THE GLOBAL WATER FUTURES CANADIAN REGIONAL HYDROCLIMATE PROJECT

A Proposal to the World Climate Research Program's GEWEX Project for an Expanded Regional Hydroclimate Project for Canada

SUMMARY PROPOSAL

Contents

1. Introduction

Watersheds and river systems in western Canada have played an important role within the GEWEX Hydroclimate Panel (GHP) for several decades, with coordinated research activities and the formation of different Regional Hydroclimate Projects (RHPs) around these efforts. The Mackenzie GEWEX Study (MAGS; www.usask.ca/geography/MAGS/) was an early Canadian contribution to GEWEX that focused on the 1.8 million km^2 Mackenzie River Basin and had the objectives to 1) understand and model the high-latitude water and energy cycles that play roles in the climate system, and 2) improve our ability to assess the changes to Canada's water resources that arise from climate variability and anthropogenic climate change (Stewart et al., 1998; Woo et al., 2008). The study was carried out between 1994 and 2005, and produced the first comprehensive large-scale assessment and synthesis of cold region atmospheric and hydrologic processes in northern Canada. In December 2012, GEWEX approved the Saskatchewan River Basin (SaskRB) Project as an initiating RHP, which was subsequently expanded in December 2014 to include the Mackenzie Basin as well. This broader RHP for western Canada mirrored the Changing Cold Regions Network (CCRN; www.ccrnetwork.ca), which was a 5-year (2013–2018), $5 million Canadian research network with the overall aims are to integrate existing and new sources of data with improved predictive and observational tools to understand, diagnose and predict interactions amongst the cryospheric, ecological, hydrological, and climatic components of the changing Earth system at multiple scales, with a geographic focus on Western Canada's rapidly changing cold interior. The SaskRB and CCRN were led by the University of Saskatchewan's Global Institute for Water Security (GIWS) and Centre for Hydrology (CfH) and included the involvement of eight Canadian universities and four Canadian federal government agencies.

Mid-way through the CCRN programme, a funding opportunity arose through the Canada First Research Excellence Fund (CFREF; http://www.cfref-apogee.gc.ca/home-accueil-eng.aspx), which invests approximately $200 million per year to support Canada's postsecondary institutions in their efforts to become global research leaders. A proposal was submitted in the second inaugural competition, led by the University of Saskatchewan's GIWS and CfH, along with key partners, the University of Waterloo, Wilfrid Laurier University, and McMaster University, and was ultimately successful in securing $77.8 million for the Global Water Futures: Solutions to Water Threats in an Era of Global Change (GWF; www.globalwaterfutures.ca). GWF is funded for seven years (2016–2023), and together with cash contributions from the four partner institutions, GWF is a $143 million programme focused on water and climate challenges for Canada and for the cold regions of the world, which supply freshwater to over half of the human population. In total, GWF combines expertise from 18 Canadian Universities and Colleges, 39 Federal and Provincial Government Agencies, and 45 International Institutions, and is the largest university-led freshwater research project of its kind worldwide.

With CCRN formally ending in March 2018, it was suggested at the GEWEX Hydroclimatology Panel (GHP) and Third Pole Environment (TPE) project meeting held in Kathmandu, Nepal in October 2017 that there could be significant benefits from a broader RHP in Canada based upon the GWF programme. Not only would this maintain the involvement of Canadian scientists and Canada's contributions to GEWEX and the World Climate Research Programme (WCRP), but it would also expand the scientific and geographic scope from the previous initiatives in western Canada. A formal proposal to GEWEX was requested at that time. This draft proposal has been produced to reflect this extension and includes summary descriptions of the expanded context, science needs, facilities, and science goals. It focusses on all of the GEWEX Science Questions and addresses all of the GEWEX Imperatives, and given GWF's geographic focus from coast to coast in southern Canada, and up to Hudson Bay and the Arctic Ocean in the North and West, it will address distinctive cold regions and transboundary aspects that are of unique interest to GEWEX. The GWF programme will also complement current proposals on *Water for the Foodbaskets of the World* in the U.S. Great Plains and California's Central Valley, as well as the ANDEX prospective RHP in the Andes Mountains, and GWF will directly link to a number of other existing GEWEX, WCRP, and other global projects through its international strategy.

2. Scientific and Societal Challenges, and the GWF Canadian RHP Geographic Domain

The world is entering an era of immense water-related threats. Climate warming and human actions are altering precipitation patterns, reducing snow levels, accelerating glacier melting, intensifying floods, and increasing risk of droughts, while pollution from population growth and industrialization is degrading water systems (Bartnett et al., 2008; Vörösmarty et al., 2010). By 2050, six billion people could face water scarcity. Nearly 80% of the world's jobs depend upon having access to an adequate supply of water and water-related services. Global trade in food and goods, as well as entire communities, industries and nations are at risk (Kundzewicz et al., 2007). With such unprecedented change, it is clear that the historical patterns of water availability are no longer a reliable guide for the future (Milly et al., 2008). Adaptation to these changes will require ***new science*** to understand the changing earth system (changing climate, land, water and ecosystems and their interactions); ***new modeling tools*** that precisely capture these interconnected forces and their societal implications; ***new monitoring systems*** with greater capacity to warn of critical environmental changes; and ***more effective mechanisms to translate new scientific knowledge into societal action*** (Wheater and Gober, 2015). This translates into the grand challenge for water science in Canada and globally: **"How can we best prepare for and manage water futures in the face of dramatically increasing risks?"**

Critical needs for addressing this grand challenge include: (A) *Improved disaster warning*. Currently, we lack the scientific knowledge, monitoring and modeling technologies, and national forecasting capacity to predict the risk and severity of potentially catastrophic events in Canada. These knowledge gaps and technology barriers have resulted in significant loss of life and property in recent years. (B) *Predicting water futures.* The world lacks water data on a scale to make informed decisions, and we cannot forecast future climate impacts without better models to assess changes in our human/natural land and water systems. These limitations create risks for water supplies, water quality and sustainability. (C) *Adapting to change and managing risk*. Nationally and globally, we lack the governance mechanisms, management strategies, and policy tools needed to reduce the risk of water threats, design adaptive strategies to cope with uncertainty, and take advantage of economic opportunities that arise as change unfolds.

GWF focuses on major river basins and key ecological, climatological, and physiographic regions across Canada (Figure 1), which are representative of the scientific and societal issues faced globally, and especially within "cold regions". Water processes including snow, ice, and frozen soils dominate cold regions, and it is here where Canada as a whole is an exemplar, has exceptional expertise and can have global impact. Canadian landscapes, ecosystems and the water environment are at the forefront of climate change. River basins are challenged by increasing water demands, high nutrient loads, warming temperatures, altered patterns of rainfall, snowfall, snowmelt and freeze-thaw cycling, glacier loss and permafrost thaw, and changes in river flow regimes. These changes have increased the severity and frequency of extreme events, leading Canada to experience catastrophic natural disasters in recent years; the 2013 Alberta floods, 2013 Toronto flood, 2016 Fort McMurray wildfire, and 2001-2004 Prairie droughts caused damages exceeding $20B. Northwestern Canada is one of the most rapidly warming regions on Earth. The scale and rapidity of recently observed warming-induced changes throughout this region indicate that it is particularly sensitive to climate warming and capable of rapid responses to perturbations. Systematic warming and cryospheric responses are leading to major landscape changes, including conversion of forests to wetlands, lakes to thaw lake basins, tundra to shrub vegetation, and changing the distribution and routing of water over the landscape, which confounds the prediction of eco-hydrological responses to combined warming and changes in precipitation regimes.

