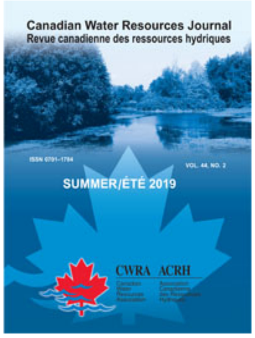

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COMMENTARY

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Prairie water: a global water futures project to enhance the resilience of prairie communities through sustainable water management

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> ‘I would walk to the end of the street and out over the prairie with the clickety grasshoppers bunging in arcs ahead of me and I could hear the hum and twang of the wind in the great prairie harp of telephone wires.... Standing there with the total thrust of prairie sun on my vulnerable head, I guess I learned – at a very young age – that I was mortal’.
>
> W.O. Mitchell, *Who Has Seen the Wind*

Introduction

The prairie region of Canada (the Canadian Prairie) lies in the southern part of the provinces of Alberta, Saskatchewan, and Manitoba and is part of the Northern Great Plains of North America. The Canadian Prairie environment poses serious challenges for water and land management tools, policies and practices that can optimize water availability, water quality, biodiversity, topsoil, economic value of water as an input in agriculture, and mining and energy development. Management decisions pertaining to the allocation and protection of both surface and subsurface water supplies are influenced by a spectrum of factors. There is much to consider when designing solutions that balance short-term needs with long-term sustainability of both natural and human systems. Developing a user-led water strategy for the diverse (and changing) physical and socio-economic landscape of the Canadian Prairie is challenging. To date, there has not been an integrated approach taken to improve understanding of how the region functions hydrologically and how this functioning influences those physical, chemical, ecological, economic, cultural and social systems of concern to the region's residents. This commentary introduces and describes the new Global Water Futures programme *Prairie Water*. This commentary is meant to permit engagement with the Canadian water community and build collaboration with the programme. Herein, information on the distinct conditions, challenges, vulnerabilities and stressors that influence current water issues on the Prairie are presented to demonstrate how the core components of Prairie Water will meet the programme's primary goal. The programme aims to provide recommendations for water management that will improve the resilience of Prairie communities via improved understanding of water cycling. Resilience typically focuses on the ability of systems to adapt to change and uncertainty. This focus has been explored in socio-ecological systems from the perspective of systems ecology, community preparedness and response to external stressors such as climate change impacts on water supply (e.g. Walker et al. 2004; Magis 2010; Berkes and Ross 2013). By improving understanding of water cycling, the assessment of supply vulnerabilities is improved. The results of Prairie Water will provide

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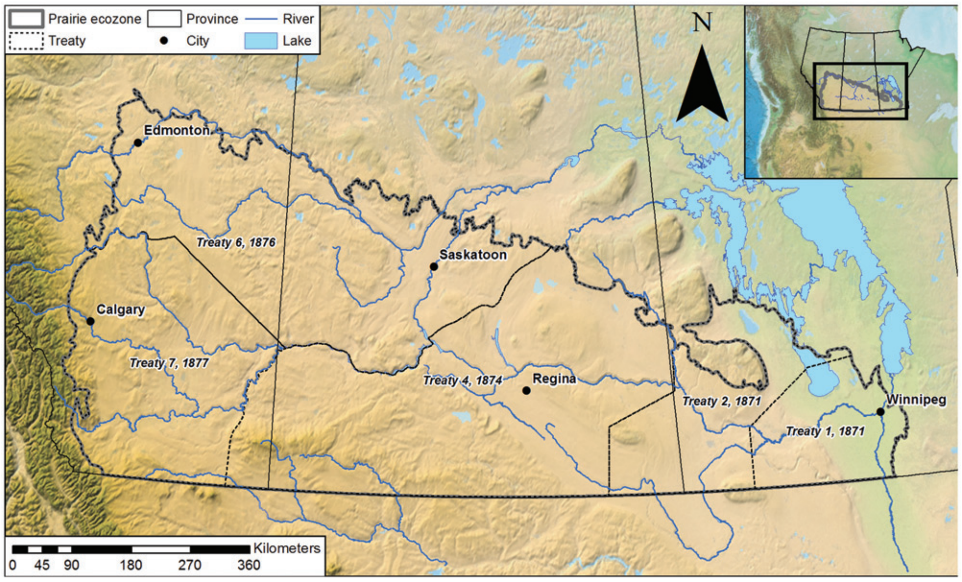

Figure 1. Map of the Canadian Prairie Ecozone, the study domain of Prairie Water, with treaty areas, provincial boundaries, major cities and topographic relief. Inset map shows location of study area in the context of western North America.

partners the decision-making information they need to understand the trade-offs between different competing demands for water and the services water supply provides. Informed decisions improve resiliency.

