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2022-2023 Ice Formation Environmental Effects Monitoring Study, Lower Churchill River 2021-87957 VC

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EXECUTIVE SUMMARY

The Ice Survey Program for the Lower Churchill Project (LCP) has been focused on surveying ice freeze-up and break-up processes in the Lower Churchill River between Lake Melville and Muskrat Falls, pre- and post-impoundment. The program during the 2022-2023 ice season was the tenth in a continuation series of monitoring studies during baseline, construction and operational periods of the LCP. The program documented baseline conditions and collected additional data to better understand ice conditions in areas potentially influenced by the LCP. The survey program has included the following objectives and activities:

- Review of web camera images at Mud Lake for planning purposes and to document ice formation and break-up at that location;
- Communications with Mud Lake residents to coordinate activities and document freeze-up and break-up processes;
- Estimation of ice floe concentrations; and
- Acquisition and interpretation of satellite imagery to document the freeze-up and break-up processes in each ice season.

A web camera at the Mud Lake crossing on the north side of the Lower Churchill River transmitted images by satellite and were uploaded as near real time data to the Government of Newfoundland and Labrador, Department of Environment and Climate Change, Water Resources Management Division (NLDECC/WRMD) web site. Daily review of images from this web camera was used to assist in planning acquisition of satellite images. Webcam images during the period from November 4, 2022, to January 1, 2023, and March 26 to May 4, 2023, were used to further document and describe the freeze-up and break-up processes, respectively. Unfortunately, web cam images were not available for period from November 22 to December 15, 2022, and were of poor quality from December 16, 2022 to January 15, 2023, so the available imagery during the freeze-up process was limited.

The timing of the freeze-up and break-up processes during the 2022-2023 ice season were documented and compared with the long-term data record over the last eleven years of observations. The date of freeze-up, as indicated by the day of the first snowmobile crossing, was December 11, 2022. The date of freeze-up was 11 days later than the long-term average (November 30), 15 days later than the freeze-up in 2021, and seven days later than the average for the last ten years 2013-2022 (December 4). The freeze-up date in 2022 was among the five latest over the period of record with latest freeze-up date on record being in 2011 (January 7). There has been a trend in previous years that the date of freeze-up has been getting later and the freeze-up date in 2022 continued the overall trend to later freeze-up dates.

The date of break-up, as indicated by the date of the first boat crossing, was April 29, 2023. The date of break-up was 17 days earlier the long-term average (May 15), eight days later than the break-up in 2022 (April 21), and 16 days earlier than the average for the last ten years, 2012 to 2021 (May 14). The average date of break-up over the last ten years (May 14) was similar to the long-term average (May 15), however the break-up in 2023 was considerably earlier than these averages and was the fourth earliest on record, all in the month of April.

An ice floe concentration analysis was performed on selected satellite images (ten images for each of the freeze-up and break-up) for the purpose of studying ice concentrations in the reach between Muskrat Falls and Mud Lake. The results included processed images with ice cover and open water classes, with their respective area as percent of coverage.

At the start of the monitoring period in 2022-2023, the highest amount of ice cover was formed above the Muskrat Falls dam (45.17%) with ice cover percentages at the lower sites (1 and 2) being the next highest (15.42 and 9.83%, respectively). The percent of ice cover increased at all sites from December 7 to 12, 2022 and then declined at Sites 4 and 5, from December 12 to 15, 2022, while continuing to increase at all other sites. Ice cover then increased rapidly at the three lowest sites (1 through 3) reaching ice cover percentages of 92.89, 94.89, and 95.30%, respectively on December 15, 2022. Ice cover percentages in the lowest three sites maintained above 90% as the ice cover progressed. The last two sites to freeze up were Sites 5 and 6, with site 6 demonstrating a large decrease in ice cover from December 15, 2022 (71.57%) to December 22, 2022 (8.68%). Site 5 was the last site to fully freeze-up with ice cover increasing from 2.53% to 99.08 from December 20 to 29, 2022. Site 4, associated with the Blackrock Bridge and causeway, was mostly ice covered (96.07%) by December 24, 2022 which is in contrast to the last two ice seasons (2021-2022 and 2022-2023) where open water was still evident at the end of the freeze up period.

The percent of ice cover during break up decreased progressively from March 26 through May 4, 2023, with Site 5 the quickest to lose ice with having 91.94% open water on April 23, 2023. Site 6, below Muskrat Falls, also began to lose ice early in the break-up period, but the pace of break-up then slowed until all ice was out by May 4, 2023. The lowest three sites, Sites 1, 2, and 3, were the last to break up with Site 3 not losing ice until April 27, 2023 (38.34% ice cover), and rapidly losing ice by the next day (April 28, 7.13% ice cover). As in previous years, Site 7, above Muskrat Falls was the last to lose ice remaining fully ice covered until April 28, 2023, and still retaining 35.68% ice cover on May 4, 2023, the last day of monitoring, The ice break-up for Sites 6 through 1, excepting Site 5, largely progressed in a downstream direction with Site 1, at Mud Lake, the last to become ice free, with the break-up occurring rapidly at this location from April 28 to May 4, 2023 (from 94.21 to 8.45% ice cover). Overall, the loss of ice cover progressed slowly from the start of monitoring on March 26, 2023 (mean of 98.63% ice cover) to April 19, 2023 (90.43% ice cover) and then accelerated from April 23, 2023 (81.69 % ice cover) to April 28, 2023 (41.53% ice cover) with a mean ice cover on 6.96% on the last day of monitoring (May 3, 2023). Four of seven sites were ice free on the last day of monitoring.

A total of 15 RADARSAT Constellation Mission (RCM) and five Sentinel-1 (S1) SAR images were analyzed during the freeze-up and break-up periods. The spatial resolution of images analyzed ranged from 20 to 50 meters. Image plans were created and modified to adjust to the freeze-up and break-up times. Local knowledge, weather data, webcam images and freely available satellite image data were tools used to assist with estimating the timing of freeze-up and break-up events. The S1 satellite cannot be tasked but image plans on the European Space Agency website were monitored routinely to acquire the required Churchill River images. Goose River, north of the Churchill River, has been a break-up indicator as the Goose River break-up typically precedes the Lower Churchill River by approximately ten days.

Three products were generated from the analyses of SAR images: (i) Ice Cover; (ii) Ice Classification; and (iii) Change Detection. The Ice Cover product identified areas of smooth ice cover or open water which helped elucidate the ice front. The Ice Classification product differentiated between three ice classes: (i) open water; (ii) non-consolidated or smooth ice; and (iii) consolidated or rough ice. The Change Detection product compared two consecutive images to determine whether there had been an increase, decrease, or no change in ice cover. A fourth classification which identified pooled water on ice was included in the analyses for images captured during break-up. These products are contained in Appendix A (freeze-up) and B (Break-up).

1.0 Introduction

Mud Lake residents are dependent on a stable ice cover across the Lower Churchill River for transportation to and from Happy Valley-Goose Bay during winter. The environmental assessment of the Lower Churchill Project (LCP) consequently paid particular attention to the possible effects of the LCP on the ice dynamics in the reach below Muskrat Falls (Nalcor 2009). Hydraulic conditions downstream of Muskrat Falls were predicted to not change as a result of the LCP, indicating there would be no effect on river crossings during the ice-free parts of the year. It was predicted, however, that downstream of Muskrat Falls in the area of Mud Lake, the freeze-up date would be delayed by two weeks and the break-up date would occur one week later than historical records (Hatch 2007; Nalcor 2009). This was predicted to affect river crossing by Mud Lake residents, as boats would be used to cross the river for two weeks longer in the fall and snowmobiles would be used one week longer in the spring.

Predictions were made during the environmental assessment of the LCP regarding the transition period during the freeze-up and break-up processes, to determine if ice cover would be stable enough for crossing by snowmobile (freeze-up) and to predict ice conditions until the river is ice-free in the spring (break-up) allowing crossings by boat. These transition periods occur each year and during this time travel by boat or snowmobile is not possible. Ice modelling predictions made in the environmental assessment did not forecast a longer transition period, therefore, crossing of the river was not expected to be substantially affected by the LCP, other than the change in timing.

Ice bridging under pre-LCP conditions occurred at an approximate distance of 0.2 km above Lake Melville and the ice cover progressed upstream from that point. The volume of ice was expected to be reduced by the Muskrat Falls hydroelectric facility under post-LCP conditions, which will act as a physical barrier to ice transport from upstream to downstream reaches. A hydraulic analysis assessed the potential for the ice bridge to form under post-LCP conditions and the analysis indicated that the volume of ice generated downstream of Muskrat Falls was sufficient for the formation of a stable ice bridge (Hatch 2010; Pryse-Phillips 2010). The strength (stability and thickness) of the ice forming the ice bridge was predicted to remain unaffected during the operation of the LCP.

Nalcor Energy (Nalcor) has been observing ice processes in the Lower Churchill River since 2006 as part of the assessment of the LCP (Hatch 2007: SNC-Lavalin 2012a and b). Historical surveys were also conducted in the 1980s and 1990s by various parties (as reviewed in SNC-Lavalin 2012b). Ice management was considered an important aspect of construction and operation of the Muskrat Falls hydroelectric facility and these studies were conducted to better understand the ice conditions in the areas to be influenced by the LCP to better predict post-project conditions. The LCP committed to surveying ice formation in the Lower Churchill River during pre- (baseline and LCP construction period) and post-impoundment (operations) conditions. This monitoring would allow Nalcor to take appropriate precautions and develop mitigation measures to manage potential problems due to ice. Nalcor initially contracted Golder Associates (Golder), who sub-contracted Sikumiut Environmental Management Ltd. (SEM), to develop and implement an ice surveying program. SEM has partnered with C-CORE (Center for Cold Ocean Research and Engineering) on the monitoring activities owing to their specialized expertise in acquisition and analysis of satellite imagery. This program has been conducted prior to and during LCP construction to confirm baseline conditions and to expand the knowledge base on the timing of freeze-up and break-up in relation to the Mud Lake crossing location. The ice monitoring program has been continued during operation of the LCP to evaluate changes in timing of the freeze-up and break-up conditions as related to the Muskrat Falls reservoir. The ice monitoring program in the 2021-2022 and 2022-2023 was contracted by the Muskrat Falls Corporation directly to SEM while Nalcor maintained overall management of the program.

This report presents the results of studies completed in the 2022-2023 ice season (Year 10) during the construction and operational phases of the LCP (SEM 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, and 2022). Satellite Synthetic Aperture Radar (SAR) images were used to monitor ice conditions during freeze-up and break-up on the Churchill River between Muskrat Falls and Goose Bay for the 2022-2023 ice season. A total of 15 RADARSAT Constellation Mission (RCM), and five Sentinel-1 (S1) SAR images were analyzed during the freeze-up and break-up periods. Images provided detailed ice surface textures and accurately delineated areas of open water. The images were processed to identify ice types and open water to assess ice cover effects on the Lower Churchill River. An ice floe concentration analysis was performed during freeze-up and break-up to study ice concentrations in the reach between Muskrat Falls and Lake Melville and to assess progression of the freeze-up and break-up events.

2.0 Materials and Methods

2.1 Objectives

The Ice Survey Program for the LCP is focused on surveying ice freeze-up and break-up in the Lower Churchill River pre- and post-impoundment. The program during the 2022-2023 ice season was the tenth survey in a continuation of previous monitoring during the baseline and construction periods and initial operations of the LCP. Objectives of the overall program were to document baseline conditions prior to operations and collect additional data during construction to better understand the ice conditions in areas potentially influenced by the LCP. Monitoring since the project has been operational has continued to assess changes in the freeze-up and break-up process related to operation of the Muskrat Falls reservoir.

The survey program has included the following objectives and activities:

- Daily review of images from the Government of Newfoundland and Labrador, Department of Environment and Climate Change, Water Resources Management Division (NLDECC/WRMD) web camera at Mud Lake for the purpose of planning satellite image acquisition;

- Communication with Mud Lake residents to support planning of surveys during the freeze-up and break-up processes and to document the date of freeze-up and break-up in the context of river crossing;

- Estimation of ice floe concentrations via analysis of satellite images during the freeze-up and break-up periods; and

- Acquisition and interpretation of satellite imagery to determine ice formation (freeze-up) and break-up at Mud Lake and document these processes.

2.2 Study Team

The study team members for this work and their area of responsibility are listed in Table 2.1. The overall project coordination and management was completed by SEM. SEM staff monitored the Mud Lake webcam and communicated with Mud Lake residents to coordinate, along with C-CORE's project manager, acquisition of satellite images. SEM coordinated completion the project report with support and input from other team members from C-CORE.

