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Operational Monitoring of River Ice on the Churchill River, Labrador

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Satellite synthetic aperture radar (SAR) has been used to support river ice modeling and flood forecasting as part of an operational river ice service for the Churchill River since 2008. Satellite imagery collection started prior to the construction of the Muskrat Falls Hydroelectric dam to establish a baseline of ice conditions and continued throughout the construction and subsequent operations. SAR imagery acquired using a wide range of incidence angles are used in concert with optical satellite images, webcams, local knowledge, weather forecasts and in-situ observations. SAR image analysis results in three products; ice cover, ice classification, and ice cover changes. The SAR classifications are frequently assessed by a local River Watch Committee who provide qualitative feedback on the classification accuracy. In 2017, triggered by a need to provide ice thickness measurements, a helicopter-borne ground penetrating radar (GPR) system was developed to determine a transect of ice thickness along the river. Beginning in 2019, four Sea Ice Mass Balance Array (SIMBA) buoys were adapted for deployment on the river. The SIMBA buoys measure and transmit, via Iridium, an ice temperature profile from which ice thickness can be derived. The buoys are deployed at four key locations on the river once the ice is thick enough to safely support installation. Manual ice thickness measurements are acquired opportunistically to validate the ice thickness measurements. The data collected are of critical importance for the Water Resources Management Division

(WRMD) of the Government of Newfoundland and Labrador, and are used as inputs for river ice flood forecast models. The diverse temporal and spatial scales of data collection afforded by satellite SAR, airborne GPR and in-situ SIMBAs allow cost-effective surveillance of the river while minimizing risk to personnel. The data products are delivered through IceSight, C-CORE's web-based platform, which offers additional analytics and facilitates inter- and intra-annual comparisons.

1. Introduction

Many northern rivers developing ice cover during the winter season are prone to ice-related flooding. In order to assess flood risk and mitigate its impact, it is imperative to monitor the ice conditions throughout the ice season, with particular emphasis on the freeze-up and ice break-up periods. Synthetic Aperture Radar (SAR) satellite imagery, augmented by visual satellite imagery, has been used to provide satellite monitoring of river ice on the Lower Churchill River in Labrador, Canada since 2008. The service was launched prior to the construction of the Muskrat Falls Hydroelectric dam to establish a baseline of ice conditions and continued throughout the construction and subsequent operations. Figure 1 shows the areas that are monitored. Mud Lake and the channel connecting it to the river are included for surveillance. The regular monitoring efforts also include a section of the Goose River as an early indicator of breakup on the Lower Churchill River. Freeze-up usually occurs between November and December, and break-up between April and May.

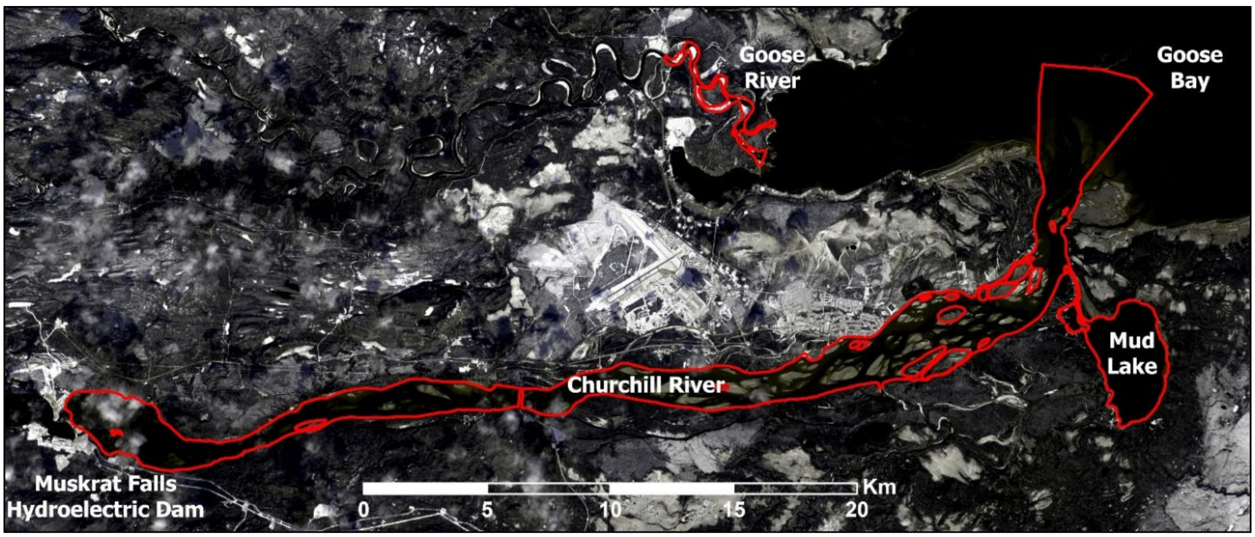


Figure 1. Areas being monitored for river ice operations. The background image was acquired by Sentinel-2 on October 30, 2020[1].

On May 17, 2017, an ice jam flood occurred at the river's outlet into Goose Bay requiring evacuation of the community of Mud Lake. An Independent Expert Technical Advisor (IETA) report (Lindenschmidt, 2017a) determined that the cumulative impact of a number of factors resulted in unusually high river flow conditions. The key recommendations from the IETA were an increase in real-time environmental monitoring and the implementation of a Flood Management Plan that included Flood Forecasting and Flood Risk Mapping. This led to the development and operationalisation of the Churchill River Flood Forecasting System maintained by the Water Resources Management Division, Government of Newfoundland and Labrador.

Ice thickness was identified as one of the key parameters that should be monitored. During the winter of 2017/18, as a means to obtain ice thickness measurements, Ground Penetrating Radar was mounted onto a helicopter for undertaking airborne surveys along the river. In 2019, to

[1] Sentinel-2 European Space Agency (ESA) (2020)

augment the helicopter surveys, four sea-ice mass balance array (SIMBA) units were adapted to be deployed at four locations along the river over the ice season. Satellite image products, ice thickness measurements and a river ice model combine to monitor the ice conditions. The ice products are made publically available through a web-browser based application called IceSight.

2. Satellite Monitoring

2.1 Ice Conditions

Radar satellites are active sensors that transmit a signal to the Earth's surface and record the energy reflected back (backscatter) to the sensor. Pixel intensity within the image is proportional to the level of backscatter. Since the sensor is side-looking, most of the signal will be deflected away from the sensor on smooth surfaces such as smooth ice. Rough surfaces such as those found with an ice jam will deflect the signal in all directions including back to the sensor, producing the bright areas seen in images. Generally, surfaces with roughness on the order of the radar wavelength and lower have low backscatter. Surfaces with complex geometry or corner reflectors have high backscatter (e.g., Unterschultz et al., 2009). Early in the ice season, there is greater backscatter due to the low water content within the snow and ice layers on the river (van der Sanden et al., 2021). However, snowfall can add weight to the ice cover, which, if the ice is thin enough and there is enough snow, can create cracks in the ice through which water can penetrate onto the ice. Water can also encroach along the edge of the ice at the riverbank to flood the ice surface. The surface water can create a slush layer that can then refreeze (Cheng et al., 2014), with the added water reducing backscatter.

In 2008, the Government of Newfoundland and Labrador commissioned a satellite-based service for the Lower Churchill River to monitor ice conditions between Muskrat Falls and Goose Bay. During freeze-up and break-up, images are usually processed daily. During the remainder of the season, the monitoring frequency is approximately twice per week. The primary data sources include the RADARSAT Constellation Mission (RCM) and Sentinel-1 (S1) SAR imagery. RCM data are accessed via the Earth Observation Data Management System (EODMS), while S1 imagery is accessed via the European Space Agency's Sentinel Hub. Imaging modes used include S1 Interferometric Wide Swath (IW) and RCM 16M, 30M and 50M. Several information products are generated from SAR, including ice cover, ice classification and ice cover change. Cloud-free, optical imagery from Landsat-8 (L8) and Sentinel-2 (S2) are used to aid in the interpretation of ice conditions.

