Canada's Contributions to the SWOT Mission – Terrestrial Hydrology (SWOT-C TH)

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ABSTRACT

The origins of the Surface Water and Ocean Topography (SWOT) mission date back to the mid-1970s with the launch of GOES-3 and SEASAT. These missions were then followed in 1992 by the Topex-Poseidon satellite, then by Jason-1 (2001), OSTM/Jason-2 (2008), and Jason 3 (2016), a series of joint satellite missions between NASA and CNES with a goal to monitor global ocean circulation. The proposed new SWOT mission will provide 120-km-wide swath interferometric coverage with a 20-km-wide gap at the nadir. The SWOT measurements will consist of water surface elevations and water surface slopes covering nearly all of the earth's land surface at least once every 21 days. In 2010, NASA invited the Canadian Space Agency to contribute, and Canadian scientists welcomed the invitation to join the SWOT Science Definition Team and contribute to the experiments. The Canadian segment of the mission is known as the "SWOT-C" project. The SWOT satellite mission will provide unique opportunities in the Canadian context for water managers in both the public domain and in the private sector. This paper provides an overview of recent scientific progress by the SWOT-C Terrestrial Hydrology team, outlining current plans and progress towards applications and calibration post-launch.

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RÉSUMÉ

Les origines de la mission SWOT (Surface Water and Ocean Topography) ont commencé dans les années 1970 avec le lancement de GOES-3 et de SEASAT. Ces deux missions ont ensuite été suivies en 1992 par le satellite Topex-Poseidon, puis par Jason-1 (2001), OSTM/Jason-2 (2008) et Jason 3 (2016); une série de missions satellites communes entre la NASA et le CNES avec l'objectif de surveiller la circulation océanique mondiale. La mission SWOT fournira une couverture interférométrique de 120 km de fauchée avec un partie vide de 20 km au nadir. Les mesures SWOT porteront sur les élévations de la surface de l'eau et les pentes de la surface de l'eau couvrant presque toute la surface de la Terre au moins une fois tous les 21 jours. En 2010, la NASA a invité l'Agence spatiale canadienne à apporter sa contribution et les scientifiques canadiens ont accueilli favorablement l'invitation à se joindre à l'équipe de définition scientifique SWOT et à contribuer aux expériences. La partie canadienne de la mission est connue sous le nom de projet «SWOT-C». La mission SWOT offrira des opportunités uniques dans le contexte canadien pour les gestionnaires de la ressource en eau des secteurs public et privé. Cet article présente les progrès scientifiques récents réalisés par l'équipe d'hydrologie terrestre SWOT-C.

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Introduction

Canada is covered by abundant surface fresh water in many parts of the country, with millions of rivers, lakes, and wetlands. Yet with all this abundance, the need to ensure an adequate supply of water at the right time of year for societal needs (i.e., urban centers, industrial operations, natural resource development) makes the ongoing monitoring of this resource critical to Canada's ecosystem stewardship and economic success. It is simply not possible to monitor all of the nation's surface water resources and thus only a representative subset (~2,800) of water bodies are actively monitored by the Water Survey of Canada (WSC), its partners, and other agencies. Coulibaly et al. (2013) highlighted that Canada falls below the World Meteorological Organization (WMO) guidelines for streamflow network density. Ungauged rivers, lakes, and wetlands make up the vast majority of hydrological features on the vast landscape covering 7 physiographic regions over 10 million square kilometers. For many regions in Canada, such as northern, high-arctic, and alpine regions, where future developments are increasingly occurring, it is currently very difficult to ensure proper water quantity monitoring to support climate change studies, as well as for development and environmental assessments.

The Surface Water and Ocean Topography (SWOT; Alsdorf and Lettenmaier 2003; Biancamaria et al. 2016; Durand et al. 2010; Fu et al. 2009) mission aims partially to address this major gap in water resources assessment through the systematic monitoring of water body elevation from earth orbit. As such, it provides a novel opportunity to map water surface elevation (WSE) of rivers and lakes; and water surface slopes (WSS) along river reaches and for larger lakes around the globe. This has particular relevance to hydrologically rich places such as Canada. Using the SWOT satellite platform, hundreds of thousands of kilometers of rivers and surface water bodies can be observed on a 10 day–15 day basis, with parts of Canada observed at a higher frequency. The new SWOT data coupled with simple hydraulic equations (e.g., flow estimation; Durand et al. 2016; Hagemann et al. 2017; Garambois and Monnier 2015) or in some cases more complex hydraulic models, in combination with conventional measurements (e.g., Oubanas et al. 2018), may allow the water resources community to infer hydrological change in both gauged and ungauged regions over the mission lifespan. Moreover, simple estimates of surface water elevation using this technology will enable the estimation of lake, reservoir, and/or wetland volume change (e.g., Lee et al. 2010; Munier et al. 2015; Solander et al. 2016), affording a new look at transient and perennial surface water bodies in Canada. SWOT will very likely provide a unique opportunity for all levels of government, industry, and the private sector to make informed decisions around development, water resources availability, and management, particularly in remote and poorly gauged regions.

The Canadian space, remote sensing, and hydrological scientific community (e.g., Pietroniro and Leconte 2000, 2005) are important partners for the SWOT mission via the contribution of hardware and research projects to this international collaboration. This overview paper: (*i*) outlines the Canadian SWOT Terrestrial Hydrology (SWOT-C TH) research strategy, plans, and progress for the pre- and post-mission phases; (*ii*) provides information regarding key research projects; (*iii*) identifies objectives; and (*iv*) discusses future applications of SWOT products in Canada and internationally. The ultimate goal of this overview is to inform and engage various user communities in Canada regarding the SWOT mission and its potential implications to future water resources monitoring and management. The focus is on the science component of SWOT, not the engineering part of the mission.

SWOT mission and science questions

Mission concept and objectives (ocean, hydrology, and synergistic applications)

The U.S. National Research Council in its Decadal Survey (NRC 2007) recommended to NASA a new satellite mission (SWOT, https://swot.jpl.nasa.gov/) to measure both the ocean and land water surface topography. Since then, SWOT has been collaboratively developed by NASA, the "Centre National d'Études Spatiales" (CNES; French space agency), and more recently the Canadian Space Agency (CSA) and the United Kingdom Space Agency (UKSA). The SWOT satellite is planned for launch in September 2021. It will observe the whole continental waters–estuaries–ocean continuum and therefore link the ocean and hydrology scientific communities. This overview paper, however, mainly focuses on terrestrial hydrology (TH), particularly the contribution from Canada.

Science questions and challenges for TH, particularly in the northern regions

According to the NASA mission plan, SWOT aims to address the following hydrologic science questions (Rodrıguez 2016):

- (*i*) What are the temporal and spatial scales of the hydrologic processes controlling surface water storage and transport across the world's continents?
- (*ii*) What are the spatially distributed impacts of humans on surface water, for example, through water impoundment behind dams, withdrawals and releases to rivers and lakes, transboundary water sharing agreements, diversions, levees, and other structures?
- (*iii*) What are the regional- to global-scale sensitivities of surface water storages and transport to climate, floodplain conditions, land cover, extreme droughts, and cryosphere?
- (*iv*) Can regional and global extents of floodable land be quantified through combining remotely sensed river surface heights, widths, slopes, and inundation edge with coordinated flood modeling?
- (*v*) What are the hydraulic geometries and 3-dimensional spatial structures of rivers globally, and can this knowledge help improve our understanding of water flow?

The scientific rationales for these questions and the measurement needs are presented in the SWOT Mission Science Document (Fu et al. 2012).

Based on these needs, the SWOT Science Requirements (Rodrıguez 2016) have been outlined; the SWOT mission is designed to observe all rivers wider than 100 m and water bodies (lakes, reservoirs, ponds, wetlands) with an area greater than 250 m × 250 m that lie within the swath coverage. Moreover, NASA and CNES teams strived to design an instrument and processing methods that will be able to observe rivers wider than 100 m and water bodies with an area >1 km^2. To meet the SWOT science requirements, a Ka-band radar interferometer (KaRIn) has been designed. The KaRIn is a synthetic aperture radar (SAR) interferometer in Ka-band (35.75 GHz frequency or 8.6 mm wavelength), with near-nadir incidence angles (between 0.6° and 3.9°, Fjørtoft et al. 2014). The sensor will estimate WSE with an accuracy of ~10 cm when averaging over water area of 1 km^2, and 25 cm when averaging over 250 m^2–1 km^2 (Rodriguez 2016). In general, WSS will be estimated with an accuracy of 1.7 cm/km for river reaches when averaging over a water area of 1 km^2, or over a maximum 10 km of flow distance for river widths greater than 100 m. Frasson et al. (2017) point out that slope-error standard deviation is inversely proportional to the width and the third power of the length, highlighting that slope accuracy is also somewhat dependent on river geometry. Mission science operations lifetime will be of 3 months of fast sampling calibration orbit (repeat period of 1 day) plus 3 years of nominal orbit (repeat period of ~21 days) covering almost all continental areas between 78° N and 78° S (Biancamaria et al. 2016). Convergent orbits will yield a higher revisit time over Canada. Despite the uneven time sampling and the regions that will not be sampled, constituting <5% of the earth between 78° N and 78° S, SWOT will provide unprecedented observations of continental surface waters at global scale.

SWOT pre-launch activities include airborne and field campaigns that have been organized by the Jet Propulsion Laboratory (JPL) (Moller and Esteban-Fernandez 2015) and CNES (Fjørtoft et al. 2014). More recently, related experiments funded by the NASA Arctic Boreal Vegetation Experiment (ABoVE; https://above.nasa.gov/) have also contributed to preparations for SWOT. One of the key tools used in preparation for SWOT is AirSWOT, an airborne analogue to SWOT (Altenau et al. 2017; Pitcher et al. 2018; Tuozzolo et al. 2019). The purposes of AirSWOT are to understand better Ka-band backscattering at SWOT-like incidence angles and to serve as a calibration and validation tool for SWOT. In brief, AirSWOT consists of the Ka-band SWOT Phenomenology Airborne Radar (KaSPAR) system, along with a Cirrus digital color infrared camera for detecting inundation extent, that have been integrated into a NASA King Air B200. The instrument package collects 2 swaths of across-track interferometry data (nadir to 1 km and 1 km to 5 km, respectively) to obtain topographic maps of water surfaces. The AirSWOT Cirrus camera also provides complementary measurements of digital airphotos for validation of surface water extent and terrain type characterization (https://swot.jpl.nasa.gov/airswot.htm). The ABoVE-funded AirSWOT campaign in summer 2017 flew over several Canadian sites en route to Alaska (https://above.nasa.gov/airborne_2017.html). Image processing and evaluation for the Canadian mission are expected to be completed in fall 2019.

Canadian SWOT team and contributions

Presentation of SWOT-C TH

Environment and Climate Change Canada (ECCC) is leading the SWOT TH component in Canada through its National Hydrological Service (NHS) and specifically the Water Survey of Canada contained with this NHS. This was established through an agreement with the CSA and as an important consideration to meet its own mandate of continuous monitoring of rivers and lakes through WSC. ECCC is looking towards this platform for operational quantitative monitoring, research, and analysis of rivers, lakes and wetlands for the longer term. ECCC interest is largely articulated through its mandated requirements to provide timely and accurate flow and water-level information to Canadians through the Meteorological Service of Canada (MSC). The WSC has 3 main functional areas of responsibility regarding water resources where it could potentially take advantage or contribute directly to the SWOT mission activities. As the national hydrological service (NHS) provider in the federal government and in partnership with all the provinces and territories in Canada, the WSC is responsible for data provision for flow and water-level information for all of Canada, carried out in partnership with all the provinces and territories in Canada. The NHS is also responsible for operational hydrological and hydraulic model development in waters of federal interest. Lastly, they are responsible for managing and/or advising on water management on transboundary water (both interprovincial and international) through established boards, acts, and treaties. In all 3 mandated obligations, there is a need and role for the SWOT observational system.