C-CORE acquired and analyzed Synthetic Aperture Radar (SAR) images from 15 RADARSAT Constellation Mission (RCM), and five Sentinel-1 (S1) SAR images. Images were analyzed to identify ice types and delineate areas of open water as part of the ongoing study to assess ice cover effects on the Lower Churchill from the LCP Project. The major advantages of SAR sensors include weather independence and the ability to acquire imagery day or night. C-CORE also completed an ice floe concentration analysis on ten satellite images taken during each of the freeze-up and break-up periods to estimate the respective proportions of ice and open water in each of the sections.

Table 2.1 Team Members for the 2022-2023 Ice Observations Surveys.

Team Member	Roles and Responsibility
SEM	
Dave Scruton, MES, Senior Scientist	SEM Project Manager, coordination, client liaison, project report
Crystal Kehoe, B.Sc., Environmental Technician	Data analysis and project report, liaison with J. Hope, Mud Lake
Jordan Hope, Mud Lake Resident	Communication on ice conditions
C-CORE	
Michael Lynch, B.Sc., Advanced Diploma GIS, Operations Manager	C-CORE Project Manager, project control, internal project coordination of resources and technical advisor. Coordination with client and reporting.
Jean Granger, M.Sc. Geography, Diploma GIS, B.Sc. Biology, GIS Specialist	Acquisition and archiving of e imagery. Satellite image analysis, generation of river ice products, ice floe analysis.

2.3 Mud Lake Web Camera

In 2010, a web camera was established by the NLDECC/WRMD, in cooperation with the LCP and Environment and Climate Change Canada, at the Mud Lake crossing on the north side of the Churchill River, near Happy Valley-Goose Bay, oriented upstream. Images from this web camera are transmitted by satellite and uploaded as near real time data to the NLDECC/WRMD web site at:

http://www.env.gov.nl.ca/wrmd/ADRS/v6/Template_Station.asp?station=NLENCL0004

Photos taken by the web camera were consulted daily during planning for timing of surveys and to document the freeze-up and break-up conditions. Images during the period from November 16, 2022, to January 1, 2023. and March 26 to May 4, 2023. were used to document and describe the freeze-up and break-up conditions at the Mud Lake crossing, respectively.

2.4 Local Consultation

SEM has consulted with Mud Lake resident Mr. Jordan Hope for assistance and experience with respect to the timing of freeze-up and break-up processes during all nine consecutive ice surveys. Mr. Hope has previously assisted SEM in determining the likely dates for freeze-up and break-up based on his knowledge and experience with the Lower Churchill River at Mud Lake. This consultation, in combination with monitoring of the webcam and C-CORE's monitoring of freely available satellite imagery, has been used to plan the acquisition of satellite imagery for detailed analyses. Mr. Hope has maintained a long-term record of the first snowmobile crossing after freeze-up and first boat crossing after break-up as important dates for the residents of Mud Lake. These dates in the 2022-2023 ice season were December 11, 2022 (first snowmobile crossing) and April 29, 2023 (first boat crossing).

2.5 Existing Conditions

River conditions during the 2022-2023 ice season were similar to the previous ice seasons (2019-2020, 2020-2021, and 2022-2023) with water impounded in the Muskrat Falls reservoir. Water levels in the reservoir were maintained at full supply level throughout the ice season. During the freeze-up and break-up periods, water was being released from the reservoir in the same amounts as during normal flows, i.e., no additional water was being retained.

2.6 Satellite Observations

2.6.1 Monitoring Area

The section of the Lower Churchill River monitored is shown in Figure 2.1, which spans approximately 40 km and covers an area of approximately 60 km^2. The width of the river varies between 100 m to 3,200 m, with the elevation ranging from 15 m immediately above Muskrat Falls to 0 m at the mouth of the river. The largest accumulation of ice has historically occurred just below Muskrat Falls where the river suddenly widens and quickly narrows again. This river morphology, along with the generation of frazil ice below Muskrat Falls, results in enormous amounts of ice being trapped at this location. Ice build-up here is a result, in part, of the powerful rapids that push ice under the existing ice cover in this area.

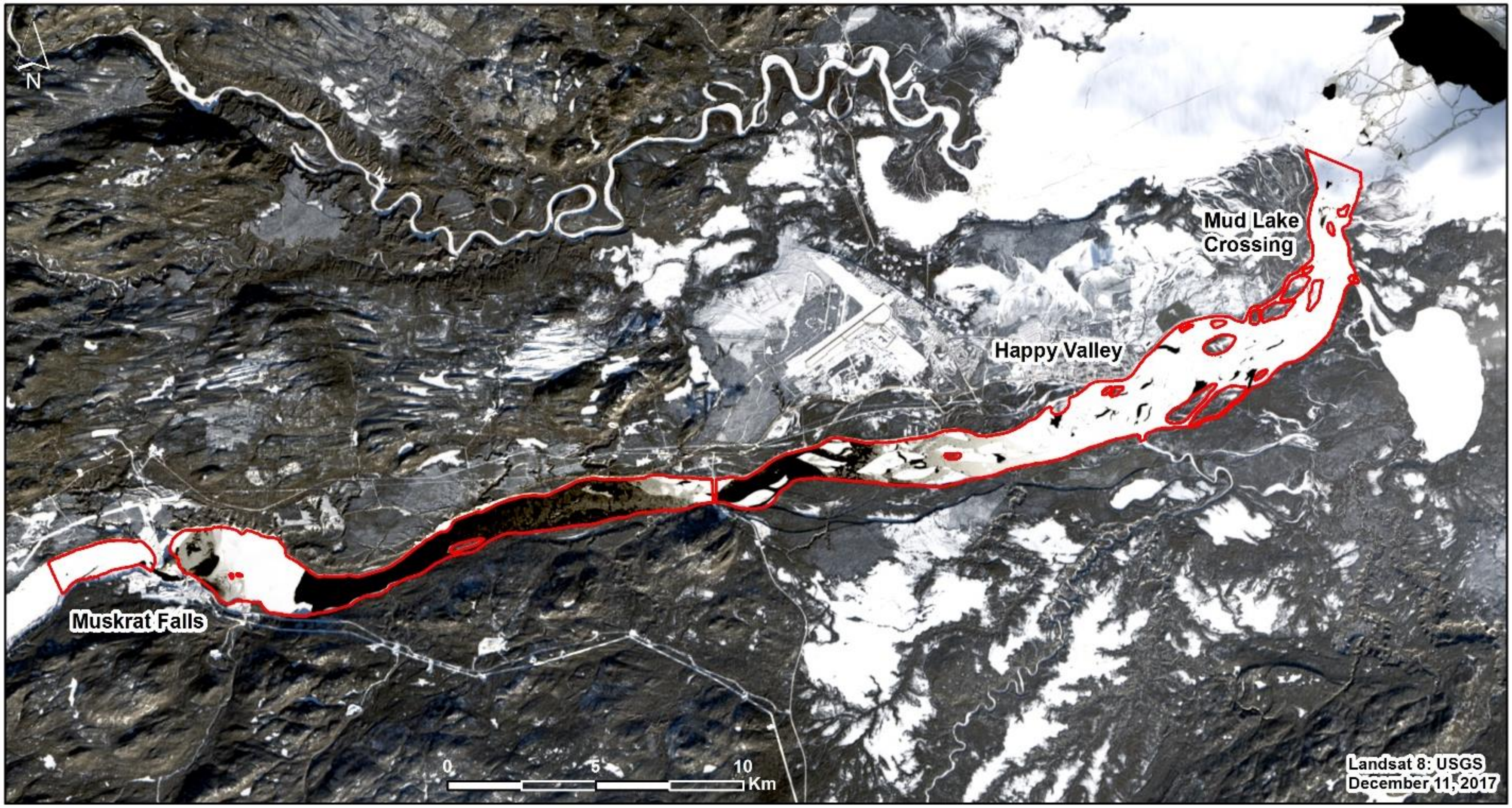

Figure 2.1 Section of the Lower Churchill River Monitored Between Muskrat Falls and Lake Melville.

2.6.2 Satellite Image Planning and Acquisition

A total of 20 images was acquired using the RCM constellation (consisting of three SAR satellites) and the S1 constellation (consisting of two SAR satellites). RCM is Canada's latest generation of SAR satellites that was launched on June 12, 2019. RCM is now actively acquiring and publishing image data at no cost to organizations who are vetted users including C-CORE. Similar spatial resolutions as S1 are available from RCM. RCM image tasking is controlled by the Canadian government and which accepts requests from Canadian provinces and territories for image tasking. Image deconfliction is not required for RCM as image plans are not submitted by users, instead RCM uses a pre-programmed operational approach. The Churchill River is included in the pre-programmed plan. S1 acquisitions cannot be tasked but image plans are published on a regular basis on the European Space Agency (ESA) website, which is monitored by C-CORE regularly to ensure the appropriate Churchill River images were acquired in 2022-2023. Requests can be made to ESA for image tasking with a valid reason such as river ice monitoring. S1 and RCM images are freely available and have been used to lower project costs.

The acquisition of images considered several factors, including spatial resolution, incidence angle, look direction, temporal frequency, and the area of interest during the likely freeze-up and break-up periods. These factors are defined by the particular application and can restrict image availability and coverage.

The 20 images acquired consisted of a combination of medium resolution SAR and spatial resolution ranged from 20 to 30 meters. Table 2.2 contains detailed specifications of the number and types of satellite images. A complete list of images processed for the Lower Churchill River ice monitoring service is provided in Table 2.3.

Table 2.2 Satellite Image Specifications for the 2022-2023 Ice Season.

Satellite	Beam Mode	Spatial Resolution (m)	Image Width (km)	Number of Images
RCM	ScanSAR 30M	30	125	15
S1	Interferometric Wide	20	250	5

Table 2.3 Satellite Image Acquisition Schedule for the 2022-2023 Ice Season.

Date	Time (UTC[1])	Spatial Resolution (m)	Satellite	Event
December 7, 2022	21:41	30	RCM	Freeze-up
December 12, 2022	10:21	30	RCM	Freeze-up
December 15, 2022	21:41	30	RCM	Freeze-up
December 20, 2022	10:21	30	RCM	Freeze-up
December 22, 2022	10:21	20	S1	Freeze-up
December 24, 2022	10:21	30	RCM	Freeze-up
December 27, 2022	21:41	30	RCM	Freeze-up
December 29, 2022	10:13	20	S1	Freeze-up
January 1, 2023	10:21	30	RCM	Freeze-up
January 9, 2023	10:21	30	RCM	Freeze-up
March 26, 2023	10:21	30	RCM	Break-up
April 4, 2023	10:13	20	S1	Break-up
April 7, 2023	10:21	30	RCM	Break-up
April 10, 2023	21:42	30	RCM	Break-up
April 16, 2023	10:13	20	S1	Break-up
April 19, 2023	10:21	30	RCM	Break-up
April 23, 2023	10:21	30	RCM	Break-up
April 27, 2023	10:21	30	RCM	Break-up
April 28, 2023	10:13	20	S1	Break-up
May 4, 2023	21:42	30	RCM	Break-up

[1] *Universal Coordinated Time*

2.6.3 Satellite Image Processing

Radar satellites are active sensors that transmit a signal to the Earth's surface and record the energy reflected back to the sensor (backscatter). Pixel intensity within the image is proportional to the level of backscatter. The scattering signature of river ice is dominated by surface and volume scattering. Surface scatter is a result of the interaction between the radar signal and an interface at which there is a change in dielectric constant. Smooth surfaces usually result in specular reflection, directing most of the energy away from the sensor in a single direction. Rough surfaces, on the other hand, tend to cause diffuse scattering, reflecting the energy nearly uniformly in all directions and directing more radiation back toward the sensor. Rougher surfaces therefore tend to generate a greater amount of surface backscatter. In the case of volume scattering, the radiation penetrates into the ice cover and the radar signal is scattered by dielectric discontinuities within the medium, such as air bubbles, liquid water pockets and particles. Inhomogeneous ice covers typically show larger backscatter coefficients than more uniform ice covers. Volume scattering requires the ice to be dry with little liquid water content. If the ice is wet, surface scattering is the dominant scattering mechanism. A graphical representation of surface and volume scattering processes is presented in Figure 2.2.

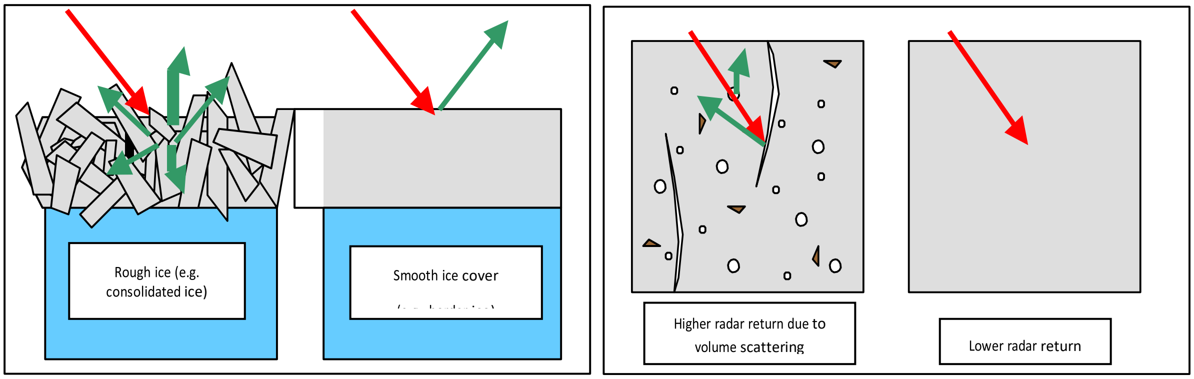

Figure 2.2 Conceptual River Ice Scattering Mechanisms (after Pelletier, Hicks and van der Sanden 2003).

