PART-1 SCIENTIFIC STRATEGY

a) Status of the Research Program

GWF aims to place Canada as a global leader in water science for cold regions, and address the strategic needs of the Canadian economy in adapting to change and managing the risks of uncertain water futures and extreme events in a time of global change. The transdisciplinary research program was designed strategically in consultation with stakeholders to achieve 3 main goals: 1) to deliver new capability for providing disaster warning; 2) to diagnose change and predict water futures; and, 3) to develop new models, tools, and approaches to manage water-related risks. GWF has reached the end of its 4th year. It is on track to meet, and exceed, its stated research goals and deliverables, and is working with its community of users to make important advances that enhance water security for Canadians and address some of the world's most important and pressing water problems.

Led by the University of Saskatchewan (USask) in partnership with the University of Waterloo (UWaterloo), McMaster University (MU), and Wilfrid Laurier University (WLU), GWF has established an unprecedented collaborative network of water researchers across Canada and the world. These include 18 Canadian universities, 8 federal agencies, and 478 partners/collaborators/knowledge users including 76 Indigenous groups (*Figure 1.1*). Research has been co-developed with these users across this broad and diverse network, and is undertaken by 6 core research/support teams and 39 projects. GWF projects are thematic or geographically focussed transdisciplinary groups, competitively funded based on international peer review (*see Part-2*). They have clear objectives to work with our partners to fill identified knowledge gaps, to build on GWF core science deliverables, work collaboratively, achieve excellence, and address issues of priority aligned with GWF's goals. GWF core teams are strategically-focussed, delivering technical development in key areas, and supporting engagement, outreach, and project operations. GWF science is addressed through 3 interrelated, strategic pillars of activity, as described in our proposal: **Pillar 1**: Diagnosing and Predicting Change, **Pillar 2**: Developing Big Data and Decision Support Systems, and **Pillar 3**: Designing User Solutions. Each has a set of deliverables and timelines (*Figure 1.2*), with most projects and core teams contributing to multiple science pillars. Further details on the project-level progress and activities can be found in previous GWF annual reports.

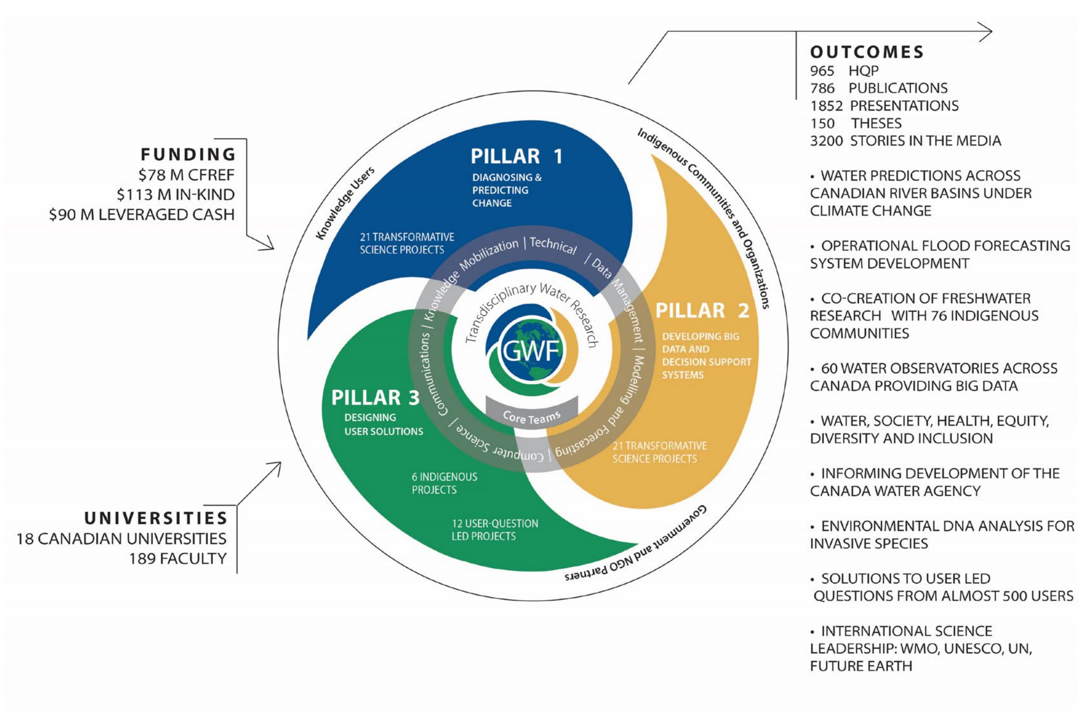

Figure 1.1 Mid-term state and summary of GWF at the end of March 2020.