In addition to global warming-induced changes, human interventions have significantly affected Canada's river basins. Infrastructure developments such as dams, diversions, and irrigation networks, along with industrialization and urbanization, have altered the natural water cycle. Pollution from population growth, industrialization, and agriculture has degraded water quality in many regions. The implications of human-driven changes and their interactions with the natural environment have not been adequately understood and characterized, however. Canada possesses a huge number of lakes, both large and small, that play a crucial role in water supply, food production, resource extraction, hydropower generation, transportation, recreation, biodiversity, and climate regulation. However, despite such water wealth, climate change, agricultural intensification, shoreline development and urbanization are exerting mounting pressures on the health and ecosystem services of lakes, and their associated social and economic benefits. In the North, resource exploration and production is expected to expand dramatically in the coming years, which will include construction of new highways, pipelines and other infrastructure.

Figure 1. Map of the GWF Canadian RHP geographic study domain across Canada and parts of the United States of America. The programme will focus on eight major river basins spanning across the country. Core observational, and climate and hydrological modelling components of the programme will focus on all of these basins (see Section 3).

The GWF geographic domain includes five major regions (Figure 1): 1) the Great Lakes and St. Lawrence in eastern Canada and the Maritimes (including the Saint John Basin), ii) the prairies in central and western Canada (western Nelson River Basin), iii) the Boreal Forest across much of northern Canada (northern St. Lawrence, eastern Nelson, Churchill, and southeastern Mackenzie Basins), iv) the western Cordillera from the U.S. Pacific northwest up to the Sub-Arctic Mountains of the Yukon and Alaska (Columbia, Fraser, and Yukon Basins, and the headwaters of the Nelson and Mackenzie Rivers), and v) the Sub-Arctic Taiga, Tundra, and southern Arctic in the North (northern Mackenzie Basin). This vast domain includes large lakes and an E-W as well as N-S transect from temperate-humid to semi-arid to mountain glaciated to boreal and then polar climates. Each of the individual regions feature unique aspects in terms of the environmental and societal challenges faced, while some issues span multiple regions (e.g. agriculture, urbanization, etc.), and others span all regions (e.g. water management, governance, policy, etc.). Further, the boundaries between regions are generally indistinct and in some cases shifting, with northward movement of the prairie–boreal forest transition due to natural and human disturbance, and expansion of shrub tundra in the North, for example.

3. What is the GWF Canadian RHP and what will it Deliver?

3.1 GWF Science Programme and Pillars of Activity

GWF's overarching goal is to deliver risk management solutions—informed by leading-edge water science and supported by innovative decision-making tools—to manage water futures in Canada and other cold regions where global warming is changing landscapes, ecosystems, and the water environment (Baltzer et al., 2014; Derksen et al., 2012; Post et al., 2009). The scientific activities focus on three main goals:
1) **Deliver new capability for providing disaster warning** to governments, communities and the public, including Canada's first national flood forecasting and seasonal flow forecasting systems, new drought warning capability, and water quality models and monitoring that warn of hazards to health and drinking water supply;
2) **Diagnose and predict water futures** to deliver improved scenario forecasting of changing climate, landscape and water for the future, with information outputs tailored to the needs of users and stakeholders. This will enable us, for example, to assess risks to human health from changing flood, drought and water quality; and
3) **Develop new models, tools and approaches to manage water-related risks to multiple sectors**, integrating natural sciences, engineering, social and health sciences to deliver transformative decision-making tools for evidence-based responses to the world's changing cold regions. This will, for example, enable farmers to plan for crop development and improved efficiencies in water and nutrient management while delivering improved productivity and environmental benefits, enable the hydropower industry to optimize future investments while protecting ecosystems, enable stakeholders to assess vulnerabilities and to take purposeful action related to their water futures scenarios, and enable government to address trans-jurisdictional water issues and balance economic development with environmental protection. New models will define changing risk from floods and drought, and allow end-users to plan sustainable infrastructure investment to manage future risk. **In sum, GWF will position Canada as a) a *global leader in water science for the world's cold regions*, where snow, ice, and frozen soils control the storage and release of water, b) a *global partner of choice for transdisciplinary water research*, and c) a *provider for Canada and the world* of strategic tools to manage water futures.**

GWF will achieve this through 3 interrelated pillars of activity. We will deliver transformative, transdisciplinary ***science*** **(Pillar 1 - Diagnosing and Predicting Change in Cold Regions)** on an unparalleled global scale across water, land and air and at the human-water interface. Informed by user needs, this comprehensive scientific approach will lead to a more complete understanding of our ecosystems and provide the necessary data that underpin cutting-edge technologies and forecasting models. We will create new sensing and modelling ***systems*** (**Pillar 2 - Decision Support Systems**) and deploy them across living laboratories in nature. These systems will feed in to our science, dramatically raise our observational power to unmatched levels and lead to the generation of the 'Big Data' required to uncover key insights and support user needs. Working with our communities of users, we will translate these systems into user-friendly ***solutions*** *(e.g. apps)* (**Pillar 3: Designing User Solutions**), providing

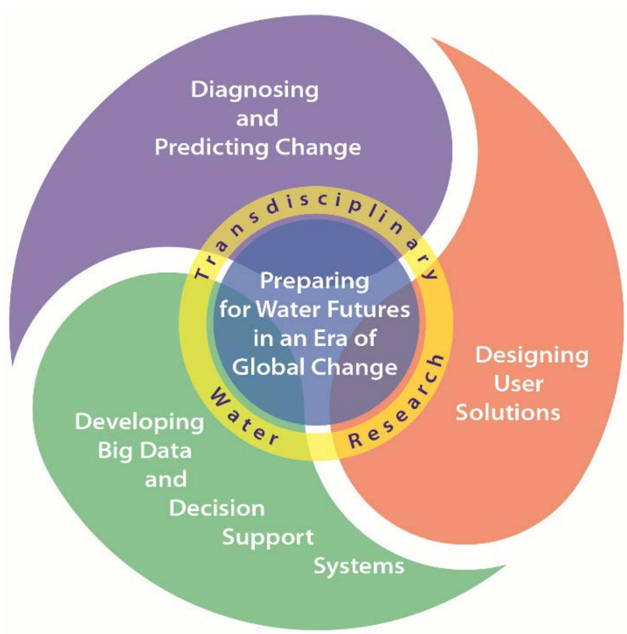

Figure 2. GWF's three major pillars of activity.

stakeholders with warning systems for impeding climate disasters, predictable water futures for planning and evidence-based decision support for optimal economic and health choices for populations. Each pillar is described in greater detail below.

Pillar 1: Diagnosing and Predicting Change in Cold Regions:

We will develop transdisciplinary and integrated science, focused on user needs, and computer simulation models to enable improved water scenario forecasting. This work will encompass five foundational science themes and the interactions among them: impact of climate change on weather and extreme precipitation (hydro-meteorology and climate change); effect of climate change on water stores and flows and land ecology (hydrology and terrestrial ecosystems); impact of climate change and land use on water quality and ecosystem health (water quality and aquatic ecosystems); impact of human actions and management on water futures (human-water systems - integrating complex environmental change with human impacts and responses); and impact of climate change on human health (water and health).