The image analysis process includes calibration, terrain correction, filtering and visual enhancement. Mask generation was required to isolate the river from the rest of the image for the purpose of classifying the river only. Filter and enhancement techniques are unique to each image, due to different spatial resolutions, incidence angle and ice cover. Filters are used to remove noise and speckle, which are characteristic of SAR images. The choice of enhancement techniques depends on weather conditions affecting the ice, ice textures and the amount of open water, all of which affect the backscatter and calibration results. Late in the ice season, rough ice textures become smoother due to warmer temperatures; resulting in less backscatter to the point that ice begins to resemble open water. At such points, prior knowledge of weather conditions, recent satellite images and field data are important factors in separating open water from water on ice. Water pooling on the surface of the ice resulting from melting ice or rainfall will appear similar to open water.

The information products generated during the service period included ice cover, ice classification and ice cover change. The *Ice Cover* product is one of three products included with this report. It is a map containing the calibrated, visually enhanced, terrain corrected SAR image. The darker sections of the river are areas of smooth ice or open water. There also may be pools of water on ice, depending on the time of year and the recent weather conditions. Figure 2.3 shows an example ice cover product from the December 15, 2022, RCM image.

The *Ice Classification* product is obtained by classifying SAR backscatter into one of three classes: (i) open water or water on ice; (ii) non-consolidated or smooth ice surface; and (iii) consolidated or rough ice surface. Figure 2.4 shows an example of the Ice Classification product from the December 15, 2022 RCM image.

The ***Change Detection*** product is the result of subtracting the previous classification from the most recent classification. The result is a product indicating where the ice surface is rougher (backscatter has increased; yellow and red) and smoother (backscatter has decreased; light blue and dark blue) as well as areas where no change (green) has occurred. This is a useful product for tracking ice break-up and freeze-up processes as well as sudden changes due to weather events, such as rain. Figure 2.5 shows an example of a Change Detection product for the comparison of classifications from December 12 and December 15, 2022, RCM images.

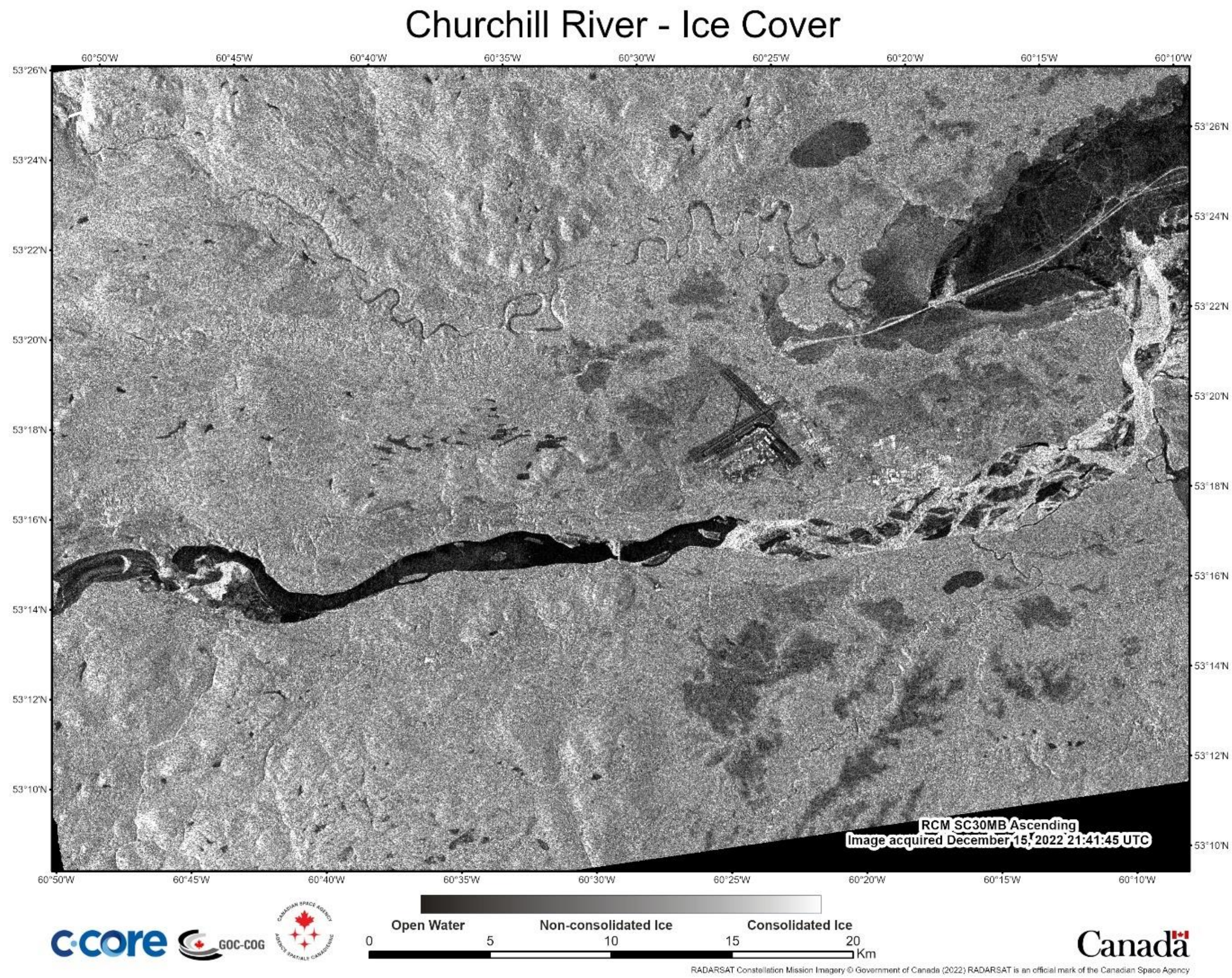

Figure 2.3 Ice Cover Product Created from the December 15, 2022, RCM Image.

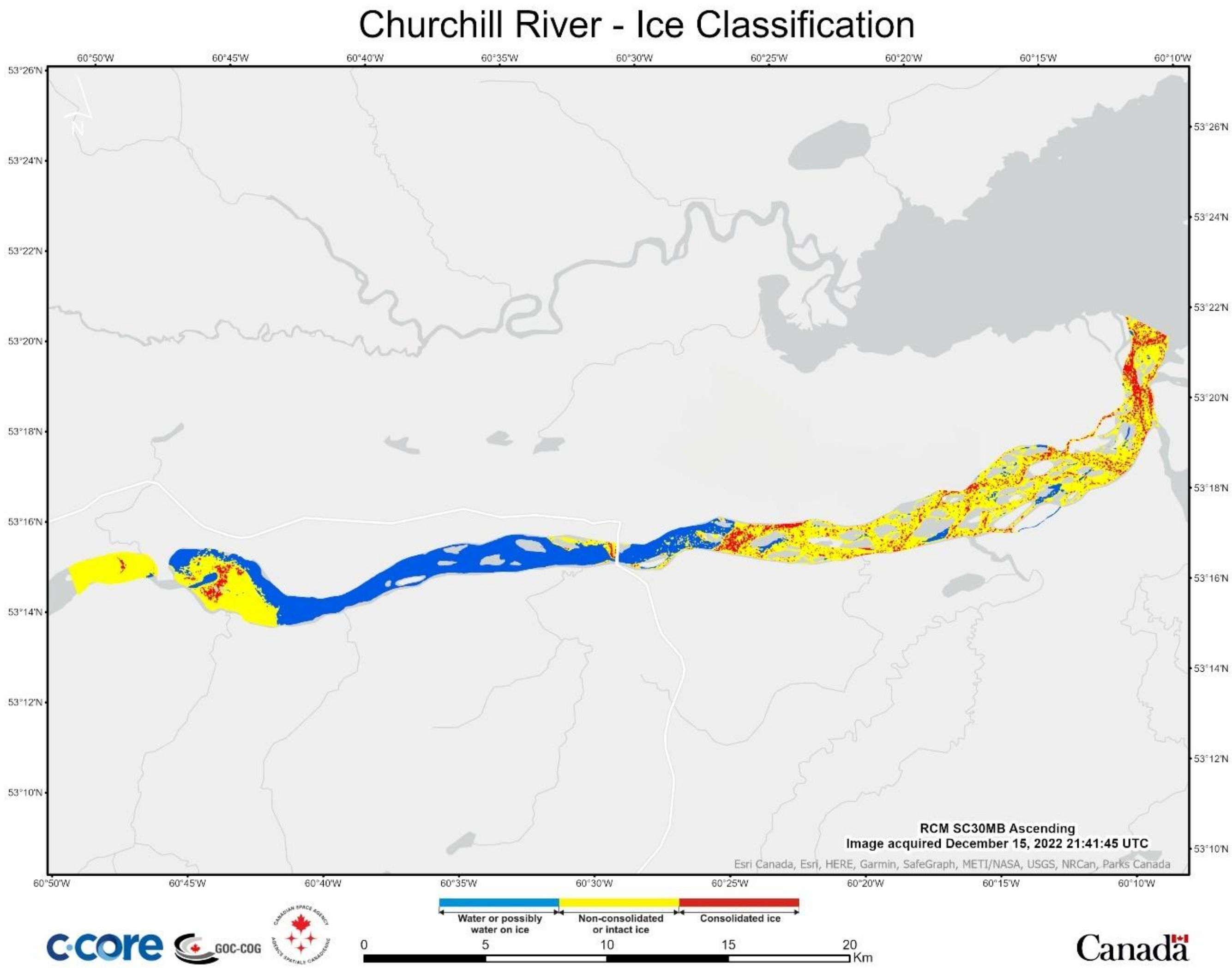

Figure 2.4 Ice Classification Product Created from the December 15, 2022, RCM Image.

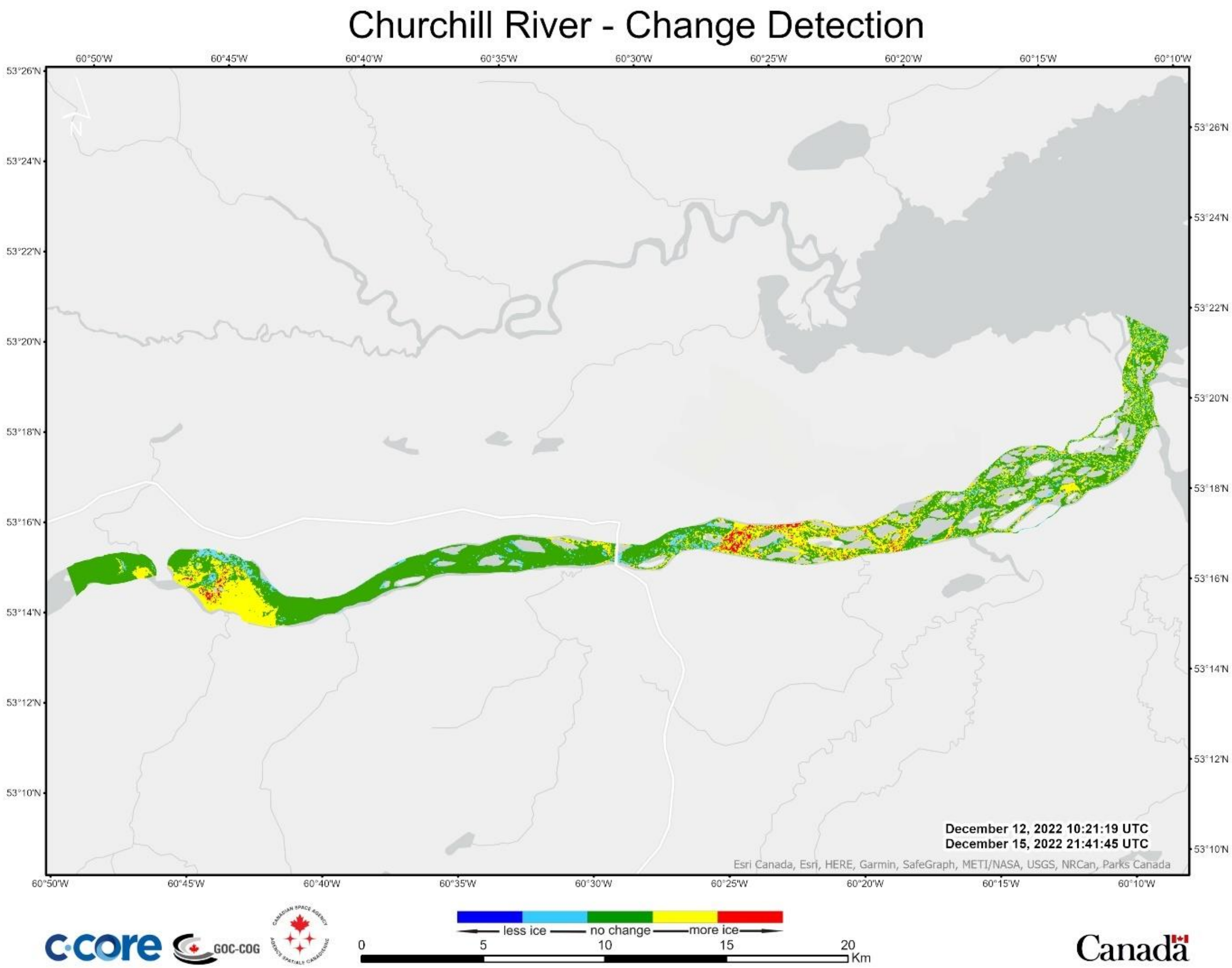

Figure 2.5 Change Detection Product Created from the December 12 and 15, 2022, Classifications.