The Canadian Prairie

Climate, landscape, hydrology and socio-economic conditions

As the quote from W.O. Mitchell implies, stories originating from the Canadian Prairie landscape are often steeped in the lore of resilience. From millennia of Indigenous Peoples' presence and adaptation in this landscape (Goebel et al. 2008) to the hard lessons learned as vast quantities of grassland were converted to agriculture beginning in the late 1800s (Marchildon 2009), there has been a healthy respect for the region's water resources challenges. This 440,000-km^2 region (Figure 1) is defined here as the Prairie ecozone from the National Ecological Framework for Canada (Ecological Stratification Working Group 1995). July average maximum daily air temperatures approach +30 °C across much of the region, while January average minimum daily air temperatures approach −30 °C. Mean annual precipitation (P) ranges from 350 to 650 mm with the lowest values in southwestern Saskatchewan, and the highest in southeastern Manitoba, with about one third occurring as snowfall depending on the location (Gray and Landine 1988). Potential evapotranspiration (PET) is generally 600–800 mm yr^{-1} (Morton 1983) and although it does not vary as much as P, in any given year the annual water deficit (ie P − PET) can exceed 300 mm, resulting in diverse climatological conditions from sub-humid to semi-arid.

Despite popular belief that the Prairie landscape is rather homogeneous, the region contains a variety of landscapes. Several uplands follow the Manitoba Escarpment and Missouri Coteau. Outside of these uplands, relief is relatively small, but the topography can vary from flat in glaciolacustrine deposits to very hummocky in some moraine and till plains (Figure 1). The tall grass prairie once common in southern Manitoba has been almost completely replaced with annual crops. Across the prairie ecozone, 114,500 km^2 of natural grassland remains (Bailey et al. 2009). Much of these native grasslands are in the (in)famous Palliser Triangle, named after the British explorer and natural scientist who surveyed the region in the 1850s on behalf of the Royal Geographical Society and reported it to be unsuitable for widespread agriculture owing to aridity (Waiser 2005). Soils in this portion of the region are predominantly brown chernozemics, but also include solonetzic soils, which can constrain agricultural practices. The region's northern and eastern fringes transition to aspen parkland, within which the brown chernozemic soils change to black. A significant portion of the Canadian Prairie overlaps with the Prairie Pothole Region where there are numerous post-glacial depressions that can be occupied by wetlands. These wetlands are hydrological, biogeochemical and ecological hotspots that provide important ecosystem services such as flood control, groundwater recharge, sediment trapping, soil formation, wildlife habitat, refugia for insects, and nutrient retention (Gray 1964; Hansson et al. 2005; NAWMP 2012; Morton et al. 2015; Bortolotti et al. 2016; Martins et al. 2017; Perez-Valdivia et al. 2017; Pattison-Williams et al. 2018).

Most of the streamflow in major rivers of the Prairies originates in the Rocky Mountains. The surface hydrology of the Canadian Prairie landscape results in much lower runoff rates. Despite long periods of winter, the dry climate results in only relatively shallow snowpacks (<50 mm as water equivalent) with occasional mid-winter melts that can be frequent in the southwest but are infrequent in the northeast. With such a sustained cold period, wind and sublimation alter the snowpack. Snow tends to be redistributed to depressions, which focuses locations of high snowmelt, infiltration and runoff production (Pomeroy et al. 2007). Snowmelt is arguably the most important hydrological event annually on the Prairie. Infiltration into frozen soils is strongly influenced by moisture content at freeze-up and tends to promote runoff at the expense of infiltration (Gray et al. 1984). In contrast, in summer, rainfall is infrequent, potential evapotranspiration high, and unfrozen infiltration unimpeded (Elliot and Efetha 1999), so runoff can be limited. The pervasive dry conditions and poorly organized natural drainage networks result in large areas that do not contribute streamflow to major river systems on a regular basis (Stichling and Blackwell 1957; Martin 2001; Shaw et al. 2012; Shook et al. 2015). This water instead often collects in the topographic depressions discussed above. However, during very wet periods these depressions fill, allowing what can be substantial volumes of water from upstream areas to be transmitted downstream. This expansion of contributing area is associated with the recent large floods in the region, particularly in the Assiniboine Basin (Pattison-Williams et al. 2018). This behaviour means the distribution (ie size, frequency, relative landscape position) of these depressions is an important influence on regional flood frequency (Shook et al. 2015)