We will integrate natural sciences, engineering, social and health sciences with big data and decision support research to deliver new water science and transformative modelling tools for improved understanding and prediction of change in the world's cold regions. And we will provide the science and underpinning computer models for development of risk management solutions, exploiting our new observational tools to deliver the new interdisciplinary science needed to manage change. Directed by the needs of our users, we will diagnose past change and develop new models with enhanced power to predict water flow and ecosystem regime shifts.

Pillar 1.1: Hydrometeorology and Climate Change will improve understanding of how climate change influences water availability and extreme events, knowledge foundational for understanding subsequent impacts of climate change on water. We will develop transformative high-resolution (1km) atmospheric models (Rasmussen, 2011) to deliver improved short- and medium-range forecasting capability, improved precipitation products (past, present and future) and improved scenarios of climate futures at scales that can be directly applied to end user needs. These products will be based on land surface models that more accurately (Eerola et al., 2014) account for cold-region processes, assimilate data from new satellites and ground-based precipitation radars, and be supported by targeted field experiments. A common platform will be developed for model development and analysis; model products will be made available through enhanced data analytics. Analysis of extreme events will include attribution studies of historic events and large scale atmospheric controls (Brimelow et al., 2014; Pomeroy et al., 2015; Szeto et al., 2015), and support new stochastic modelling of precipitation time-series for flood risk management (Asong et al., 2016; Wheater et al., 2005). The research will improve understanding of land-atmosphere feedbacks in changing cold environments. Data will be readily available to user communities and the public.

Pillar 1.2: Hydrology and Terrestrial Ecosystems will improve understanding of how hydrological and terrestrial ecological processes will co-evolve under a changing climate (Arneth et al., 2010; Avis et al., 2011; Callaghan et al., 2013; Hinzman et al., 2013), providing critical information on landscape and water futures. We will use big data to develop next-generation observation platforms such as observatories, sensors, UAVs, and satellites, providing data to quantify biome shifts, snowpack decline, glacier loss, permafrost thaw, wetland dynamics and feedbacks, ice cover (Brown and Duguay, 2011) and change in flow rates of rivers and streams. Fundamental new understanding of ecological-hydrological coupling will lead to new multi-scale eco-hydrological prediction systems for cold regions (Pomeroy et al., 2005). Through paleo and historic reconstructions, state-of-the-art observatories, and model simulations driven by data from Hydrometeorology and Climate Change, we will evaluate cold-region eco-hydrological resilience in response to multiple climatological, ecological and land use stressors (Williams et al., 2013), and deliver improved prediction of ecosystem regime shifts in Canada and other cold regions. We will deliver global-leading ability to assess impacts of climate change on cold regions hydrology and water resource systems (by prediction of naturalized flows and response of water management and use) and support a new level of multi-scale cold region disaster prediction and avoidance, underpinning national forecasting for hazards including flood, drought and related agricultural risks.

Pillar 1.3: Water Quality and Aquatic Ecosystems will improve understanding and predictive modeling of how changes in climate, hydrology, and land use impact water quality and the health of aquatic ecosystems in cold regions, including Canada's large lakes. This research, combined with 2.1, will develop and deploy new observing systems tailored to cold environments. Using wireless monitoring systems, new chemical fingerprinting techniques and environmental DNA (eDNA), we will transform capabilities to diagnose ecosystem health and priority contaminants, support improved regulation, and provide early warning systems to protect drinking water and ecosystems (Allan et al., 2006; Peng et al., 2016; Schloz et al., 2012). National water isotope sampling will transform understanding of water flow paths and contaminant movements in Canadian landscapes (Jashecko et al., 2016). We will conduct whole-watershed nutrient and contaminant dynamics studies, including industrial sites. As nutrients are one of the world's major water quality threats and cause of serious degradation of Lake Winnipeg and Lake Erie, new nutrient models will be developed to reflect cold region processes, and support Canada-wide regional modelling of river and lake eutrophication under current and future climate (Preston et al., 2011; Hipsey et al., 2015). This will be linked with real-time water quality forecasting and warnings to support communities, the public and water utilities. We will study the biogeochemistry of cold region lakes and develop improved models of the water quality and ecosystems of Lake Winnipeg and the Laurentian Great Lakes and the many small and mid-sized lakes and rivers in the landscape which are crucial sources of drinking water and other ecosystem services. Our research will support a new hydrological-biogeochemical-ecosystem watershed model platform for cold regions, with ecological risk assessment, water quality and e-flow forecasting capabilities (Bastola and Misra, 2015 ; Poff et al., 2016 ; Pomeroy et al., *Hydrol Proc* 21: 2650), delivering much improved assessment and predictions of Canada's water quality futures and biodiversity impacts of economic development and environmental change.

Pillar 1.4: Human-Water Systems will address the human dimensions that will determine water futures by: (1) integrating human behaviour, economic valuation, and policy decisions into water resource models (van Tol Smit et al., 2015 ; Taylor and de Loë, 2012), (2) building adaptive governance models to deal with problems of uncertainty (Garrick et al., 2013 ; Armitage et al., 2015), (3) developing and testing economic tools and incentives for managing water futures (Brouwer et al., 2011; Dellink et al., 2012 ; Brouwer and Schaafsma, 2013), (4) conducting basic social science research into the social processes and learning embedded in stakeholder engagement (Gober and Wheater, 2014), and (5) building an indicator system that enables benchmarking performance for governance deficiencies, policy transfer, and social learning (Garrick and Hall, 2014 ; Wiek and Larson, 2012). The end goal is to link the above five tasks into all aspects of the programme, for example by using economic assessment tools to value ecosystem services, testing water resource models under different policy conditions, benchmarking water quality to various governance strategies, and investigating flood risk in the face of different assumptions about social learning (i.e. the "levee effect" whereby investment in flood mitigation infrastructure reduces the perception of risk and increases vulnerability to high-impact extreme events) (Rockström et al., 2014). We envision the emergence of a new paradigm of stakeholder engagement whereby public participation in water resources modeling is an iterative, collaborative, two-way exchange, and scientific knowledge is co-produced (Gober and Wheater, 2014 ; Feldman and Ingram, 2009). A professional stakeholder engagement support team will ensure that the knowledge produced is relevant to stakeholder needs, credible (scientific and technical evidence is of the highest standard), respectful of stakeholders' divergent values and beliefs, and unbiased in its treatment of views and interests.