2.7 Ice Floe Concentrations

An ice floe concentration analysis was performed on the Lower Churchill River using classified satellite images acquired during the freeze-up and break-up processes. Separate analyses were conducted for ice break-up and freeze-up periods. Seven areas were selected for analysis based on the same locations of analyses completed in previous ice season to provide a comparable analysis to previous years (Figure 2.6). The analysis studied the dynamics of changing ice cover during the freeze-up and break-up over the reach between Muskrat Falls and Lake Melville. Using the river ice classification products as input, the ice floe analysis evaluated the respective proportions of ice and open water in each of the sections under investigation. Categories of non-consolidated and consolidated ice classes were combined to represent total ice cover.

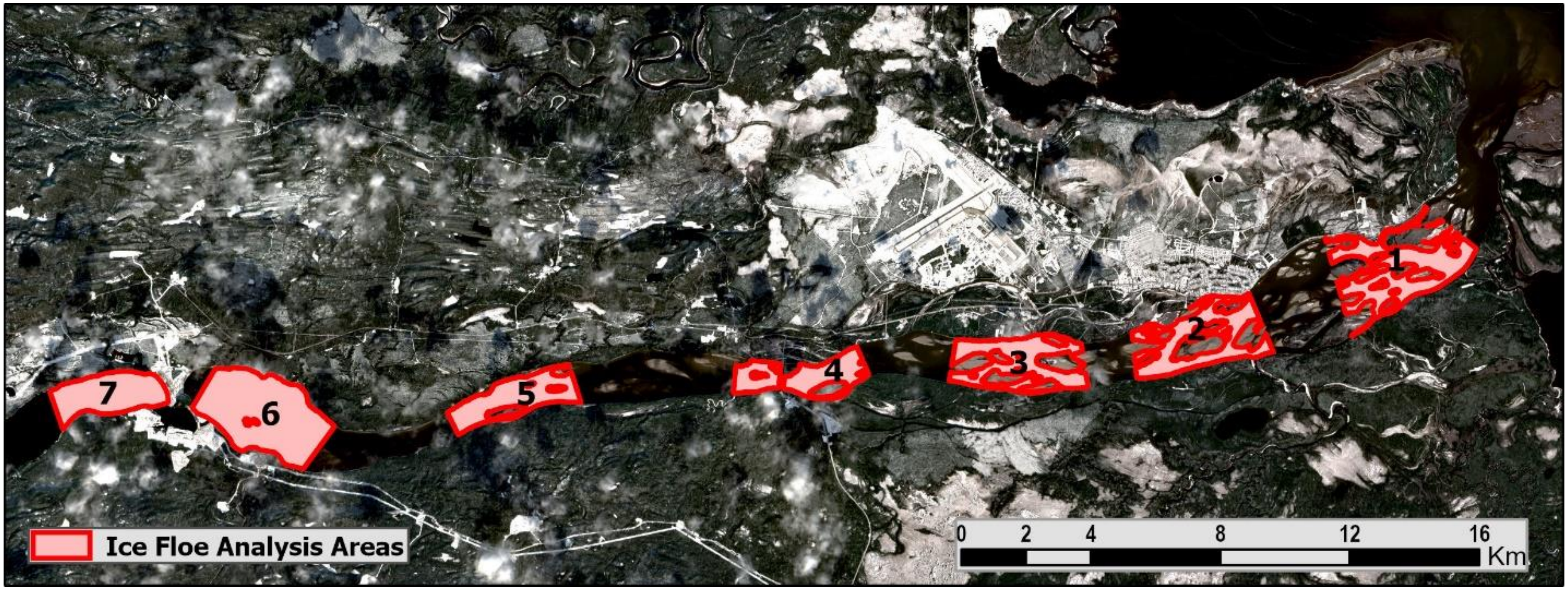

Figure 2.6 Ice Floe Analysis Sections for the 2022-2023 Ice Season. The Background Image was Originally Acquired by Sentinel-2 on October 30, 2020.

3.0 Results

3.1 Mud Lake Web Camera

Images from the NLDECC/WRMD web camera at the Mud Lake crossing site were viewed frequently, when available, from the Government of Newfoundland and Labrador website during 2022-2023 to monitor and document the freeze-up and break-up processes. Images were subsequently provided by the Government of Newfoundland and Labrador, Department of Environment and Climate Change, Water Resources Management Division (WRMD) as digital files (Randy Parsons, pers. comm.) so that the highest quality images could be included in this report. Images used in this report were typically for 1:00 p.m. each day. Unfortunately, there are no images from November 22, 6:00 pm. to December 15, 4:00 p.m. and many images from December 16, 2022 to January 15., 2023 were of poor quality and could not be used in the report.

Much of the imagery during the freeze-up period was unavailable or of poor quality and only a few selected images are provided for the period from November 16, 2022, to January 1, 2023, in Figure 3.1. These images only document the river before any ice formation had started (November 16 and 21) and after ice was fully formed at the Mud Lake crossing (December 16, 18 and 29, 2022, and January 1, 2023). The ice bridge was considered formed on December 11, 2022, the date of the first snowmobile crossing for the 2022-2023 ice season (Jordan Hope, pers. comm.).

The break-up sequence for the period from March 26 to May 4, 2023, is shown in Figures 3.2 and 3.3. The images from March 26 through April 10, 2023, document the period pre-break-up where the river was still frozen over completely. Some minor melting of the snow cover was apparent starting April 16 and 23, 2023. Melting along the southern margin of the river was apparent starting April 27, 2023 and progressed April 28 and 29, 2023. The break-up then started on May 30, 2023, and appeared to start on the south side of the river and the river was fully ice free by May 1, 2023. The date of first crossing by boat was April 29, 2023 (Jordan Hope, pers. comm.). The duration of the major break-up was about four to five days, which is comparable with observations from previous years and as reported by SNC-Lavalin (2012a) for 2012 (six days), 2014 (seven days, SEM 2014), 2015 (five to seven days, SEM 2015), 2016 (seven days, SEM 2016), 2017 (seven to nine days, SEM 2017), 2018 (five days, SEM 2018), 2019 (five days, SEM 2019), 2020 (four days, SEM 2020), 2021 (four days, SEM 2021) and 2022 (four to five days, SEM 2022).

Figure 3.1 Mud Lake Web Camera Images During the Freeze-Up Process, November 16, 2022, to January 1, 2023.

Figure 3.2 **Mud Lake Web Camera Images During the Break-Up Process, March 26 to April 23 2023.**

Figure 3.3 Mud Lake Web Camera Images During the Break-Up Process, April 27 to May 4, 2023.

3.2 Timing of Freeze-Up and Break-Up

The timing of the freeze-up and break-up processes during the 2022-2023 ice season, in comparison to the long-term data record, and in comparison, with the last ten years of record, is provided in Table 3.1.

The date of freeze-up, as indicated by the day of the first snowmobile crossing, was December 11, 2022. The date of freeze-up was 11 days later than the long-term average (November 30), 15 days later than the freeze-up in 2021, and seven days later than the average for the last ten years 2013-2022 (December 4). This is the second latest freeze-up date over the period of record with latest freeze-up date on record being in 2011 (January 7).

The date of break-up, as indicated by the date of the first boat crossing, was April 29, 2023. The date of break-up was 17 days earlier the long-term average (May 15), eight days later than the break-up in 2021 (April 21), and 16 days earlier than the average for the last ten years, 2014 to 2023 (May 14).

There had been a trend in previous years that the date of freeze-up has been getting later, with the latest date on record in 2011 (January 7), and 2019 being the second latest freeze-up date over the last ten years (December 13). Since 2000, freeze-up has occurred in December in 17 of 23 years. The freeze-up date in 2022 was the among the five latest on record continuing the overall trend to later freeze-up dates.

Table 3.1 Long Term Record of Freeze-Up and Break-Up at the Mud Lake Crossing.

Date	Freeze-Up (First snowmobile crossing)	Break-Up (First boat crossing)
1972	22-Nov-72	5-Jun-72
1973	-	-
1974	-	-
1975	25-Nov-75	30-May-75
1976	17-Nov-76	17-May-76
1977	30-Nov-77	15-May-77
1978	19-Nov-78	27-May-78
1979	24-Nov-79	14-May-79
1980	29-Nov-80	17-May-80
1981	23-Dec-81	15-May-81
1982	28-Nov-82	1-May-82
1983	29-Nov-83	14-May-83
1984	23-Nov-84	15-May-84
1985	18-Nov-85	28-May-85
1986	13-Nov-86	7-May-86

Table 3.1 Long Term Record of Freeze-Up and Break-Up at the Mud Lake Crossing. (Cont'd)

Date	Freeze-Up (First snowmobile crossing)	Break-Up (First boat crossing)
1987	28-Nov-87	23-Apr-87
1988	1-Dec-88	12-May-88
1989	24-Nov-89	15-May-89
1990	1-Dec-90	22-May-90
1991	2-Dec-91	26-May-91
1992	19-Nov-92	27-May-92
1993	13-Nov-93	17-May-93
1994	27-Nov-94	22-May-94
1995	29-Nov-95	11-May-95
1996	1-Dec-96	4-May-96
1997	23-Nov-97	24-May-97
1998	30-Nov-98	12-May-98
1999	23-Nov-99	10-May-99
2000	25-Nov-00	11-May-00
2001	4-Dec-01	14-May-01
2002	22-Nov-02	22-May-02
2003	7-Dec-03	17-May-03
2004	7-Dec-04	18-May-04
2005	11-Dec-05	8-May-05
2006	4-Dec-06	4-May-06
2007	30-Nov-07	17-May-07
2008	5-Dec-08	7-May-08
2009	9-Dec-09	18-May-09
2010	7-Jan-11	20-Apr-10
2011	2-Dec-11	12-May-11
2012	2-Dec-12	15-May-12
2013	2-Dec-13	1-May-13
2014	24-Nov-14	19-May-14
2015	1-Dec-15	18-May-15
2016	5-Dec-16	17-May-16
2017	7-Dec-17	21-May-17
2018	21-Nov-18	17-May-18
2019	13-Dec-19	19-May-19
2020	30-Nov-20	8-May-20
2021	15-Dec-21	21-Apr-21
2022	11-Dec-22	13-May-22
2023	TBD	29-Apr-23
Long Term Average	30-Nov	15-May
Average 2012 – 2021 (Last 10 Years)	4-Dec	14-May

The average date of break-up over the last ten years (May 14) has been similar to the long-term average (May 15), however the break-up in 2023 was considerably earlier than these averages. The break-up date in 2023 (April 29) was the fourth earliest on record, all in the month of April.

The length of time between the freeze-up date and the break-up date have been used to determine the total length of the ice-covered period or ice season (Table 3.2). The freeze-up date in 2022 (December 11) and break-up date in 2023 (April 29) resulted in total ice-covered period of 140 days for the 2022-2023 ice season. Historically the ice season has ranged between 125 and 190 days, averaging 164.7 days since 1975-76 and 160.5 days over the last ten-year period (2014-2023). The ice season in 2022-2023 (140 days) was the fourth shortest on record only being less in 1981-82 (129 days), 2009-10 (132 days), and 2010-11 (125 days).

Table 3.2 Long Term Record of Duration of the Ice-Covered Period at the Mud Lake Crossing.