The ice cover product is derived from SAR imagery that has been terrain corrected, calibrated, filtered, visually enhanced and annotated. The ice classification product classifies the ice cover into ice types. An unsupervised classifier is used along with a mask (to isolate the classification to the river only). The output from the unsupervised classifier contains 30 classes that are manually aggregated by an image analyst. There are three ice classes during freeze-up and mid-winter monitoring: open water, non-consolidated ice, and consolidated ice. For break-up, the three classes are augmented by a fourth class, water on ice.

The change detection product highlights the difference between two ice classification products and are used to illustrate how the ice cover is developing or deteriorating. It is generated by subtracting the most recent ice classification from the previous ice classification. The resultant differences are binned into one of five categories: two categories of more ice, a category of no change and two categories of less ice. More ice represent a change from open water to consolidated ice and less ice represents a change from consolidated ice to open water. The two classes or more ice and for less ice are used to represent subtle and more extensive changes. A similar approach is adopted to create annual change products by subtracting the ice classification products that are approximately one year apart.

Examples of satellite-derived ice information products for the Lower Churchill River are presented in Figure 2, Figure 3 and Figure 4.

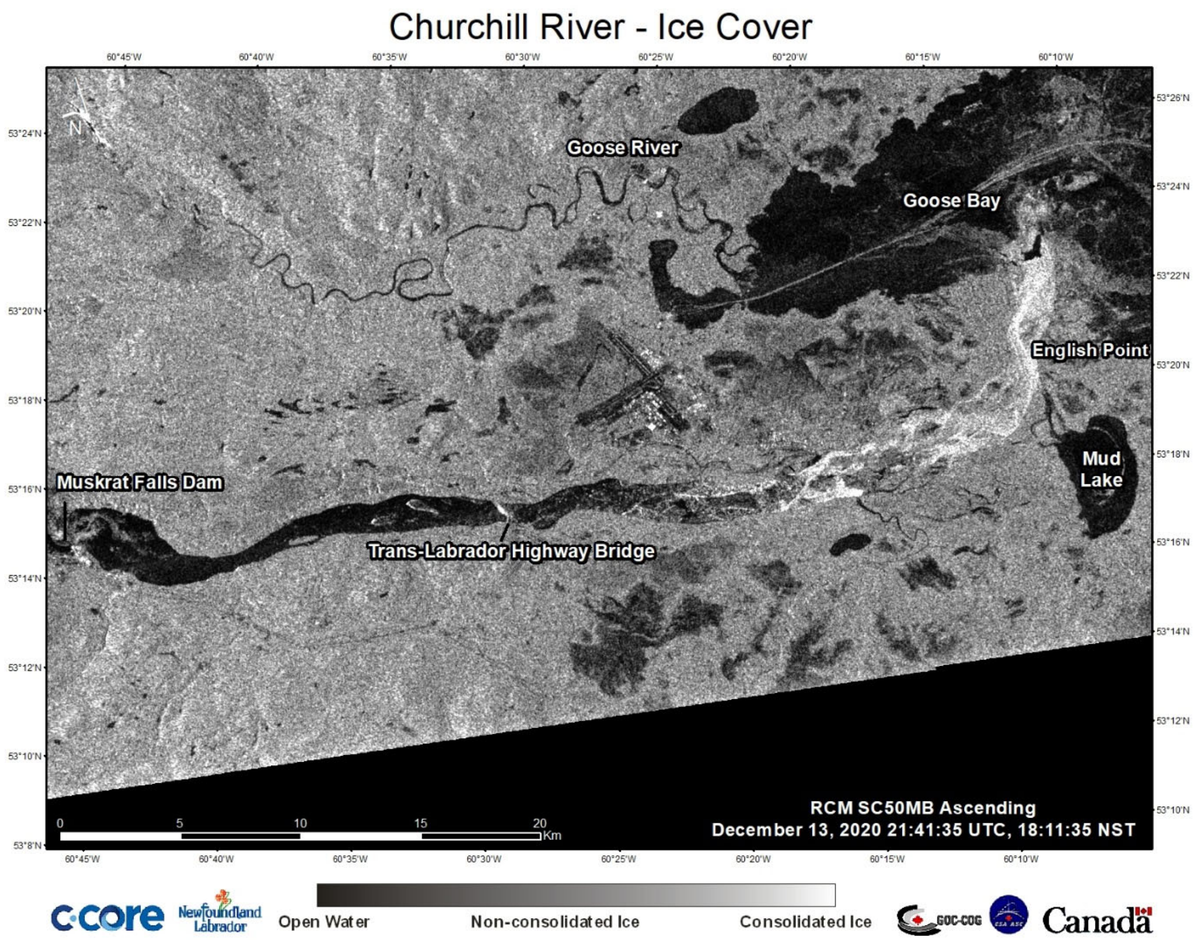


Figure 2. An ice cover product derived from a satellite SAR image[2].

[2] RADARSAT Constellation Mission Imagery © Government of Canada 2020 RADARSAT is an official mark of the Canadian Space Agency

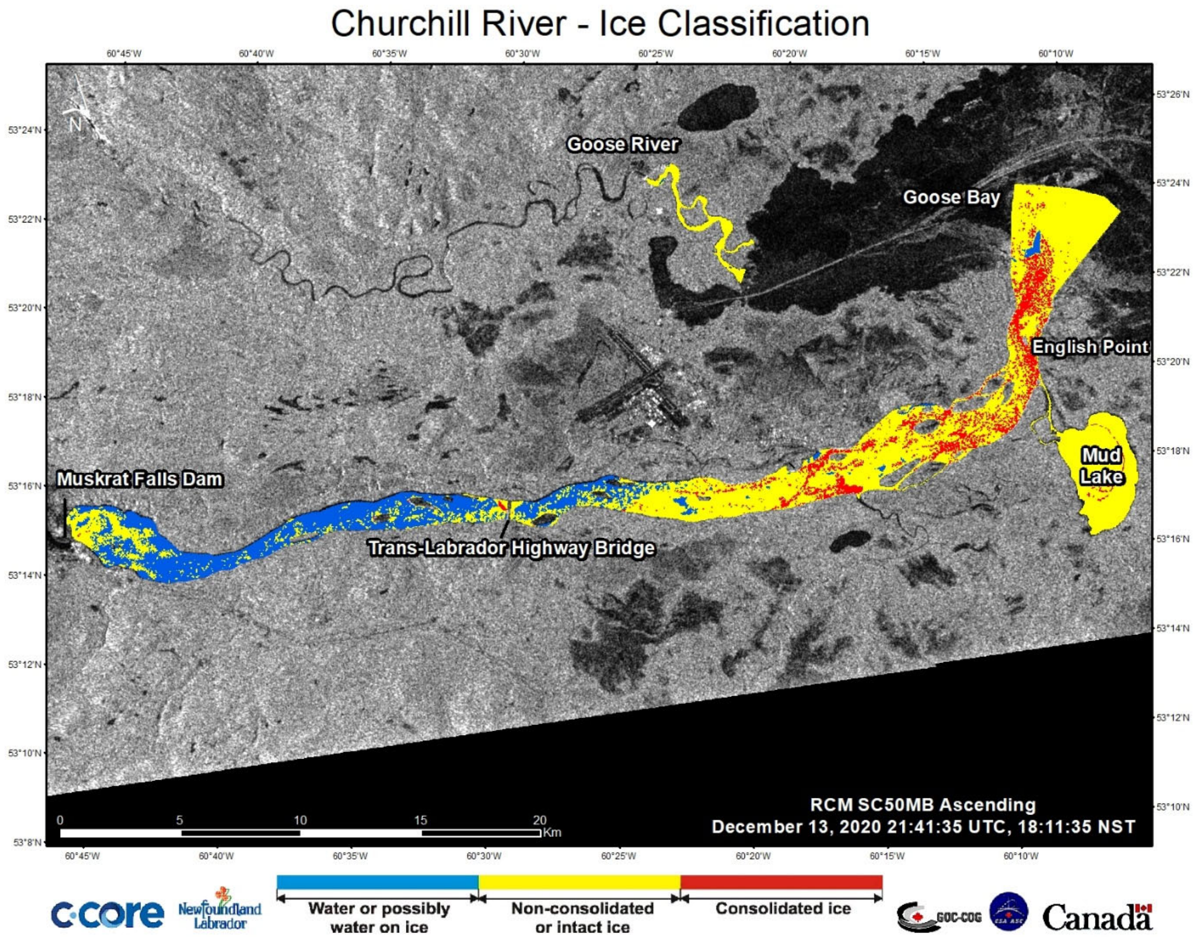


Figure 3. An ice classification product derived from a satellite SAR image[3].