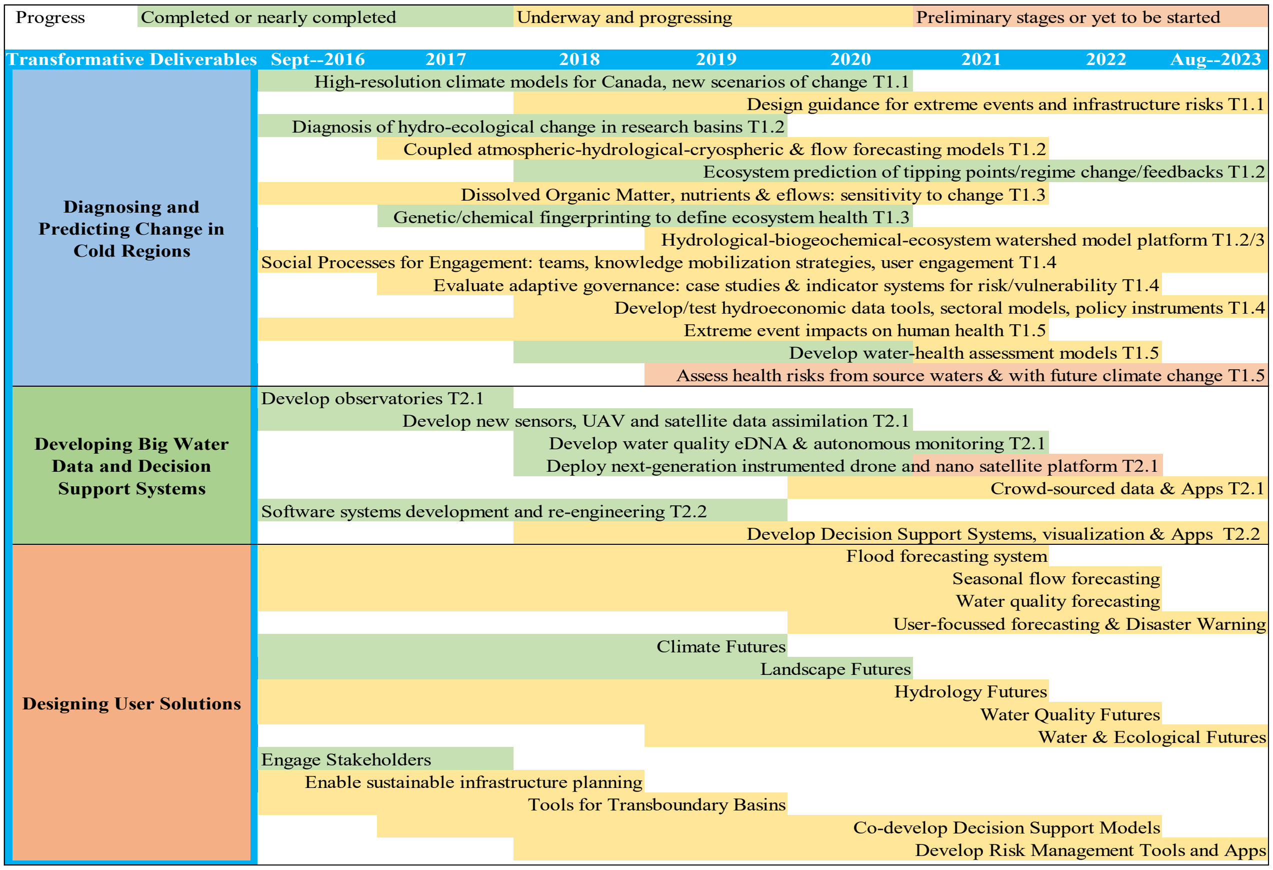

Figure 1.2. Gantt chart showing GWF program deliverables as specified in the original proposal. Numbers refer to themes in the first two pillars of activity. Colour codes indicate progress.

a.1 Pillar 1: Diagnosing and Predicting Change in Cold Regions

This pillar of activity is delivering transformative, transdisciplinary science, leading to a more complete understanding of physical and ecological systems, and providing the observational data to underpin cutting-edge technology and forecasting models. Activities here also contribute strongly to Pillar 3.

***a.1.1 Hydrometeorology and Climate Change*:** This theme improves understanding of how climate change influences water availability and extreme events through the development and application of high-resolution atmospheric models. Thematic research is in collaboration with both the US National Center for Atmospheric Research (NCAR) and Environment and Climate Change Canada (ECCC). The Weather Research and Forecasting (WRF) climate model has been run at unprecedented high-resolution (4 km), providing realistic climate simulations over Canada for historical (1995–2015) and future (2080–2100) periods. These form the basis for coupled modelling of water futures and provide key insights on precipitation extremes and dynamics that are being used to downscale and interpret a wide range of climate change models. In western Canada, WRF simulations have been described, verified, and used to characterize extreme precipitation events and to drive hydrological models at higher resolution and with greater veracity than previously possible(1–5). Results are available to the public and partners using the GWF Cuisinart model data output management system, and have been used in atmospheric and hydrological research across GWF. Contributions to this theme have also been supported through other atmospheric and regional climate model outputs and datasets such as the Global Environmental Multiscale (GEM) model, the Canadian Precipitation Analysis (CaPA), and the fourth-generation Canadian Regional Climate Model (CanRCM4)(6–11). This provides foundational knowledge for understanding subsequent impacts of climate change on water and of land–atmosphere feedbacks in changing cold environments.

GWF has contributed to the National Research Council and its efforts to develop guidance on impacts of climate change on infrastructure. This work has also informed an extensive ECCC-led assessment of projected changes in Canadian engineering design values(12), focussing on extreme return levels for much longer return periods than currently required in Canada's building codes.