Ice Season	Duration (Days)
1975-76	174
1976-77	181
1977-78	178
1978-79	176
1979-80	174
1980-81	169
1981-82	129
1982-83	167
1983-84	167
1984-85	187
1985-86	170
1986-87	162
1987-88	165
1988-89	165
1989-90	179
1990-91	176
1991-92	176
1992-93	180
1993-94	190
1994-95	165
1995-96	156

Table 3.2 Long Term Record of Duration of the Ice-Covered period at the Mud Lake Crossing. (Cont'd)

Ice Season	Duration (Days)
1996-97	175
1997-98	170
1998-99	161
1999-2000	169
2000-01	171
2001-02	169
2002-03	176
2003-04	162
2004-05	153
2005-06	144
2006-07	164
2007-08	158
2008-09	165
2009-10	132
2010-11	125
2011-12	165
2012-13	152
2013-14	169
2014-15	175
2015-16	167
2016-17	167
2017-18	161
2018-19	179
2019-20	155
2020-21	142
2021-22	150
2022-23	140
Long Term Average	164.7
Last 10 Year Average	160.5
Minimum	125
Maximum	190

3.3 Ice Floe Analyses

3.3.1 Freeze-Up Period

The result of the freeze-up analysis is presented in Table 3.3 and is presented graphically in Figures 3.5 and 3.6. Ten images were selected for analysis during the freeze-up period; December 7, 12, 15, 20, 22, 24, 27, 29, 2022, and January 1 and 9, 2023. The site numbers correspond to the numbered sections in Figure 2.6.

At the start of the monitoring period in 2022-2023, the highest amount of ice cover was formed above the Muskrat Falls dam (45.17%) with ice cover percentages at the lower sites (1 and 2) being the next highest (15.42 and 9.83%, respectively). The percent of ice cover increased at all sites from December 7 to 12, 2022, and then declined at Sites 4 and 5, from December 12 to 15, while continuing to increase at all other sites. Ice cover then increased rapidly at the three lowest river sites (1 through 3) reaching ice cover percentages of 92.89, 94.89, and 95.30%, respectively on December 15. Ice cover percentages in the lowest three sites maintained above 90% as the ice cover progressed. The last two sites to freeze up were Sites 5 and 6, with site 6 demonstrating a large decrease in ice cover from December 15 (71.57%) to December 22 (8.68%). Site 5 was the last site to fully freeze-up with ice cover increasing from 2.53% to 99.08 from December 20 to 29. Site 4, associated with the Blackrock Bridge and causeway, was mostly ice covered (96.07%) by December 24. This was in contrast to the last two seasons (2021-2022 and 2022-2023) where open water was still evident at the end of the freeze up period.

Table 3.3 Ice Cover and Open Water Percent Coverage for the Freeze-Up Period in 2022-2023.

Site	7-Dec-22		12-Dec-22		15-Dec-22		20-Dec-22		22-Dec-22	
	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)
1	84.58	15.42	14.83	86.17	7.61	92.89	8.94	91.06	9.23	90.77
2	90.17	9.83	24.34	75.66	5.11	94.89	7.71	92.29	6.11	93.89
3	93.53	6.47	51.05	48.95	4.7	95.3	9.2	90.8	6.88	93.12
4	97.37	2.63	76.09	34.91	76.42	23.58	77.35	22.65	31.03	68.97
5	94.7	5.3	89.96	10.04	100	0	97.47	2.53	87.39	12.61
6	95.23	4.77	71.84	28.16	28.43	71.57	75.32	24.67	91.32	8.68
7	54.83	45.17	7.65	92.35	0.87	99.13	0.84	99.15	0.56	99.44
Mean	87.20	12.80	47.97	53.75	31.88	68.19	39.55	60.45	33.22	66.78
Std. Dev.	14.88	14.88	32.70	31.53	40.09	40.14	41.70	41.70	39.55	39.55

Site	24-Dec-22		27-Dec-22		29-Dec-22		1-Jan-23		9-Jan-23	
	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)
1	7.38	92.62	7.26	92.74	4.37	95.63	4.29	95.71	1.02	98.98
2	4.95	95.05	6.21	93.79	3.63	96.37	4.46	95.54	0.57	99.43
3	6.24	93.37	5.67	94.33	2.59	97.41	2.15	97.84	0.5	99.4
4	3.93	96.07	4.14	95.86	0.9	99.1	4.27	95.73	0.61	99.39
5	78.37	21.63	39.19	60.81	0.92	99.08	1.21	98.79	0.24	99.76
6	62.8	37.2	12.41	87.59	9.84	90.16	3.94	96.06	0.68	99.32
7	0.38	99.62	0	100	0	100	0	100	0	100
Mean	23.44	76.51	10.70	89.30	3.18	96.82	2.90	97.10	0.52	99.47
Std. Dev.	32.59	32.56	13.10	13.10	3.34	3.34	1.79	1.79	0.33	0.33

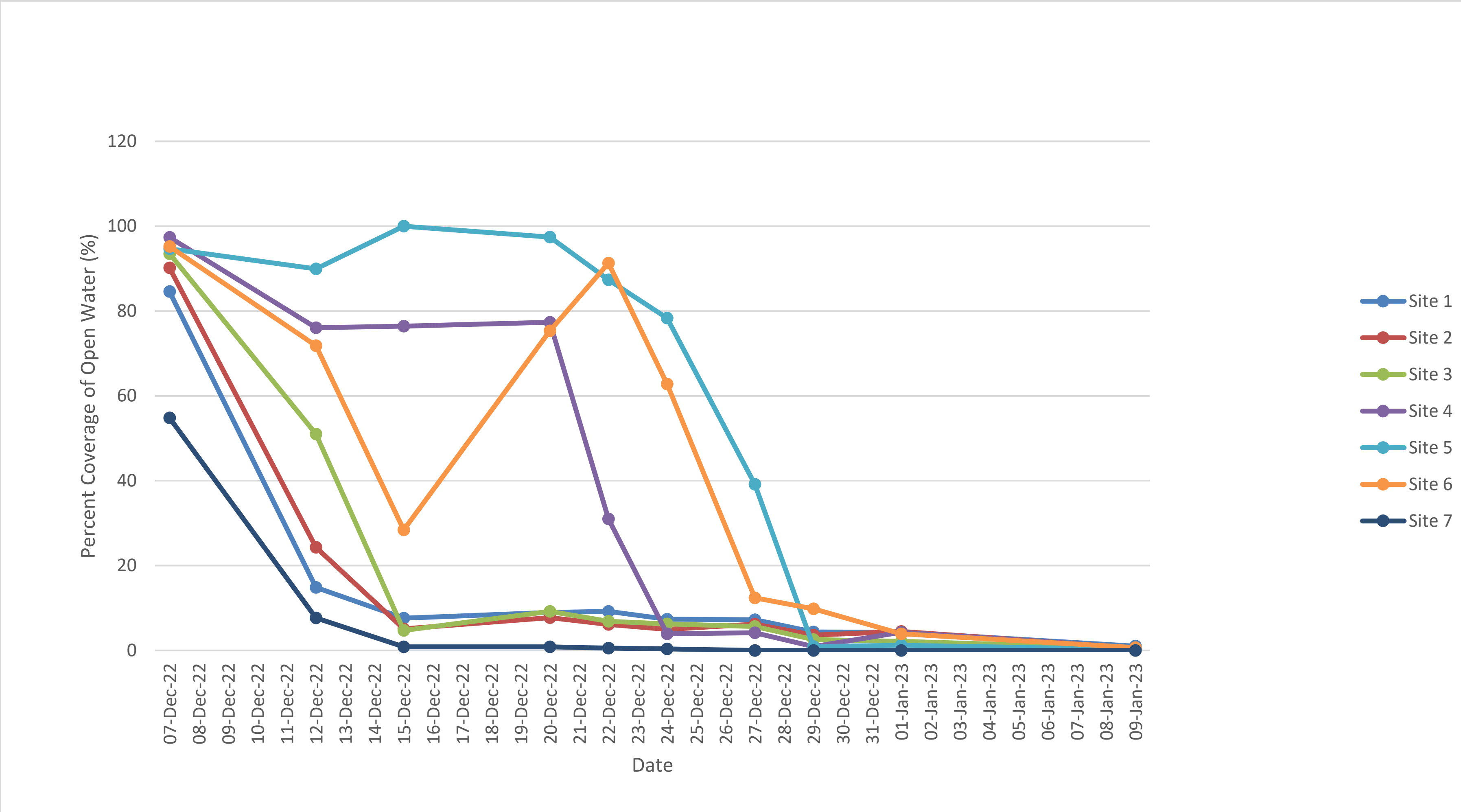

Figure 3.4 Open Water Percent Coverage for Freeze-Up in 2022-2023.

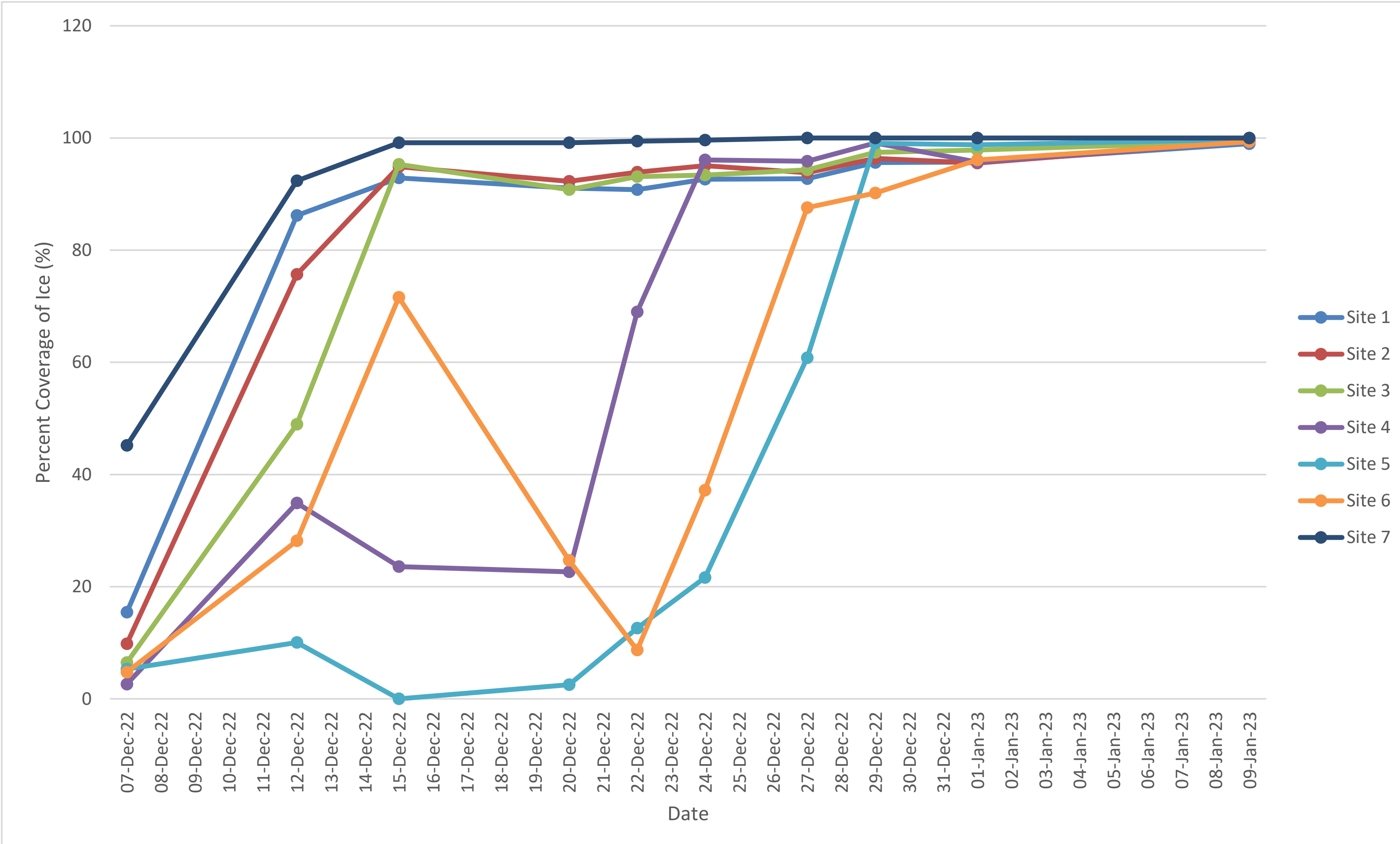

Figure 3.5 **Ice Cover Percent Coverage for Freeze-Up in 2022-2023.**

3.3.2 Break-Up Period

Table 3.4 and Figures 3.7 and 3.8 shows the results of the break-up ice floe analysis. Ten images were selected for analysis for the break-up period: March 26 and April 4, 7, 10, 16, 19, 23, 27, 28, and May 4, 2023. The site numbers correspond to the numbered sections in Figure 2.6.