Pillar 1.5: Water and Health will determine how changes to climate, extreme events and water quality will affect human health in urban, rural and Indigenous communities. For instance, we will address the critical questions on source water protection from Indigenous people: "Is the water safe to drink? Are the fish safe to eat?" We will address risks to health from a wide range of water-related sources. Given increasing water extremes in a changing climate, greater flooding can cause increased injuries and death, mental stress due to social and economic disruption, and risks from contamination, whilst increased droughts and temperatures degrade source water quality; contribute to proliferation of toxic cyanobacteria; limit use of water for recreation and drinking; increase the incidence of vector-borne (insect-borne) diseases (Dickin et al., 2014); increase respiratory risks associated with wildfires; and contribute to mental stress associated with broader economic and social disruption (Yusa et al., 2015). Water quality degradation from natural and human sources can cause a wide range of serious health concerns from toxicity as is recently evident in Flint, MI and Toledo, OH. With Health Canada and the Public Health Agency of Canada, we will analyse historic extreme events, develop regional models and use our scenarios of climate and water futures to assess future risks. We will determine how climate change, land use change, and extreme events will affect water quality and public health, and develop adaptive solutions that include online monitoring (Li et al., 2016) and early warning systems (Park et al., 2015; Gunda et al., 2014 ; Zhai et al., 2014). We will evaluate current and future risks to water sources, including natural contamination (e.g., arsenic and uranium), source water pollution from industry and agriculture, emerging contaminants and pathogens, changing dissolved organic matter concentration, and carcinogenic disinfection by-products of current water treatment technologies (Peng et al 2016; Zhai et al., 2014).

Pillar 2: Developing Big Data and Decision Support Systems

This work exploits the power of information technology and novel observations to develop water data, models and visualisation systems needed to deliver water information and decision support tools to user communities and the public. We will develop new capabilities for cold region water observation and monitoring by creating world-leading, multi-scale watershed observatories and expanding watershed monitoring through development and use of new sensors and observing systems and cloud-based data and modelling tools.

Pillar 2.1: Big Data for Water will deliver transformative new capabilities for observation, focussed on development of our world-leading multi-scale observatories. Through small catchments instrumented with hundreds of observation stations within our large river basin observatories (Figure 3), we will diagnose environmental change in key biomes and develop the large-scale science associated with global-scale modelling, land-atmosphere feedbacks and landscape change. These observatories also provide a key platform for science integration to address management/governance dimensions (Wheater and Gober, 2015). We will enhance the Mackenzie River Basin Observatory, expand the Saskatchewan River Basin Observatory to include the Nelson-Lake Winnipeg Basin, and develop the international Columbia-Lake Okanagan, Fraser and Yukon as new basins (Figure 1). In Central Canada, we will focus on the Great Lakes and their basins, expanding the Southern Ontario Watershed Consortium's pioneering 'intelligent watershed' monitoring systems to include the Grand River Basin. Working with IBM and other IT companies, we will spawn a new generation of watersheds that will provide real-time data and analytics to support operational management of flows and treatment utilities. In Eastern Canada, we will focus on the international and interprovincial Saint John River Basin to better understand aquatic ecosystem and transboundary water management issues and Quebec's BEREV experimental basin.

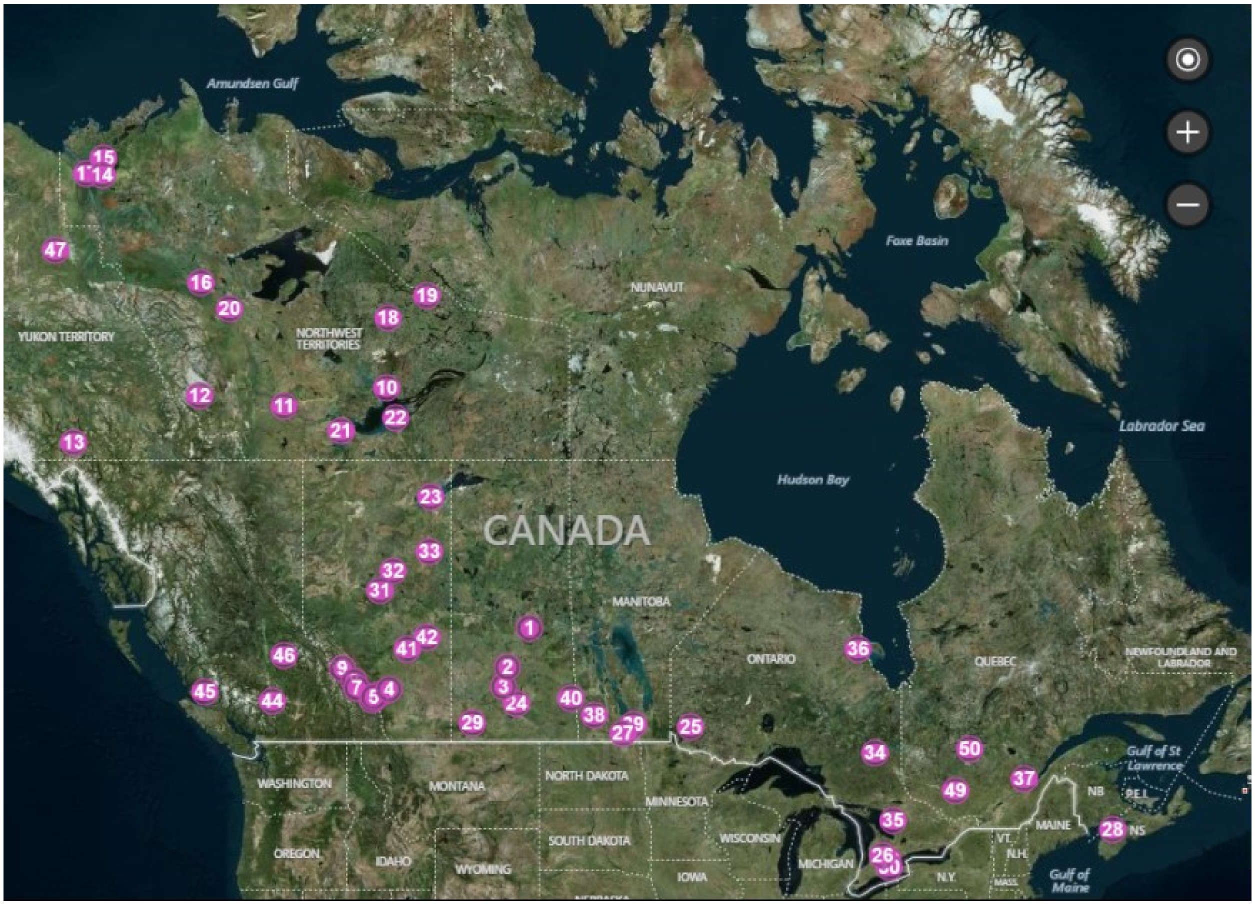

Figure 3. GWF's network of intensive surface observational sites, building upon previous initiatives in western Canada such as CCRN, and expanding across other parts of the country. See Table 1 for list of site names. Further details on the sites are available at http://giws.usask.ca/meta/index2.html.

We will develop and deploy new sensors and observing systems, linking them with state-of-the-art data retrieval, management, and distribution systems (http://www.nytimes.com/2016/03/17/opinion/the-water-data-drought.html?_r=0; Contreras-Naranjo et al., 2016). A new drone platform and novel satellite data assimilation will transform the observation of large remote cold region areas by detecting change on short time scales, deploying LiDAR (laser-based distance measurement), snow sonar, high-resolution monitoring of water elevations, and multi-spectral monitoring of land and water systems (Gunn et al., 2015; Kinar and Pomeroy, 2012). We will use new acoustic sensors to measure snowpack properties remotely for the first time, and GPS and neutron scattering to measure frozen/unfrozen soil moisture. We will develop new in-stream water quality sensors and further develop chemical fingerprinting and eDNA techniques, transforming capability for ecological monitoring and risk assessment. A high-performance, cloud-based geospatial data platform will be used to collect, manage, and analyze large quantities of multi-dimensional data for decision support. We will work with Indigenous and other communities to develop citizen science monitoring capability (Newman et al., 2012).

