interactions between human society and the natural environment, and that to address them requires holistic assessment and the need to address significant challenges of science, policy and governance.

4. The Saskatchewan River basin

The 336 000 km² SRB (figure 1) presents science and management challenges stemming from scale dynamics, growing complexity and growing uncertainty, which reflect the multiple dimensions of water security outlined above. Traversing the three provinces of Alberta, Saskatchewan and Manitoba, the SRB encompasses a large swath of western Canada and is one of the world’s larger river systems. With an area approximately half the size of France, it experiences one of the most extreme and rapidly changing climates in the world and, as discussed below, embodies a set of critical environments of major importance to Canada and globally.

The Canadian Rocky Mountains in Alberta are the dominant sources of river flow, providing some 80% of run-off [57]; the Saskatchewan River’s two major tributaries flow east from the continental divide. The South Saskatchewan River passes through the Canadian Prairies, home to 80% of Canada’s agriculture and a region with high natural climate variability (figure 2). While most agriculture in the SRB is based on natural precipitation (in which snow plays a major role), the provinces of Alberta and Saskatchewan account for approximately 75% of Canada’s irrigated agriculture [59], most of which is located in the south SRB. Diversions for irrigated agriculture account for 82% of consumptive water use in the SRB [60].

The North Saskatchewan River passes through Prairie landscapes and boreal forest. The boreal forest is an important global ecosystem that represents 35% of Canada’s total land area [61]. 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), marking the downstream limit of the SRB catchment, and enters Lake Winnipeg, ultimately discharging its waters into Hudson Bay [62,63].

In addition to irrigation use, the large-scale development of the river includes dams for hydropower, water supply for industry and urban centres, and flood relief. The largest of these is the 225 km long Lake Diefenbaker multipurpose reservoir in Saskatchewan, which stores 9.4 billion cubic metres of water [64] (figure 1).

The climate of the SRB is characterized not only by an extreme temperature range (−40°C to +40°C), but also by extreme events. Such extremes are in fact a defining feature of the Prairie’s climate and culture. The Palliser expedition in 1857–1860 observed drought conditions in the ‘Palliser Triangle’ and declared it unsuitable for agricultural development [63,65], though later developments saw the Palliser Triangle become a major Canadian agricultural zone. Recent examples of these natural extremes include the major drought of 1999–2004, 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 (e.g. [66]), and extensive flooding in 2011, which 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 [67].
Figure 1. Saskatchewan River basin.

Figure 2. Naturalized flow in the South Saskatchewan River at the Alberta–Saskatchewan border [58].

Management concerns include: provision of water resources to 3 million inhabitants, including indigenous communities for whom quality of drinking water supply remains an issue of concern; balancing the needs for industrial and natural resource development with those of agriculture; issues of water allocation between upstream users in Alberta and downstream users in Saskatchewan and Manitoba; managing risk of flood and drought; and water quality impacts of discharges from major cities and agricultural production. Current pressures are severe: the south SRB is fully allocated in southern Alberta and has been described as Canada’s most threatened river by the World Wide Fund for Nature (WWF, World Wildlife Fund) [68]; as noted above, 2011 flooding and 2000 drought caused major economic damage; and water quality in Saskatchewan’s major reservoir (Lake Diefenbaker) is deteriorating, with increasing concern over eutrophication and water supply [69].

These pressures are occurring against a background of rapid environmental change. In the west, 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 [70–72]. 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 eastwards into the SRB [73]. In the Prairies, changing climate is affecting agriculture, flood and drought risk, and water quality. Farming practices, such as drainage and wetland removal, are changing the landscape and the ecological services that it provides. Changes in flow now threaten the basin’s delta, one of Canada’s richest regions for its abundant and
Figure 3. Annual hydrograph of the SSRB pre- and post-construction of the Lake Diefenbaker reservoir (average monthly discharge). Drawn from data in [74].

diverse wildlife, with declining river flows. The problem stems from upstream water withdrawals and river regulation, in particular, the operation of Lake Diefenbaker (figure 3) and other hydropower dams. Changes in the ecosystem are of profound and personal concern to the First Nations peoples who have traditionally occupied the region, affecting hunting, fishing, trapping and subsistence agriculture.