Groundwater resources in the Canadian Prairie are drawn from a variety of aquifer types (Grasby et al. 2014). The Carbonate Rock aquifer of Manitoba, the Judith River Formation in Saskatchewan and the Paskapoo Formation in Alberta are regional bedrock aquifers, which are important for domestic, agricultural and industrial water supplies. Throughout much of the rest of the Prairie Water domain, and particularly where shallow bedrock aquifers are absent, inter-till sands and gravels and buried valley aquifers are often targets for groundwater withdrawals. Glacial till and glaciolacustrine clays act as confining units over most of the Prairie, and Cretaceous shales are also important confining units for deeper bedrock aquifers. Groundwater recharge through these confining units is often low (5–40 mm yr^{-1}) (van der Kamp and Hayashi 1998) and there are numerous documented cases of groundwater with a long residence time (e.g. >10,000 years) in the region (Ferguson and Jasechko 2015). Groundwater recharge usually occurs under topographic depressions that collect snowmelt runoff water and allow it to infiltrate and percolate below the rooting depth (Hayashi et al. 2003). Much of the infiltration water for shallow groundwater recharge may be exhausted by evapotranspiration (Parsons et al. 2004), but a small fraction leads to low and steady deep groundwater recharge rates (van der Kamp and Hayashi 1998) important to the region's shallow aquifers (100–200 m deep) commonly used for rural and urban water supply.

The population of the region has increased by 32% in the last 20 years (https://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/demo62h-eng.htm) to 6.5 million people, and will likely continue to grow and concentrate in urban areas as it has since the 1960s. The economy across the region is diverse, and predominantly resource-based, including mining, oil and natural gas production and refining, and light manufacturing. There are nine operating potash mines, all in Saskatchewan. The Prairie ecozone contains five coal mines, two in Alberta and three in Saskatchewan. In 2014, oil production in the Prairie ecozone in Manitoba, Saskatchewan and Alberta was 16, 190 and 280 million barrels of oil, respectively. This production relies heavily on groundwater resources. The most widespread economic activity is agriculture. Of the annual cropland in the three Prairie Provinces in 2016, approximately 16% was allocated to canola production, and 12% to spring wheat (the two largest crops by area). In 2016 the agricultural industry represented 4.0%, 10.3% and 13.5% of the provincial gross domestic product for Alberta, Manitoba and Saskatchewan, respectively (Statistics Canada 2017). The region accounts for the majority of Canada's wheat production and is a lead contributor to global wheat and pulse markets (Bekkering 2014; Agriculture and Agri-Food Canada 2017). Canola is a significant cash crop across the region, especially in the black soil zone. Production amounted to 21 million tonnes in 2017 (http://www5.statcan.gc.ca/cansim/a26?lang=eng&id=10017). Ranching is also widespread, particularly in the southwest part of the region. This is reflected in the estimated number of cattle in 2017 in each province, which was 1,135,000 in Manitoba, 2,625,000 in Saskatchewan, and 5,145,000 in Alberta (https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3210013001).

Provincial water governance systems evolve in response to extreme events that push society outside of its water-secure positions (Gober and Wheater 2014). Extreme hydrological events and society's vulnerability to them triggered the water governance frameworks for Alberta Water for Life, the Saskatchewan 25 Year Water Security Plan, and the Manitoba Water Stewardship Strategy. Each evolved from political responses to establish governance structures that distribute risk and attempt to instill resilience in the face of water crises. Alberta Water for Life evolved in response to the 1999–2002 drought that caused a $5 billion loss in the Canadian economy (Wheaton et al. 2008). The Saskatchewan 25 Year Water Security Plan reflects the governance framework for source water protection in response to water contamination in North Battleford, Saskatchewan in 2001 (Saskatchewan Water Security Agency 2012; Gober and Wheater 2014, Strickert et al. 2016) and flooding that arose in 2010 as a result of multiple years with multi-day summer rain events (Pomeroy et al. 2014; Dumanski et al. 2015). The Manitoba Water Stewardship Strategy continues to evolve as a result of several flood events and the eutrophication of Lake Winnipeg. Although the provinces have differences in their governance frameworks and their application, they all have two common elements: They are predominantly provincially funded and they seek to support locally based water stewardship planning groups that are based at the watershed scale (Government of Alberta 2003; Manitoba Water Stewardship 2003; Saskatchewan Water Security Agency 2012).