***a.1.2 Hydrology and Terrestrial Ecosystems*:** Here the focus is on improving understanding of how hydrological and terrestrial ecosystems will co-evolve under a changing climate, with diagnosis and prediction of hydro-ecological change being central to many of the projects. This work has utilized a vast network of instrumented research observatories across the country (*see Section 2.1 below*), in conjunction with the coordinated application of the Cold Regions Hydrological Modelling (CRHM) platform at many of these sites to analyze complex interrelationships between climate, vegetation, snow, glaciers, permafrost, land management, surface–atmosphere fluxes, and runoff(13–18). Work has led to the development and improvement of coupled atmospheric-hydrological-cryospheric and flow forecasting models, and has demonstrated substantial variations in the sensitivity of hydrological regimes to climate and vegetation change across the country. There have been notable advancements in understanding ecosystem dynamics in the face of rapid climate change, permafrost thaw, and increasing wildfire(19–34), which have profound impacts on water quantity and quality. In the North, work is ongoing to link wildfire and permafrost thaw-driven changes in landcover with water quality and fish health. Through GWF's Indigenous Community Water Research projects (*see Pillar 3 below*), there have been considerable efforts to support community engagement and capacity building in water sciences. These include assessment of watershed and ecosystem health, establishment of baseline data and continuation of monitoring practices, and gathering of Indigenous Knowledge and water stories. Further, these projects bring an Indigenous worldview that greatly strengthens and enhances GWF's "western science" approaches. This is leading to valuable co-production of knowledge on water cycling and ecosystem functioning, and allowing research teams in GWF to focus on the most relevant and pressing concerns of Indigenous Communities.

***a.1.3 Water Quality and Aquatic Ecosystems*:** This theme improves understanding and predictive modelling of water quality impacts and health of aquatic ecosystems in response to changing climate, hydrology, and land use. Models have been developed and advanced through field studies to predict the environmental exposure and effects of emerging contaminants of concern in wastewater treatment effluents. Environmental stressors and contaminants, and their impact on aquatic ecosystems, have been documented(35–36). Progress has been made on the impacts of warming on mobilization of metals, particularly arsenic. A prototype algal bloom forecasting model based on high frequency lake buoy data has been developed(37), which is an important new tool for water treatment operators and shows that simple approaches to forecasting can be employed in shallow lakes to inform drinking water treatment. There have been many other advancements in understanding the drivers of algal blooms and water body eutrophication, consequences, and likely future conditions(38–41). Lake and basin models have been developed for the Great Lakes to identify and track dominant controls on annual and seasonal nutrient loads, and understand biogeochemical cycling within lake systems(42). Knowledge gaps have been filled in understanding controls on nutrient loads from agri and livestock systems(43–44), and best practices for nutrient management are being incorporated into decision support tools in Ontario and the Prairies.

GWF has advanced genetic/chemical fingerprinting, specifically establishing environmental DNA (eDNA) and next generation sequencing platforms for enhancing biomonitoring and risk assessment of Canadian freshwater ecosystems. The system has been optimized for various ecosystems, standard operating procedures have been developed, and eDNA libraries are being established. This allows characterization of bacterial, algal, protozoan, and metazoan communities in surface waters and sediments as indicators of ecosystem health under varying degrees of natural and anthropogenic stress(45–48). High-resolution mass spectrometry is being used to characterize chemicals and dissolved organic matter in water samples from diverse environments(49). 'Omics' approaches such as proteomics, lipidomics and metabolomics have been used as powerful tools to monitor the status of ecosystem structure and function.

Together, this will transform the way we diagnose ecosystem health, support improved regulation, and provide early warning systems. A notable application of these methods is in the search for evidence of community-level COVID-19 infection in municipal wastewater.

A new hydrological-biogeochemical-ecosystem river basin model platform for risk assessment, water quality, and environmental flow forecasting is being developed by expansion of two platforms: the CRHM platform and the Modélisation Environmentale Communautaire (MEC) – Surface and Hydrology (MESH) model. CRHM has expanded from hydrology to water quality and introduced simple plant growth parameters, and MESH has integrated plant growth and community carbon dynamics through ECCC's Canadian Land Surface Scheme including Biogeochemical Cycles (CLASSIC) model for ecosystem dynamics. Further development and integration of these modelling platforms with terrestrial plant growth, water quality, sediment movement, and water temperature for small and large river basins is underway. The work will deliver superior assessment and predictions of Canada's water quality futures and biodiversity impacts of economic development and environmental change.

a.1.4 Human–Water Systems**:** Human dimensions have a strong role in determining water futures, and are being linked into all aspects of the program. This work integrates economic tools with water resources systems models to improve valuation of ecosystem services and to assess different policy conditions and governance strategies. In the Great Lakes, research has focussed on the problem of external politico-socio-economic drivers of nutrient management in the Lake Erie Basin, and how immigration influences water governance in the basin. A first prototype hydro-economic Input-Output (I-O) model, representing the interdependencies between different sectors of regional economies, has been developed for the Great Lakes Basin (GLB)[(50)], and an extended GLB I-O model was built that includes phosphorus flows in the economy surrounding the GLB. An I-O model was also developed for the Nelson-Churchill River. This was coupled with the generalized river basin Decision Support System, MODSIM, to allow for the evaluation of direct and indirect economic impacts of shocks such as water supply shortages at sub-basin, provincial, and river basin scales. Understanding of complex human–agricultural system interactions has been advanced, including governance, decision-making, and economic considerations. In the Prairies, CRHM wetland hydrology simulations were linked to an economic model to examine the ecosystem goods and services impact of wetland drainage. Research has identified opportunities to transform the conflict over agricultural drainage, suggesting that processes for governing natural resources need to have mechanisms to facilitate relationship building and shared understandings, need to be adaptable to people's changing needs and concerns, and should focus on inclusivity and empowerment of various actors to address conflict. A water management model has been developed for the Saskatchewan River Basin, including reservoirs and irrigation[(51)], which can be used to assess proposed policy and management options. Integrated water resources assessment tools have been developed, which couple anthropogenic factors with natural systems models, including ecosystem constraints and economic trade-offs.