The percent of ice cover decreased progressively from March 26 through May 4, 2023, with Site 5 the quickest to lose ice with having 91.94% open water on April 23, 2023. Site 6, below Muskrat Falls, also began to lose ice early in the break-up period, but the pace of break-up then slowed until all ice was out by May 4, 2023. The lowest three sites, Sites 1, 2, and 3, were the last to break up with Site 3 not losing ice until April 27, 2023 (38.34% ice cover), and rapidly losing ice by the next day (April 28, 7.13% ice cover). As in previous years, Site 7, above Muskrat Falls was the last to lose ice remaining fully ice covered until April 28, 2023, and still retaining 35.68% ice cover on May 4, 2023, the last day of monitoring, The ice break-up for Sites 6 through 1, excepting Site 5, largely progressed in a downstream direction with Site 1, at Mud Lake, the last to become ice free, with the break-up occurring rapidly at this location from April 28 to May 4, 2023 (from 94.21 to 8.45% ice cover). Overall, the loss of ice cover progressed slowly from the start of monitoring on March 26, 2023 (mean of 98.63% ice cover), to April 19, 2023 (90.43% ice cover), and then accelerated from April 23, 2023 (81.69 % ice cover), to April 28, 2023 (41.53% ice cover), with a mean ice cover on 6.96% on the last day of monitoring (May 3, 2023). Four of seven sites were ice free on the last day of monitoring.

Table 3.4 Ice Cover and Open Water Percent Coverage for the Break-Up Period in 2023.

Site	26-Mar-23		4-Apr-23		7-Apr-23		10-Apr-23		16-Apr-23	
	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)
1	0.2	99.8	0.03	99.97	0.17	99.83	0.35	99.65	0.08	99.92
2	0.29	99.71	0.04	99.6	0.5	99.5	0.79	99.21	0.17	99.83
3	0.04	99.96	0	100	0	100	0	100	0	100
4	0.3	99.7	0.07	99.93	0.15	99.85	0.23	99.77	0	100
5	6.23	93.77	20.93	79.07	20.44	79.56	36.58	63.42	50.49	49.51
6	2.52	97.48	2.49	97.51	1.28	98.72	4.39	95.61	3.81	96.19
7	0	100	0	100	0	100	0	100	0	100
Mean	1.37	98.63	3.37	96.58	3.22	96.78	6.05	93.95	7.79	92.21
Std. Dev.	2.32	2.32	7.80	7.77	7.61	7.61	13.55	13.55	18.88	18.88

Table 3.4 Ice Cover and Open Water Percent Coverage for the Break-Up Period in 2023. (Cont'd)

Site	19-Apr-23		23-Apr-23		27-Apr-23		28-Apr-23		4-May-23	
	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)
1	0.08	99.92	0.25	99.75	0.89	99.11	5.79	94.21	91.55	8.45
2	0.28	99.72	0.39	99.61	13.14	86.86	56.33	43.67	95.4	4.6
3	0	100	0	100	61.66	38.34	92.87	7.13	100	0
4	0.32	99.68	17.13	82.87	86.68	13.32	97.54	2.46	100	0
5	55.19	44.81	91.94	8.06	95.23	4.77	96.84	3.16	100	0
6	11.13	88.87	18.47	81.53	50.06	49.94	59.83	40.17	100	0
7	0	100	0	100	0.05	99.95	0.06	99.94	64.32	35.68
Mean	9.57	90.43	18.31	81.69	43.96	56.04	58.47	41.53	93.04	6.96
Std. Dev.	20.53	20.53	33.52	33.52	39.87	39.87	41.58	41.58	13.08	13.08

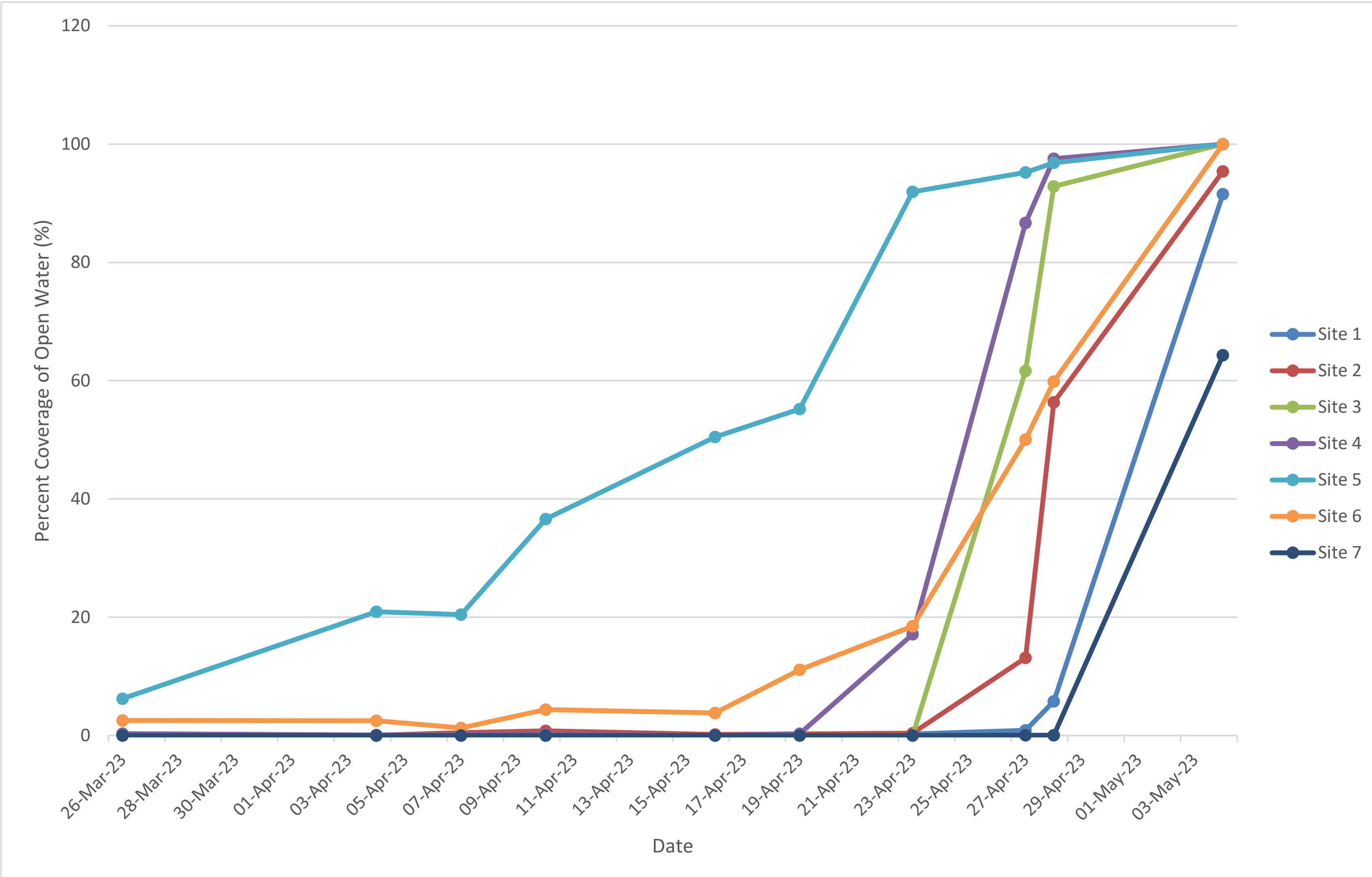

Figure 3.6 Open Water Percent Coverage for Break-Up In 2023.

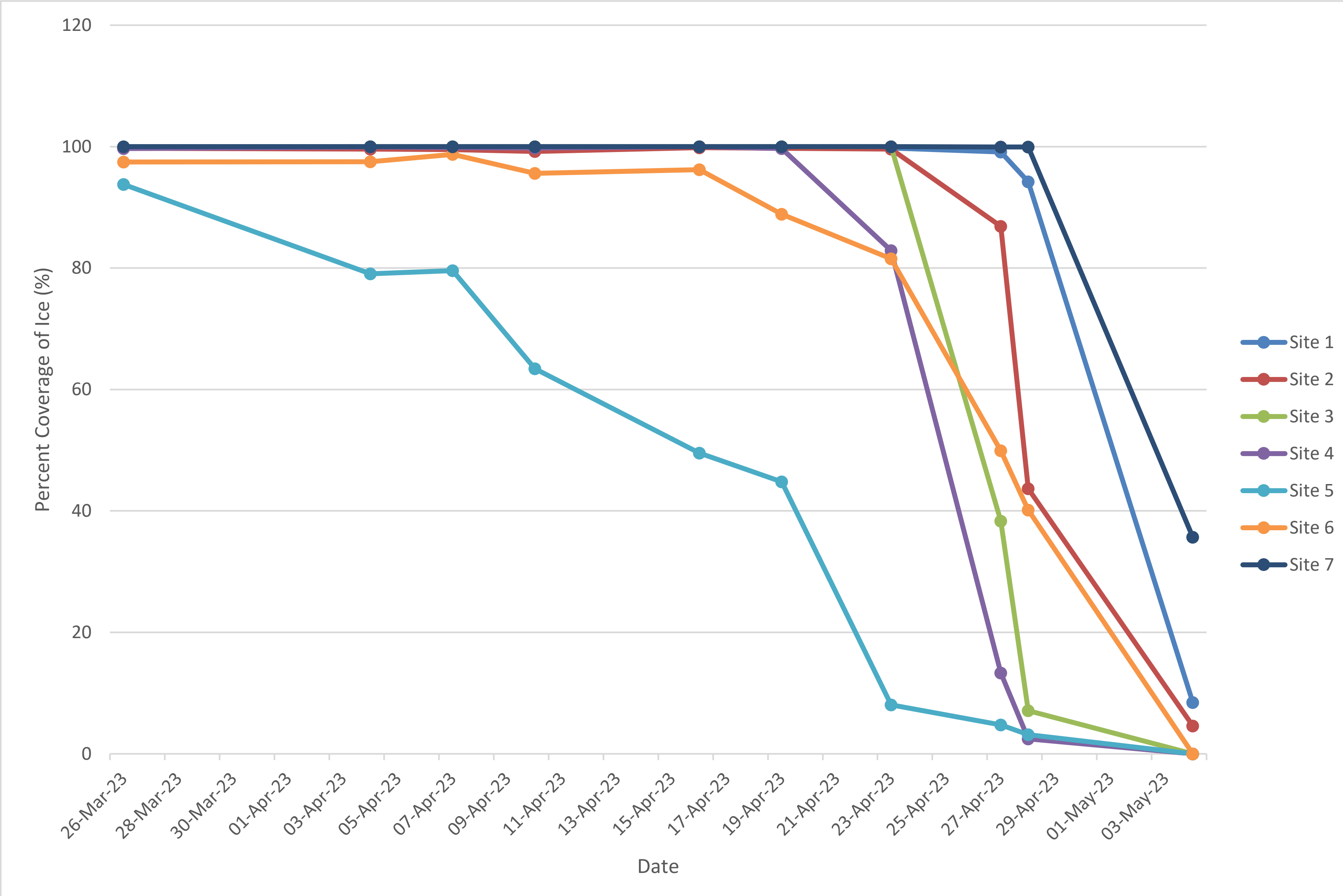

Figure 3.7 Ice Cover Percent Coverage for Break-Up in 2023.

3.4 Satellite Image Analyses

The following sections document the results of the Lower Churchill River freeze-up and break-up monitoring for the 2022-2023 ice season. SEM and C-CORE worked closely to estimate the likely timing of break-up and freeze-up using a variety of tools and methods, including local knowledge, weather data, webcam images, and freely available satellite imagery. Freeze-up begins with a period of freezing air temperatures and ice accumulation in Goose Bay which then prevents ice from leaving the river triggering freeze-up. Break-up on Goose River (Figure 3.8), which is just north of the Lower Churchill River, is normally key indicator of the break-up as it typically precedes break-up on the Lower Churchill River by approximately ten days (J. Hope, pers. comm.). Image acquisition plans were created and modified to adjust to the freeze-up and break-up times. During image analysis and classification, islands and sand bars were masked out and not included in the classifications for the freeze-up and break-up events. Ice cover and ice classification products were generated for all images. Change detection products were generated for all pairs of current and preceding images.