Water management challenges

Two major challenges facing sustainable water use in the Prairie are (1) climate, and (2) land management. The region, like everywhere else in Canada, has experienced statistically significant warming since the mid-twentieth century, especially in winter (Dumanski et al. 2015; De Beer et al. 2016; Coles et al. 2017), and this is expected to continue (Asong et al. 2016; O'Neil et al. 2017). Annual precipitation amounts continue to be cyclical, but there is a trend towards more rain at the expense of snow (Vincent et al. 2015). Summer rainfall is typically composed of short, intense local thunderstorms and larger frontal events. Shook and Pomeroy (2012) and Dumanski et al. (2015) found multiple-day rainfall events are increasing in frequency relative to shorter events in some parts of the Prairie. These longer events are not necessarily gentler but can include embedded convection which in 2012 and 2014 caused the first recorded extensive rainfall-runoff flooding over the east-central Prairie. In this portion of the region, mean annual precipitation was ~400 mm from 1942 to 2014, with statistically significant increases in rainfall in spring (March), early summer (May and June) and fall (October) (Dumanski et al. 2015). Higher fall and spring rainfall can increase the likelihood of saturated frozen soil conditions, which can decrease infiltration rates during snowmelt, further increasing runoff. These changes in precipitation have reduced the predictability of runoff derived from regular spring snowmelt, and added uncertainty to water management and agricultural decision-making.

Deeper aquifers containing saline water are commonly accessed by the fossil fuel and potash industries for both water supply and waste disposal (Ferguson 2015). Management of groundwater resources can be a challenge because it is regionally disconnected and has often been in isolation from surface water resources. Groundwater mapping efforts are not consistent across the region (e.g. Betcher et al. 2005) and the sustainability of these resources is often unknown (Council of Canadian Academies 2009). Groundwater withdrawal from the Estevan buried valley system has resulted in one of Canada's few documented cases of unsustainable groundwater use (van der Kamp and Maathui 2012). It is expected that any expanded use of groundwater in the Prairie will lead to similar outcomes because many deeper aquifers are poorly connected to the rest of the hydrological cycle (Ferris et al. 2017).

Understanding linkages between surface and subsurface water is critical to the management of the Prairie landscape. However, the linkages and rates of surface–subsurface water exchange are difficult to quantify over large areas and are poorly understood. This situation makes it difficult to develop comprehensive, defensible and robust water management plans and policies that integrate both surface and subsurface water resources. Wetlands are known to be key features that connect surface and subsurface systems through recharge and discharge (Hayashi et al. 2016). Recharge rates are strongly influenced by the complex processes involving drifting snow, snowmelt runoff and infiltration into frozen soil (e.g. Hayashi et al. 2003). Ponds expand and shrink within

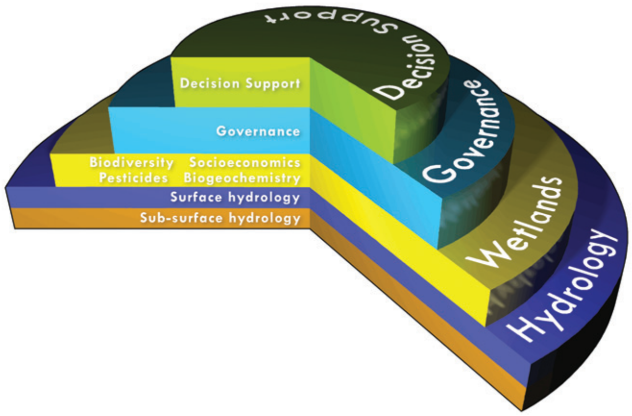

Figure 2. Conceptual diagram illustrating the integration of Prairie Water's four major research themes (surface and subsurface hydrology, wetlands, and governance). Text inside the wetland layer denotes its sub-themes. While layered here, each theme is linked, with the programme underpinned by the outcomes from the hydrology themes. The research programme will collectively contribute decision support tools for increased resilience of Prairie communities.

depressions and across the landscape with wet–dry climate cycles (van der Kamp et al. 2008). This is expected to result in variable recharge over decadal scales. However, which wetlands are most important for recharge, and when, and on which landscapes has not been completely resolved. The balance between recharge and discharge over long periods is a key part of sustainable groundwater management (e.g. Pierce et al. 2013), and this knowledge gap decreases the resilience of the Prairie communities and industries that rely on groundwater resources.