Table 1. List of GWF intensive surface observational sites. The list is preliminary and growing as sites are added and the surface network expands to include both new and existing sites across Canada. While most are well-established legacy sites from previous initiatives such as CCRN, some are at a more early stage of development and are being enhanced to bring them up to standard as part of our integrated network.

1. Boreal Ecosystem Research and Monitoring Sites, SK
2. St. Denis National Wildlife Area, SK
3. Kenaston/Brightwater Creek Mesonet Site, SK
4. West Nose Creek, AB
5. Marmot Creek, AB
6. Fortress Mountain, AB
7. Lake O'Hara, BC
8. Wapta Icefield/Peyto Glacier, AB
9. Columbia Icefield, AB/BC
10. Baker Creek, NT
11. Scotty Creek, NT
12. Brintnell-Bologna Icefield, NT
13. Wolf Creek Research Basin, YT
14. Havikpak Creek, NT
15. Trail Valley Creek, NT
16. Norman Wells, NT
17. Mackenzie Delta, NT
18. Wekweeti, NT
19. Daring Lake, NT
20. Smith Creek, NT
21. Kakisa, NT
22. Fort Resolution, NT
23. Peace-Athabasca Delta, AB
24. Buffalo Pound, SK
25. Experimental Lakes Area Kenora, ON
26. Consetogo Reservoir, Grand River, ON
27. Tobacco Creek, MB
28. Annapolis Valley, NS
29. Swift Current Creek, SK
30. Grand River Brantford, ON
31. Slave Lake, AB
32. Wabasca, AB
33. Fort McMurray, AB
34. Timmins, ON
35. Parry Sound, ON
36. Attawapiskat, ON
37. Forêt Montmorency, QC
38. Broughton's Creek, MB
39. La Salle River Basin, MB
40. Smith Creek, SK
41. Camrose Creek, AB
42. Vermillion River Basin, AB
43. Sibbald Wetlands
44. Bridge Glacier, BC
45. Southern Coast Icefields, BC
46. Cariboo Alpine Mesonet, BC
47. Dempster Highway Transect, YT
48. SOWC (Alder, Hopewell), ON
49. Gatineau River (Baskatong), QC
50. Saint-Maurice River (Gouin), QC

Pillar 2.2: Decision Support Systems will develop next generation decision support tools, visualisations and apps that will give our stakeholder communities targeted, user-friendly access to the capabilities of our novel data and modeling tools. We will establish a professional support team to assist researchers with software architectures, and develop new processing frameworks for computer-intensive and widely distributed modelling and re-engineering of existing code. We will develop novel tools for collaborative modeling and visualization (Isenberg et al., 2011) and tailor mixed-media decision support systems for specific users. We will develop fixed and mobile "decision theatres" with multi-screen displays and interactive surfaces that will help engage stakeholders as we frame problems and design decision support tools (Fayyad et al., 2002 ; Andrienko et al., 2007), and explore 3D visualization and virtual reality displays. Development of cloud-based apps will facilitate two-way interactions with the public (Fernando et al., 2013) to provide warnings, context-specific education about water issues and to enable 'citizen science', including through game-based platforms. We will also deliver a high-performance-computing community platform (Chauhan et al., 2014) to support a modular toolkit for custom-built solutions, including Environment Canada's family of atmospheric and large-scale hydro-ecological models and new integration of water quality and terrestrial ecosystems.

Pillar 3: Designing User Solutions

Guided by our users, we will provide tools and solutions that Canada and similar cold regions currently lack, but urgently need, to manage the water environment in the face of unprecedented change. Enabled by new data, analyses and models developed in our other two pillars, we will deliver water futures information and "decision support tools" to communities of users and the public by developing the data access, models and new visualisation and interactive decision-making systems (such as "decision theatres") that these groups need to predict and manage risk. We will launch a new era of public water warning and information through apps and social media and open a new era of water-related public engagement, drawing on social media with apps that engage and inform the public, crowd-source data and provide place-based real-time information. Our scientific breakthroughs in defining the needs for a *healthy water environment* will lead to new tools to balance competing needs for water and support better-informed regulation of water quality and waste management through improved understanding of environmental risks. Our breakthroughs in *observational capacity* will support improved operational management of water infrastructure and regulatory oversight of land management and water use, and new capability for forensic diagnosis of contamination. Our breakthroughs in understanding *human-water systems* will support adaptive governance and social engagement.

3.2 Essential Scientific Questions as an RHP

This study will integrate the insights and capabilities from a large and diverse team representing a number of disciplines to address water and climate issues across Canada and other cold regions for which Canada is an exemplar. To address the needs of user and stakeholder communities across Canada, and more broadly, the world, the research will strive to answer the following science questions:

1. How will extreme atmospheric events and other changes to the climate system be translated by the hydrological system into hydrological extremes?
2. How will hydrological storage in lakes, managed reservoirs, glaciers, permafrost, groundwater and wetlands interact with a changing climate and shifting terrestrial ecosystems to create new hydrological regimes?
3. How can humans better manage, mitigate and adapt to this change and conserve ecosystems through water and land management, prediction, and governance?

Our various pillars of activity described above will provide significant interdisciplinary research thrusts in the areas necessary to answer these questions. The activities and science questions will be pursued and led by a number of projects and core teams as part of the GWF programme, discussed below.

3.3 GWF Management Structure, Core Teams, and Projects

The GWF programme includes 388 Canadian researchers from 18 Canadian Universities and Colleges, 39 Federal and Provincial Government Agencies, and 45 International Institutions (Appendix A). The programme is funded for seven years (2016–2023) through the CFREF initiative, and leverage substantial cash and in-kind contributions through its partner universities and government agencies, and other users and collaborators. Management of the programme is by a Strategic Management Committee (SMC), which directs the scientific progress and plans major activities, and approves and monitors the formation and progress of smaller projects and core teams with GWF (see below). The SMC is chaired by the Director of GWF, Distinguished Professor John Pomeroy, Canada Research Chair in Water Resources and Climate Change, and Director of the Centre for Hydrology, University of Saskatchewan. An Oversight Committee oversees the organizational and financial accountability of the programme, while an International Science Advisory Panel (ISAP) provides external advice and oversight, and facilitates liaison with the international research community. There are also several strategic advisories to the SMC (most notably, Professor Howard Wheater, the PI for CCRN and previous Director of GWF), and a User Advisory Panel is in the process of being formed. The IAP includes members of GEWEX GHP and CliC SSG, and the science lead of NASA's ABOVE initiative. Further details on the structure, organization, and management of the GWF programme are available in Appendix B and through the GWF website at: www.globalwaterfutures.ca.