The Canada SWOT team SWOT-C TH includes project partners from ECCC research divisions (e.g., Watershed Hydrology and Ecology Research Division, Meteorological Research Division), CSA, and University of Sherbrooke and has also teamed up with the Global Water Futures Program being led from the University of Saskatchewan. The team strives to make important contributions to the SWOT mission and the successful application of novel SWOT products/tools across Canada, particularly via the advancement of remote sensing techniques in hydrologic research and applications, including hydrometric data collection by WSC and state of the ecosystem assessments by agencies (e.g., Parks Canada). The SWOT-C team has developed a research plan/strategy and several projects to collect/prepare field data and develop/test model tools before the satellite launch in 2021. Other key activities include participation and contribution of the Canadian members to the SWOT (*i*) Science Definition Team (SDT), (*ii*) the Discharge Algorithm Working Group (DAWG), (*iii*) calibration and validation (Cal/Val) working group, and (*iv*) with an ambitious number of Cal/Val sites selected across the country that will provide representative hydrological systems to develop and test algorithms and prepare the necessary datasets prior to and after the launch of the satellite package.

International collaboration with other SDT/ST projects

The SWOT-C team is also involved in research projects from the United States Geological Survey (USGS), University of California, Los Angeles (UCLA), and NASA JPL; ECCC is co-investigator in all these projects. The JPL project is aimed at characterizing the contribution of SWOT measurement to global climate and hydrologic models. The USGS plans to focus on general hydrodynamic characterization on numerous sites around the world, while the UCLA collaboration focuses on northern rivers and wetlands that include Canadian sites. ECCC have and will continue to provide historical information and enhanced water-level measurement gauges at select sites (i.e., install pressure transducers and conduct geodetic surveys) to help the USGS and UCLA studies in Canada, such as characterizing the dynamics of river and lake systems. These projects are hydrology oriented and include Cal/Val and discharge algorithm development components. There is also a collaboration between ECCC, JPL, and Rouen University for the “Terre Solide, Océan, Surfaces Continentales et Atmosphère” (TOSCA) proposal to study estuaries with SWOT data, with the aim of characterizing tides and water exchanges and transport along the freshwater–marine continuum. For instance, the St Lawrence River is a site of interest because it is one of the few estuaries under the Cal/Val orbit and it has historical datasets, real time monitoring, and hydraulic models (Matte et al. 2017).

Discharge Algorithm Working Group

In addition to the operationalization of surface water elevation measurements, the SWOT-C TH team is interested in the development of algorithms to estimate river discharge from optical and SWOT observations, especially for ungauged systems. The successful development of these algorithms will be of great value to the NHS as it will expand its national capabilities, particularly in remote regions of Canada. To date, SWOT-C has provided historical simulations of the St Lawrence River between the port of Montreal and the end of Lac Saint-Pierre in Trois-Rivières, Québec (Morin and Champoux 2006). These simulations have allowed the DAWG to test their algorithms in a fluvial lake with a slope close to the minimum detectable threshold by the SWOT mission (1.7 cm/km when averaging over water area of 1 km^2; Biancamaria et al. 2016; Rodriguez 2016). Although more work is needed into discharge algorithm applicability, initial work by Durand et al. (2016) has shown that at least 1 of the algorithms tested has been proven to work under these hydraulic conditions, and it is our understanding that similar results from the other international SWOT Cal/Val sites are pending.

SWOT Canada Cal/Val plan

For the SWOT and AirSWOT missions, several Cal/Val and DAWG sites are being established in the U.S., Canada, France, and other countries. The goal is to develop the sites prior to launch and operate them during the mission. Evaluation sites have been selected by the international SWOT Science Team in a range of eco-geographic regions and for varying hydrodynamic flow regimes, such as the high-gradient streams, regulated and unregulated rivers, as well as reservoirs, lakes, wetlands, and floodplains. To ensure consistency across the sites, field parameters and methods proposed by the Cal/Val Steering Committee and referenced in the SWOT Cal/Val plan were used to guide the Cal/Val process.

The selected Cal/Val evaluation sites will be instrumented and monitored to validate:

(*i*) Water surface elevations
(*ii*) Inundation extents
(*iii*) Dynamic water surface area in lakes and wetlands in river-associated floodplains
(*iv*) River surface slopes
(*v*) River discharge
(*vi*) River velocity
(*vii*) Bathymetry
(*viii*) Manning's *n* for slope-area method
(*ix*) River tides

The SWOT-C TH team has worked closely with the international SWOT Mission to develop the Cal/Val plans for the Canadian contribution to this international effort. The SWOT-C TH team participated in Cal/Val meetings and proposed several evaluation sites based on data availability, potential for fieldwork, particularly for AirSWOT flights in northern Canada, and the development of hydraulic models. The following sites have been noted as potential Canadian contributions to the Cal/Val plan, with those shown with an asterisk as confirmed by the Cal/Val team:

(*i*) The Ottawa/St Lawrence Seaway*
(*ii*) The Lake Champlain and Richelieu River
(*iii*) The Laurentian Great Lakes*
(*iv*) The Slave River
(*v*) Great Slave Lake and nearby shield lakes
(*vi*) Lake Athabasca*
(*vii*) The Peace-Athabasca Delta*
(*viii*) The Mackenzie River
(*ix*) The North Saskatchewan River*
(*x*) Select prairie lakes and ponds*

The SWOT-C TH team has been asked to provide water-level data for some big northern lakes in Canada, namely Great Bear Lake, Great Slave Lake, and Lake Athabasca. Because of the remoteness of the Great Bear Lake and the absence of actual data or gauging stations, SWOT-C TH will provide data for Lake Athabasca and Great Slave Lake; the latter is under a crossover diamond (overlaps between 2 KaRIn swaths) during the Cal/Val phase orbit and thus very useful to the Cal/Val working group as they provide points observed by both ascending and descending passes that can be used for data consistency checks, calibration, etc. The SWOT-C team set up sites near Saskatoon and Yellowknife, i.e., Redberry Lake and nearby ponds, and lake and ponds near St Denis and Yellowknife for lake water surface elevation and water extent survey.

The Cal/Val phase may take place during the Northern Hemisphere winter season when most Canadian sites will be covered by snow and ice, and possibly not suitable for water detection. SWOT Cal/Val will thus need sites to explore the detection of ice-covered water and the differentiation between water and ice, for which, given the geographic location, ECCC will play a key role by providing ice-covered sites where there are sufficient data to carry out this evaluation. For instance, the St Lawrence River estuary is already monitored and routinely cleared of ice for seaway shipping access; it will provide an excellent site for the detection of open water with coastal ice. This site will make unique contributions to the SWOT mission should the Cal/Val phase take place during the winter. Similarly to Lake Champlain, Richelieu River, and Great Lakes, the Saint Lawrence River and estuary all have hydrodynamic models that are already operational. These sites also have a high-resolution digital elevation model (DEM), and the domains are well characterized in terms of water bodies, wetlands, rivers, substrate, depth, water elevation, and slope. Work is currently ongoing to bring up the Peace-Athabasca Delta (PAD) to such a characterization, and operational 2-dimensional (2-D) hydrodynamic model. Other sites, such as the Slave, Mackenzie, Saskatchewan and Ottawa rivers, are part of projects funded by NASA SWOT and ABoVE programs, as well as ECCC monitoring and research programs. SWOT-related work over these sites will imply sharing data and likely require Global Navigation Satellite System (GNSS) adjusted water levels to establish a common framework and accurately measure water slopes close to an AirSWOT and SWOT overflights.

SWOT-C TH projects and objectives

To support the SWOT mission and to meet Canada's needs (e.g., large rivers, lakes, and wetlands in the northern regions) for remote sensing hydrology and water resources research, monitoring, and management, the SWOT-C TH team has developed several research projects to support the international effort. The section below provides a summary of each specific project, including background, research goal, progress, and future plans.

Project 1 – streamflow estimation and lake level measurement

The National Hydrometric Program (NHP) carried out by the WSC uses traditional field-based methods (i.e., water-level measurement and stage–discharge curve) to develop and derive flow estimates at approximately 2,500 sites across Canada (https://wateroffice.ec.gc.ca/). The program has been continuously operated since 1908, and as a cost-shared program with provinces and territories since 1975. The current breakdown of stations is highlighted in Figure 1 with the total number of stations that the NHP is paid to operate on behalf of the federal

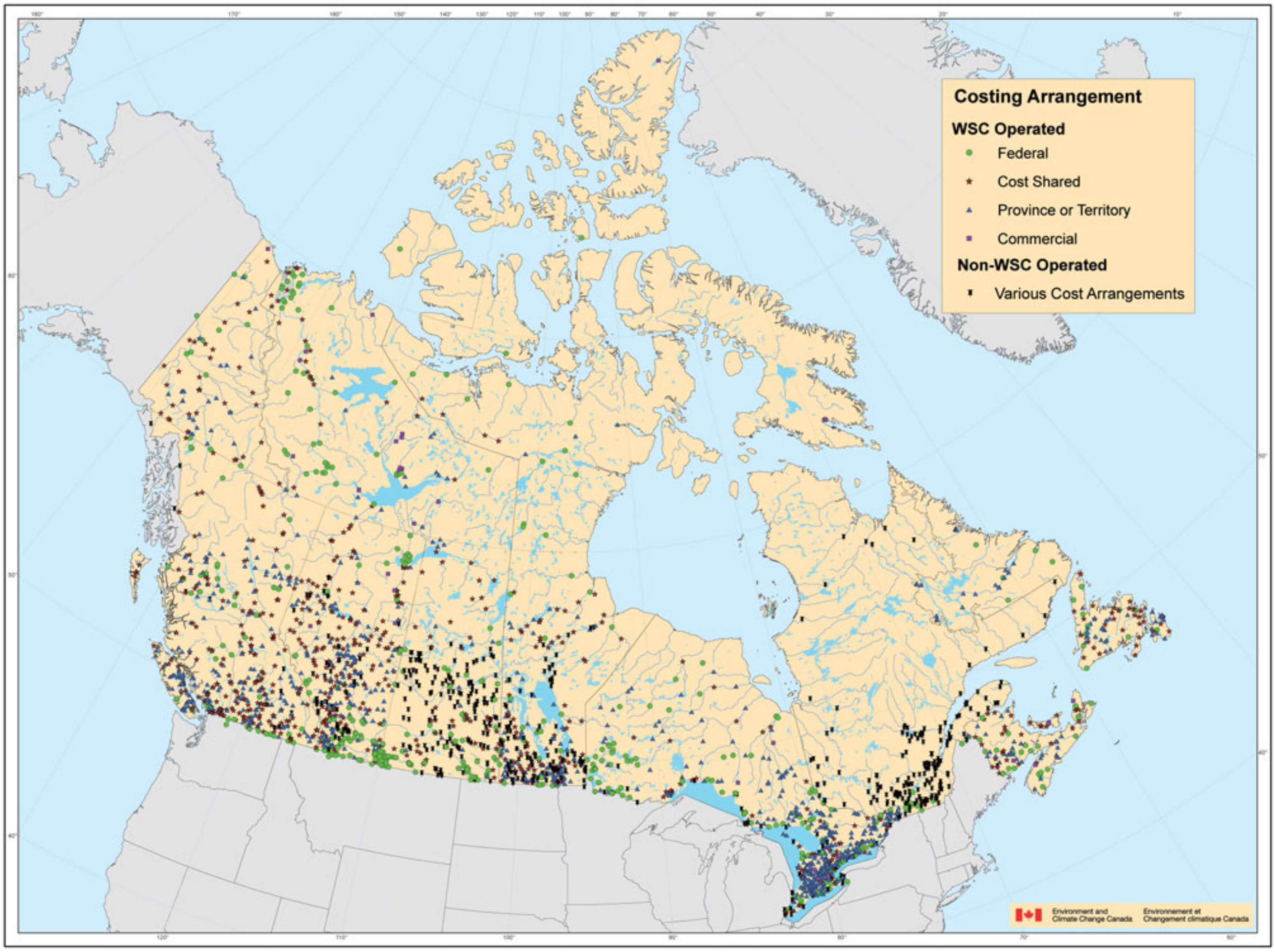

Figure 1. Hydrometric stations (levels and flow) operated by or contributed to the Canadian National Hydrometric Program.

government and by our cost share partners, namely the 13 provinces and territories.