Agricultural practices in the region are constantly evolving, with changes in equipment and crop variety technology, input and output markets and climate patterns. Consequently, the Prairie is arguably one of the most intensely managed landscapes in Canada, often in an attempt to maximize the benefits of scarce water, or minimize impacts of overabundance. Government policy often encourages increases in crop production to enhance economic growth. For instance, the 2012 Saskatchewan Plan for Growth has a stated objective of an approximately 30% increase in crop production and a stated goal of a 50% increase in exports of agriculture and food products by 2020 ($10 billion to $15 billion) (Government of Saskatchewan 2012). These goals will potentially impact Saskatchewan water resources with increased intensity of production (e.g. fertilizer, pesticides) and increased pressure for expanding cropped acreage (e.g. wetland drainage and irrigated land).

Wetland management has caused some governance challenges in portions of the Canadian Prairie where extensive drainage in upland regions to increase agricultural production has been associated with exacerbating flooding downstream (http://www.cbc.ca/news/canada/saskatoon/farmers-sue-water-security-agency-claiming-stop-flooding-1.4608944; http://www.cbc.ca/news/canada/manitoba/wetland-loss-manitoba-policy-1.3917086; http://leaderpost.com/news/saskatchewan/pasqua-chief-wary-of-quill-lakes-project-withdrawal). Wetland drainage may impact downstream water quality, for instance through elevated nutrient export (Brunet and Westbrook 2010). Deterioration of wetland water quality may also coincide with occurrence of agrochemical products, including pesticides (Main et al. 2014; Stanton et al. 2018). This can lead to ecologically impaired ecosystems with high losses in biodiversity, which in turn compromises future provisioning of important ecosystem services.

Key challenges for water governance on the Prairie include designing the best ways to interact and coordinate among partners across all levels of government. For example, Indigenous communities often confront poor integration because they can be 'between' jurisdictions when facing a hazard (e.g. flooding, source water protection). Challenges for decision-making processes revolve around balance. This includes learning which processes balance multiple forms of evidence and resolving scientific evidence with local experience. There are often many emotions around water supplies and water management decisions. It can be difficult to disentangle how choices are made.

These conditions and challenges create major issues for which society does not necessarily have the answers. The role of wetlands in sustaining surface and subsurface water resources through wet and dry climate cycles is unclear, as is how land management choices exacerbate or suppress runoff and groundwater recharge rates through these cycles. How farm-scale land management choices scale up to impact regional recharge rates, flood frequencies and magnitudes, biodiversity and water quality has been very difficult to quantify. The most appropriate and effective mechanisms with which to provide information to decision makers and policy generators remain elusive. It is unclear how important values are to decision-making, and how they interact with evidence.

Prairie water

Prairie Water is organized along four integrated themes that address some of these issues of broad interest to the region's stakeholders and rightsholders who partner in the programme (hereafter referred to collectively as partners): surface hydrology, subsurface hydrology, wetlands and governance (Figure 2). Partners from all three provincial governments, indigenous governments, industry, agricultural producers, non-governmental agencies and watershed stewardship groups are actively engaged in the research programme design. Partners establish research priorities, facilitate research through data sharing, and co-design tools and outcomes urgently needed to guide land and water management decisions. These groups include agencies from multiple levels of government, Indigenous Peoples, agricultural producers, non-renewable resource extraction industries, and watershed stewardship organizations. The surface hydrology and subsurface hydrology themes are designed to improve understanding and prediction of water processes and regimes on the Prairie. The wetlands theme is focused on arguably the key landscape component that controls hydrological linkages between the surface and subsurface (Hayashi et al. 2016) and the movement of water and constituents across the landscape. The fourth theme, governance, is focused on learning how management and policy decisions are made about surface and subsurface water resources and wetlands, determining the predominant roles of different segments of society in policy processes, and making recommendations on how best to inform decision-making. The goal of the project is to enhance the resilience of Prairie communities through improved understanding of water cycling and providing recommendations for water management. The resources of the large rivers of the Saskatchewan system provide crucial supply to the region, but the focus of Prairie Water is on the prairie landscape. There are many other water resource management issues as well (e.g. growth of cities), but because of resource limitations these are not considered by Prairie Water.