Superimposed on these current pressures is the need to understand and manage uncertain water futures, including effects of economic growth and environmental change, in a highly fragmented governance environment. Water planning is based primarily on provincial jurisdictions but with various responsibilities for the federal government and other agencies, and different legal frameworks for First Nations land and associated water rights, with the result that there is a lack of catchment-based integrated water resources planning and management. Water transfers between the provinces and water management are facilitated by an agreement between the Prairie Provinces [75], which is overseen by the federal government. This agreement requires that 50% of natural flow be permitted to flow across provincial boundaries on an annual basis. In southern Alberta, where the ‘first in time, first in right’ principle applies, and licence trading takes place, flows are very close to the limit in dry years and there are concerns for the capacity of interprovincial agreements to meet apportionment commitments during future multi-year droughts.

The SRB thus encompasses many of the challenges faced worldwide in addressing water security. We turn next to a discussion of the research needs to address water security in the basin. A key aspect of these is the recognition that a river basin is a complex human–environment system, multifaceted and containing strong interdependences and feedbacks, between climate, land and water systems, and people. Not only do we need to address changes to the climate, to terrestrial and to aquatic environments, including water quantity and quality, ecosystem response and land–atmosphere feedbacks, but we must also address the human dimension, including effects of human activities on land and water management, and efforts to bridge the science policy divide through stakeholder engagement, scenario planning, knowledge translation and social learning.

5. A science agenda for water security

With support from the Canadian and Saskatchewan governments, and the University of Saskatchewan, a science agenda is being implemented at the Global Institute for Water Security (GIWS) to support the analysis of water security for the SRB. The SRB poses globally important science challenges owing to the importance of, and diversity in, its cold region hydroclimate...
and ecological zones, the rapid rate of environmental change and the need for improved understanding, diagnosis and modelling of change. Biomes of regional and global importance include the Rocky Mountains, boreal forest and the Prairies. Key science challenges include the need to improve understanding and modelling of (i) climate variability and change over the basin, including, in particular, the extremes of floods and droughts, (ii) effects of land-use/management change on environments of regional and global importance, and (iii) societal controls on water management, including operational constraints, water management vulnerabilities, and policy and governance opportunities. To address these requires integrated, coherent, multi-scale, multidisciplinary research. For example, current models have not considered the full range of feedbacks between the atmosphere, hydrosphere, cryosphere and terrestrial ecosystems that occur from small to large scales and are anticipated to be particularly intense in this region. This shortcoming already degrades model predictability and resource management; for instance, the North America Regional Climate Change Assessment Program (NARCCAP) simulations of current climates show up to 6°C positive air temperature bias over this region [76] and errors in precipitation ranging from +90 to −45% (N. Khaliq 2012, personal communication). Limited data and flow forecasting capability, coupled with changing flows due to climate warming, exacerbated problems with operational management of the 2011 floods [77].

(a) Cross-scale dynamics

The river basin is a natural hydrological unit and the focus for integrated water management. Hence, the SRB has been designated as a large-scale observatory to provide the basis for improved understanding of key biomes and their integration at catchment scale, the associated hydrological, ecological and atmospheric interactions and feedbacks, and vulnerabilities to change, and new socio-hydrology research [21,78,79] into societal controls and perspectives on water management and water security.

The SRB observatory provides the multiple scales of observation and modelling required to develop: (i) new climate, hydrological and ecological science and modelling tools to address environmental change in key environments and their integrated effects and feedbacks at large catchment scale, (ii) new tools to support river basin management under uncertainty, including anthropogenic controls on land and water management, and (iii) the place-based focus for new interdisciplinary science. To achieve this, existing research sites are being augmented to provide more comprehensive interdisciplinary monitoring, and combined with multi-scale monitoring data from ground and satellite observations to create a large-scale observatory.