Core support teams to deliver national modelling capability, advanced computer science, new observational science and knowledge mobilization. These include the following five teams:

- Computer Science – Human Computer Interface, Data & Re-engineering Codes
- Technical Team: Observatories & Observations
- Data Management
- Modelling Core Team
    - Hydrological & Water Quality Forecasting
    - Climate Change, Diagnostic Hydrological & Water Quality Modeling
    - Water Resources Modelling
- Knowledge Mobilization

In addition, 33 smaller projects have been funded and, linking with the core teams, have begun to address critical issues across the three GWF pillars. These have been funded for three years with the possibility for renewal for a further three years. A call for further projects addressing GWF's Indigenous Communities Water Research Strategy is in progress and will address issues of source water protection, climate change impacts, upstream industrial water impacts, water rights, and governance. The current projects include:

- 21 transformative research, big data and decision support tool projects approved for Pillars 1 & 2
    - Atmospheric science, Hydrology, Water Quality, Water Management & Governance, Health
    - Sensors, crowdsourcing, computing
- 12 user-question led projects funded for Pillar 3
    - Regional – e.g. Great Lakes, North, Prairies, Mountains, Boreal
    - Sectoral – e.g. Agriculture, Mining
    - Topical – e.g. First Nations co-development, modelling & prediction, algae, climate extremes

Details on all of the core teams and projects are available on the GWF website, www.globalwaterfutures.ca, while many of the projects feature their own websites and links to these are available on GWF's site. Further details on our data management initiatives, including our policy and data management framework, are in Appendix C.

3.4 Relevance to GEWEX and Benefits of an Expanded Canadian RHP

The CCRN project has been the only active North American RHP during its time (2013–2018), and one of only two fully working RHPs globally. It has thus filled a void in the global programme for North America in general and Canada in particular. Through CCRN a much-needed regional-scale focus for integration of GEWEX science based on detailed ground-based observations and integrated modelling and data assimilation of atmospheric, land surface and hydrological processes has been established. As noted and discussed at the GHP-TPE meeting in Kathmandu, Nepal in October 2017, CCRN has a lot to teach to new and initiating RHPs, and the emphasis on recent and ongoing extreme events at the regional scale, as exemplified by CCRN, is something that all RHPs can and should pursue. The GWF programme continues and significantly builds upon these activities from CCRN and earlier Canadian initiatives [e.g. the Mackenzie GEWEX Study (MAGS; http://www.usask.ca/geography/MAGS/; Stewart et al., 1998; Lawford et al., 2004; Woo et al., 2008), the Boreal Ecosystem-Atmosphere Study (BOREAS; http://daac.ornl.gov/BOREAS/bhs/BOREAS_Home.html; Sellers et al., 1997; Hall, 1999), the Drought Research Initiative (DRI; http://www.drinetwork.ca/; Stewart et al., 2011; Hanesiak et al., 2011), the

International Polar Year (IPY; http://www.api-ipy.gc.ca/), the Western Canadian Cryopsheric Network (WC2N; http://wc2n.unbc.ca/), and the Improved Processes and Parameterization for Prediction in Cold Regions Hydrology Network (IP3; http://www.usask.ca/ip3/)]. The continued involvement and contributions of this research to the GHP, and the expansion of geographic extent and science focus to include much of the Canadian landscape and new disciplinary perspectives is therefore important.

The GWF Canadian RHP will further complement existing and proposed initiatives, such as the "Water for the Foodbaskets of the World" in the U.S. Great Plains and California's Central Valley, and in conjunction with this initiative, GWF will provide unparalleled scientific focus through the North American Great Plains and most of North America's agricultural and food producing regions. GWF has projects focusing on agricultural water availability, use, and quality that will complement the American efforts (see https://gwf.usask.ca/science/pillar-1-2-projects.php and https://gwf.usask.ca/science/pillar-3-projects.php). GWF will directly link to a number of other global initiatives. Connections are being actively developed in the South American Andes (Chile and Argentina) to examine hydro-climatic change and water management impacts, with important ties to the ANDEX prospective RHP. GWF, in part through the International Network for Alpine Research Catchment Hydrology (INARCH; http://www.usask.ca/inarch/), which is also led by Distinguished Professor John Pomeroy, is exploring and planning collaborative links with the Pan-Third Pole Environment Program, which is focused on the high mountains of central and eastern Asia and which addresses climate and Earth system changes and their impacts to the social and economic development of China, India, Nepal, Tajikistan, Pakistan, Afghanistan, Bhutan, and Bangladesh. GWF and INARCH are pursuing a focus on climate impacts to high mountain environments and river systems globally, with plans to model and explore climate sensitivity scenarios and impacts on water resources across 25 mountain basins globally, representing every continent but Antarctica. This will also form the basis of a working group under the Future Earth Sustainable Water Futures Programme (SWFP; https://water-future.org/), led by GWF as the Canadian node for SWFP, and will provide global leadership and contributions to the International Decade for Action on Water for Sustainable Development, 2018-2028 (http://www.un.org/en/events/waterdecade/). The tools and scientific insights developed under GWF will be applied globally, with particular scientific leadership in the areas of cold regions hydrology and hydro-climatology, and the links to these other International programmes will facilitate and further enhance GEWEX's core mission to observe, understand, and model the hydrological cycle and energy fluxes in the Earth's atmosphere and at the surface. The benefits of a Canadian RHP extend far beyond Canada and reinforce Canada's role as a significant contributor to the WCRP.

GWF contributes to all of the GEWEX Science Questions:

- Observations and Predictions of Precipitation:
  - How can we better understand and predict precipitation variability and changes?
- Global Water Resource Systems:
  - How do changes in land surface and hydrology influence past and future changes in water availability and security?
- Changes in Extremes:
  - How does a warming world affect climate extremes, esp. droughts, floods, and heat waves, and how do land area processes, in particular, contribute?
- Water and Energy Cycles and Processes:
  - How can understanding of the effects and uncertainties of water and energy exchanges in the current and changing climate be improved and conveyed?

These are all addressed within our pillars of activity and essential scientific questions (see 3.1 and 3.2 above). Further, GWF members are leading or involved with several GHP cross-cut initiatives including INARCH, the Cold/Shoulder Season Precipitation Near 0°C project, and Human Regulation of the Water Cycle project (https://www.gewex.org/panels/gewex-hydroclimatology-panel/crosscutting-projects-ccs/), which also contribute to these science questions.

GWF firmly supports the GEWEX Imperatives:

- **Data Sets**: Foster development of climate data records of atmosphere, water, land, and energy-related quantities, including metadata and uncertainty estimates.
- **Analysis**: Describe and analyze observed variations, trends, and extremes (such as heat waves, floods, and droughts) in water and energy related quantities.
- **Processes**: Develop approaches to improve process-level understanding of energy and water cycles in support of improved land and atmosphere models.
- **Modelling**: Improve global and regional simulations and predictions of precipitation, clouds, and land hydrology, and thus the entire climate system, through accelerated development of models of the land and atmosphere.
- **Applications**: Attribute causes of variability, trends, and extremes, and determine the predictability of energy and water cycles on global and regional bases in collaboration with the wider WCRP community.
- **Technology Transfer**: Develop new observations, models, diagnostic tools and methods, data management, and other research products for multiple uses and transition to operational applications in partnership with climate and hydrometeorological service providers.
- **Capacity Building**: Promote and foster capacity building through training of scientists and outreach to the user community.