Surface hydrology

The foundational research in Prairie Water is separating the influence of climate, landscape and land management regime (e.g. crop selection, wetland management) on hydrological response across the diversity of Prairie watersheds. This has been challenging for previous studies (e.g. Dumanski et al. 2015; Ehsanzadeh et al. 2016) because both climate and predominant agricultural practices have been changing simultaneously. To tackle this problem, Prairie Water researchers and their partners will first classify all Prairie watersheds of roughly 100 km^2 based on their hydrological regimes and physiographic traits. This type of exercise has been conducted in other regions of Canada (Ouarda et al. 2000; Cavadias et al. 2001; Spence and Saso 2005) with success. The only recent classification of the Canadian Prairie was limited to Manitoba watersheds (Burn 1990), and there has been no Prairie-wide classification. The closest such work was by MacCullough and Whitfield (2012) who classified Prairie streamflow regimes. A watershed-based system is intended to enhance the capacity to provide solutions to water management challenges across a greater spatial extent of the region, and will be a useful framework on which to generate, catalogue and disseminate information.

The assumption is that with similarities in climate, topography, wetland distribution and predominant land use, etc., watersheds in each class will respond to the influence of climate, landscape and land management the same way. Each watershed class will be modelled in a virtual manner (Weiler and McDonell 2004; Pomeroy et al. 2011) using the Cold Regions Hydrological Model (CRHM). The CRHM is a modular simulation platform that has proven very capable of representing prairie hydrological processes and properly emulating water fluxes (Pomeroy et al. 2007; Fang and Pomeroy 2009; Fang et al. 2010; Pomeroy et al. 2014). This approach means specific watersheds will not be modelled, but rather a representation of each watershed class will form the basis of modelling efforts. Simulation success will be evaluated by comparing model output to broad characteristics of the hydrological regime of the watershed class (e.g. hydrograph shape, number of zero-flow days, etc.). Modelled virtual basins that are robust in their representation of hydrological traits of highest interest to the research team and partners (e.g. spring snow depth) will be subjected to a variety of future climate and land management scenarios. This will help identify those watershed classes that are hotspots of hydrologic change, and permit investigations of how these changes interact with stressors and conditions (e.g. pesticide and nutrients). This will enable identification of Prairie watersheds most vulnerable to change. These scenarios are being guided by the requirements of Prairie Water partners and informed by current management and policy objectives of each province. Co-designed participatory research with partners has proven crucial to the success of similar programmes (Parsons et al. 2016) and the intent is to follow this approach to ensure the spectrum of modelled time series will be useful to both partners and investigators within Prairie Water. Scenarios could include warmer climates, a variety of wetland distributions, shifts in crop types and practices, or expansion of permanent cover or irrigation.

Subsurface hydrology

The research plan for Prairie Water includes the development of a simple numerical model representing the essential processes of depression-focussed groundwater recharge. Such a model is capable of estimating the rate of aggregate recharge from thousands of depressions and will provide a useful tool for regional groundwater resource management. The model is based on the Versatile Soil Moisture Budget (VSMB), which has been widely used in the Prairie for soil moisture modelling (e.g. Akinremi et al. 1996) and recently modified to improve the representation of snow and frozen soil processes (Mohammed et al. 2013). It will be driven in part by key outputs from the CRHM virtual basin scenarios. The size and distribution of recharge areas is critical for deeper subsurface recharge (Noorduijn et al. 2018), and determining how this manifests at the watershed or regional scale or through wet–dry precipitation cycles (Hayashi and Farrow 2014) is a research goal of Prairie Water. Prairie Water seeks to better understand the connections between Prairie aquifers and the rest of the hydrogeological system, considering both background conditions and cases where groundwater withdrawals are occurring. Better understanding surface–subsurface linkages across the diversity of Prairie aquifers and landscape, and under different climate and land management scenarios, will address many of these unknowns about sustainability of groundwater withdrawals.