Major research sites are shown in figure 4. These include detailed observations, from local to small basin scale, and build on legacy data to provide a historical context for the improved understanding and diagnosis of environmental change [80–82]. These sites provide the basis for the development of improved process understanding and fine-scale models for the key biomes, and the application of those models in the detection and attribution of environmental change at local scales.

Upscaling is needed for improved atmospheric modelling and basin-scale prediction and management. While current large-scale weather, climate and hydrological model applications are typically based on 10–15 km grid scales, less than 4 km resolution is becoming available for high-resolution modelling and raises important questions concerning appropriate process representation. For example, explicit representation of convection, complex topography and effects such as irradiance on slopes and snow redistribution by wind is increasingly feasible. The proposed modelling strategy includes hydrological, cryospheric, ecological and meteorological modelling, and builds on previous work on cold region processes and modelling [83–85], as well as multi-scale modelling and data assimilation [86–88]. It presumes that, owing to the emergence of key Earth system processes at large scales, there are ‘scale-appropriate’ sets of processes, system behaviours and appropriate descriptive algorithms. Developing and parametrizing large-scale models from finer-scale models therefore requires not only assembling and testing fine-scale algorithms and examining their spatial variability for statistical representation, but also ensuring
that large-scale models are of appropriate complexity, capture dominant processes and display appropriate feedbacks so that the system behaviour is well described (recent application to large-scale modelling of prairie systems is reported by Mekonnen et al. [89]). These principles apply equally to hydro-ecological and water quality models. We also note that the modelling of land–atmosphere interactions at multiple scales is needed to understand and predict feedbacks to the climate system due to large-scale environmental change, and that, for local-scale impact assessment, downscaling of climate model outputs is required [90,91].

(b) Complexities

The SRB is situated in a heterogeneous climate regime with gradients extending from semi-arid to subhumid, with important elements of the natural water cycle involving snow, ice and ground frost. Cold region hydrological processes are complex [92,93] and underlying science and supporting data are limited. Precipitation is difficult to characterize, particularly in mountainous regions, where altitude effects on precipitation phase are critically important. Blowing snow is a major factor in both alpine and prairie environments [83,94], snow accumulation is dependent on land cover [95], and snow sublimation can be a major element of the water balance [96]. Important interactions for snow accumulation and melt include forestry management in the mountains and agriculture (e.g. stubble height affects snow trapping and hence crop water availability) in the Prairies. Run-off processes are often dominated by snow melt over frozen ground and are critically dependent on temperature history [97]. The fact that snow and ice conditions dominate for four or five months per year introduces a natural storage component that has been central to the way in which water is managed and adds heightened sensitivity to climate warming owing to its influence on energy storage and phase changes. Responses to climate change are therefore particularly sensitive to temperature, as well as precipitation, and associated hydro-ecological feedbacks. While the Rocky Mountains present difficulties due to high relief, complex process interactions and limited data (particularly for precipitation), the Prairies also present particular challenges. Some 40% of the SRB land area does not normally connect to the main river [60]; internal drainages predominate, but, given the low relief, are difficult to characterize without high-resolution digital elevation data (e.g. LiDAR). Features such as roads and culverts can be important hydrological controls. The difficulties of characterizing contributing areas are a major constraint on hydrological and water quality modelling.

Within the SRB, rapid warming is being observed. The sensitivities to climate change are most notable in the west, where changing temperatures are producing smaller snow packs and earlier melt, decreasing glacier size and shifts in the river’s run-off regimes. Glacier coverage has
declined by approximately 25% in the last quarter century [98,99], and the spring snow-covered period has shortened by approximately one month [100]. Associated with these declines is a shift from snow to rain on the eastern slopes and a decrease in streamflow across both glaciated and non-glaciated streams [101–103] in the headwaters of the Saskatchewan River. The western boreal forest and Prairies have experienced large swings in climate that have resulted in severe weather, with some of the driest and wettest periods in the last 140 years occurring since the turn of the twenty-first century [104]. This has resulted in extensive areas experiencing large soil moisture deficits, drought-induced dieback of major tree species [105], wetland and stream disappearance, and recorded minimum groundwater levels during the drought of 1999–2004, as noted above, associated with multi-billion dollar economic losses to agriculture. By contrast, the recent wet periods of 2010 and 2011 produced extensive (more than 1 in 500 year) flooding in the Prairies, inundation of wetland vegetation and record groundwater levels. Because of the interactions between hydrology and vegetation, the southern boreal forests of western Canada are expected to be an area of maximum ecological sensitivity to stressors in the twenty-first century [106–108].