a.1.5 Water and Health**:** Changes in climate, extreme events, and water quality will affect human health and are a critical issue for society, with special impacts in Indigenous communities. Health is addressed directly and indirectly (i.e., through changes affecting source water quality and quantity) in many projects. Some bring Indigenous Traditional Knowledge perspectives and are co-developed with and mostly co-led by Indigenous partners. Agent-based modelling has been used as a tool to investigate comprehensive Indigenous health impacts of flooding in Saskatchewan and to update emergency management planning. Human health risks from wells in Saskatchewan have been examined[(52)] and an analysis of drinking water advisories in Indigenous and rural communities was conducted[(53)]. In the Northwest Territories, GWF is working with communities on linkages from land cover change, to water quality, to fish health, to human bioaccumulation. This is guiding adaptive modification to fishing practices. In northern Ontario, fish tissue samples are being analyzed to assess metals and other contaminant concentrations and better understand variables that affect their spatial and temporal patterns. In southern Ontario, a focus has been on health assessments in relation to metals and bacteriological testing, and on gaining insights into the water-related mental health stressors faced by the Six Nations of the Grand River. The Ohneganos Six Nations Youth Mental Wellness Advisory and Research Development Committee has been formed to inform and guide the work. Regular meetings have been held to better understand both the needs of the community and culturally appropriate methods of conducting research in the community. A scoping review of mental health applications for Canadian Indigenous communities has been conducted and has identified a gap, particularly with respect to water elements.

While the project-level activities are well underway, some of the stated activities/deliverables have yet to be undertaken at a national scale. The next steps will deploy GWF atmospheric and hydrological modelling tools for predicting and assessing changing extremes and water quality to health to address potential human health impacts across the Canadian population under various scenarios.

a.2 Pillar 2: Developing 'Big Data' and Decision Support Systems

This pillar of activity is creating new and improved data, sensing and modelling systems, and deploying them across Canada and the world. These systems increase our observational capabilities to unprecedented levels and lead to the generation of the 'big data' needed to uncover key insights and support user needs.

***a.2.1 Big Data for Water*:** An early priority for GWF was to develop a national network of water research observatories. This was achieved by integrating existing sites operated by GWF partner institutions into the network and supplementing these sites with CFI funding grants. Maintenance and logistics are supported by a GWF Core Technical Team, comprised of 20 research technicians across the 4 partner institutions. Most of the sites have a history of research that has produced extensive and long-term hydrometric, hydrometeorological, ecological, and geophysical datasets. The network now includes 60 water observatories in different physiographic settings and ecological regions across Canada's major river basins. Hydrometeorological and hydrometric data are collected hourly and used for bias correction of weather and climate model products; they are essential for the development, testing, and validation of predictive Earth system models. The scope and scale of this long-term observational network is unprecedented for a university-led water research program, and is a fundamental program strength. This also supports and links to global research initiatives (*see Part-1d*). GWF is developing a custom data management platform, GWFNet that takes into consideration the unique aspects of water and associated data including sharing and privacy concerns when human data and Traditional Knowledge are involved.

Various sensors have been developed and deployed that detect the presence of nutrients and contaminants in water (i.e., pathogens, heavy metals, oxidants), and measure snowpacks, frozen soil moisture, soil thermal conditions, greenhouse gas emissions from ponds, and streamflow[54–71]. Integrated sensing systems for long term monitoring of water quality are being developed. LiDAR and hyperspectral sensors have been deployed on remotely piloted aerial vehicles, leading to very high resolution observation of environmental variables. A new patent-pending technology has been developed called "Wobblestones", which are stones that can be tracked to within millimeters for studying stream and river morphology. A 'Smart' sensor network is being developed for datalogging with transmitters currently being deployed and tested for communication from observatories to satellites and across Canada. One goal is a water management microsatellite mission design; several researchers work with the Canadian Space Agency on the design concept, mission potential, and funding. Several possible funding/mission development opportunities are being considered, and the team has continued the development and testing of technologies (including airborne campaigns) planned for the mission concept. Existing satellite data assimilation has been used to improve snow process representation in models[72].

Crowd-sourced data and apps research is ongoing, including development of an application programming interface (RESTful), server support, and a desktop based map application for GWF's Mobile Nutrient App. The Nutrient App supports the reduction of nutrient export to rivers and lakes by engaging citizens, farmers, and water quality managers in real-time monitoring of dissolved nutrient concentrations (N, P) in freshwater. More apps are under development that will allow user communities to share geo-located and time-stamped photographs, complementing traditional forms of data acquisition.

a.2.2 Decision Support Systems**:** GWF is developing and engineering software systems and visualization tools for decision support systems to give our stakeholder communities targeted, user-friendly access to the capabilities of our novel data and modelling tools. The CRHM platform was reengineered through migration to a modern C++ compiler, thereby improving computational efficiency for GWF application. The improved user interface and automated testing framework (i.e., unit testing, system test, and user acceptance testing) will ensure ongoing CRHM functionality as new features/modules are added and be portable to other models. A common problem faced by researchers and practitioners in the hydrological sciences is difficulty manipulating large model data products that often encompass larger temporal and spatial domains than the user requires. In response, GWF has conceived, developed, and deployed the Cuisinart platform for "slicing and dicing" large environmental datasets. Cuisinart provides a Google Maps-like interface where researchers can request arbitrary subsets of data products. Users choose from a list of data products, and then select the desired date range, variables, and spatial domain of interest. GWF's Visualization Task Force guides and coordinates the development of innovative visualization products. This includes a set of software services that can be configured to address a broad range of GWF visualization and decision support needs, with a focus on end-user facing applications and long-term sustainability. The software development and management team has begun to develop and support the platform with guidance from the Visualization Task Force. Two visual interfaces have been developed: 1) the DAta and model VISualization tool, DAVIS, an online visualization platform for a wide range of spatio-temporal data, including model outputs and socio-economic data such as population or gross domestic product; and 2) 'User Centric Decision Support System,' UC-DSS, a decision support platform for exploration of management options under future water uncertainty.