[3] RADARSAT Constellation Mission Imagery © Government of Canada 2020 RADARSAT is an official mark of the Canadian Space Agency

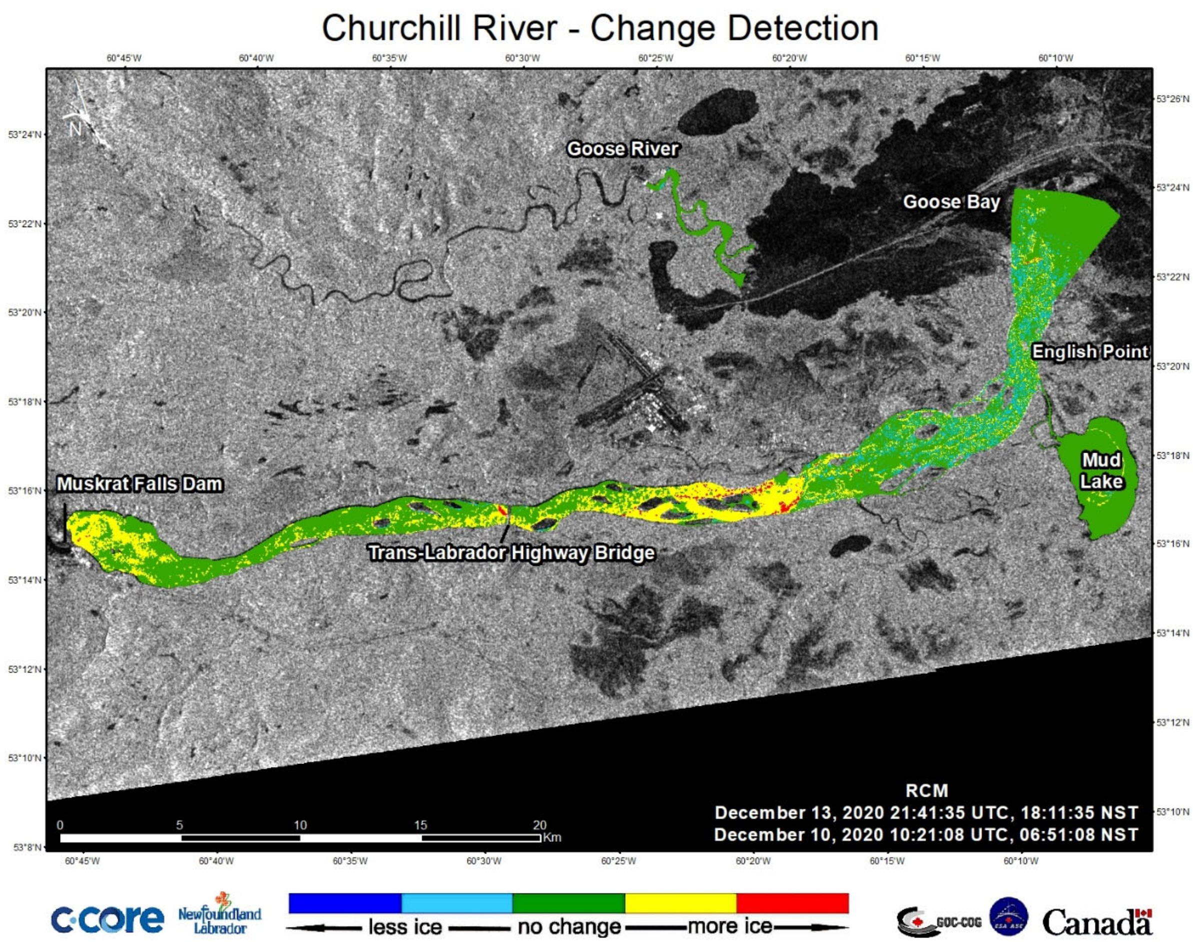


Figure 4. An ice cover change detection product resulting from the comparison of two ice cover classifications[4].

All ice information products are reviewed by experienced ice analysts to ensure quality and consistency. The products are made available as annotated maps, Google Earth KML files and through a publicly accessible web app (see Section 4)[5]. The SAR classifications are frequently assessed by a local River Watch Committee who provide qualitative feedback on the classification accuracy.

2.2 Sandbars

Sandbar analysis is a key component to support river ice monitoring on the Lower Churchill River. Optical satellite images are analyzed every year just before the ice season as part of an ongoing effort to assess the effects of changing sandbars on the river ice cover. The ice cover can grow thick enough to reach submerged sandbars and create the potential for ice jamming (Lindenschmidt, 2017b). Knowing the locations of shallow sandbars can help in the assessment of

[4] RADARSAT Constellation Mission Imagery © Government of Canada 2020 RADARSAT is an official mark of the Canadian Space Agency

[5] www.churchillriver.app

potential ice jam hazards. The last cloud-free S2 or L8 image available prior to ice formation on the river is chosen for the sandbar analysis (see Figure 5). The number of sandbars, shape, and size evolve due to the water flow, erosion and sediment deposition. The results of the sandbar analysis help with updating the river mask used for satellite-based river ice monitoring during the upcoming season.