GWF meets the criteria for a full working RHP:

- A science plan with an overall science and applications goal and proposed tasks to achieve it.
- A coordination mechanism (e.g., a Science Steering Group or equivalent) that includes a GEWEX contact (e.g., SSG chair, or project coordinator).
- An end date and an exit plan that includes a science and applications synthesis and data archival procedure.
- Adequate resources and personnel with potential sources of funding or existing funding identified.
- A mechanism for collecting, managing, and providing access to hydroclimatological data sets with participation in the international exchange of scientific information and data.
- An up-to-date web presence.
- Demonstrate progress to contribute to the development and diagnosis of atmospheric-hydrologic-land surface models.
- Participate in joint RHP studies in cross-cut activities.
- Participate in other ESSP activities with other Panels and groups outside GEWEX if feasible.
- Share its new knowledge, experience, and models through the publication of scientific results, open science meetings, and relevant GHP meetings and activities.

The project plan here and the information provided in the appendices include details on all of these elements. GWF includes strong links to GEWEX through its Director and other members of the SMC (Section 3.3 and Appendix B) who also lead other cross-cutting projects within the GHP. GWF has a strong field observation programme with core teams to support it, and an established data management framework and policy that promotes good stewardship and the open access of GWF data (Appendix C). GWF has played a key role in preparation and planning of the 8th GEWEX Open Science Conference in Canmore, AB, Canada in May 2018, and will continue to provide leadership and involvement in future international science meetings.

4. Resources and Timescale

The GWF programme was initiated with funding through CFREF and from its partners totaling $143 million, providing support for observational infrastructure, research staff and HQP training, software and technology development, data management and storage, and travel and meeting costs. The programme is funded to 2023 but is actively securing further funds to extend and enhance various elements and to provide longer term security to research infrastructure, predictive modelling systems, and the data management framework.

As of March 2018, the programme has allocated $185 million in cash and in-kind support to GWF project and core team funding for the first three years, consisting of:

- $ 23.5M GWF cash grant awarded to projects
- $ 14.6 M GWF funding to operate core teams
- $26.8M leveraged by projects (cash)
- $119.7M leveraged (in-kind support)

5. Conclusions

The Canadian river basins exemplify the scientific and societal issues faced globally, with rapid and dramatic changes to climate and Earth system functioning, rising cost of extreme events, globally important ecosystems, a major area of the world's natural resource, food, and energy production, human activities exacerbating the impacts of climate and land cover change, and significant management, policy, and governance challenges in the face of this change. The GWF Canadian RHP study will bring together Canadian and international scientists and build on world-class observational facilities to develop the understanding and modelling tools needed to address the challenges of managing water futures. The study has the capability to make a significant contribution to GEWEX, addressing each of the Science Questions and Imperatives, and has the potential to make a major contribution to international hydroclimate science, particularly for cold region environments. This carries on a long and proud tradition of Canadian contribution to GEWEX.

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Appendix A. List of Canadian and International Partners

Canadian Universities & Colleges

1. University of Saskatchewan
2. University of Waterloo
3. McMaster University
4. Wilfrid Laurier University
5. University of Guelph
6. University of British Columbia
7. University of Northern British Columbia
8. University of Calgary
9. University of Laval
10. McGill University
11. University of Quebec at Montreal
12. University of Alberta
13. University de Montreal
14. University of Manitoba
15. University of Victoria
16. Brock University
17. Canadian Rivers Institute (University of New Brunswick and University of Prince Edward Island)
18. Yukon College

Federal and Provincial Government

1. Environment and Climate Change Canada (ECCC) – Atmospheric Science and Technology Directorate & Water Science and Technology Directorate
2. ECCC – Meteorological Services of Canada
3. Agriculture and Agri-Food Canada
4. Health Canada
5. Public Health Agency Canada
6. Indigenous and Northern Affairs Canada
7. Parks Canada
8. Natural Resources Canada (NRCan) - Forest Services
9. NRCan - Canada Centre for Mapping and Earth Observation
10. NRCan - Geological Survey of Canada
11. Canadian Space Agency
12. Alberta Innovates
13. Alberta Environment and Parks
14. BC Hydro
15. BC Ministry of Energy and Mines
16. BC Ministry of Environment
17. Government of Northwest Territories (GNWT) - Department of Education, Culture and Employment
18. GNWT - Department of Health and Social Services
19. GNWT - Department of Industry, Tourism and Investment
20. GNWT - Department of Lands
21. GNWT - Department of Municipal and Community Affairs
22. GNWT - Department of Public Works and Services
23. GNWT - Ministry of Environment and Natural Resources
24. GNWT - Premier
25. GNWT - NWT Power Corp

26. Great Lake Fisheries Commission
27. Hydro-Quebec
28. Innovation Saskatchewan
29. Mackenzie River Basin Board
30. Manitoba Hydro
31. Manitoba Ministry of Conservation and Water Stewardship
32. Ontario Ministry for Agriculture - OMAFRA
33. Ontario Ministry of Environment and Climate Change
34. Ontario Ministry of Research and Innovation
35. Ontario Power Generation
36. Prairie Provinces Water Board
37. South Basin Mayors & Reeves
38. Yukon Government - Executive Council Office
39. Yukon Premier

<u>International Institutions</u>

1. AirMOSS - University of Southern California
2. Alfred Wegener Institute for Polar and Marine Research (Germany)
3. Australian National University
4. British Geological Survey
5. Centre for Ecology and Hydrology, Wallingford UK
6. Chinese Research Academy of Environmental Sciences
7. CliC, GEWEX
8. CNR-IASC Bologna, Italy
9. Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences
10. ETH Zurich, Switzerland
11. Future Earth - Montreal
12. GEWEX, WCRP
13. Gorgan University of Agricultural Sci.& Natural Resources, Iran
14. University of Idaho, USA
15. Imperial College London, UK
16. Indian Institute of Sciences, Bangalore, India
17. Instituto Pirenaico de Ecología, Spanish National Research Council (CSIC), Spain
18. International Arctic Research Center (US), Univesity of Alaska
19. LTHE Grenoble, France
20. NASA ABoVE - JPL USA
21. National University of Columbia
22. National Centre for Atmospheric Research, USA
23. Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration (NOAA), US Department of Commerce
24. Norwegian Institute for Water Research - NIVA
25. Oregon State University, USA
26. SLU, the Swedish University of Agricultural Sciences
27. Smithsonian Tropical Research Institute
28. Snow Research Center, Grenoble, Meteo-France
29. Sustainable Water Futures, International Secretariat
30. Swiss Snow and Avalance Institute (WSL), Davos, Switzerland
31. The Commonwealth Scientific and Industrial Research Organization (CSIRO) - Australia
32. UD Department of Agriculture
33. UNESCO - International Hydrological Programme

34. Universidad Austral de Chile
35. University of Aberdeen, Scotland
36. University of California at Los Angles, USA
37. University of Chile
38. University of Edinburgh, UK
39. University of Innsbruck, Austria
40. University of Natural Resources and Life Sciences, Vienne (BOKU), Austria
41. University of Northumbria, UK
42. University of Queensland, Australia
43. University of Utrecht, Netherlands
44. University of Washington, Seattle, USA
45. University of Wellington, Victoria, New Zealand