It will be clear from this limited discussion that an understanding of complex interactions between atmospheric science, hydrological and cryospheric processes, terrestrial ecology and land use is essential to diagnose and predict change in the SRB. However, diagnosis of these effects is not straightforward, given the high levels of historical climate variability, extensive changes in land use and land management, data limitations and high levels of uncertainty in model simulations. New research is needed to test for parameter and process non-stationarity within a statistical framework of uncertainty analysis [82], for example extending the work of Vaze et al. [109].

We turn now to complexities associated with human-induced change to the natural environment. These include effects of land management—the extensive effects of agricultural land management in the rural environment, and more localized effects of urbanization. The former can be subtle but important. For example, extensive changes to zero tillage have taken place in the Prairies, with implications for run-off processes. Agricultural drainage has also been extensive, but the effects on run-off, and in particular extreme events, are unclear and controversial. Both urban development and arable and livestock agriculture are generating significant loads of nutrient pollution. While urban pollution is readily straightforward to characterize, effects of agriculture are complex, and not well understood. Similarly, while agricultural beneficial management practices are understood to have an important potential role in mitigation of adverse effects, results of interventions are often complex and site-specific [35]; no adequate characterization has been undertaken of their potential on the SRB scale.

Moving from land to water management, it will be evident from the previous discussion that the SRB is a heavily managed river. Alberta has a responsibility to pass 50% of the annual flow to Saskatchewan; in drought years, their allocation is fully used, with extensive withdrawals for irrigation. Figure 3 illustrates the dominant effect of Lake Diefenbaker in Saskatchewan in determining downstream flows. Clearly, basin-scale hydrological and water resource modelling must account for these interventions. This raises challenges of complexity, and in particular the extent to which local complexity is important for large-scale simulation. The south SRB in Alberta has approximately 11 000 licences for withdrawals and is subjected to complex operational management, including constraints due to the needs for effluent dilution and environmental flows [58,110]. Determination of the appropriate level of complexity for large-scale modelling remains an important area of research.

**c) Uncertainties**

From the above discussion, it can be concluded that underlying the analysis of water security in the SRB is a complex and multifaceted set of science issues. An important aim, therefore, is to use the multi-scale data from the SRB to improve process understanding and to reduce uncertainty in predictive models. Ideally, predictive modelling would be accompanied by formal analysis of the associated uncertainties. In recent years, improved computational capacity has
provided the capability for major developments in the formal quantification of uncertainty in hydrological models (e.g. [111,112]). We note, for example, that recent research has addressed the assimilation of multiple sources of information to constrain model parametrizations [87] and consider the cascade of uncertainty in moving from detailed physically based to simpler meta-models for large-scale simulation [88]. However, more generally, an important set of technical issues arise in the context of the design, development and implementation of integrated models—i.e. models that include, for example, hydrology, agriculture, ecology, water resources (including licences and other legal constraints), economics and social behaviour. Guidance is needed on the strengths and weaknesses of alternative modelling approaches, e.g. coupled complex models, meta-models, system dynamics models, Bayesian network models or some hybrid of these [113]. Related issues include appropriate levels of model complexity (scale of representation, what to include, what not, and what is tractable in terms of stakeholder accessibility) and available tools (modelling platforms). At a technical level, some model elements are amenable to formal analysis using classical (e.g. Monte Carlo-based) methods, but not others—techniques such as Bayesian networks [114] have the potential to address integrated uncertainty assessment.