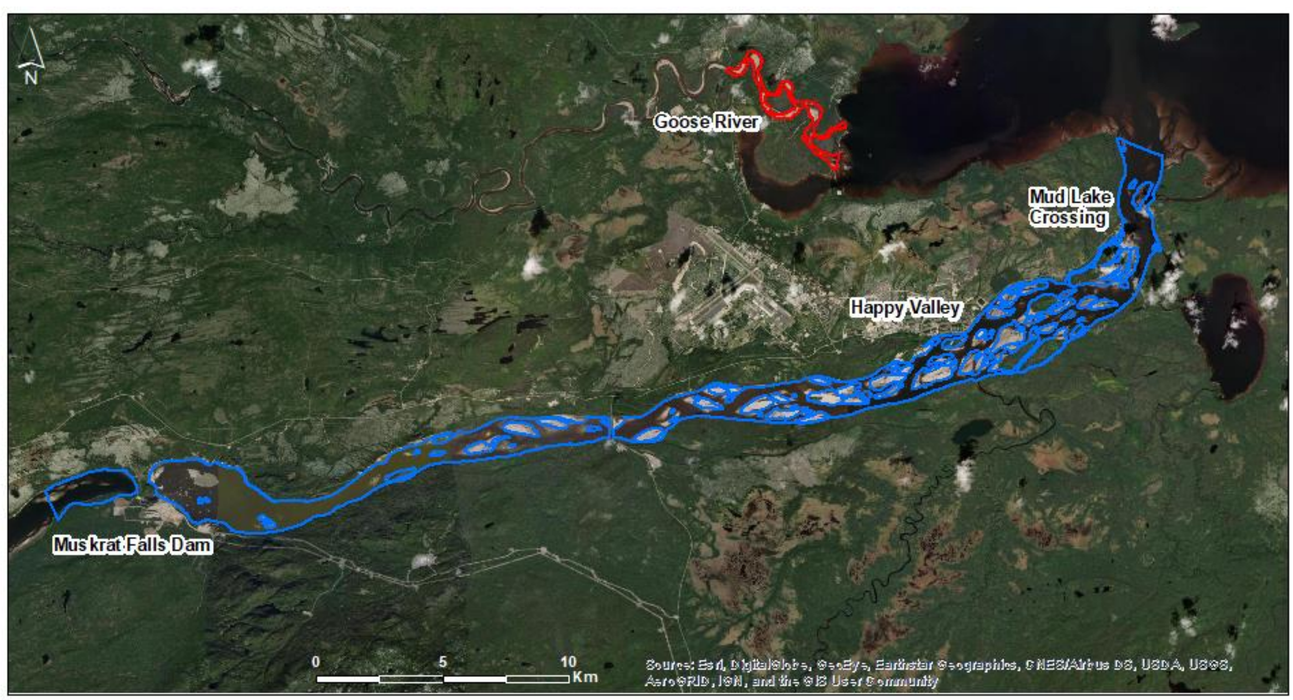

Figure 3.8 Goose River (Red) is Located North of the Churchill River (Blue).

3.4.1 Freeze-Up Period

Appendix A contains the results of the ice analysis for the freeze-up period. Ten SAR images were used for freeze-up analysis between December 7, 2022, and January 9, 2023. Table 3.5 contains the monitoring dates for the past six seasons for comparison. Ice cover, ice classification, and change detection products were produced for all images except for December 7, 2022, where no change detection was produced because it was the first image in the series. Figure 3.9 shows the maximum and minimum temperatures, as recorded by Environment Canada for Goose Bay, Labrador, between November 1, 2022, and January 14, 2023. There was significant precipitation on November 6 and 7, 2022. The highest snowfall occurred on November 17 when 12 cm of snow fell and 9 mm of rain fell on November 9. Freezing temperatures occurred throughout the November 1 to January 15 period reaching -24 on January 15. Daytime high temperatures were mostly below freezing after November 9.

Table 3.5 Freeze-up Monitoring Dates for the Last Six Seasons.

Ice Season	Monitoring Start Date	Monitoring End Date
2017-2018	December 11, 2017	December 19, 2017
2018-2019	November 14, 2018	December 2, 2018
2019-2020	December 3, 2019	December 27, 2019
2020-2021	November 27, 2020	January 1, 2021
2021-2022	December 8, 2021	January 9, 2022
2022-2023	December 7, 2022	January 9, 2023

During the early stages of freeze-up, ice accumulates at the mouth of the Churchill River due to ice buildup in Goose Bay and on the borders of sandbars and islands. Ice also forms on the river above the Muskrat Falls hydroelectric dam. Figure 3.10 shows the ice classification for December 7, 2022. Over the next five days, ice had accumulated in the river extending the ice cover upstream to Traverspine River due to ice buildup in Goose Bay and Lake Melville. Ice accumulated upstream towards Muskrat Falls over the next 28 days until the entire section of river was ice covered. One area remained open about 6 km downstream of the dam.

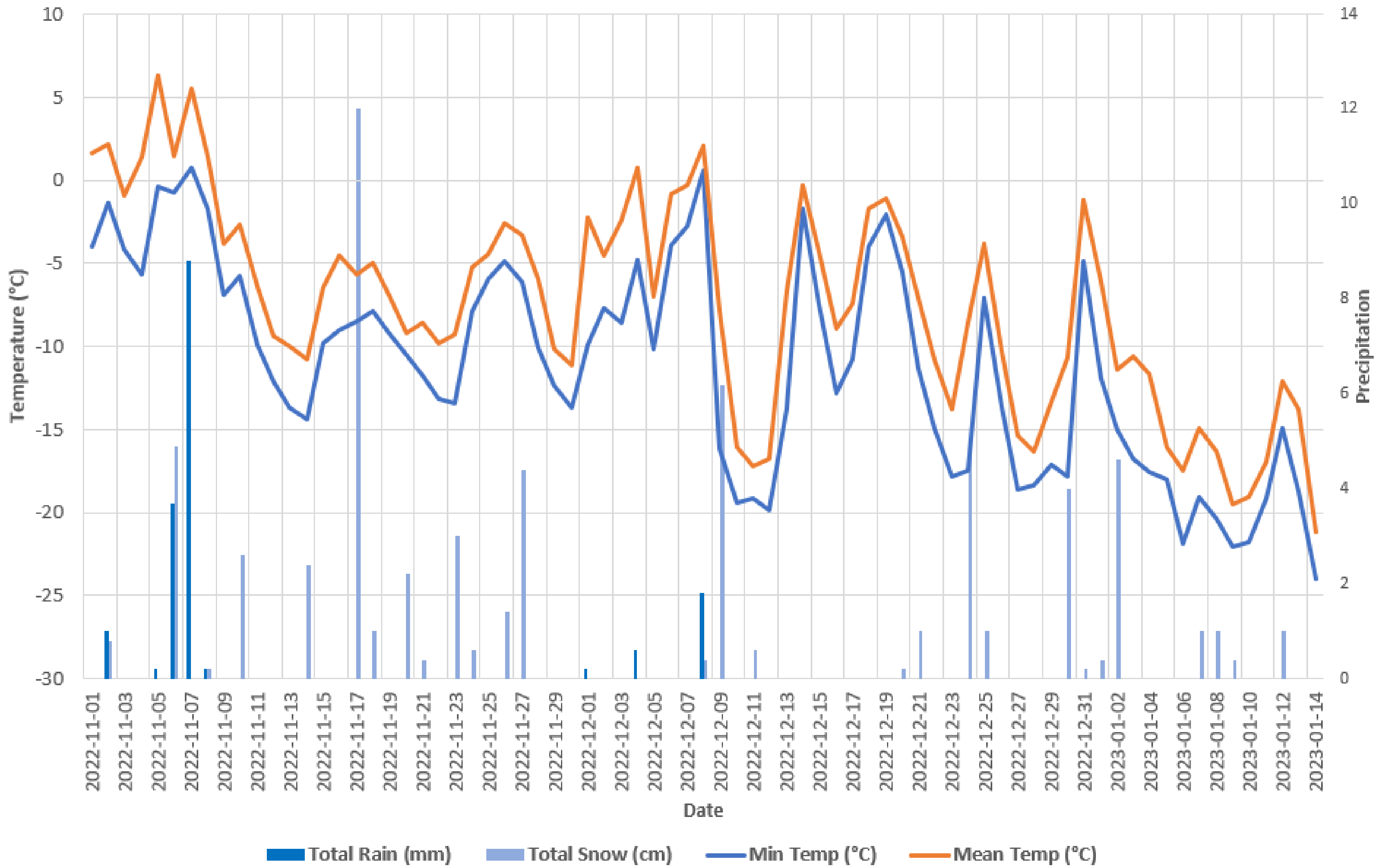

Figure 3.9 Maximum (red) and Minimum (blue) Daily Temperatures for Happy Valley – Goose Bay, Labrador with Precipitation Amounts and Types During Freeze-up from November 1, 2022, to January 14, 2023.

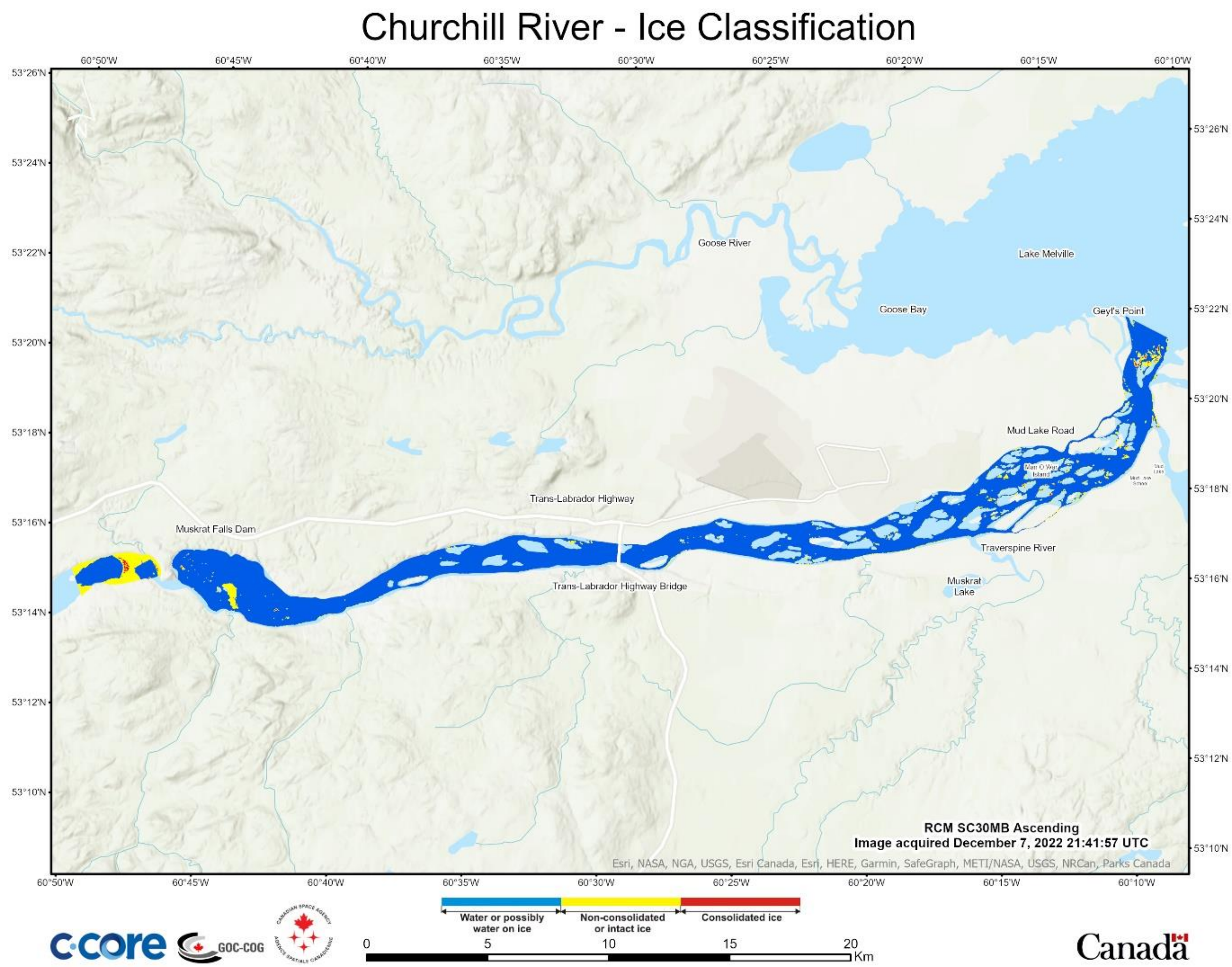

Figure 3.10 Ice Classification Product for December 7, 2022.