How is water level (and flow) currently measured?

In situ flow estimation is based on well-established procedures modified for Canada and consistent with international practices (WMO 2010). Contrary to a common misconception that WSC measures discharge in streams, time-based water level (stage) is measured continuously at each hydrometric station and periodic discharge (Q) measurements are made indirectly by measuring velocity (v) and cross-sectional area (A) to calculate instantaneous flow according to the formula:

$$Q\ \left(\mathrm{m}^3/\mathrm{s}\right) = v\ (\mathrm{m/s}) \times A\ \left(\mathrm{m}^2\right).$$

Traditional discharge measurements are made using the "mid-section" method where the river cross-section is divided into 20 panels (see Figure 2). The water depth and velocity are measured in the center of each panel and, by knowing the width of the panels, the cross-sectional area, average stream velocity, and average discharge can be calculated. The velocity is measured using current meters or hydroacoustic technology at 0.6 × depth for depths less than 0.75 m and at both 0.2 × depth and 0.8 × depth for deeper streams. A stage–discharge curve is established once a sufficient number of Q measurements have been made. Hourly or daily discharge is derived from the water-level record based on the curve and manual interpretation. An example of the relationship and translation from stage to discharge is shown in Figure 3.

The example provided in Figure 3 illustrates how the increase in stage during the ice-covered period (November–April) does not translate into increased discharge values, even if the stage–discharge curve suggests that it should. The measured discharge value does not fall on the predetermined open water curve during the ice-covered period. This is because other factors influence the hydraulic capacity of a stream and relationship between stage and discharge, such as: ice genesis and break-up; aquatic vegetation growth and die off; aggradation/degradation of the channel; beaver activity; and tides or more will influence the curve. Periodic discharge measurements, manual interpretation, and local knowledge are used to adjust for the changes in the relationship using "shifts." As a result, hydrometric technicians continue with periodic discharge measurements even after a curve has been established in order to know when shifts to the rating curve are required.

The accuracy of river water level and discharge data are influenced by many factors, such as metering sensitivity and calibration, and the frequency of actual discharge measurements (~0.17% of the hourly Q is measured and verified annually) that are used to confirm the need of stage–discharge shifts. Hence, both instrumental and logistical challenges make existing measurements prone to error, particularly under non-stationary or extreme conditions.

While a simple rating-curve approach can relate discharge estimates to water-level data, this method becomes unsuitable under backwater or non-stationary (e.g., tidal) conditions, for which there is not a unique water level associated with a given river

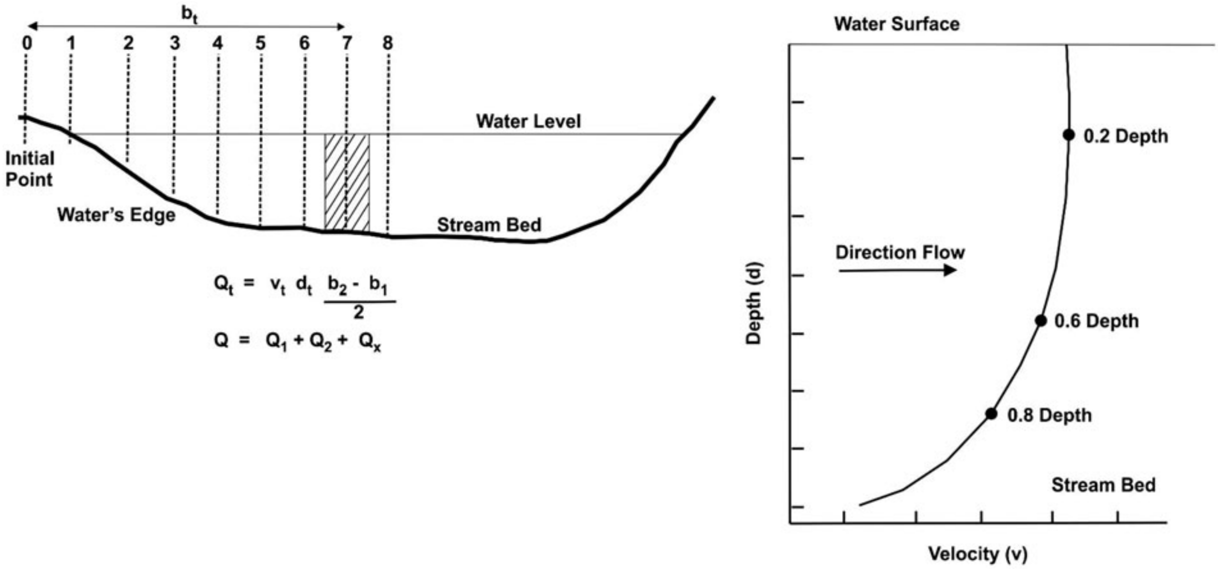

Figure 2. Diagrams illustrating the mid-section discharge measurement method (left) and the depth of velocity measurements (right).

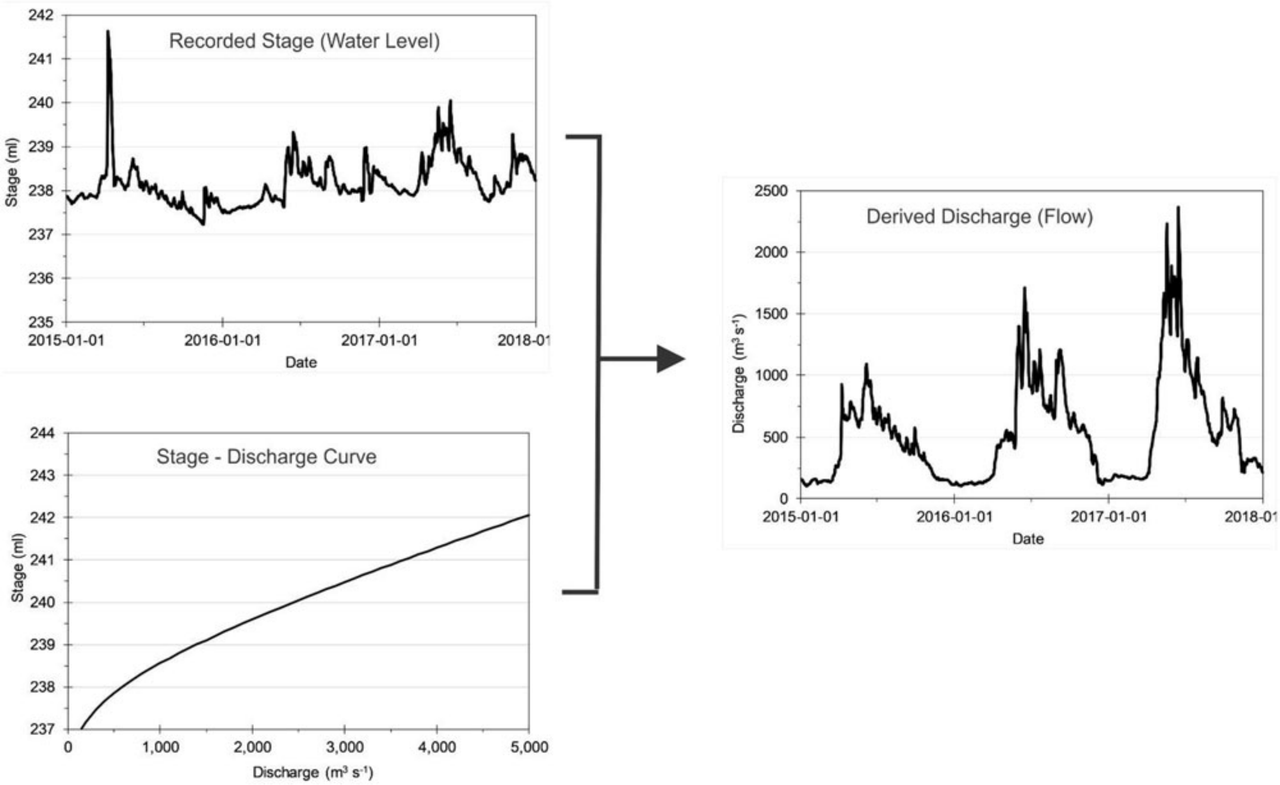

Figure 3. Examples of a stage record (top left), a stage–discharge curve (bottom left) and a derived daily discharge record (right). Data from Athabasca River just below Fort McMurray (07DA001) hydrometric station in northeastern Alberta, Canada.

discharge (Di Baldassarre and Montanari 2009). More advanced dynamic rating curves mitigate some of these issues (Dottori et al. 2009) and the use of relations with multiple water-level gauges has also proven effective in tidally-influenced rivers (Moftakhari et al. 2016). Nonetheless, accurately and efficiently estimating freshwater discharges in estuaries remains a challenging problem, particularly because tides are modified by multi-scale non-stationary signals, such as river flow and storm surges.

Discharge estimation from space

As outlined in Biancamaria et al. (2016), space-based estimates of river discharge started over 20 years ago via measurement of variations in river width used with limited *in situ* discharge data to develop rating curves (Brakenridge et al. 2005; Smith 1997; Smith et al. 1995, 1996; Smith and Pavelsky 2008). Subsequent attempts to derive Q using satellite-derived water elevation, slope, width, and velocity were specific to individual river reaches because of the parametrization and requirement of *in situ* data (Bjerklie et al. 2005). More recently, Pavelsky and Durand (2012) identified that new algorithms that need to be derived to estimate discharge from SWOT data (e.g., water elevations, slopes, and inundation extent). SWOT has ushered in a new paradigm for river science – the mass conserved flow law inversion (McFLI) approach (Gleason et al. 2017). An example McFLI outlined in Biancamaria et al. (2016) is the MetroMan algorithm developed by Durand et al. (2014) that used the Manning equation with the continuity equation in a Metropolis algorithm to invert bathymetry, friction, and discharge. In essence, MetroMan (and all McFLI approaches) uses what we shall observe from SWOT to solve for unobserved river parameters using a numerical or heuristic approach, but the problem remains ill-posed. Thus, we are left with an equifinal solution of unobserved parameters that can produce the right discharge, if not the correct values of the unobserved parameters (e.g., friction, bathymetry). Durand et al. (2016) describe a robust comparison of several SWOT discharge algorithms and document much recent progress in this area. The precise performance of different algorithms for different classifications of river reaches (e.g., Frasson et al. 2017) remains an area of study, and testing of algorithms with simulated and real SWOT data to assess realistic errors and suitability of algorithms is crucial. The SWOT-C team will provide *in situ* field measurements necessary to test a suite of algorithms in a range of channel and river types found in the sites listed above and described below.