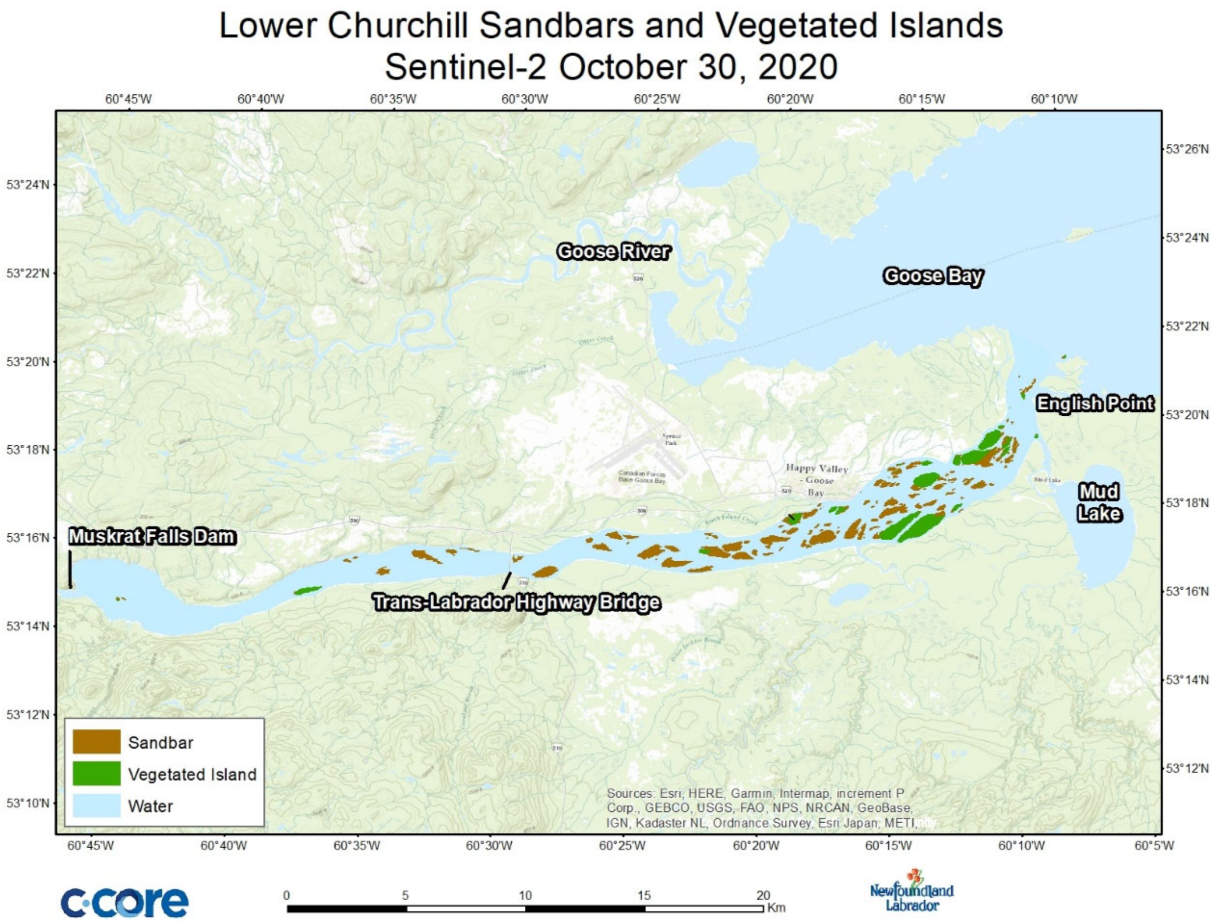


Figure 5. Sandbars detected from a S2 image.

3. Ice Thickness Monitoring

Ice thickness is a critical input into the Churchill River Flood Forecasting System. Ice thickness is determined using three methods, from manual measurements of boreholes drilled into the ice, from a helicopter mounted GPR and from SIMBA units that have been adapted for river ice. Each of the techniques have benefits and deficiencies that are described briefly below and then summarised in Table 1. Manual measurements of the snow depth and ice thickness are made using a Kovacs ice auger to bore a hole through the ice and a measuring tape. Borehole measurements take place during the deployment of the SIMBA units and opportunistically with the GPR surveys. The manual measurements are used for validation of the ice thickness derived from the SIMBA units and GPR. The locations (Figure 6) were determined by the developers of the Churchill River Flood Forecasting System (discussed in Section 5) based on an assessment of the typical winter flows, high and low flows, and bathymetry. The helicopter mounted GPR surveys are conducted once per winter from one end of the monitored portion of the river to the other avoiding islands, shallow water (sandbars), and intercepting each of the four SIMBA installations to enable data inter-comparison.

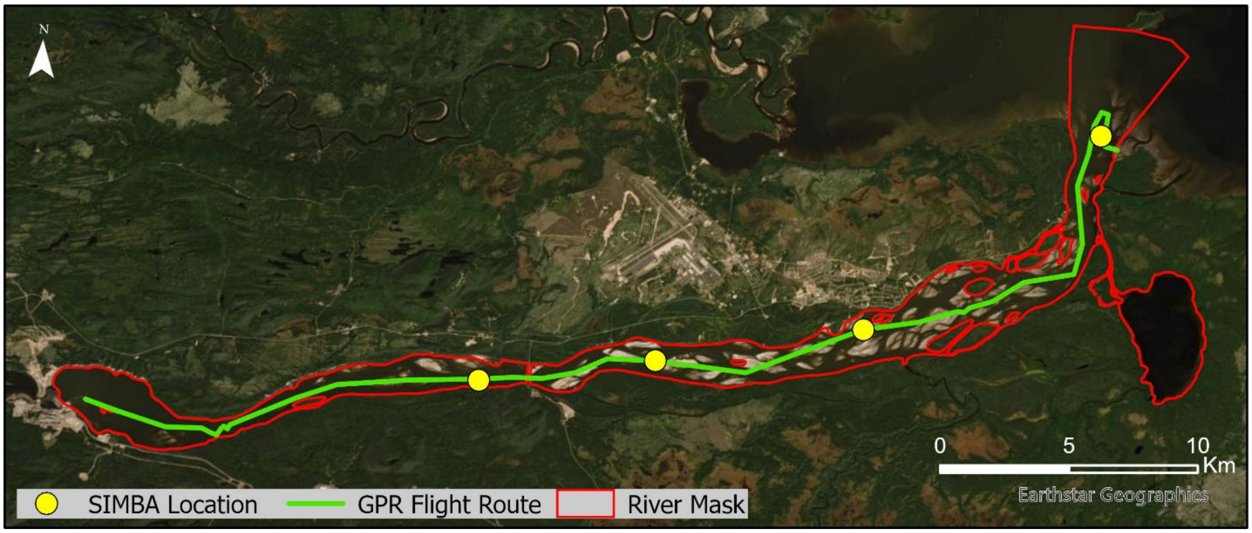


Figure 6. SIMBA installation locations. The background image was acquired by Sentinel-2 on October 30, 2020[6].

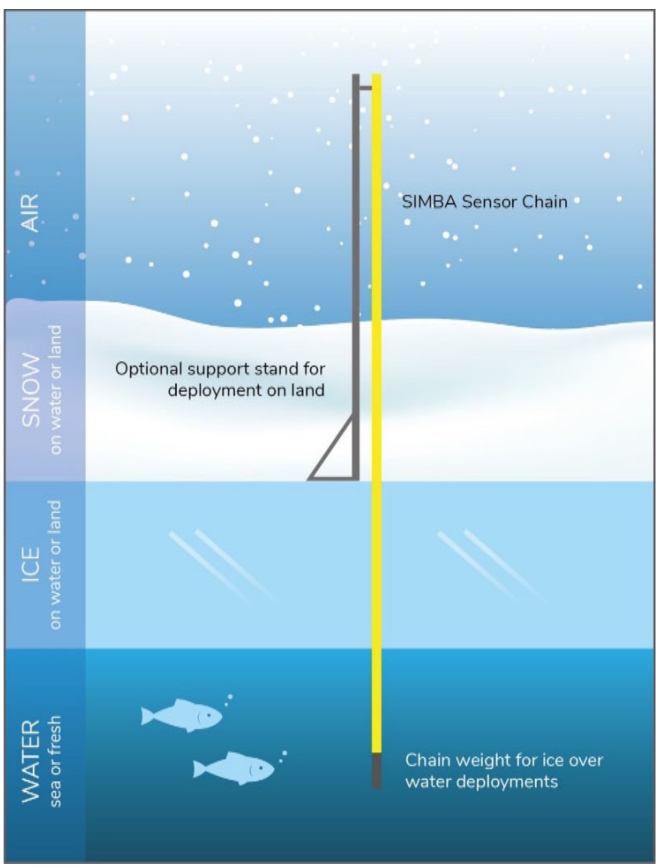
3.1 SIMBA Units

The SIMBA units, manufactured by SAMS Enterprise, are designed for long-term (seasonal to annual) deployment on sea ice. They were adapted for river ice deployment for this program. The units consist of a chain of thermistors mounted every two-centimeters along a cable, the cable is connected to a waterproof box containing a battery, data-logger, GPS unit, and an Iridium satellite communication module. The thermistor chains are installed vertically in a borehole (that has to be drilled into the ice) and record a temperature versus depth profile.