a.3 Pillar 3: Designing User Solutions

Guided by GWF's users and partners and supported by Pillars 1 & 2, Pillar 3 aims to provide tools and solutions that Canada and similar cold regions currently lack, but urgently need, to manage water in the face of unprecedented change. This transdisciplinary approach began with an extensive national stakeholder engagement to assess needs and priorities to inform the priorities of the user-question led science program, followed by the establishment of a Core Knowledge Mobilization (KM) Team to support user interaction. All Pillar 3 projects and Indigenous Community Water Research projects (*see below*), and most Pillar 1 & 2 projects, were co-developed with stakeholders in order to align with partner/user needs and are operated with substantial involvement by and investment from the users. Consultations and user co-development of these projects has identified new pressing research needs that these projects are addressing in addition to the original stated program deliverables. This is leading to expanded science goals and a richer, more relevant program (see *Part-1c* and the research impact profiles).

a.3.1 Co-Creating Water Research with Indigenous Communities**:** An important issue for GWF is the extraordinary water challenges facing Indigenous communities (ICs). Canada is changing rapidly and Indigenous Nations are taking their place as managers of water resources, co-developers of science and management tools, and custodians of nature. GWF has partnered with ICs to develop an IC Water Research Strategy to share knowledge, develop solutions to water problems, and advance concepts of water governance. Many of its projects accomplish this through fostering engagement and participation by ICs, respectful sharing and co-learning of different knowledge systems, and co-created research outputs, as exemplified by this recent article on Climate, Community, and Indigenous Resilience. The goal is to foster a greater appreciation and create a solid bridge between Indigenous and Western ways of knowing. GWF has funded 6 new IC water research projects, each of which were co-created with and are co-led by an IC and a GWF academic Co-Principal Investigator. The review process and criteria for these projects were co-created with ICs from across Canada. These Indigenous-led water research projects involve 14 ICs and 11 GWF universities and are training 36 HQP using $1.6M of funding from GWF. Advancing water solutions and management for ICs is one the most critical and unique advances that GWF is making.

a.3.2 Core Modelling and Forecasting**:** Two of the major science goals of GWF are to deliver new capability for providing disaster warning and to develop new models, tools, and approaches to manage water-related risks for water users. This core team was formed to address these goals, in collaboration with the projects. GWF has partnered with ECCC to develop a Canadian national water modelling strategy, advancing and applying the MESH model to Canada's major river basins. Physical process representations of snow, permafrost, glaciers, evapotranspiration, runoff generation, and human activity simulations such as reservoir operation and water withdrawal, have been improved substantially. MESH has been applied under future climates and land cover scenarios to explore water futures. Full implementation of the MESH model (10-km resolution) on the Mackenzie, Saskatchewan-Nelson, Yukon, and St. John River basins is an unprecedented advance towards national water modelling for Canada. Initial runs for future hydrological conditions have been completed for the Saskatchewan and Smoky River basins and are underway for the Mackenzie, Yukon, and St. John River basins. A higher resolution MESH model (4-km) was set up for more detailed process understanding of the Bow and Elbow Rivers (Alberta) and Kluane Lake Basin (Yukon), forced with WRF (4-km) to derive future conditions (2086–2100) in response to user needs for flood plain mapping in Calgary and infrastructure design in Kluane Lake.

GWF committed to develop a national water forecasting and prediction system, and to work with ECCC on their national flow guidance system. To that end, ECCC has adopted the MESH modelling framework used in the Mackenzie River in their own operational system. A pilot project in partnership with ECCC and Yukon Environment set up, calibrated, validated, and operationalized a coupled version of GEM-MESH as an operational streamflow forecasting system for the Yukon River and its tributaries. The forecast system is run on Amazon Web Services to provide daily streamflow predictions to the Yukon Government. This system is novel and cutting-edge for Canada, representing unprecedented technological sophistication, including glaciers and frozen soil impacts on streamflow, and a strong collaboration with a territorial flood-forecasting agency. Next steps are to extend this approach to other river basins in Canada and other parts of the world (*see Part-1d*).

GWF's Core Modelling team has advanced many other computer modelling tools to aid in infrastructure planning, design and decision support, and risk management. A water management model has been completed for the Saskatchewan River Basin (SaskRB), and, in light of the transboundary agreement requirements between AB, SK and MB, is being used to generate a range of hydro-climate scenarios for the SaskRB using weather generators and RCMs. CRHM was used to generate future hydrological conditions (representing a full range of cold region processes) due to changing climate or land use in small to medium mountain, glaciated, forest, tundra, and agricultural basins in YT, NT, BC, AB, SK, MB, ON, and QC. The Canadian Hydrological Model (CHM), is a new, next generation, multiphysics hydrological model that was developed to advance prediction across a range of spatial scales[(73)]. The model allows for large (70%+) reductions in computational elements while preserving critical land-surface heterogeneity. A new component, WindMapper, has been developed to downscale wind fields over large complex topography, a critical component for estimating land surface processes in mountains. New numerical solutions to problematic thermal-hydraulic-mechanical processes have been developed, which have practical applications in assessing the threats of water main breaks in urban centres as well as buried petroleum pipeline infrastructure in the North.