Project 2 – Great Lakes water balance

The Great Lakes surface water elevations are closely monitored by both the United States (through NOAA's National Ocean Service) and Canada (through the Canadian Hydrographic Service). Daily mean lake-wide levels, obtained by averaging a subset of U.S. and Canadian gauges from around the lakes, can be obtained from the U.S. Army Corps of Engineers (USACE; https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Water-Levels/). As noted by Fortin and Gronewold (2012), surface water elevation dynamics of the Laurentian Great Lakes exhibit long-term persistence on decadal time scales and the changes in surface water elevation over these time scales are driven mainly by climate dynamics. On shorter time scales, regulation of Lake Superior and Lake Ontario outflows contributes to mitigating extreme water levels. Mean water level can vary by a few centimeters on a daily basis, but very abrupt changes in water level on the order of a meter can still occur due to storm surges and seiches.

Many key science questions facing the International Joint Commission (IJC) and other agencies operating within the Great Lakes basin are commonly addressed through understanding the water balance of the Great Lakes. Through a better understanding of the water balance, water managers could more effectively manage the water of the Great Lakes toward improving hydrologic forecasts, ecological restoration, water conservation, navigation and hydropower operations, and many other functions which benefit our society.

The 2 approaches most commonly used to estimate net basin supply (NBS) include the component method, which derives NBS using a water balance of the components of the hydrological cycle, and the residual method, which is more indirect and is based on change in storage of the lake. With the component method, NBS is computed as the precipitation occurring over the lake plus runoff to the lake from the surrounding basin, minus evaporation from the lake surface. Runoff to the lake from the surrounding watershed is a composite of measured flow from gauged tributaries and modeled flows from ungauged tributaries. It should be noted that runoff measured by conventional stream gauges reflects all upstream impacts on the available water supply including any upstream diversions, consumptive use, or changes due to land use. Computing NBS by the component method requires an estimation of over-lake precipitation and evaporation and condensation, which are not directly measured but can be derived using a combination of numerical and geostatistical models. For example, precipitation over the Great Lakes may be estimated based on interpolated point measurements from inland stations near the lake, but it can also be estimated using models or analyses that combine models, point observations, and radar observations. The uncertainty associated with the estimation of over-lake precipitation and evaporation has been estimated to range from 15% to 60%.

An alternative approach for estimating NBS, which is of particular relevance to the SWOT mission, is through what is termed "reverse routing" or the residual method (Bruxer 2010). Reverse routing is a mass balance of streamflow entering and leaving the system plus or minus any changes in storage on the lakes, which are approximately proportional to changes in mean water level. Determining the lake-wide average level is currently done by averaging readings from near-shore stations, and is subject to measurement error.

The upper Great Lakes as well as the St Lawrence River have both recently experienced record low and high levels, which has proved challenging for the current regulation plans. An adaptive management strategy is being proposed for the Great Lakes, which would allow for proactive adaptation measures, including changes to the regulation plan. However, this strategy requires accurate and near real-time information on recent changes in storage for each of the Great Lakes, as well as forecasts and scenarios of future water levels. On short time scales, observed changes in lake levels are potentially quite noisy, making it very difficult to obtain reliable estimations of changes in storage on time scales less than 1 month.

Efforts are currently underway to use hydrodynamic (in particular the NEMO ocean model) and river routing models coupled to atmospheric models (Dupont et al. 2012; Durnford et al. 2018), to characterize better the spatial and temporal variability of Great Lakes water levels for the purpose of water balance estimation and water cycle prediction. While assimilation of near-shore observations of water level may be possible with NEMO, information provided by SWOT should be useful for the purpose of model calibration and verification. An open question is whether or not real-time SWOT data could be useful for data assimilation purposes. In this case we would update the model water-level estimates by adjusting the NBS inputs to match the SWOT observations;

however, given the size of the lakes and the multitude of factors that can affect water levels, there is no easy way forward and numerical experiments using SWOT simulations derived from NEMO are being considered at this point. This project will use existing ECCC infrastructure and models around the Great Lakes, the Water Cycle Prediction System (WCPS; Durnford et al. 2018), and fieldwork. The WCPS was implemented as an experimental system at Canadian Center for Meteorological and Environmental Prediction (CCMEP) operations in June 2016.

Project 3 – hydraulic and hydro-ecology applications on the St Lawrence River and tributaries

The St Lawrence River is the downstream water body of the Great Lakes and Ottawa River systems and is subject to large variability at all scales (Figure 4). While decadal time scale variability is caused by climate dynamics, management of its upstream sources can significantly affect water levels on the seasonal time scale, in particular in the Montreal archipelago. Between Montréal and Trois-Rivières, more precisely downstream of Sorel, the river widens significantly. The area, known as Lac St-Pierre, is a UNESCO biosphere reserve. This ecosystem is host to a vast number of migratory birds, and sustains an important recreational and commercial fishing industry. Downstream of Trois-Rivières, significant tidal influences are observed, with water-level differences between low and high tide (i.e., tidal range) reaching 6 m at Québec City. In the St Lawrence fluvial estuary, the tidal signal is being distorted and damped by friction, whose effects are modulated by the river discharge. Located upstream of the salinity intrusion limit, it is composed of vertically well-mixed fresh water. Flow reversals are observed along most of the fluvial estuary reach, thus complicating the estimation of discharges. The upstream limit where the flow becomes unidirectional depends on the respective strength of tides and river flows. With these characteristics, the fluvial estuary represents a unique ecosystem.

Given the importance of the river for navigation, water supply, and as a main ecological corridor in the province of Québec, a detailed hydrodynamic model was required to understand, protect, and manage complex ecosystems along the St Lawrence River. The model was built based on high-quality and high-resolution LiDAR observations and bathymetry. Calibration and validation were carried out using detailed water-level and velocity data. Each of the implemented configurations is based on the 2-D H2D2 hydrodynamic model software platform developed at the "Institut National de la Recherche Scientifique, Centre Eau Terre Environnement" (INRS-ETE; (http://www.gre-ehn.ete.inrs.ca/H2D2; Secretan

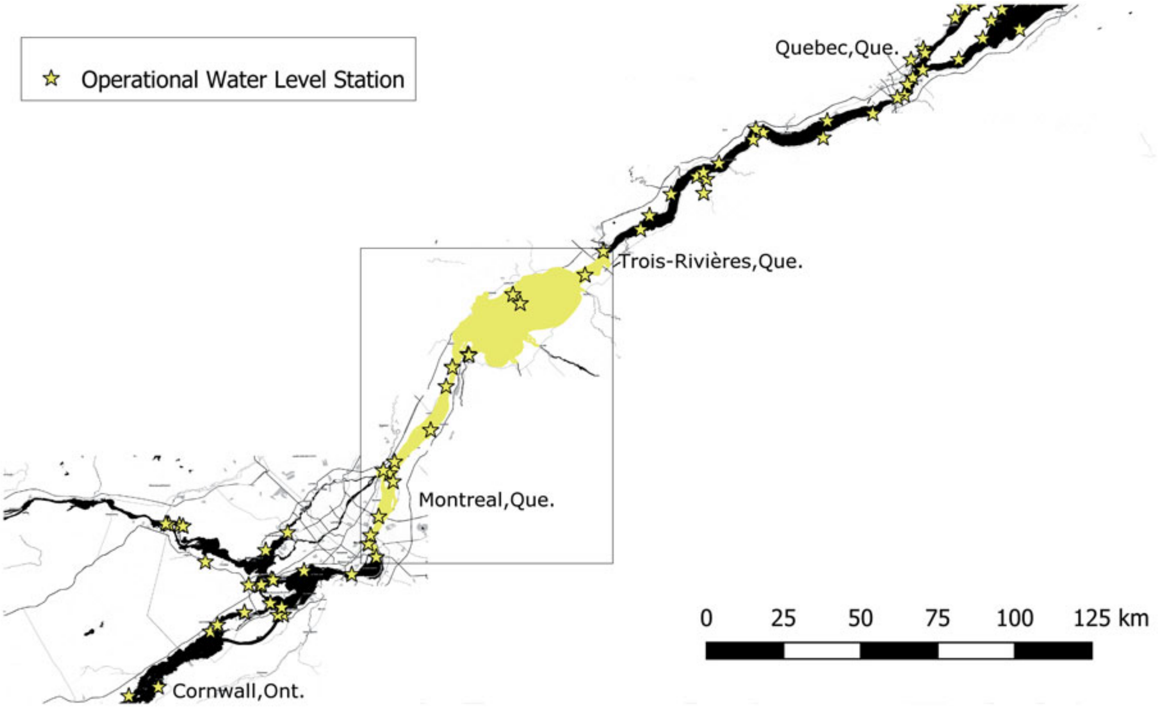

Figure 4. Domain of ECCC's eco-hydraulics modeling system for the St Lawrence River. Red dots show the location of operational federal water level gauges.

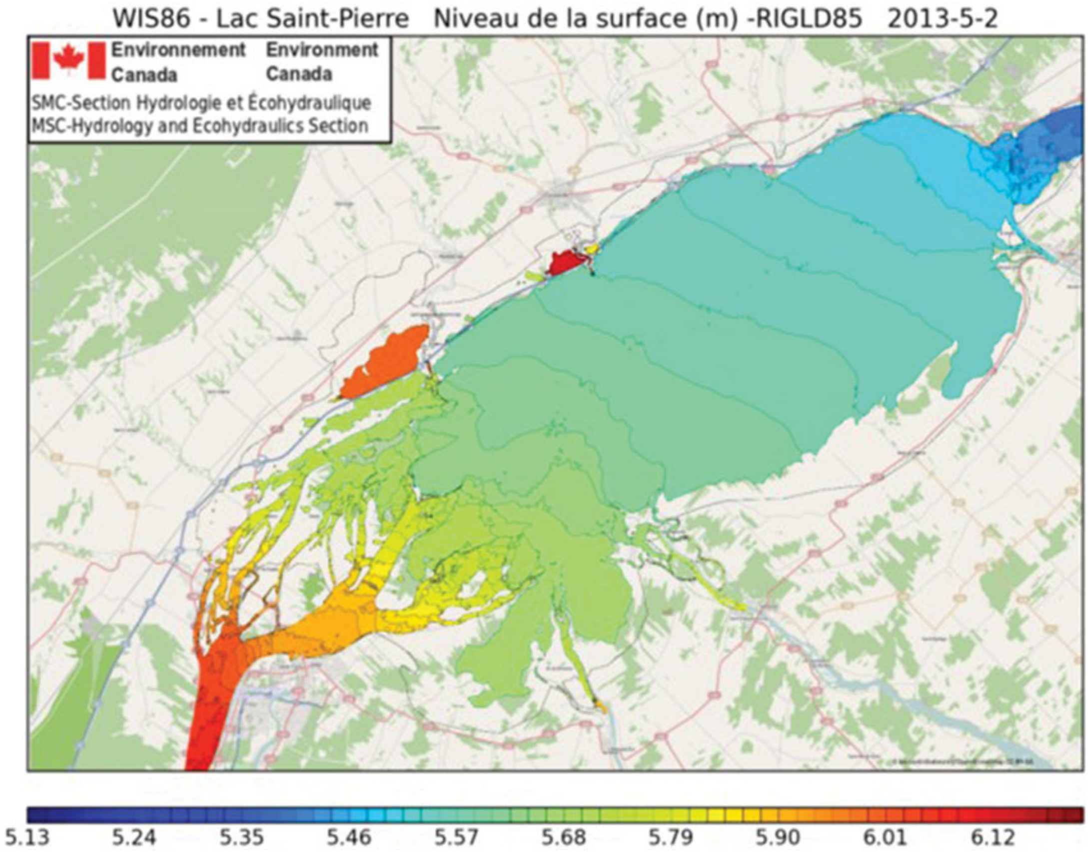

Figure 5. Water-level prediction for Lac St Pierre based on ECCC's 2-D hydrodynamic prediction system. Mean daily level valid for May 2, 2013.