A typical SIMBA setup on the ice is show in Figure 7. The yellow case contains the electronics. It is mounted on a raised platform and secured using ratchet straps. It is raised to prevent it from being buried in excessive snowfall (in theory the unit can still transmit if snow covered up to about 60 cm), and to prevent damage in the case of flooding and freezing. The platforms are constructed from wood and protected with boat fenders in order to provide flotation and to help protect the SIMBA electronics from ice in case the equipment cannot be retrieved before break-up. The platforms are secured to the ice using ice screws and rope to prevent the platform from tipping over due to strong winds. The white vertical pipe acts as a support pole for the thermistor chain and has an air temperature sensor mounted within. The chain is inserted into a hole drilled in the ice cover with a weight attached to the end making sure the chain stays taut for more accurate thickness measuring as the ice cover thickens. The thermistor chains are five meters long containing thermistors at two cm intervals totaling 240 thermistors per chain. A conceptual schematic illustrating the thermistor chain installation through the air-snow-ice-water system is presented in Figure 8 (left).

[6] Sentinel-2 European Space Agency (ESA) (2020)

Figure 7. A complete SIMBA installation.



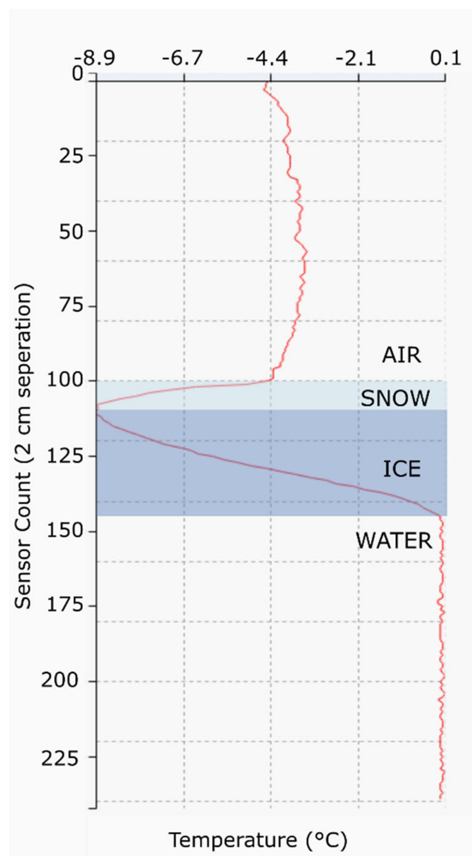


Figure 8. SIMBA thermistor chain schematic (SAMS Enterprise) (left); thermistor temperature profile from a SIMBA installations (right).

Figure 8 (right) presents the temperature recorded at each thermistor sensor along the length of the chain. The SIMBA units frequently record (typically set at every six hours) temperature profile measurements – from which ice thickness can be determined – throughout most of the ice season at single-point locations along the river. The vertical axis is the sensor count. The horizontal axis is the temperature in degrees Celsius. Thermistor 0 represents the thermistor positioned closest to the SIMBA unit where it is connected to the electronics. Thermistor 239 is the last sensor in the chain hanging in the water. Thermistor 110 was recorded as being at the top of the ice upon installation of the buoy (although ice can accrete and melt from the surface meaning the sensor at the top of the ice might change over time). The air temperature is just less than -4.4 °C. The water is at freezing point. Inflections in the slope on the temperature profile are indicators of interfaces. The temperature decreases from the top of the snow pack until the signal is inflected at the top of the ice. The top of the snow is located at thermistor 100, and the bottom of the snow/top of the ice at position 110; the sensors are spaced 2cm apart, therefore the snow depth is approximately 20 cm. The bottom of the ice is at approximately position 145, 35 thermistors below sensor 110; the thickness of the ice is therefore estimated to be about 70 cm.

The heat map in Figure 9 shows the temperature depth profile for each data set collected (one data set every 6 hours). Thermistors 1 to 110 are located between the SIMBA electronics case and the ice surface. These thermistors were measuring the air and near-surface snow temperature and are heavily affected by sun radiation. Thermistors 110 is the top of the ice cover, the remaining thermistors (110 to 239) are embedded onto the ice then the water. The red arrow points to the bottom of the ice layer. The ice can be seen to be migrating downwards over time, indicating the ice is thickening.

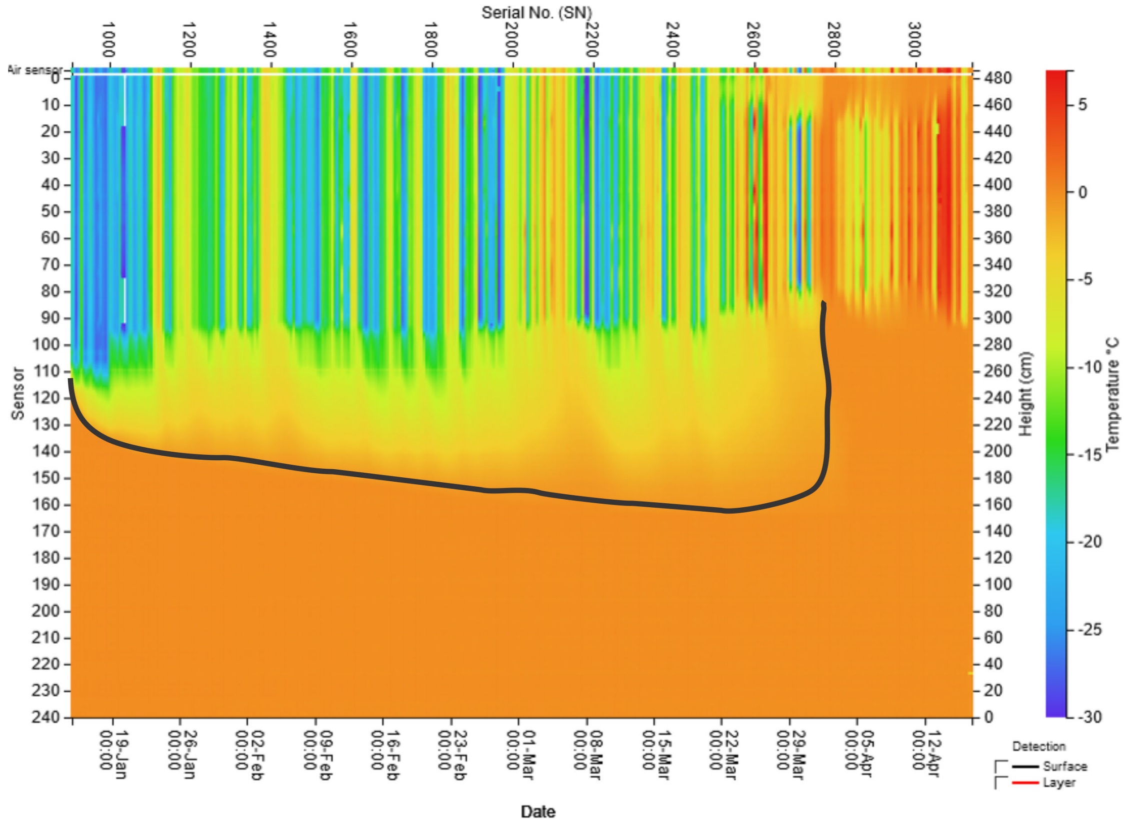


Figure 9. Temperature heat map from one of the SIMBA installations with red arrow indicating the bottom of the ice layer.

In total, four SIMBA units are deployed along the Churchill River, as previously shown in Figure 6. Installation typically occurs in January once the ice cover is safe to work on. This is determined through local knowledge and the results from the ice cover and ice classification products. The SIMBAs are programmed to measure and transmit (via Iridium satellite communication) temperature data, GPS position, system and battery health every six hours. The frequency of measurement is programmable. The temperature profiles (Figure 8) and heat maps (Figure 9) are displayed in a secure web application from which the ice thickness is determined at each site.