b) Extent to which the CFREF Grant has furthered Institutional Research Capacity

b.1 Investments in new or improved research infrastructure and facilities: Leveraging the CFREF grant, USask established the $12M Smart Water Systems Laboratory (SWSL) with primary support from Western Economic Diversification. In addition, $1M was secured from CFI to establish the Airborne Cold Regions Observatory (ACRO) and $0.9M from Compute Canada to secure significant computational storage and processing capacity for data and modelling. CFI funds supported the establishment of a $2.5M state-of-the-art ultra-high resolution mass spectrometry lab with a range of capabilities relevant to water quality, including aquatic chemistry and toxicology. The SWSL and ACRO support development of novel water, soil and snow sensing technologies and bring them towards commercialization. These are essential investments that directly support the GWF mission and activities. Institutional funds supported doubling the office space for GWF in Saskatoon to 20,000 ft^2 to accommodate GWF core teams and new water faculty hires ($1.4M). A new 3,455 ft^2 Coldwater Research Lab was leased in Canmore, AB ($600K) to include office space and a lab for logistical access to over 35 nearby stations in major river basin headwaters. These facilities are used by many GWF projects.

WLU established the CFI-funded Changing Arctic Network (CANet; Cash: $3.2M from CFI Cash:, $1.9M from WLU; In-Kind: $0.45M from Industry, Cash and in-kind $2.6M from the GNWT). CANet is a network of 12 living laboratories and 19 supporting sites spread throughout Northwest Canada, including new dedicated lab and warehouse space in Fort Simpson, Inuvik, and Norman Wells. This infrastructure is complemented by long-established research sites, maintained and operated by WLU's Cold Regions Research Centre, throughout Canada's North, with a particular concentration in NT. The research conducted through these significant investments continues to support the development of predictive tools and evidence-based policy. WLU has made a $32K annual investment in opening a research office in Yellowknife in collaboration with local government. The facility hosts several GWF core team members on a full-time basis and provide 'hoteling' spaces for WLU faculty, students, and technical staff during their trips to the field. This office has been instrumental in facilitating close collaboration with partnering organizations and ensures that researchers can effectively work with all GNWT departments/agencies, and communities throughout the NT in supporting their present and future research need. The opening of a university facility in the NT is a groundbreaking movement towards research and academic achievement in the North.

MU opened a field office in the Yukon in collaboration with Yukon Environment with investments of $75K per year. This co-location of university water research with government operations provides excellent collaborative opportunities and allows for close integration of academic–government scientists, leading to early adoption of GWF observational, modelling and forecasting capabilities by Yukon Government. There has been a strong investment by MU in deepening ties with Six Nations of the Grand River. MU has supported upgrades to research infrastructure at the Turkey Point research observatory.

UWaterloo committed $1.6M of institutional funds to support the maintenance and improvement of facilities. Additional institutional funds support the offices and shared resources of the Water Institute, including core members and support staff. UWaterloo upgraded its CFI-supported Environmental Particle Analysis Laboratory (EPAL) through the acquisition of a microcalorimeter ($150K, NSERC-RTI), CHNS analyzer ($75K, CERC) and a portable Spectral Induced Polarization unit ($55K, Schwartz-Reisman Foundation). These instruments are used by GWF researchers to characterize soil biogeochemical properties and to identify and monitor contaminant degradation processes, including petroleum hydrocarbons and microplastics. Examples of additional investments are a new high-throughput Gallery nutrient analyzer ($110K, UWaterloo), a continuous methane analyzer ($45K, CERC), automated water samplers and sensors ($75K, NSERC-SPG and UW) that support a broad range of GWF field projects. A network of sampling sites in the Greater Toronto Area is jointly operated by GWF researchers and TRCA personnel to assess urban contaminant export to local streams and Lake Ontario (joint investment: approximately $200K). Current laboratory and office renovations for existing and new GWF faculty and staff are estimated at $250K (UWaterloo matching funds).

b.2 Investments in new faculty positions: GWF has recruited 16 new high-performing junior to senior faculty members using partner investments (see *Part-5b* for details). These faculty are leading or contributing to various GWF projects and carrying out research contributing directly or indirectly to GWFs overall mission.

b.3 Enhancements to the training environment: The CFREF investment has enhanced and broadened training opportunities at all partner institutions, as well as at other Canadian universities. GWF has developed, sponsored, or contributed to numerous professional development and training opportunities, international short courses, and full credit courses as part of various degree programs in water science (see *Appendix C* and *section 9* of our previous *annual report* for more details). Through various international partnerships (*Part-1d*) we have implemented many student exchanges, in particular, with the Indian Institute of Science and Beijing Normal University.

GWF has three formal seminar series as well as topical seminars at the four partner universities that are broadcast online, recorded, and widely available through the GWF website. The Distinguished Lecture Series includes the global top water experts and is held from September to November. The Women and Water Lecture Series runs from January to April and includes the best water research from GWF and abroad, whilst providing a forum for exploring how to further advance the role of women as scientists and in the sciences. The Knowledge Mobilization Webinar Series runs between October and April and shares examples of successful initiatives in action, discussing and troubleshooting common challenges.

b.4 Development of partnerships and collaborations

GWF provides evidence and policy support advice to municipalities, First Nations, provincial and territorial governments and to federal departments with an interest in water. This includes frequent collaboration and interactions with scientists and policy analysts, briefings to the DG, ADM, and departmental DMs, meetings with Ministers and Parliamentarians at the federal and provincial level, and meeting 1:1 with relevant officials at all levels.