2013). It solves the 2-D depth integrated Navier–Stokes equations over a finite-element discretized domain, with special treatment of drying–wetting areas. Hence, information on water level and currents is available at all points of the modeling domain. Between Montréal and Trois-Rivières, accuracy of water-level predictions is on the order of a few centimeters (Morin and Champoux 2006). Both upstream and downstream of this river section, the system is much more complex, and accurate hydrodynamic modeling is challenging. Upstream, work is underway to fine-tune the Upper St Lawrence River model near the Great Lakes. Downstream, a detailed and calibrated model has recently been set up and calibrated in the fluvial estuary, with accuracies in water level better than 5% of the local tidal range at the most energetic stations (Matte et al. 2017). Both the Upper St Lawrence River and the estuarine transition zone (ETZ) at the downstream limit of the St Lawrence fluvial estuary are under the fast sampling orbit and will thus have more SWOT overpasses than elsewhere in the system.

Building on this work, ECCC has developed a sophisticated 2-D eco-hydraulic modeling system to simulate the physical, chemical, and biological components of the aquatic environment. Application of this system is currently being implemented operationally on the St Lawrence River, from the outlet of Lake Ontario at Cornwall (ON) to its marine estuary. A first section, extending from downstream of the Montréal Archipelago to Trois-Rivières, has been successfully implemented at the Canadian Meteorological Center (Figures 4–6).

Tributaries of the St Lawrence River also receive considerable attention in the context of flood forecasting and warning. One area of interest lies south of Montreal: the Richelieu River, which flows from Lake Champlain in Vermont down to the St Lawrence River in Sorel. Following very significant flooding during the spring of 2011, the governments of Québec and Canada are both investing in flood warning systems for this major river, including the development of hydraulic models to predict accurately the water levels and flood extents. Similarly, a flood forecasting system is under development for the Chaudière River, another tributary of the St Lawrence River, based on a hydrodynamic model, coupled with ensemble hydrological forecasts and including water-level and discharge assimilation. This project is carried out at Laval University and supported by the governments of Québec and Canada through FloodNet – an NSERC

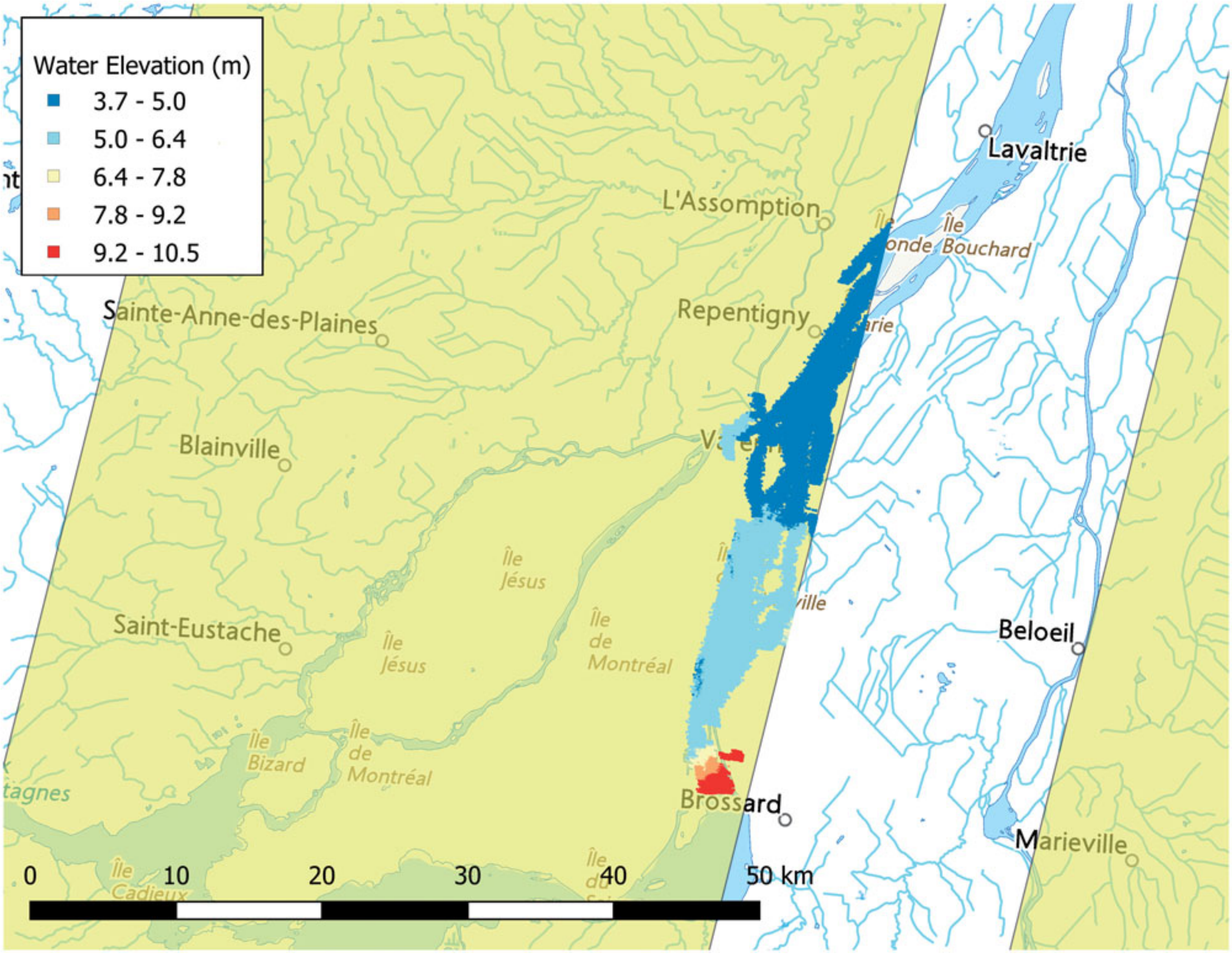

Figure 6. SWOT Cal/Val orbit over the St Lawrence River with an enlarged section showing a SWOT simulation for a standard orbit image overpass.

Canadian strategic network. It is of particular relevance to the SWOT mission as its low-slope downstream reach and floodplains will be covered by the fast sampling orbit. Finally, ECCC also has an operational version of the H2D2 model running in the Rainy-Namakan region near Lake of the Woods, along the U.S./Canada border. We are currently examining the feasibility of using this region as a SWOT Cal/Val site and as a site for hydraulic model assimilation and verification.

In each of these systems, SWOT could provide valuable information on water level for the purpose of calibration and validation of the hydrodynamic models. We are also examining the feasibility of using SWOT water-level information in a data assimilation context to update model elevations and model states. Numerical experiments using the current SWOT simulator to evaluate this possibility are being contemplated. To that end, ECCC has successfully implemented this simulator using output from the operational St Lawrence River hydraulic model as the background field. Efforts are ongoing to resample the surface water elevation maps to a resolution compatible with the simulator. A procedure has been developed to combine the daily model output and static digital elevation data in an operational context. Work is being completed for the automation and optimization of the process, so SWOT simulations will be available on a daily basis to all members of the SWOT mission science teams and work groups (Figure 6).

Work on tidal signal reconstruction from SWOT water levels is underway. It has already been demonstrated that SWOT's spatial and temporal resolution should be sufficient to recreate the spatiotemporal variability in tides in the St Lawrence estuary. In this regard, a new analysis method (constrained harmonic analysis) was developed, combining satellite data with *in situ* tide gauge data (Matte et al. 2018a). This method limits tidal aliasing, resolves multiple tidal constituents within each tidal band, and is

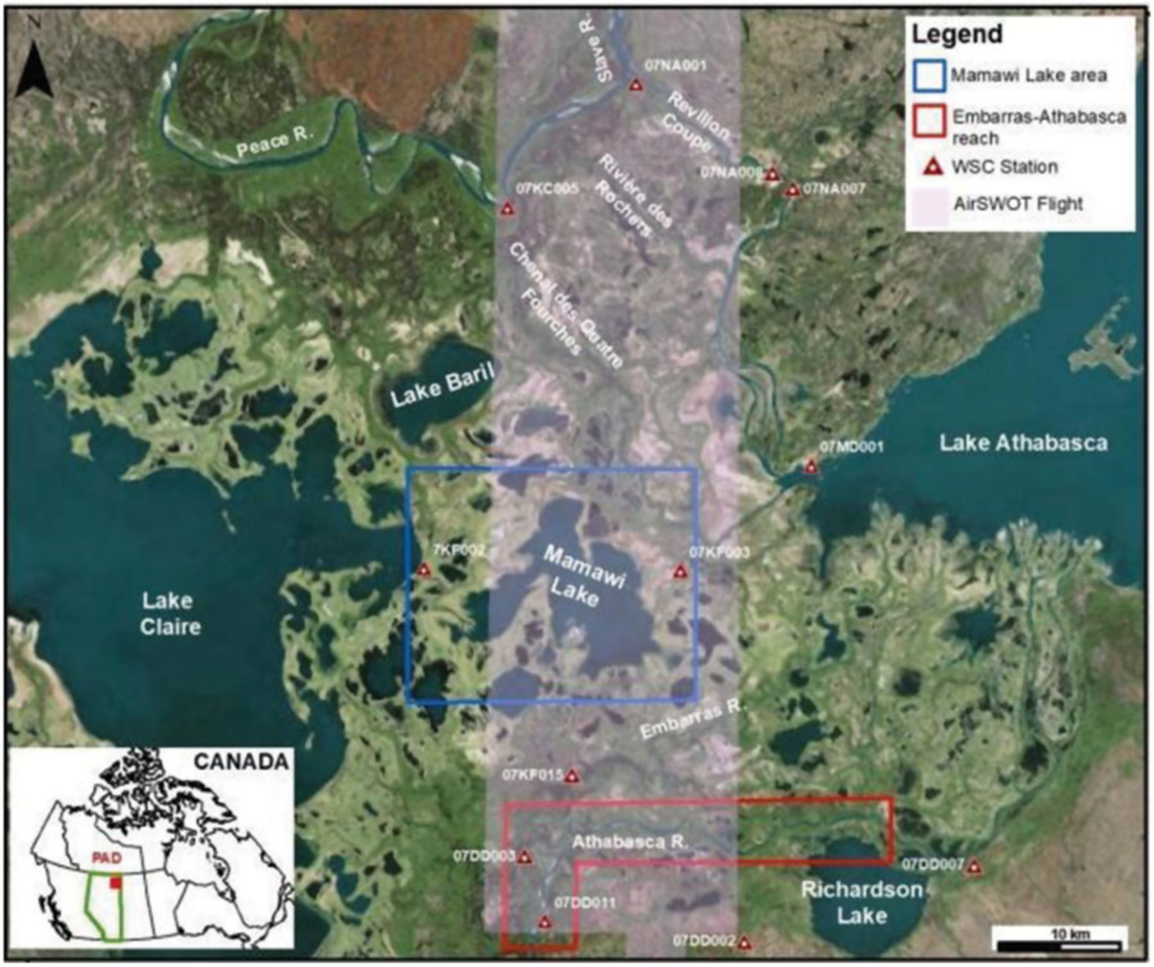

Figure 7. Peace-Athabasca Delta and processed areas over the PAD. Distribution of Water Survey Canada (WSC) hydrometric stations is represented as well as the 2017 AirSWOT over-flight. Sources: ESRI, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