Further information: https://gwf.usask.ca/about/about-us.php#Partners

Appendix B. Structure, Organization, and Management of GWF

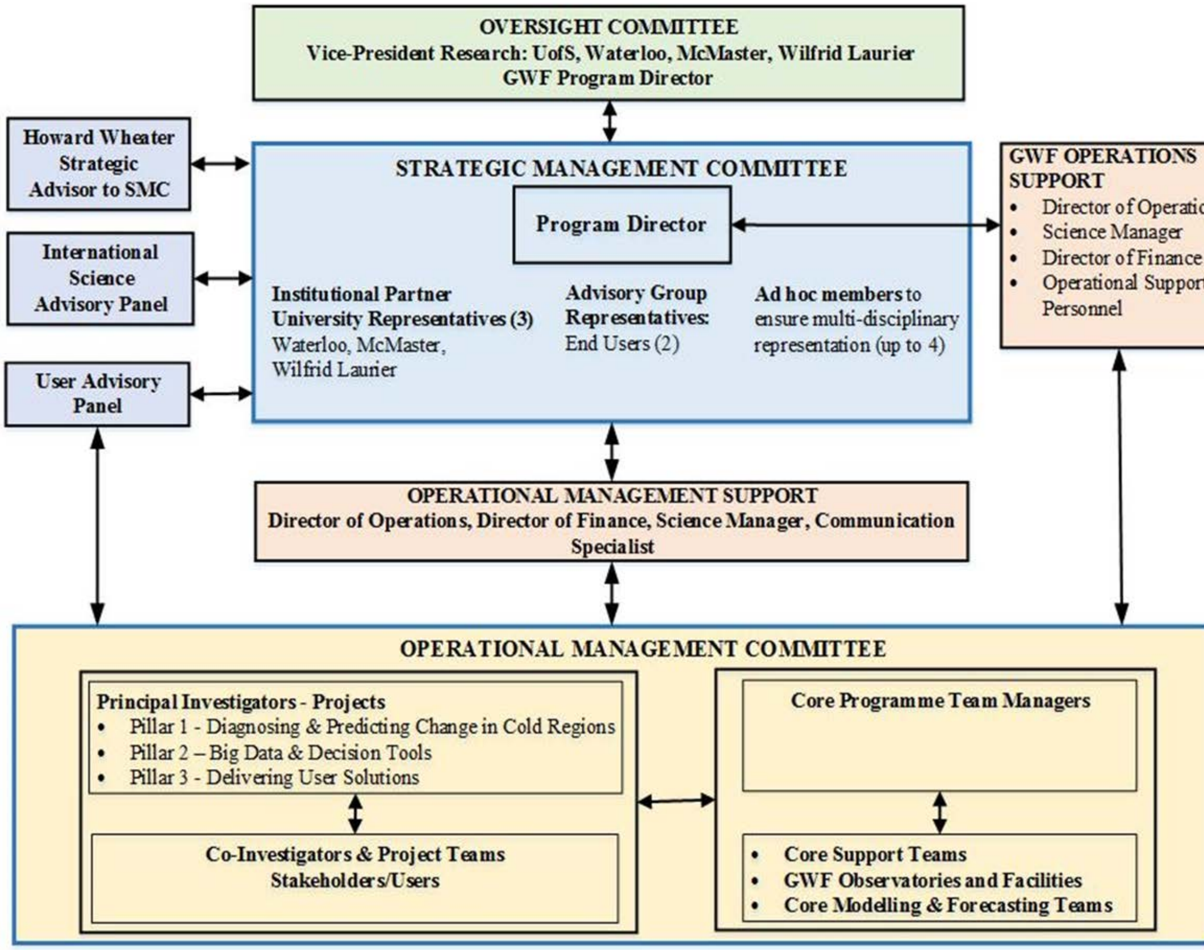

Figure B1. GWF Governance and Organizational Structure.

The management and governance of the GWF programme is described in part 3.3 of this proposal and shown schematically in the diagram in Figure B1. The *Operational Management Committee* consists of PIs and project managers from each of the funded GWF projects, along with leads of GWF core teams, GWF's SMC and secretariat.

The Strategic Management Committee (https://gwf.usask.ca/about/committees1/strategic-management-committee.php) is currently comprised of the following members, representing various disciplinary perspectives and institutions:

- Program Director – **John Pomeroy**, UofS
- University of Waterloo lead – **Philippe van Cappellen**
- Wilfrid Laurier University lead – **Jennifer Baltzer**
- McMaster University lead – **Sean Carey**
- Socio-hydrology – **Patricia Gober**, UofS
- Water Environment – **Helen Baulch**, UofS
- Climate and Atmospheric Science – **Ronald Stewart**, University of Manitoba
- Big Data, Urban Communities, and Groundwater – **David Rudolph**, University of Waterloo
- Water Resources Management, Communities – **Lawrence Martz**, UofS

- Stakeholders/Users, Government, Measurements, Modelling and Forecasting – **Alain Pietroniro**, Environment and Climate Change Canada

Strategic Advisors to the SMC are:

- **Howard Wheater**, founding Director of GWF, Emeritus Professor and Canada Excellence Research Chair in Water Security
- **Merrell-Anne Phare**, Executive Director, Centre for Indigenous Environmental Resources Inc., Winnipeg, MB

The International Science Advisory Panel membership includes (https://gwf.usask.ca/about/committees1/international-science-advisory-panel.php):

- **Anthony Jakeman**, Australian National University, Australia
- **Blanca Jimenez Cisneros**, Director of the Division of Water Science, UNESCO, Paris
- **Eric Kasischke**, University of Maryland, USA
- **Dennis Lettenmaier**, University of California at Los Angeles, USA
- **Xin Li**, Director of Laboratory of Remote Sensing and Geospatial Science, CAREERI/Chinese Academy of Sciences
- **Claudia Pahl-Wostl**, University of Osnabrück, Germany
- **Roy Rasmussen**, National Center for Atmospheric Research, USA

The Oversight Committee (https://gwf.usask.ca/about/committees1/oversight-committee.php) includes representatives from each of the four partner institutions and is chaired by the VP Research of the University of Saskatchewan. Its member currently include:

- **Karen Chad**, Vice-President Research at the University of Saskatchewan
- **Rob Baker**, Vice-President, Research, McMaster University
- **Rob Gordon**, Vice-President of Research, Wilfrid Laurier University
- **Charmaine Dean**, Vice-President of Research, University of Waterloo

The GWF Secretariat (https://gwf.usask.ca/about/secretariat.php) are all based at the University of Saskatchewan's GIWS and CfH. Current members include:

- **Dr. Phani Adapa**, Director of Operations
- **Dr. Chris DeBeer**, Science Manager
- **Kelly McShane**, Director of Finance
- **Viet Truong**, Financial Officer
- **Stacey Dumanski**, Outreach Coordinator
- **Mark Ferguson**, Communications Specialist
- **Branko Zdravkovic**, Data and IT Manager
- **Michelle Martel-Andre**, Human Resources and Facilities
- **Sherry Olauson**, Clerical Assistant Finance

Appendix C. GWF Data and Information Management

GWF has a firmly established data management policy, and data management system and plan for archival and accessibility of data. Data Management is overseen by our core data team, led by Branko Zdravkovic, and reporting to the Director and SMC. As a condition of funding, all GWF projects and core teams have agreed to our data policy and have made commitments to adhere to it and make their data freely available, subject to various caveats and with exceptions only in special circumstances and with full justification. The formal data policy is available on our website and can be downloaded through this link: https://gwf.usask.ca/documents/GWF_Data_Policy_March-1-2017-Final.pdf

Our data management team and the framework are described in a document available for download here: https://gwf.usask.ca/documents/GWF_Data_Management_Framework_and_Team_March-1-2017.pdf