3.2 Ground-Penetrating Radar (GPR)

GPR is a geophysical remote sensing technique that uses high frequency electromagnetic waves to penetrate the shallow subsurface (meters through to 10's of meters). The transmitter emits a pulse of high-frequency electromagnetic waves into the ground or ice below the GPR. As the wave propagates through a medium, it is distorted due to the electromagnetic properties of the material through which it passes. At the interface between different materials, where the electromagnetic properties change abruptly, the signals may undergo transmission, reflection and/or refraction. A receiving sensor records the reflected waves. The GPR system then processes the transmitted and received signal and computes the amplitudes and travel times (e.g., Jol, 2008).

The integrated signals are represented using a radargram as shown in Figure 10. The greyness represents the amplitude of the signal with higher amplitudes represented by darker grey and black areas. The horizontal x-axis represents the distance along track. The vertical y-axis can represent either (i) the two-way travel (the time to and from the transmitter to the reflector back to the receiver); or, (ii) if the radio wave velocity in the medium being studied is known, by the depth (or thickness) of the material. For determining ice thickness, the speed of electromagnetic waves in ice is typically set as a constant of 0.16 m/ns (e.g., Davis & Annan, 1989; Sensors & Software, 2021). By identifying the top and the bottom of the ice, the ice thickness can be computed. For river ice, up to four interfaces can potentially be seen: top of snow, top of ice, top of water and, depending on water-depth, the surface of the river bed. The strongest reflection is usually from the ice/water interface.

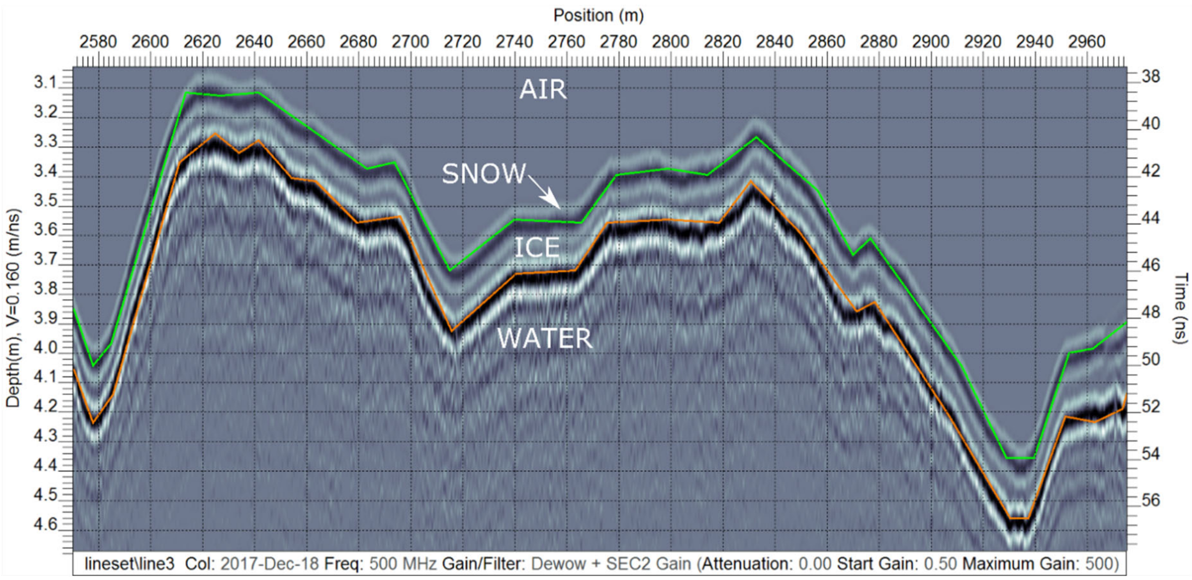
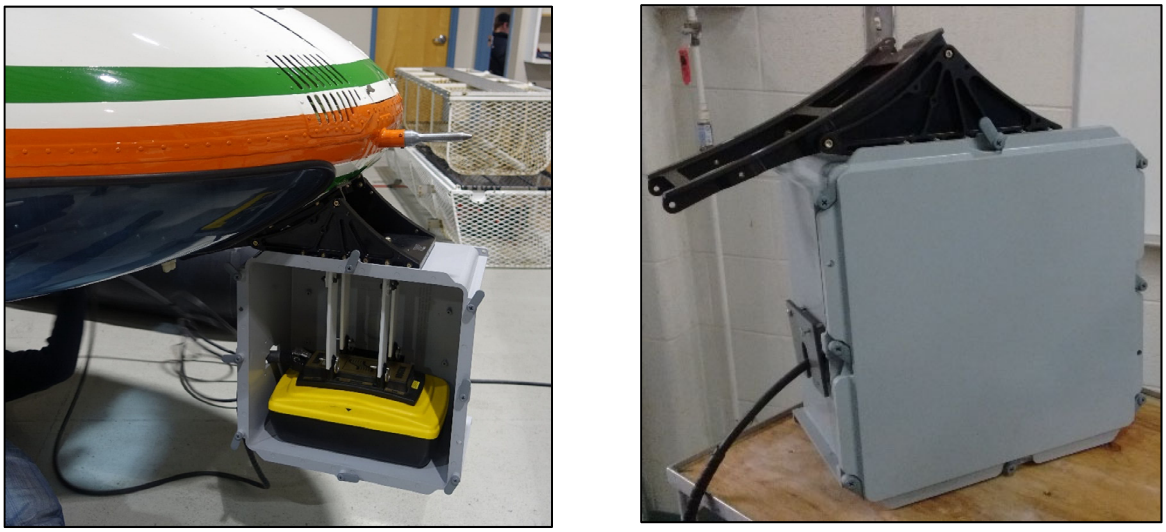


Figure 10. Radargram of a section of the Lower Churchill River.

For the river ice helicopter GPR survey, a Sensors and Software Noggin 500 MHz GPR system was adapted. It is configurable, allowing it to be used for a variety of different applications and operating conditions (e.g., searching for deeper targets vs. shallower targets, required sampling frequency and accuracy). A critical step in using a GPR system is to determine the optimal configuration for the survey being undertaken. For the helicopter-borne river ice survey, the optimal configuration maximizes the resolution at which the data can be collected while ensuring that the helicopter can fly at a speed that allows the proposed survey route to be covered within the available flight time and at an altitude and speed that is safe to operate. A number of short test flights were undertaken to determine these parameters, along with input from the GPR manufacturers, with the results being verified with manual ice thickness measurements (Briggs, 2018b).

To undertake the river ice survey, the GPR must be flown as close to the surface of the ice as possible. A target altitude of 10 m or less is ideal, however, this altitude is usually adjusted to accommodate for flying conditions. Operations over a river, frozen or otherwise, require the helicopter to be outfitted with floats so that, in the event of an emergency, it can land on water. A Bell 206L helicopter with floats, operated by Universal Helicopters, was used for the survey. To mount the GPR to the helicopter, it is first secured in a weatherproof enclosure that is attached to the helicopter using an Airfilm G1 nose-mounted utility bracket used for aerial videography. The G1 mount is a certified mounting system for the Bell 206L. Figure 11a shows the GPR installed on the helicopter. Figure 11b shows the GPR hardware within the enclosure prior to mounting to the helicopter. The data logger that controls the GPR is operated from inside the helicopter.

The GPR aerial surveys are conducted along the approximate midline of the Churchill River intersecting SIMBA locations and avoiding islands and shallow sand bars. The survey route is approximately 45 km long and takes about 2 hours.



(a) (b)

Figure 11. Photographs of the GPR hardware: (a) mounted inside the enclosure (grey box) attached, using the G1 mount (black angled bracket), to the nose cowling of the helicopter; (b) enclosure, dismounted from the helicopter, with the side panel secured.