independent of the system geometry, thus making it easily transferable to other estuaries. The method was applied to the St Lawrence ETZ using a 2-D SWOT sample derived from the 2-D model of the St Lawrence fluvial estuary. It was shown that a stable accuracy in reconstructed tides could be achieved after 1 year of the science mission. Some progress has also been made on the estimation of tidal discharges from water levels in estuaries, using a newly developed multiple-gauge rating curve approach. Provided that the chosen tide gauges are appropriately located (e.g., half a tidal wavelength apart), relative errors in reconstructed discharges lie between 4% and 15% of the tidal discharge range in the St Lawrence fluvial estuary, depending on the location, with Nash–Sutcliffe efficiency coefficients systematically higher than 0.95 (Matte et al. 2018b). Future research should evaluate whether or not these tidal and discharge reconstructions can be adapted to ungauged systems using SWOT-only data.

Project 4 – the Peace-Athabasca Delta

The Peace-Athabasca Delta (PAD; ~6,000 km^2) is a freshwater wetland lake ecosystem of international ecosystem service importance recognized by the Ramsar Convention and partially protected (about 80%) within the Wood Buffalo National Park, which is a UNESCO World Heritage Site. The PAD formed in northeastern Alberta where the Peace and Athabasca Rivers converge at the west end of Lake Athabasca River (Figure 7). The Athabasca River is the largest direct inflow to the PAD and Lake Athabasca complex. While the Peace River usually flows north to the Slave River, it occasionally contributes water to the complex when river levels are extremely high, leading to reversing flow into the delta (Peters and Buttle 2010).

Topographic relief within the delta is low, and reconnection of abandoned channels and overland flow into inland basins occurs during over-topping of levees as a result of ice jams, large runoff, and the expansion of the central lakes Claire, Mamawi, and Athabasca beyond their shoreline (Peters et al. 2006a). The deltas contain more than 1,000 small basins with varying degrees of hydraulic connection depending on location and elevation (Jaques 1989; Pavelsky and Smith 2008; Peters et al. 2006a; Wolfe et al. 2007). Basins perched above the connected waterway rely on occasional flooding to sustain aquatic conditions (Peters et al. 2006b). Grasses, sedges, and willows are the dominant vegetation types in the active and semi-active portions of the delta, while coniferous, deciduous, or mixed forests grow in the inactive portions, on bedrock outcrops, and along the higher levees. The range of habitat is essential for wildlife such as waterfowl, muskrats, and bison (PAD-PG 1973).

In response to upstream flow regulation and climate change effects on the delta hydrology, the PAD has been extensively monitored and studied over the past 40+ years. For instance, a 1-dimensional (1-D) model developed by ECCC was used to simulate the hydrodynamics behavior of the PAD to assess the hydrology under natural flow conditions (Leconte et al. 2001; Peters et al. 2006a). Model output includes lake/channel levels and flow along the various river reaches in the PAD. The model provided satisfactorily flow results in this complex system of interconnected lakes and rivers, although it has inherent 1-D approximations that can result in significant over- or under-predictions of some components of the PAD water budget. For example, the floodplain wetlands and perched basins are approximated in the model. Although this approach bears some merits, at least to investigate whether or not the wetlands would be replenished during high water-level conditions, an improved, 2-D model is required so that more accurate quantitative estimations of wetland replenishment and depletion can be achieved for projections of future climate change and/or upstream development impacts.

It was recognized in the 1990s that aerial and satellite remote sensing imagery analysis would be a useful approach to monitor water conditions in the remote PAD environment, including high-resolution DEM via LiDAR surveys, and provide useful information to update/calibrate hydraulic models. For instance, Toyra et al. (2001, 2002) and Töyrä and Pietroniro (2005) developed and operationalized a geomatics-based approach to monitor surface water extent using a combination of SPOT, Landsat and RADARSAT data. SPOT and ASTER satellite images were used to map suspended sediment concentrations across the PAD revealing strong variations in water sources and flow patterns, including flow reversals in major distributaries, while MODIS was used to track hydrologic recharge of floodplain lakes revealed by episodic infusions of sediment-rich water from the Athabasca River (Long and Pavelsky 2013; Pavelsky and Smith 2009). More recently, RADARSAT images were combined with airborne LiDAR data to derive water levels of a 40-km reach of the Athabasca River and to use the information for calibrating a hydrodynamic model (Desrochers 2017). Aerial extent of open water, saturated vegetation, and dryland areas has been mapped by Wood Buffalo National Park since 1996 using this approach supplemented with water-level data from the WSC hydrometric network established in the early 1970s and recently resurveyed to comply with the Natural Resources Canada Geodetic Vertical Datum 2013 framework (CGVD2013: https://www.nrcan.gc.ca/earth-sciences/geomatics/geodetic-reference-systems/9054). All elevation data in the PAD are now referenced to CGVD2013.

Given the international importance and extensive research/monitoring activities, the SWOT-C team selected the PAD as one of the key Canadian Cal/Val sites for AirSWOT and SWOT missions. It is anticipated that AirSWOT and SWOT data will be useful in refining new PAD hydraulic models by providing unprecedented spatially-distributed channel, lake, and wetland water levels. Building on prior studies, the project goal is to investigate the potential of SWOT remote sensing observations, jointly with other remotely sensed data (e.g., RADARSAT-2, RADARSAT Constellation, Sentinel Constellation) and field-based data, for improving the understanding of the water balance of the PAD, with a particular attention to storage variations of the large lakes and floodplain wetlands. To achieve this goal, the SWOT-C team is developing a 2-D model of the PAD based on the H2D2 hydrodynamic model software platform (Secretan 2013). Specifically, the current project focuses on a sector of the Embarras-Athabasca reach, Lake Claire, and Mamawi Lake areas (Figure 7). As SWOT is scheduled to be launched in 2021, simulated SWOT imagery will first be used to investigate water balance in the PAD.

The SWOT-C team implemented a fieldwork plan during the summers of 2016, 2017, and 2018 to collect critical bathymetric data, augment the WSC hydrometric network with pressure sensors to measure water surface elevations, acoustic Doppler current profiler (ADCP) velocities, and weather stations for the H2D2 model development of the Athabasca-Embarras

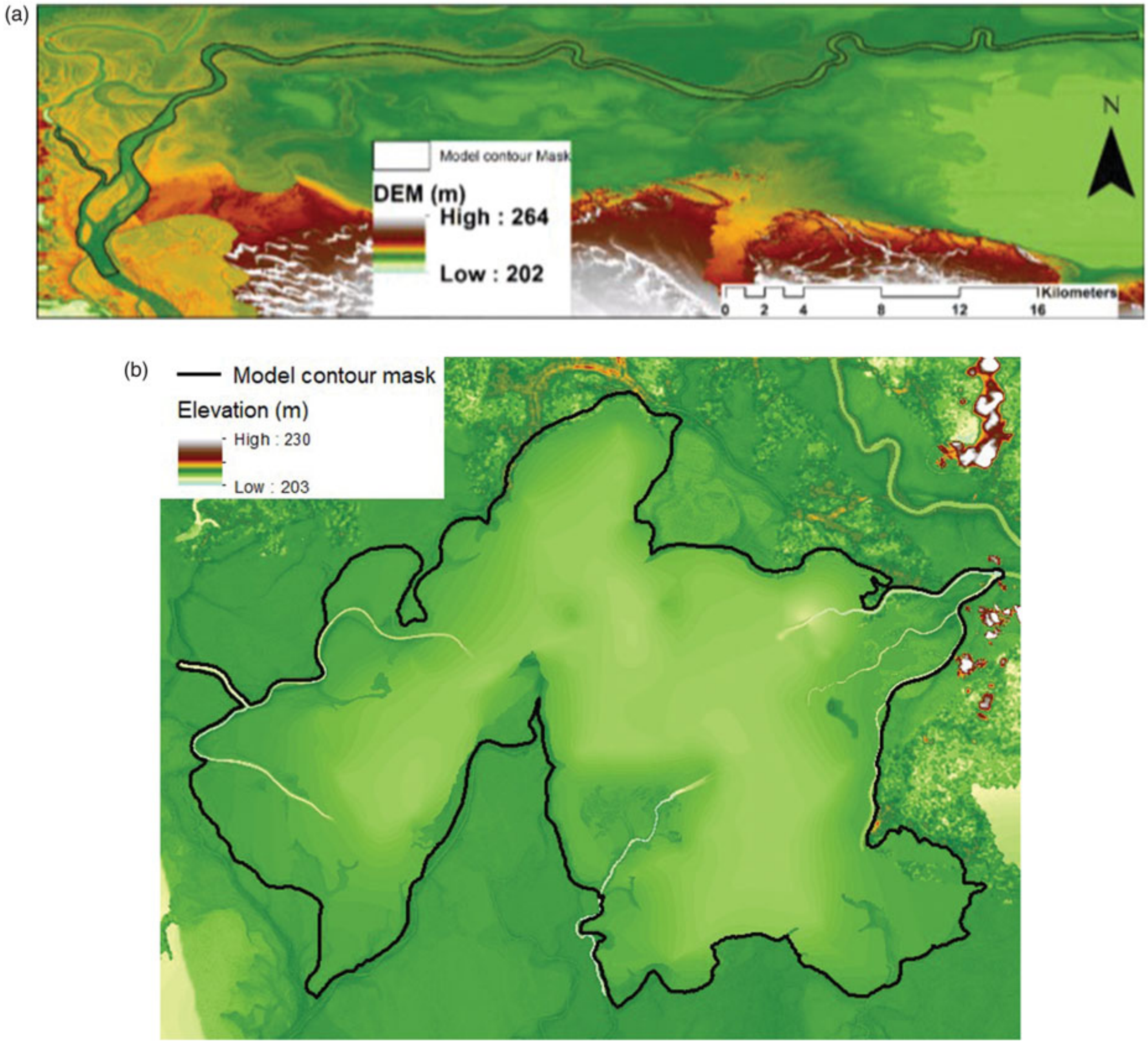

Figure 8. The topobathymetry of the (a) Embarras-Athabasca reach and (b) Mamawi Lake area, as well as a contour mask used to delimit the hydrodynamic model.