GWF organized an important national meeting of 65 academic and government water scientists and managers in Ottawa in November, 2018. The meeting was co-led and hosted by the 3 science directorates of NRCan and included senior science representation from ECCC, Statistics Canada and Agriculture and Agri-Food Canada as well as GWF. The meeting evaluated how GWF and federal departments can better coordinate to promote more effective national water security research and development. A highlight of the meeting was the signing of an MOU between GWF and NRCan that forms a framework for cooperation in collaborative investigations and scientific exchanges to support water futures research. One aspect of the collaboration with NRCan is a state-of-the-art water prediction system that GWF is developing for the Bow River Basin, funded by NRCan, Government of Alberta, and the City of Calgary.

In 2019–2020, exhibitions of science and art reflecting some of GWF's scientific findings and observatories were held in Alberta, Ontario, England, and Belarus. **"Transitions"** is a transdisciplinary collaboration of GWF with UK-based artist Gennadiy Ivanov and Professor Trevor Davies (Tyndal Centre for Climate Change, Univ. of East Anglia). The art was used to illustrate GWF presentations to the UN COP19 Climate Change Conference in Madrid. An electronic publication describes some of Ivanov's photographs, sketches, and paintings.

c) Quality and Impact of Research Outputs and Fostering of Innovation

c.1 Activities and Achievements in Knowledge Mobilization: GWF research has already had far-reaching impact and helped to shape a number of policy and practice directions, and has generated much interest amongst user communities, the media, and the general public. GWF has a dedicated KM Core Team, whose role is to support bi-directional user engagement, the transfer of science to policy, and the uptake of findings and knowledge into active use. The KM Team has produced a **supplementary report** documenting the many GWF KM activities. The success thus far is due in part to the novel, parallel, and synergistic program-wide and individual project approach to KM. Cross-network capacity building has focused on increasing awareness of KM, fostering researcher-practitioner relationships, building useful KM resources, and documenting the research impact of effective KM. Particular emphasis has been placed on HQP training to strengthen skills in KM planning, communication, plain language writing, and poster design. The KM goal is to support all GWF projects to incorporate two-way engagement approaches in their research design and project delivery. See some of the research impact profiles.

GWF projects have adopted many ways of engaging with partners and users of research methods, results, data and products through interactive feedbacks throughout the research process. These engagement mechanisms include advisory committees, Digital Storytelling, social media training, participatory working groups, and stakeholder oversight teams that offer regular feedback and assist in co-developing annual meetings and gatherings to ensure agendas of interest. Successful KM is highly dependent on building trust and personal relationships. This has been achieved through regular phone calls, email exchanges, conference networking, and working meetings that inform the work required to advance mutual needs. GWF projects host workshops dedicated to sharing results or to solicit feedback on certain products, circulate regular newsletters and updates to keep their partners informed, and respond to many requests to visit communities, present findings, and contribute their expertise to local or regional water resource management projects and issues.

c.2 National-Scale Water Prediction and Forecasting**:** GWF has worked closely with federal, provincial, and territorial partners to develop national-scale capability and consistency. In February 2019, GWF led and organised with ECCC and NSERC's FloodNet, a unprecedented National Workshop on Flow Forecasting. The workshop included presentations by streamflow forecasters from every Canadian province and territory, many from industry, ECCC, the GWF Core Modelling Team and the Integrated Modelling Program for Canada GWF project. Workshop participants found advantages to pooling information products and resources for a Canada-wide community of practice to support forecasting as well as linking provinces/territories, federal government, and universities to help with development and co-ordination. GWF is committed to enhancing models for forecasting systems (see *Part-1a*) and is strengthening partnerships to test and implement these systems with the provinces, industry, and ECCC.

c.3 Water Security for Canadians, and towards a Canada Water Agency**:** GWF's goal is to contribute to a revitalized water strategy for Canada. GWF has partnered with the Forum for Leadership on Water, the Centre for Indigenous Environmental Resources, the POLIS Program on Ecological Governance, and the UN University to directly engage parliamentarians and inform policy through the translation of GWF science outcomes. This has involved national-level discussions, roundtables, webinars, media engagement, and strategic briefing documents as part of the Water Security for Canadians: Solutions for Canada's Emerging Water Crisis initiative. This has contributed to a mandate to the federal Ministers of ECCC and AAFC to develop a Canada Water Agency that will centralize water information, prediction, and decision-support services; strengthen intra- and inter-national transboundary water management; strengthen reconciliation with Indigenous Peoples; and, improve collaborative river basin planning with provinces, territories, and Indigenous communities. GWF is currently consulting with regional and sectoral stakeholders/practitioners across Canada on the issues, concerns, and the collaborative responses needed to tackle the emerging water-climate crisis through a Canada Water Agency.

d) Global Positioning, International Reputation, and Level of Research Excellence

GWF is the largest and most cited freshwater research programme in the world and through its collaborations and outputs, influences policy and program development nationally and internationally. This unprecedented investment in university-led water research has strengthened the international reputation of the partner institutions and enhanced their level of research excellence in this field. According to the recently published 2020 Shanghai Ranking Consultancy's Academic Ranking of World Universities, USask and UWaterloo are ranked first and second in Canada, respectively, for water resources research, and 20th and 36th in the world. They have been ranked amongst the world-leading universities for the past four years (no stats are available before 2017). MU has been ranked in the top 4-5 in Canada and the top 76-100 globally for the same period. GWF's productivity and recognitions are a testament to its research excellence and influence (see *Part-5*).