While an important goal of scientific research is to reduce uncertainty, as noted above, the translation of GHG scenarios to local impacts is subject to such large uncertainties that conventional approaches may be unable to effectively inform decision making. A critical issue is how to represent and communicate uncertainty to decision makers [31], which we turn to below.

6. Knowledge translation for water security: decision making under uncertainty

We turn from the needs for underpinning science for water security to its application, that is, the translation of science into useful information for decision makers and other stakeholders. One issue is the development of effective decision support tools. A second, interrelated aspect is the process of engagement. In that latter context, we note that the GIWS programme has embraced socio-hydrology as one of its four core themes. The term ‘socio-hydrology’ has been put forth by Sivapalan et al. [78] to highlight the importance for water science of the complex and dynamic interactions between humans and the environment. Although there is some heated debate as to whether this is a new science or reformulation of Falkenmark’s original conceptualization [79] of hydro-sociology, the concept of socio-hydrology [115] is broad enough to encompass both the human drivers of hydrological change and the social processes through which hydrological science is translated and communicated to relevant decision makers. A key feature of both the scientific and translational components of socio-hydrology is the issue of uncertainty.

In the field of water resources management, a key source of uncertainty is associated with non-stationarity. Water resources modelling and management have traditionally been based on the assumption of stationarity—in simple terms, the concept that the statistical properties of the past will be unchanged in the future (e.g. Lins [116] for a more complete discussion). This has been the conventional basis for optimization models and predict-and-plan methods of long-term water planning and management. The profound uncertainties about the future climate led to Milly et al. [117] asserting that ‘stationarity is dead’. Streamflow non-stationarity arises from multiple causes, including climate change, land-use modification and water management. While climate uncertainties are large, the uncertainties around these other aspects can also be substantial. Nevertheless, the discussion of climate change is instructive, as uncertainties are large and potential feedbacks are wide-ranging, and include effects on land, water and their societal controls.

New methods are needed to handle the large, but unquantified, uncertainties in climate models for decision support in the water sector. The science discussed above is being used to improve the quality of downscaled climate information for scenario assessment, to support the development of improved large-scale hydrological and water quality models for the SRB, and to develop water resource systems dynamic models that can support interactive engagement with stakeholders. At the same time, novel approaches are being used for vulnerability and scenario analyses. Vulnerability analysis systematically explores system response to a priori-defined feasible
Figure 5. Analysis of water resource vulnerability to climate change, South Saskatchewan River, Alberta. (Online version in colour.)

ranges of climate futures, as discussed by Brown & Wilby [118] and implemented for the Saskatchewan River by Nazemi et al. [110]. Figure 5 is based on simulation modelling of the South Saskatchewan River water resource system in Alberta, a complex system with some 11 000 licence holders, using the Water Resources Management Model [119], a linear programming-based simulation model that optimally allocates water to competing demands given the state of the system and the operational policies. The figure illustrates the potential risks to the system as a function of potential impacts of climate change, as represented by changes in annual run-off volume and the timing of the seasonal hydrograph peak (system infeasibility refers to the failure to meet prespecified system constraints under current operational policies, i.e. without adaptive management). This analysis can be used to define current and future system vulnerabilities. However, it also provides the opportunity to map alternative scenarios from regional and global climate models onto the vulnerability analyses (following Reynard et al. [120]), as indicated schematically by the ellipses in the figure, which represent points and associated uncertainty, as might be derived through conventional climate scenario-based assessment and hydrological modelling. In this way, the range of outcomes derived from multi-modelling of scenarios can be viewed in the context of system sensitivity and vulnerability.

The socio-hydrology programme has been designed to address human-induced changes to water system dynamics through exploratory modelling and decision support using these tools. Emphasis is on designing viable land-use and policy scenarios that represent alternative futures to enable DMUU processes to emerge with stakeholder engagement. For example, there is active discussion in the Province of Saskatchewan about increasing irrigated agriculture from its current area of 109 879 acres [121] to as much as 500 000 acres to increase productive capacity and food exports. Research and policy discussion centre on the ramifications of increasing irrigated agriculture for instream flows, hydropower generation, homeowners and recreationalists concerned about lake levels, and, most critically, for future mining and other economic development. These ramifications can be modelled as a set of competing demands, including the needs of farmers, mining companies, homeowners, anglers, boaters and society at large. The social scientists have convened water stakeholders in the SRB to elicit their evaluation concerns as a prelude to modelling and development of decision support tools [56,122].