River reach, Mamawi Lake, and Lake Claire. The 2017 hydrometric field data campaign was performed to link up with the ABoVE Project AirSWOT flight over a large portion of the PAD (Figure 7). During the 2018 fieldwork, more hydrological and meteorological information along various channels of the PAD and over the large central lakes were collected to improve the preliminary 2-D models. In coordination with the SWOT-C TH team, the US SWOT team (academics/students from UCLA, UMass, the University of Colorado, and University of North Carolina (UNC)) conducted extensive and detailed hydrometric surveys and monitoring during late summer of 2018.

In order to perform the SWOT simulations, a number of datasets are required, such as a high-quality water-terrain DEM (Frasson et al. 2017). Equally, a water mask that distinguishes the water–land transition is needed. This mask can be determined by using height, radar, and/or optical information. Meteorological data such as wind information can also be incorporated in the SWOT simulations. In our case, a 2 m LiDAR-based DEM and a 2-D water elevation map, derived from the H2D2 simulations, were employed. For the 2-D modeling, bathymetric and topographic data were first assembled on a coherent triangular finite element mesh that was latter used in the hydraulic model. By solving the Saint-Venant equations, H2D2 estimates the 2-D flow velocities, discharge, and water levels. For the Embarras-Athabasca river section, the H2D2 model was set up to match the water-level and discharge measurements taken on July 5 of the 2016 field campaign. For the Mamawi Lake area, the measurements used were those taken on July 9 during the 2017 field campaign. Figures 8a and 8b show the water mask and topobathymetry model of the Embarras-Athabasca reach and

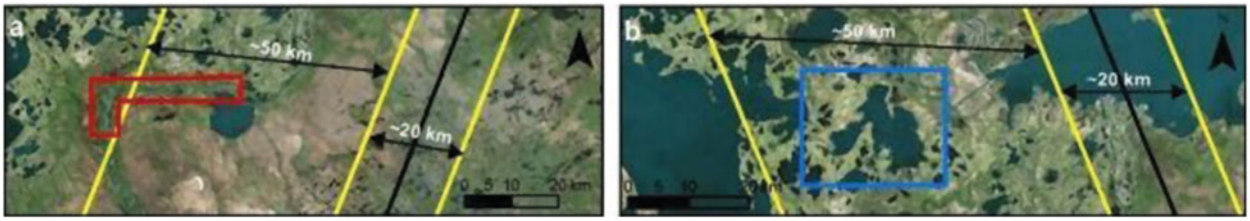

Figure 9. SWOT orbital pass over the 2 study areas (a) Athabasca Lake and (b) Mamawi Lake. The swaths sensed from the instrument (∼50 km), no-data nadir gap (∼20 km), and the nadir (black line) are highlighted.

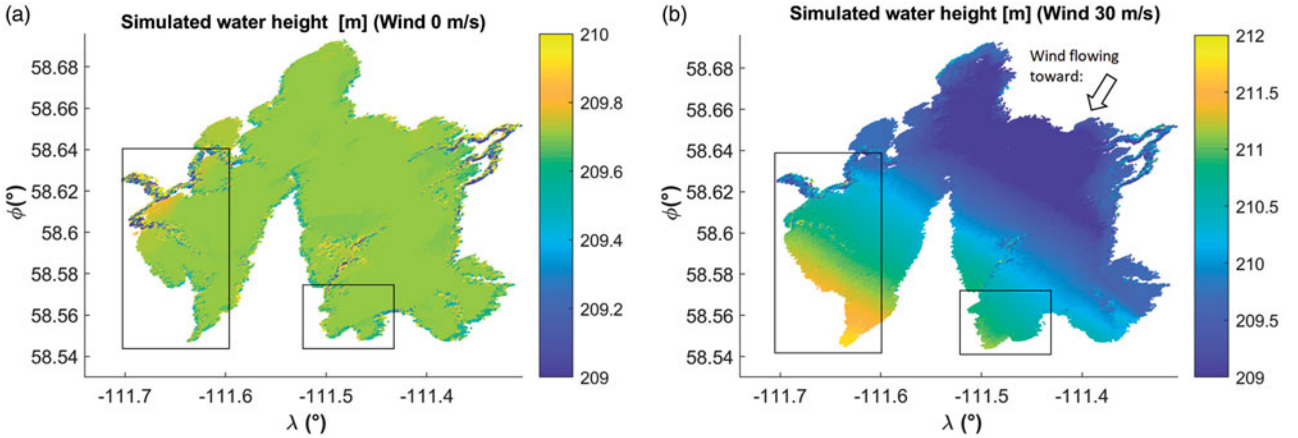

Figure 10. Simulated pixel cloud of the water heights of Mamawi Lake for 2 different conditions: (a) non-wind scenario; and (b) scenario with wind speed at 30 m/s and direction 240°. The black rectangles illustrate areas reflecting important changes of water elevation and extent.

Mamawi Lake area. The H2D2 simulations, assumed to represent the synthetic "true state" of the river and lake, were performed in stationary mode. Scenarios were simulated along the Embarras-Athabasca reach and the Mamawi Lake area. For the first case, high and low flow conditions are considered, whereas windy and non-windy scenarios are modeled for Mamawi Lake.

Figure 9 illustrates the SWOT orbit passes selected for this study over the regions of interest in the PAD. The nadir ground track and the internal and external edges at 10 km and 60 km, respectively, are identified. By using as input the derived products from the H2D2 simulations along the Embarras-Athabasca river sector and over Mamawi Lake, we mimic the SWOT imaging observations and evaluate its performance under different flow and wind conditions. Figures 10 and 11 illustrate the results from the SWOT simulations, that is, pixel clouds of surface water elevations and land cover classification, respectively, using as inputs the products generated by H2D2 for Mamawi lakes and Embarras-Athabasca reach, respectively.

As observed from Figure 10b, the water surface elevation generated by the SWOT hydrology simulator tends to increase notably towards the southwest (SW) part of the lake under the effect of strong winds blowing at 30 m/s toward that same direction. On the other hand, reduced water heights are noted at the northeast (NE) part of the lake, where the wind is coming from. The water extent is also modified by the imposed wind conditions; a larger flooded area is observed southwards when comparing Figures 10a and 10b.

Figure 11 shows an example of the classification from the SWOT hydrology simulator. This classification includes 4 groups: "Land", "Land near water", "Water near land," and "Interior water." Although these preliminary results show some of the promising capabilities of the SWOT mission, further investigation is required regarding the different types and sources of errors affecting the quality of the water heights estimation, their magnitude, and possible approaches to mitigate their influence.

Project 5 – Redberry Lake and ponds

The Redberry Lake Biosphere Reserve is one of the key Canadian SWOT Cal/Val sites located on the Prairies. This site is a UNESCO research and education facility, and importantly has long-term water-level data and bathymetry information. The lake is located in the North Saskatchewan River Basin, with

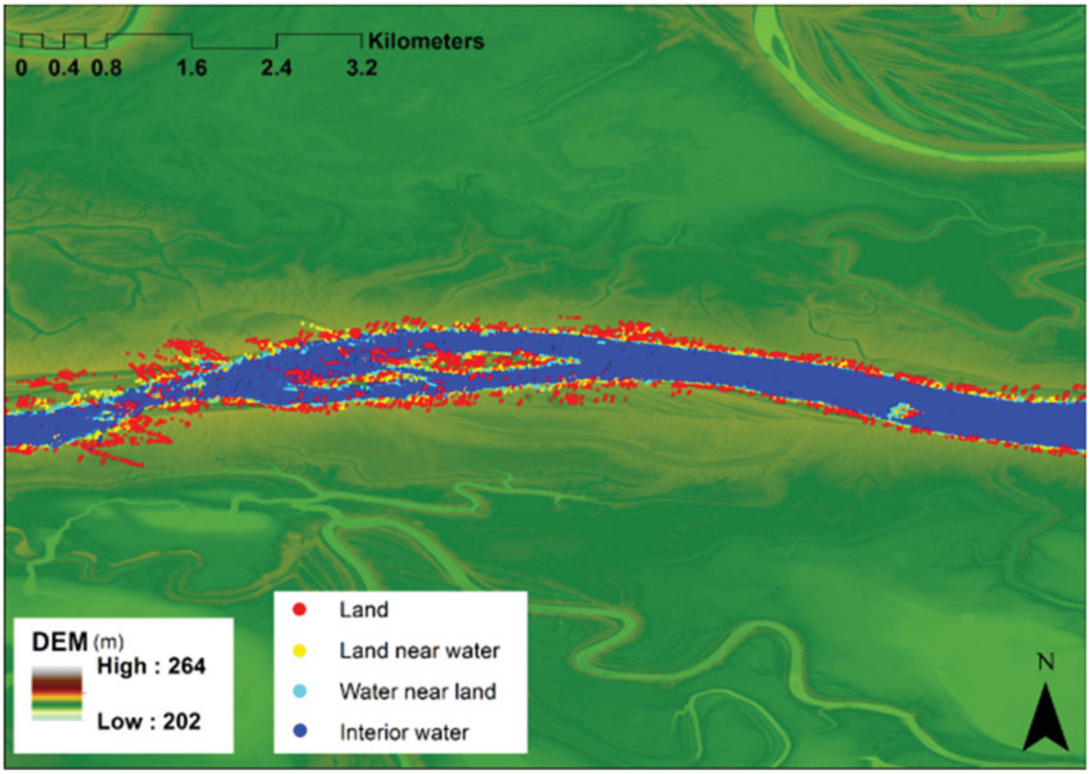

Figure 11. Simulated pixel cloud of the classification of portion of the Embarras-Athabasca reach for the conditions observed on July 5, 2016.

easy access all season from Saskatoon. This lake is under the SWOT 1-day repeat orbit (also close to the North Saskatchewan River SWOT site), and it was imaged by the 2017 AirSWOT flight lines campaign over the U.S. and Canada carried out through the NASA ABoVE program.

The main goals for the Redberry Lake project are to: (*i*) support SWOT lake calibration and validation activities in Canada; (*ii*) study lake water balance and climate change with national/international collaboration; (*iii*) link SWOT research with the Climate Adaptation Program of Environment and Climate Change Canada; and (*iv*) establish/enhance research collaborations with local organizations.

In summer 2017, the SWOT-C team worked closely with U.S. colleagues on lake hydrology observations, particularly during the July and August AirSWOT over-flights. Four water-level gauges were set up over the lake and 1 meteorological station was installed on the island (Figure 12). Water level was measured over the open-water season with the gauges and regular optical survey at the CGVD2013 benchmark sites. Figure 13a provides an example of the water elevation data over the summer of 2017. GPS surveys were also carried out around ponds near the Redberry Lake site to quantify the water level and lake extent, so as to link and compare with the AirSWOT data (Figure 13b). Similar work was also carried out at several ponds near the St Denis SK and Yellowknife NT area in summer of 2017. During the summer of 2018, GPS floats were also used to measure the water-level slope over Redberry Lake and compare with the gauge data. Efforts are underway to analyze the meteorological data conditions, water level and slope, and lake area GPS surveys. The unique data sources and new knowledge from this project/site will benefit and support the water resource community to understand better regional hydrological conditions and their changes due to climate and human factors.