Through GWF's international scientific engagement and profile, the partner institutions are well poised to shape global water research and are regularly called upon to lead global initiatives. GWF has developed a number of important relationships with leading UN organizations and research initiatives to expand its activities and influence well beyond Canada to address the issues of global climate and Earth system change and water security. Key linkages include:

- UNESCO's International Hydrological Programme (IHP) and UN Water through its International Water Action Decade: Water for Sustainable Development, 2018–2028. GWF is leading a Canadian contribution to the Decade that is addressing the targets of Sustainable Development Goal 6 (Ensure the availability and sustainable management of water and sanitation for all) of the 2030 Agenda for Sustainable Development (see the report *Water Futures for the World We Want*).
- Endorsement as a Regional Hydroclimate Project (RHP) in 2018 as part of the World Climate Research Programme (WCRP) and the Global Energy and Water Exchanges (GEWEX) project. GWF is the only RHP in North America and interacts closely with the International Network for Alpine Research Catchment Hydrology (INARCH), which is a GEWEX cross-cut project that links to other GEWEX research in the Andes, Tibetan Plateau, and Eastern Europe.
- A memorandum of understanding for cold regions research between GWF and the Chinese Academy of Sciences' Third Pole Environment (TPE) initiative—a proposed RHP under GEWEX that is resulting in joint research, faculty exchange, and publications.
- GWF as the Canadian node of the Sustainable Water Future Programme (SWFP) of Future Earth, leading important Canadian and international research initiatives focussing on water resources and climate change in cold regions..
- Formal linkages to the World Meteorological Organization (WMO). GWF co-chaired a *High Mountain Summit* in Switzerland in October 2019 and attended by 44 nations. A Call to Action was issued, with commitment for an Integrated High Mountain Observation and Prediction Initiative, organized as campaigns of analysis and prediction in high mountains headwaters around the world.
- Collaboration with the Arctic Council, currently led by Iceland. GWF has been asked to shape one of the keystone elements, Polar Prediction.

***d.1 Planetary Water Prediction Initiative*:** This internationalizes GWF's modelling capabilities by contributing sophisticated hydrological modelling products and geospatial intelligence approaches to expand the direct impact of GWF beyond Canada. This initiative focusses on better predicting vulnerable cold region water sources globally in the high altitudes and high latitudes and in their downstream river basins that support over half of humanity. Canada has shown global leadership through its GWF modelling efforts and can make a major contribution to predicting the changes occurring in global hydrological and energy cycles. By advancing the computational infrastructure (datasets, modeling capabilities) necessary to produce global-domain simulations and predictions of hydrological risks, this initiative uses state-of-the-art modeling capabilities to develop new and strategic collaborations with organizations and countries through mutually beneficial, internationally focused projects. The program involves collaboration with countries in the Americas, Asia, and Europe to develop, support, test, and apply coupled climate–hydrology and eventually water quality–water management models globally with an emphasis on river basins where high mountain water supplies feed local and downstream water demands and ecosystem needs. This will put greater capacity behind GWF's commitments to the WCRP through GEWEX, Future Earth through the Water Futures initiative, UNESCO through the IHP, and the WMO through its High Mountain Initiative and Polar Prediction Program.

e) Sustaining the Momentum and Transformative Change

At this stage, GWF's research program is fully developed, partnerships are functional, competitive funding allocations to projects and core teams are complete, most faculty and HQP have been recruited, an unprecedented team of research personnel is active, research infrastructure for GWF is established, and research is fully under way. GWF has long-term viability through its strong user-base and is tied in to society in many different ways. GWF has been holding annual science meetings, cross-cutting workshops, international workshops/webinars, and cross-country topical webinars and science tours. In doing so, GWF has developed a large community of invested stakeholders and partners. This critical mass of personnel, expertise, partnerships, and infrastructure is essential to maintain, as there remain many pressing water challenges for Canada and the world as we enter further into global water and climate crises. The synergies among the partner institutions is a unique aspect of GWF and it is anticipated that the partnership will carry on after the end of the grant.

The future will focus on several priority topics and themes. GWF's Core Modelling, DM, and other teams produce highly valued information products and it is expected that the research personnel will carry on beyond the grant, supported by our user-grants, a Canada Water Agency and/or a new research network. We fully intend to keep this powerful aspect of the program intact and functioning. This is also the case for some projects for which new faculty have been hired and will continue to pursue funding for their research. There will be a need to seek out program-level funding opportunities in future to maintain the size of GWF. One consideration has been a fee for service model, which involves high-end research and collaborative partnerships with government and other stakeholder organizations. For follow-on networks, water as the nexus between food, energy, environment and health has been identified as a possible theme. Ensuring sustainable water management under climate change adaptation is a critical challenge for Canada and the world, that involves quantifying water supply and allocations, whilst improving governance and exploring priorities and trade-offs under the stress of the climate crisis. This and the need for better social equity, inclusion, and diversity is becoming recognised as a global priority to which GWF is poised to contribute. Building upon the ground-breaking IC water research advances Indigenization and decolonization of water management in Canada in the spirit of Reconciliation. The new Canada Water Agency may provide opportunities to advance these important areas of transdisciplinary water research, and GWF is now in a position to influence and shape its development to address these priorities in future.

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