3.3 Summary of Ice Thickness Measurement Techniques

A summary of the key characteristics of the three measurements is presented in Table 1.

Table 1. Key characteristics of the ice-thickness measurements.

Method	Frequency of Measurement	Spatial Resolution	Accuracy
Manual	Frequency dependant on personal being deployed onto on the ice. Manual measurements are acquired when SIMBA units are installed, retrieved, and opportunistically during a GPR flight.	Point source Measurement.	A strong ice/water boundary yields better than ±1 cm. The accuracy degrades if the ice base is slushy.
GPR	Frequency dependant on a GPR helicopter deployment. Usually once per year, in March.	Data acquired along the helicopter flight track. Approximately 45 km track length taking 2 hrs.	Data quality is good when ice temperature is cold (approximately ± 6.2 cm (Briggs, 2018a)). As ice warms, or water becomes present on the ice, the accuracy deteriorates.
SIMBA	Every 6 hrs but can be programmed to be more frequent (consumes more battery and increases data transmission costs) or less frequent.	Point source Measurement.	Sensor (thermistor) spacing is 2 cm. Interfaces between mediums (e.g., ice and water) can usually be located to align within ± one sensor allowing accuracies of about ± 2 cm.

4. IceSight

River ice service products are delivered using IceSight, which is a browser based application that does not require the installation of additional software, and can be accessed on any device (smart phone, tablet, or computer) using any operating system (see Figure 12). It is a secure service delivery platform that ingests data, analyzes images, reports geospatial information and archives products. This is accomplished by maintaining an internal spatial database of information products, together with a set of analytics tools to derive data-driven insights. The Web-accessible platform serves its geospatial data via Open Geospatial Consortium's (OGC)'s Web Map Service (WMS) and Web Feature Service (WFS) protocols to an interactive online map. Ice classification and change detection with corresponding bar graphs show areas for each class. IceSight provides access to ice information and allow user-driven analytics to be applied to spatial and temporal distributions of ice thickness data. The additional seasonal analytics provided through this platform, such as the percentages of ice categories has the potential for additional analyses to be performed on a time series of satellite-derived ice classification products.

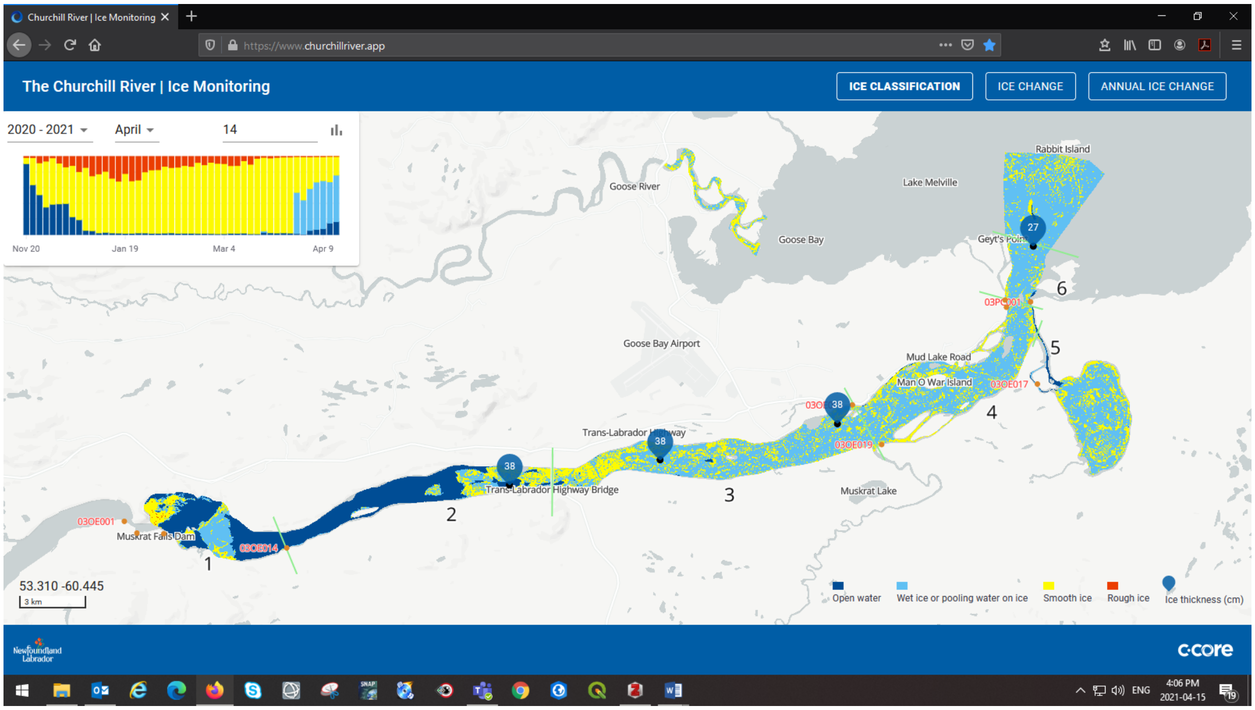


Figure 12. The IceSight app (www.churchillriver.app) can be accessed on computers and laptops with any web browser.

5. Lower Churchill River Flood Forecasting System

Following the May 2017 flood the Lower Churchill River Flood Forecasting System (CRFFS) was developed by Engineering Consultants KGS Group and 4DM Inc. The CRFFS (see Figure 13) was deployed in May, 2019, and is used operationally by WRMD to provide daily alerts. The CRFFS is an automated flood forecasting model that simulates flows and water levels in the Lower Churchill River between the Muskrat Falls Dam and Lake Melville. It operates throughout the year. The forecast cycle proceeds through the following four modes: Open Water, Ice Freeze-up, Winter Stable Ice and Ice Break-up. It runs once a day and forecasts 72 hour water levels for the Churchill River from Muskrat Falls to English Point for either of the river conditions – open water, ice generation, ice break up, or ice jams.

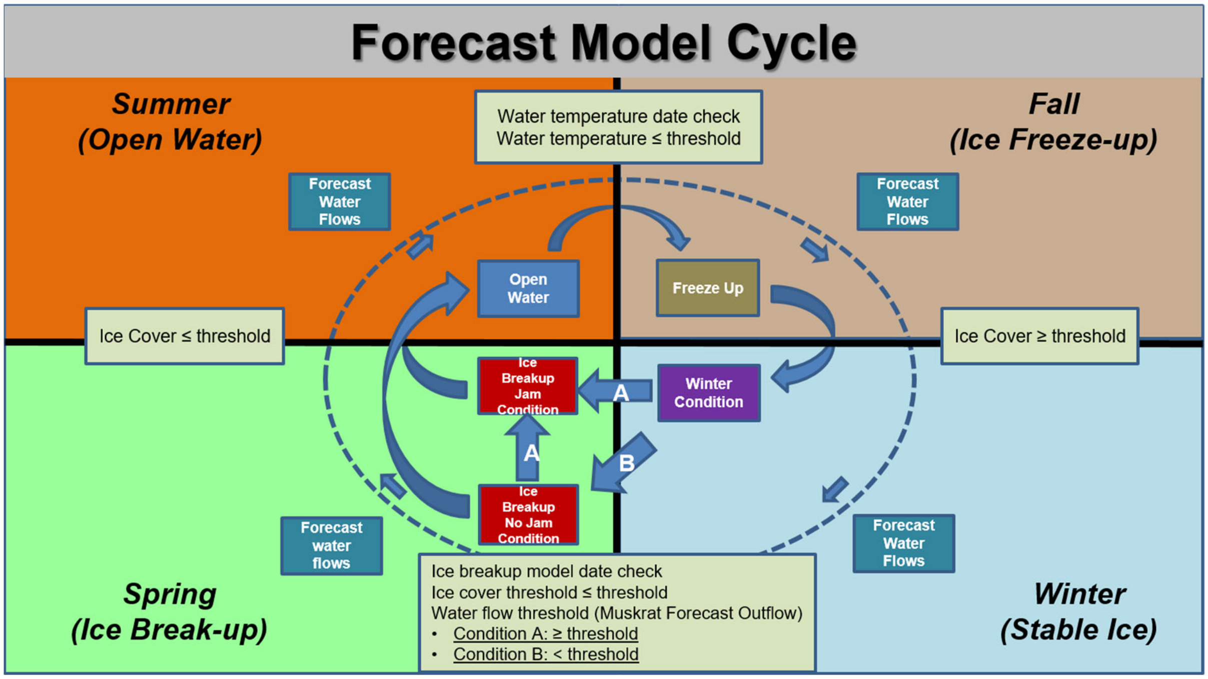


Figure 13. CRFFS Forecast Cycle (KGS Group and 4DM Inc.)