Project 6 – North Saskatchewan River

ECCC established the North Saskatchewan as a Tier 1 SWOT Cal/Val site in the summer of 2016. Major positive features of this location are the ease of access, the relatively stable nature of the river, and the fact that there are no man-made controls (Figure 14). Characteristics of the site are as follows:

(*i*) Operational hydrometric gauges
(*ii*) Falls under the SWOT Cal/Val orbit and 2017 AirSWOT path

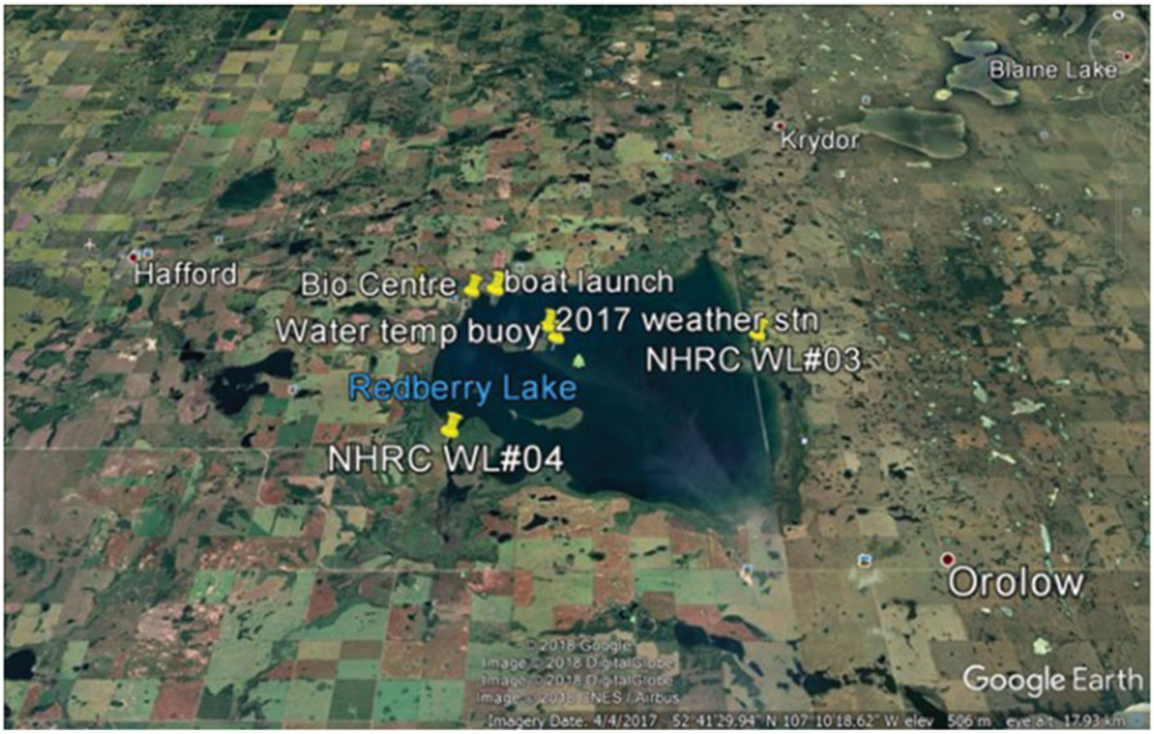

Figure 12. Redberry Lake and water-level gauge sites for the SWOT project.

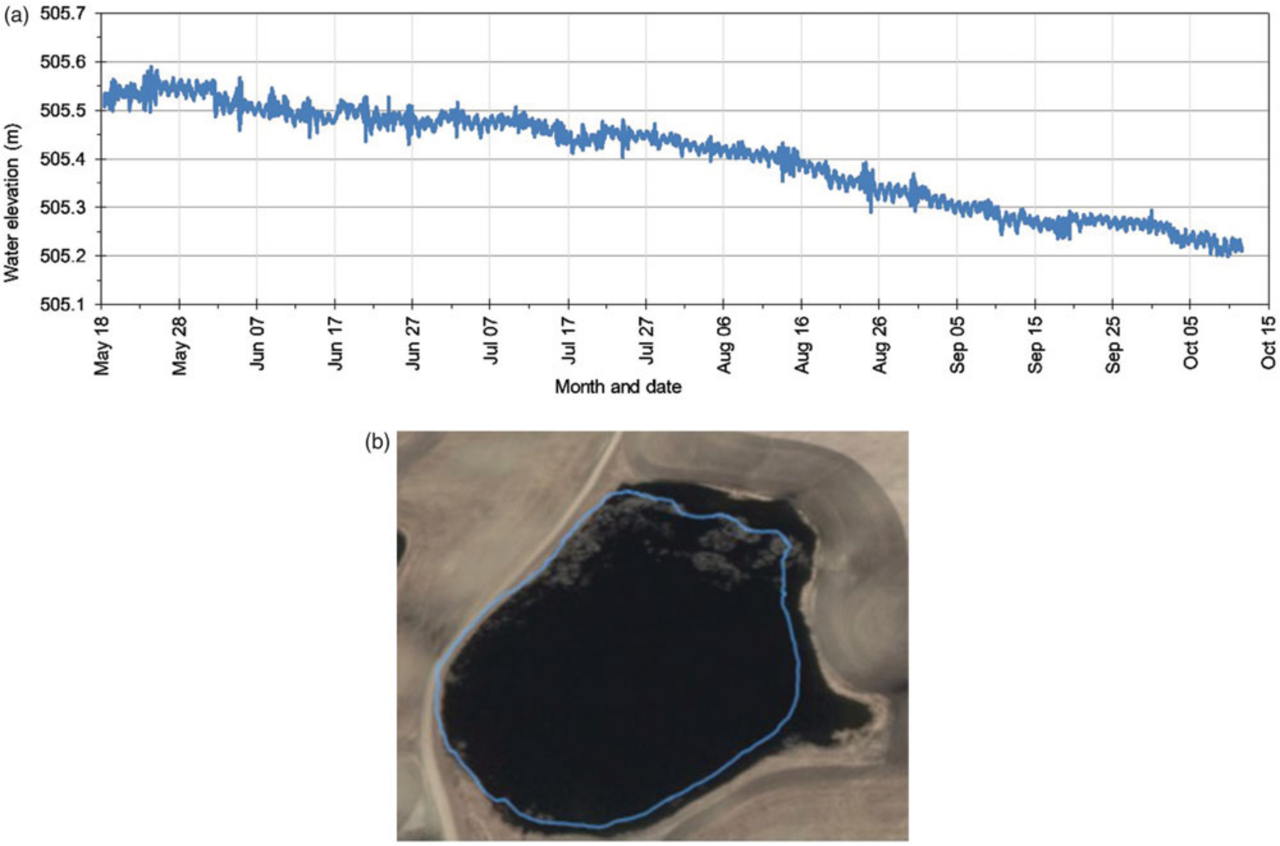

Figure 13. Redberry Lake water level data (a) and pond surface water extent GPS survey (b) in summer of 2017.

Figure 14. The Tier 1 North Saskatchewan River Cal/Val Site.

(*iii*) Total length: ~45 km but can be extended in either direction
(*iv*) Width varies between 200 m and 300 m
(*v*) Flow ranges from 200 m^3/s to 1200 m^3/s
(*vi*) No major tributary inflows
(*vii*) No controls
(*viii*) Slope is very low
(*ix*) Multiple boat launch sites with reasonable river access.

There are many science challenges associated with this river. As shown in Figure 15, there are many bifurcations (typically every 2 km–3 km) and flow may be ephemeral (can be dry or may disappear depending on water level). There is also the issue of very low slope that needs to be resolved in the ground-mapping aspects of this site for calibration purposes. Given that this river reach is representative of most mid-western rivers in North America, and perhaps similar hydrological regimes globally, a robust ground-mapping plan for this river was carried out.

A permanent WSC streamflow gauge near the Pretrofka bridge will be established in 2019 as the key discharge measurement site. In addition, 10 pressure transducers operated during ice-off period (season April–October) were installed in 2017 and will be put into operation in the spring of 2019. These stations will use GOES transmission for real-time water-level reporting. GPS surveys were carried out to reference all measurements to CGVD2013. The SWOT-C TH team, in collaboration with the U.S. SWOT team (academics/students from UCLA, UMass, the University of Colorado, and UNC), conducted detailed hydrometric surveys and monitoring during the 2017 AirSWOT July and August over-flights: bathymetric and cross-sectional data, augmented WSC hydrometric network with pressure sensors to measure water surface elevations, ADCP velocities, and GPS floating rafts surveys. Similar work was carried out during the summer of 2018. Overall, the challenging aspects of the North Saskatchewan River reach site make it ideal as a water-level and discharge algorithm Cal/Val site.

Summary and future plans

This paper has summarized existing plans, field sites, and potential for the SWOT mission as it relates to water resources issues and management in Canada. The SWOT-C TH team has been actively engaged in helping the mission in setting specifications, developing important calibration and validation locations along the SWOT mission calibration orbit and AirSWOT over-flights, and developing useful

Figure 15. Details of the complex bifurcation and split channels on the North Saskatchewan River.

applications that will have large potential benefits for Canada.

Along with national-scale water surface elevation monitoring of lakes and wetlands, a key long-term goal of SWOT-C is to estimate flows in the ungauged basins across Canada. The SWOT mission will directly measure some of the quantities required by slope-area scaling methods, including river width and along-channel slope. Recent advances suggest that it may be possible to estimate river discharge from just these SWOT observables, despite the fact that other components of discharge, including base flow depth and channel roughness, will not be directly measured (Durand et al. 2016; Gleason et al. 2017). (These discharge estimates will likely not achieve the accuracy of *in situ* measurements or rating curves, but they can be efficiently made across all ungauged Canadian basins with acceptable and well-characterized error.)

The SWOT-C TH team has made significant advances over recent years in planning, field data acquisition, modeling, and SWOT simulation. For instance, we planned our activities to ensure the data collections over the PAD were complete in anticipation of the AirSWOT over-flights and upcoming SWOT launch in 2021. We have also capitalized on existing established sites with operational models, such as the St Lawrence River. With work at the PAD, St Lawrence, and other Cal/Val sites progressing well, we are interested in expanding the geography of our SWOT-related work to other sites that have decent DEM and surface water monitoring. There are opportunities to expand SWOT-C TH research to the northern regions, such as the Mackenzie River and Delta.

Overall, with the collaboration of several internal government and academic partners, SWOT-C has established a strong and vibrant scientific team in Canada to finalize the Cal/Val specifications for the Canadian targets. We have gained expertise in SWOT simulation and applications in select regions of Canada. We have provided the SWOT international program with useful advice and critical information on Cal/Val specifications. Our goal is to continue to contribute in a substantial way to the discharge algorithm efforts and the overall SWOT mission, particularly the Cal/Val plans and research in the northern regions that are experiencing rapid change from climate and development. The potential for Canada with a platform such as SWOT is consequential and needs to be examined carefully. It is clear that although

SWOT will not replace *in situ* estimates of flow, it will, however, provide unique and important opportunities to estimate discharge in ungauged regions, it will allow for monitoring of water levels in wetlands, lakes, and reservoirs previously too expensive to carry out, and will likely lend itself well to hydraulic model application in large rivers, lakes, and floodplains, providing important information in assimilation cycles of these models.

Canada needs to be prepared to evaluate and understand the potential and possible difficulties with the SWOT system. Given the potential, it is prudent and wise for the Canadian hydrological and space community and its international partners to be engaged in both the design and implementation of this technology. To that end, we have successfully been engaged and feel we shall contribute significantly to the overall mission design and eventual success.

Acknowledgments

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