Wetlands

An outcome of Prairie Water is to produce reliable state-of-the-art information about the role of wetlands for water quality, nutrient retention and agrochemical loading, biodiversity, and land management economics. Through this work, Prairie Water seeks to determine which wetlands provide critical short- and long-term services that enhance the resilience of Prairie communities and inform policy development to influence wetland management on agricultural land.

The wetland researchers and partner organizations will work to identify the types of wetlands that act as key ‘gatekeepers’ by attenuating streamflow during high discharge periods, retaining nutrients, and maintaining biodiversity. Forecast simulations of virtual basin hydrology will be integrated with three decades of biodiversity monitoring data to understand wetland conservation priorities. Likewise, this work will investigate the risk that pesticides pose to wetland ecosystems, coupling spatial wetland pesticide patterns with hydrological processes. Nutrient retention processes will be quantified and modelled, with these models driven by outputs from the CRHM virtual basin scenarios to understand how nutrient retention responds to changing hydrological and land use patterns. This information on wetland biodiversity, risk from pesticides, and nutrient retention behaviour will be overlaid with the catchment classification, to provide spatial, mapped outputs and serve as decision-making tools for Prairie Water partners. In addition, the research team plans to work with partner organizations, including producers, to design a wetland manipulation experiment. The current regulatory environment in Saskatchewan encourages consortia to propose, coordinate and assess drainage activities. This presents partnership opportunities to measure relevant hydrological and chemical variables in control and impacted wetlands, before and after manipulation, and to evaluate current understanding of wetland behaviour while testing model predictions. Integrating understanding of the influence of wetlands and wetland drainage on nutrient retention and runoff, pesticide distribution and biodiversity with the economics of wetland drainage at the farm and regional scale will enable more informed communication with partners to help develop locally acceptable management and policy approaches to prairie wetlands.

The economics of wetland management will be estimated and used to develop a socio-economic watershed model linking land management decisions with hydrological function and other environmental indicators. Addressing these questions across farms, watersheds and provinces will provide information about the influence of land management choices at multiple scales and will inform policy. Examples of scenarios that will be addressed (in concert with the other themes) include how climate and agricultural management practices (including wetland drainage, or restoration) affect surface and subsurface hydrological regimes, wetland functions, wetland valuation and the economics of agricultural production. Balanced scientific and economic information will thus be provided to land owners and decision makers, together with work pursued in the governance theme, to advise

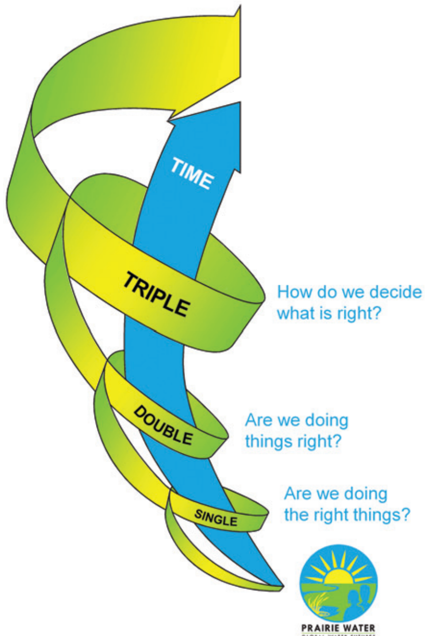

Figure 3. Triple-loop learning and engagement with partners are fundamental to Prairie Water. The programme will progress iteratively through this triple-loop cycle, allowing feedback to prior phases, while pursuing tasks and realizing outcomes (Table 1) associated with questions central to each loop. The research impact will broaden in later years as the decision support tools are applied.

water management decisions and wetland policy development to minimize risk.

Governance

Prairie Water's governance theme will examine how water is shared among diverse interests, and the components that make these relationships successful; inclusivity in policy and planning processes; efficacy of policies; and how science can address questions that are salient and accessible to decision makers and public audiences. These questions will be approached through two complementary procedures: a systematic review of the water governance discourse and approaches on the Prairie, and community-based workshops to assess water decision-making and public values. The review will examine academic, policy and media documents to identify reoccurring themes about water governance to evaluate current state of practice, policy, and problems. It will review reports and grey literature across federal, provincial and Indigenous governance bodies to better understand how issues are characterized. Community workshops will build upon this understanding by working with watershed stewardship groups and Indigenous partners to learn how actors and governance mechanisms can work together on the ground more effectively and identify policies and narratives that best support watershed-scale decision-making.