An important issue relevant to knowledge translation is the new learning that must occur when scientists and stakeholders unite for policy discussion and DMUU. The traditional model of science-driven decision making has not proved to be effective in translating climate science for decision making in climate-sensitive sectors [123–125]. Reasons include inflexible
decision rules, informal arrangements that prefer established and tested practices over innovative prediction tools, organizational culture and reward structures, risk-averse and vulnerable cultural contexts, lack of meaningful interaction between scientists and decision makers, hard-to-interpret presentation of scientific information, cascading uncertainties when climate model results are used from regional and local prediction, and user difficulty in translating probability information into action. Potential remedies are many, but Dilling & Lemos [55] 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. Clark and Clarke [50] highlighted the importance of active negotiation processes to support the creation of usable scientific knowledge as well as social networks between researchers and decision makers. It is increasingly clear that sustained engagement between stakeholders and scientists is vital for successful adaptation, and that the local knowledge that it provides is sometimes supplemented, but not replaced, by traditional scientific inquiry [15]. The SRB study therefore includes active engagement with a range of stakeholders concerning both the design of experimental programmes (e.g. with local residents concerning anthropogenic effects on the water quality of Lake Diefenbaker and with First Nations communities concerning changing ecosystems in the SRB delta) and the development of water resource simulation tools for decision support.

7. Conclusions

In the face of widespread unsustainable water use and a future in which increasing demands for water from population and economic growth are superimposed on a rapidly changing environment, water security is increasingly being recognized as one of the major challenges for society in the twenty-first century. However, water security is a multifaceted concept, often oversimplified and viewed differently by different audiences. It encompasses basic societal needs for drinking water, food and energy, the needs of aquatic and terrestrial ecosystems, threats to water quality from pollution and the extremes of flood and drought. At the current stage of global development, human impacts on the natural environment can no longer be ignored. Society will need to manage a complex and dynamic human–environment system if it is to achieve water security.

We have identified the emerging field of socio-hydrology and what it has to contribute to water science and policy. To science, it means that human drivers are at least as important as biophysical ones in understanding system dynamics. Sivapalan et al. [78] argue that it is not possible to predict water cycle dynamics over decadal or longer time periods without considering interactions and feedbacks of natural and human components of the water system. These feedbacks have the capacity to move water systems beyond critical tipping points into new, previously unobserved, states. Socio-hydrology also has consequences for the social processes through which scientific knowledge is used for policy analysis and decision making. Knowledge for decision making will increasingly be co-produced by scientists and decision makers through processes like the ones initiated in the SRB.

Water security offers a valuable framework to integrate across science and social science, to link science with decision making and to enable people facing very different water challenges to unite for policy action. We set out a research agenda that seeks to improve the basic understanding of societal and environmental change and the interactions between the two and a policy agenda that seeks to contribute to long-term water planning in the SRB. They are in fact interrelated agendas in the sense that science augments local knowledge to reduce vulnerability, and deeper understanding of public values leads to new science questions and modelling activities. We assert that these interwoven agendas will, at the end of the day, facilitate water security in the SRB, Canada and worldwide.

Acknowledgements. The support of many colleagues at the Global Institute for Water Security in developing the Saskatchewan River basin as a large-scale observatory is gratefully acknowledged. Particular thanks are
due to Alberta Environment, and specifically Dave McGee and Tom Tang, for their provision of the Water Resources Management Model for southern Alberta.

**Funding statement.** This research is supported by the Federal and Saskatchewan Provincial Governments and the University of Saskatchewan through the Canada Excellence Research Chair grant to H.W.

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