The CRFFS ingests the forecast temperature and precipitation data from Environment and Climate Change Canada's Numerical Weather Prediction, as well as the Churchill Falls Generating Station outflows, into the hydrological model HEC-HMS which computes forecasted water flows on all hydrometric stations and at some selected points downstream of Muskrat Falls. These forecasted water flows, which are then converted to water levels using the hydraulic model HEC-RAS for open water conditions and the hydraulic model RIVICE for ice freeze-up, stable ice and ice break-up conditions. The CRFFS uses the ice extent that is derived from the satellite imagery and the ice thickness measurements to compute an estimate of the volume of ice available to form an ice jam. The CRFFS uses the percentage ice coverage as well as threshold temperature at two monitored locations to switch from Fall to Winter freeze-up mode and then again to switch from Winter to Spring modes.

The system informs the Local River Watch Committee and first responders where water levels will exceed river banks in the next 72 hours. The automated flood forecasting system is the first system in the country to incorporate real time remote sensing data with real time water flows, ice thickness, and weather data. During May, 2019, based on the CRFFS predictions for Mud Lake, the following advisory messages were automatically generated and transmitted:

- May 10: there is an approximately 50 % chance of reaching the low bank elevation of 1.2 m and consequently an Ice Jam Advisory was issued.
- May 12: there is an approximately 50 % chance of reaching the low bank elevation of 1.2 m and 10 % chance of exceeding 2 m.
- May 13: there is an approximately 50 % chance of reaching the low bank elevation of 1.2 m and 10 % chance of exceeding 2 m.

- May 15: there is an approximately 50 % chance of exceeding 1.4 m (the low bank elevation is 1.2 m) and 10 % chance of exceeding 1.96 m.
- May 16: there is an approximately 50 % chance of exceeding 1.5 m (the low bank elevation is 1.2 m) and 10 % chance of exceeding 2.1 m.
- May 19: there is an approximately 50 % chance of exceeding 1.7 m (the low bank elevation is 1.2 m).

On May 20 the advisories were lifted as the model was showing forecasted flows being below the bank elevations. Figure 14 shows the water levels recorded at Mud Lake. The peak in water level coincides with advisories issued by CRFFS.

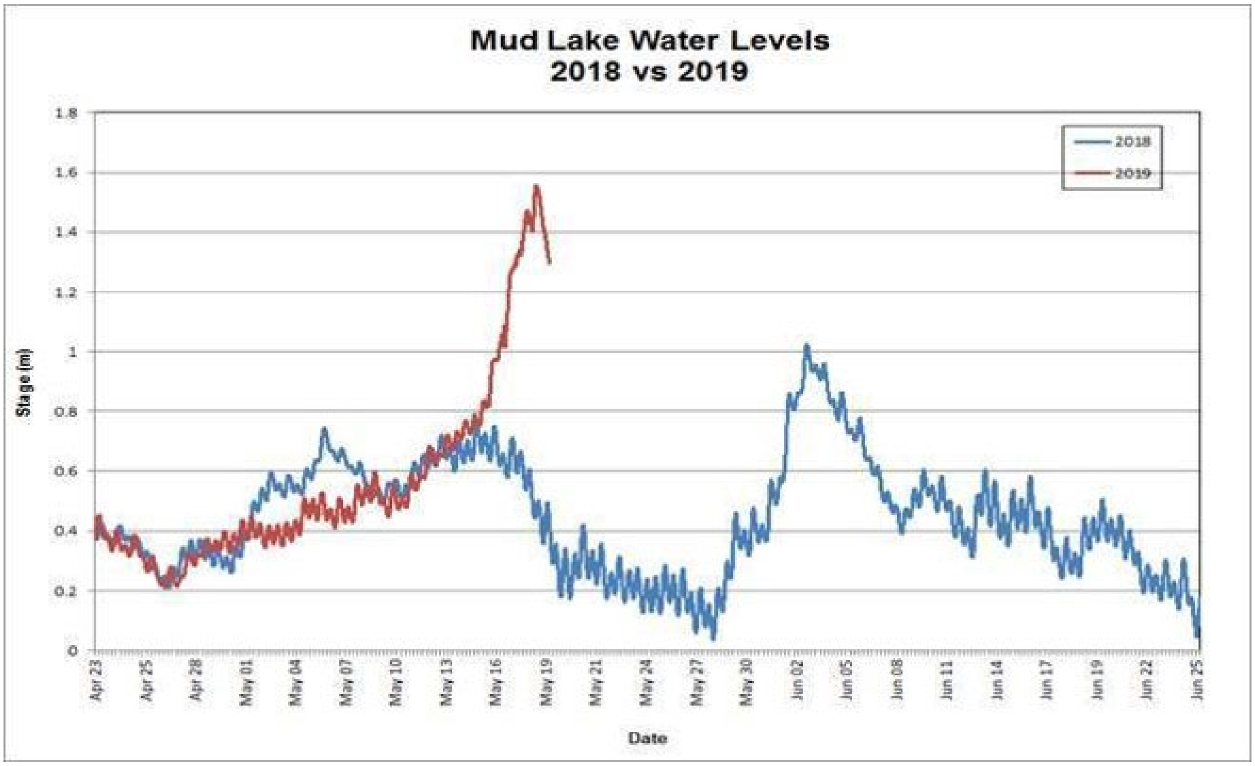


Figure 14. Water levels recorded at Mud Lake.

6. Conclusion

Operational satellite image ice classification, SIMBA and GPR ice thickness monitoring, and the CRFFS flood forecasting model is providing the first automated ice jam forecasting system in the country. CRFFS incorporates real-time remote sensing data with real-time water flows, ice thickness, and weather data for the residents living along the Churchill River. The future of freely available satellite imagery is secure with frequent satellite launches providing imagery with high revisit rates and medium spatial resolutions. Currently, RCM and S1 together have five active SAR satellites with plans to launch two more S1 satellites within the next couple of years to replace the current S1 satellites[7]. SIMBAs are a reliable method for remotely monitoring ice thickness and most of the unit parts can be reused season after season with only the thermistor chains and

[7] https://www.thalesgroup.com/en/worldwide/space/press-release/thales-alenia-space-wins-eu402-million-contract-esa-build-copernicus

batteries to requiring replacement. Helicopter-borne GPR is a safe method of ice thickness measurement along the flight line without field staff working on the ice. Research continues with all methods of ice monitoring to improve ice forecasting and understanding of the ice cover. During the past 2020/2021 season, the SIMBA and GPR surveys did not occur due to the COVID-19 pandemic, but the ice monitoring continued with satellite ice monitoring.

7. Acknowledgements

The authors are grateful to the following organisations without whom this project would not have been possible. The Government of Newfoundland and Labrador has provided funding, impetus and backing to this program since its inception. SAMS Enterprises and Sensors and Software provided invaluable support in adapting the SIMBA units and the GPR respectively. Universal Helicopters provided a safe and professional service. Local Wood staff recovered the SIMBA units during the early stage of the COVID pandemic.

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