Knowledge gained from the review and community workshops will be integrated to assess values and trade-offs in water decisions, discern the current and potential roles of diverse partners in policy generation, and develop recommendations for decision-making, policy and management. Experimental decision laboratories in workshops will apply lessons learnt and test major factors of decision-making under the same management, policy, climatic and land management scenarios used to inform the virtual basin models. Information produced by the other three Prairie Water themes – surface and subsurface hydrology, and wetlands – will be used to frame these exercises. By sharing insights from other themes on the hydrological, ecological and economic consequences of climate and land-use change, a holistic understanding of the consequences of water decisions will be gained. The obverse is also true; insights gained in understanding the state of water governance in the Prairie will help to inform questions raised by other research teams and the development of future scenarios that regional actors may wish to consider.

Knowledge mobilization

The backbone of Prairie Water's design and knowledge mobilization efforts adapts a theory of social learning that describes learning outcomes through a series of loops, in which each loop refers to a deeper understanding of the problem's identification and potential resolution (Pahl-Wostl 2009). Continual collaboration with a focus on co-producing knowledge with partners is emphasized (Figure 3). Ongoing activities within the first loop are identifying shared goals and existing knowledge gaps, and highlighting governance and management mechanisms that could be improved (Table 1). For example, at the Prairie Water kick-off meeting (Saskatoon, January 2018), several partners identified aquifer recharge rates across a spectrum of wetland distribution scenarios as a key knowledge gap. There are few clear mechanisms for this kind of information to be distributed among all the economic sectors that both influence and are influenced by these recharge rates. Nor are there clear governance mechanisms that allow for integrated catchment-scale decisions by these sectors.

The second loop will see sharing of research outputs, and evaluating partners' adoption of this

Table 1. Building of tasks and outcomes in each phase of the triple loop learning cycle (Figure 3).

Learning loop	Question	Task	Outcomes
Single loop	Are we doing the right things?	• Define our user communities • Engage stakeholders and rights holders on water needs • Begin systematic review of water documents	• User-informed objectives and approach • Co-design Prairie Water outcomes • Knowledge gaps and needs identified
Double loop	Are we doing things right?	• Re-engage user community in participatory modelling workshops • Expand community and partners • Knowledge sharing of emerging results	• Align plans to new insights • Identify lessons learned and strategies to translate and mobilize in communities • Decision support tools for sustainable watershed management
Triple loop	How do we decide what is right?	• Integrate thematic information • Develop tools and best practice recommendations • Mobilize results and recommendations to and with user communities	• Resilient communities • Strong relationships for ongoing research • Evidence-based decision support tools for sustainable watershed management

information for water and land management decisions, economic values and governance structures. This provides information on what changes could be recommended to those water and land management tools and governance structures. The third loop will seek to involve partners in transforming those tools and structures. During the first Global Water Futures funding cycle (2017–2020) Prairie Water will focus on the first and second loops, with pilot approaches to the third. As such, the focus during the current cycle will be to use work in the first and second loops to lay the groundwork for progress into the next phases which will make recommendations for improved water governance that relies on multiple forms of evidence.

Summary

Prairie Water is a Global Water Futures research programme with four major themes: surface hydrology, subsurface hydrology, wetlands, and governance. The themes together seek to achieve four key outcomes that address key issues of Prairie water and land management. First, researchers will develop a typology of prairie catchments and use model-based approaches to understand how water availability, water quality and wetland services are affected by changing climate and land management decisions. Second, by improving understanding of the dynamics of surface–subsurface linkages through climate cycles and under different land management scenarios, researchers will reduce uncertainty in groundwater resource assessments. Third, by assessing decision-making activities by key partners, recommendations will be developed about how to build effective processes for governance, outreach and knowledge exchange. Finally, by sharing data, information and 'lessons learnt' through regular interactions, collaboration and pragmatic knowledge mobilization, partners and scientists will co-design tools and policy instruments believed to be most urgently needed to guide short- and long-term decisions about water management in this region. These outcomes will be integrated to inform the production of water and land management and agricultural decision support tools for the Canadian Prairie provinces. It is anticipated that the ongoing exchange between scientists and partners that Prairie Water promotes will enhance the ability of citizens, governments and communities to enact these decision support tools. The major outcome will be to improve community and water resource management resilience to the challenges of Prairie life that W.O. Mitchell alludes to.

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