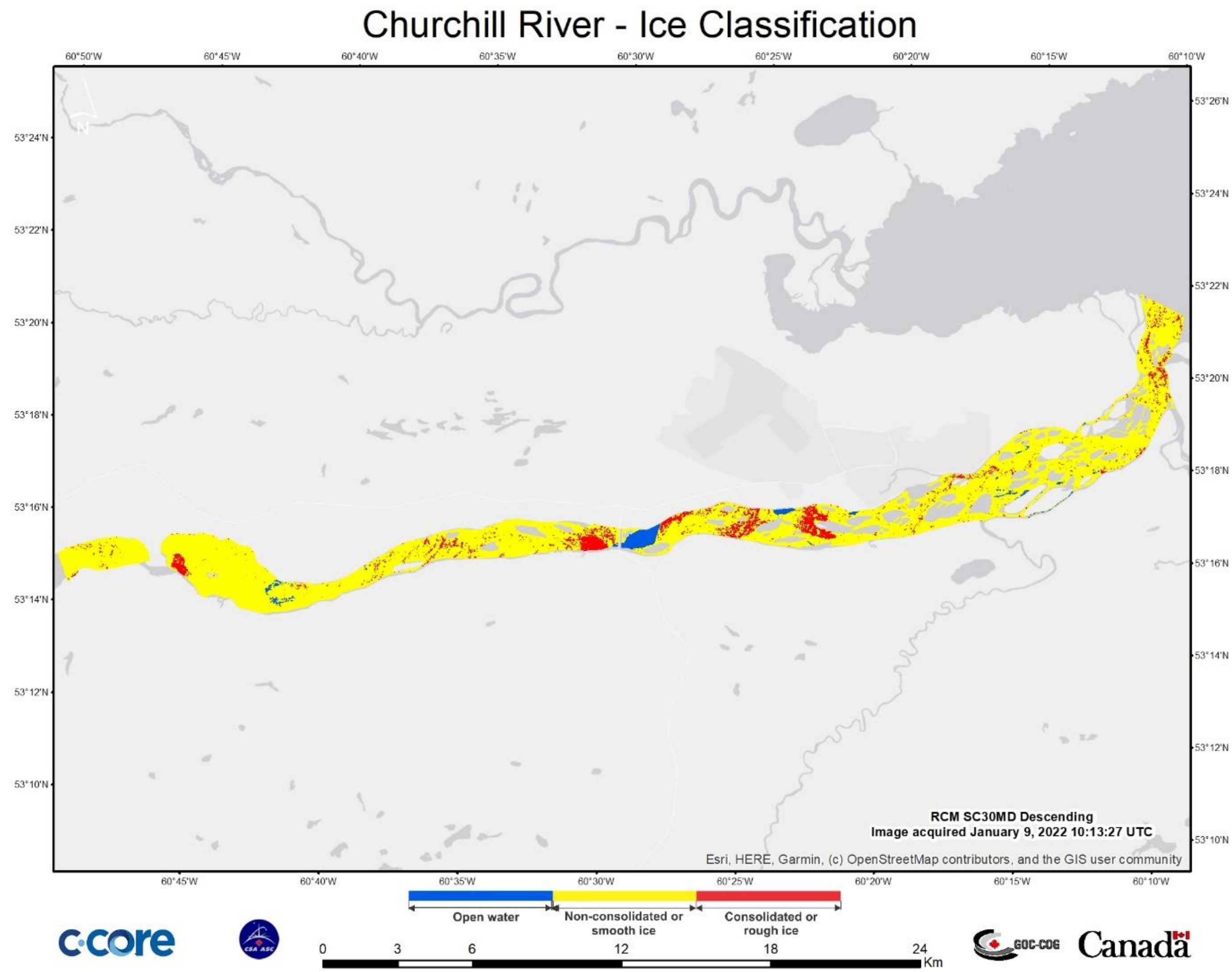

Figure 3.11 Ice Classification Product for January 9, 2023

3.4.2 Break-Up Period

Appendix B contains the results of the ice analysis for break-up. Ten SAR images were used for freeze-up analysis between April 10 and May 4, 2023. Ice cover, ice classification, and change detection products were produced for all images except for April 10 where no change detection was produced because it was the first image in the series. Figure 3.12 shows the maximum and minimum temperatures and precipitation from April 1 to May 15, 2023, as recorded by Environment Canada for Goose Bay, Labrador. Beginning on April 10, maximum daily temperatures were above freezing and continued until the river was free of ice on May 4. Daytime low temperatures were below freezing during most of the period. There was only one precipitation event to note when about five centimeters of snow fell on April 2.

The first signs of ice cover deterioration were found with the March 26, 2023 SAR image (Figure 3.13) where open areas of water appeared downstream of the dam. With the break-up analysis, a third ice class is used to represent areas of pooling water on the ice cover. The open water areas continued to grow into April. Pooling water continued to increase on the ice surface as air temperatures warmed in April (Figure 3.14). The open water and pooling water areas continued to grow at which point the ice cover had reduced to about 50% by April 27 (Error! Reference source not found. 3.15). On May 4, 2023 the Churchill River was ice free below the dam. Some ice remained above the dam at this time.

Table 3.6 Break-up Monitoring Dates for the Last Six Seasons.

Ice Season	Monitoring Start Date	Monitoring End Date
2017-2018	May 2, 2018	May 20, 2018
2018-2019	May 1, 2019	May 22, 2019
2019-2020	April 18, 2020	May 14, 2020
2020-2021	April 5, 2021	April 28, 2021
2021-2022	April 26, 2022	May 26, 2022
2022-2023	April 10, 2023	May 4, 2023

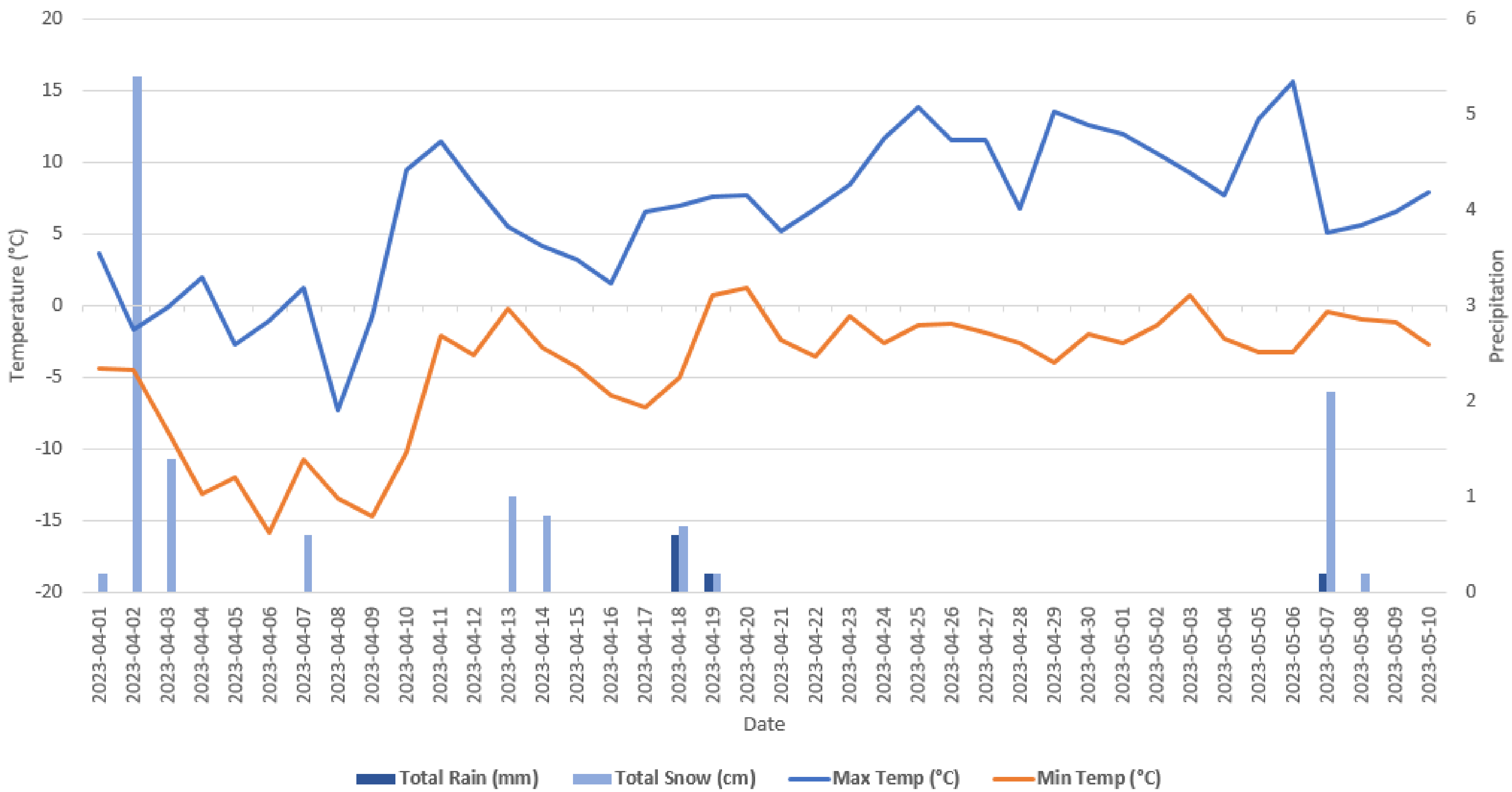

Figure 3.12 Maximum (red) and Minimum (blue) Daily Temperatures for Happy Valley – Goose Bay, Labrador with Precipitation Amounts and Types During Break-up from April 1 to May 10, 2023.

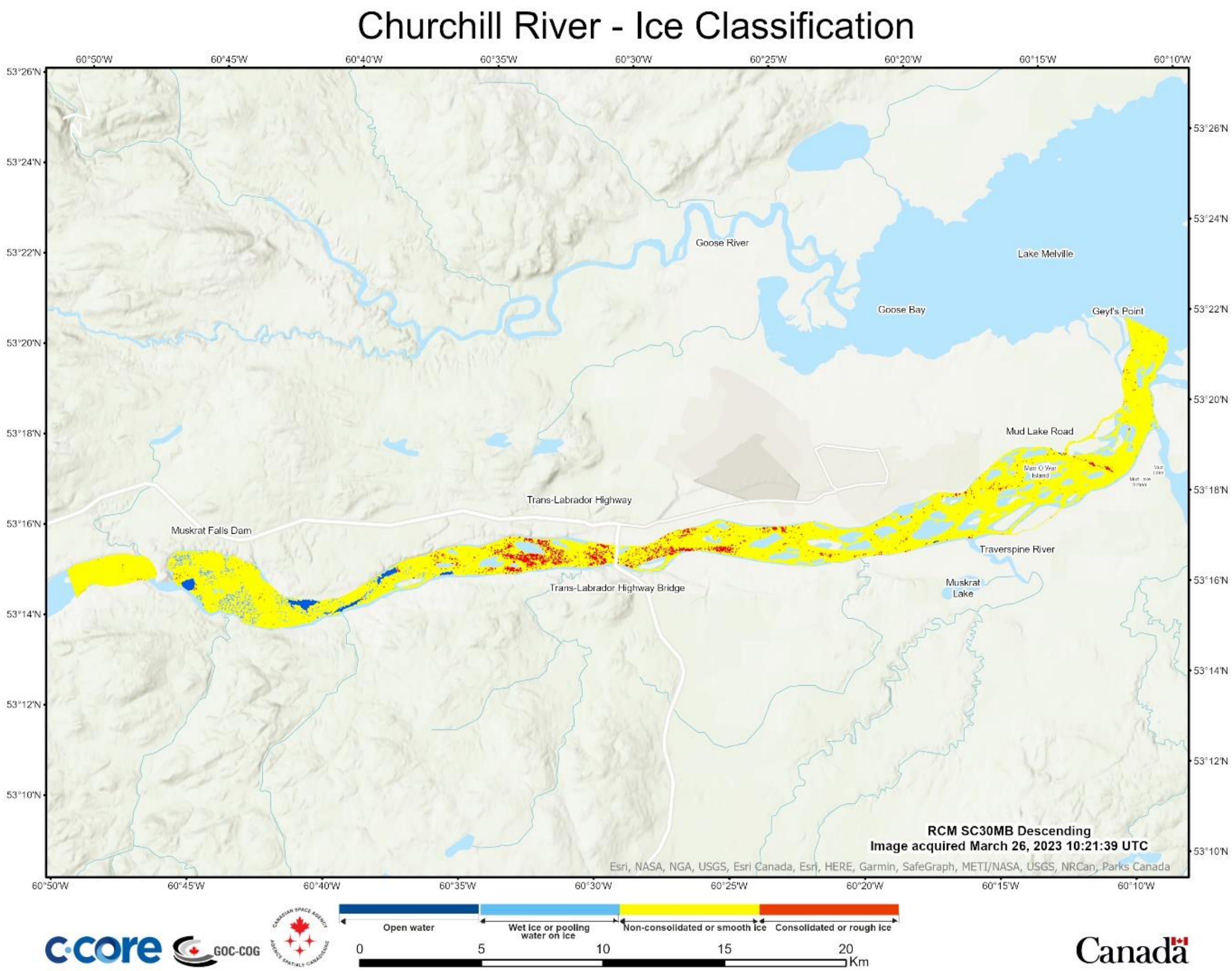

Figure 3.13 Ice Classification Product for March 26, 2023.

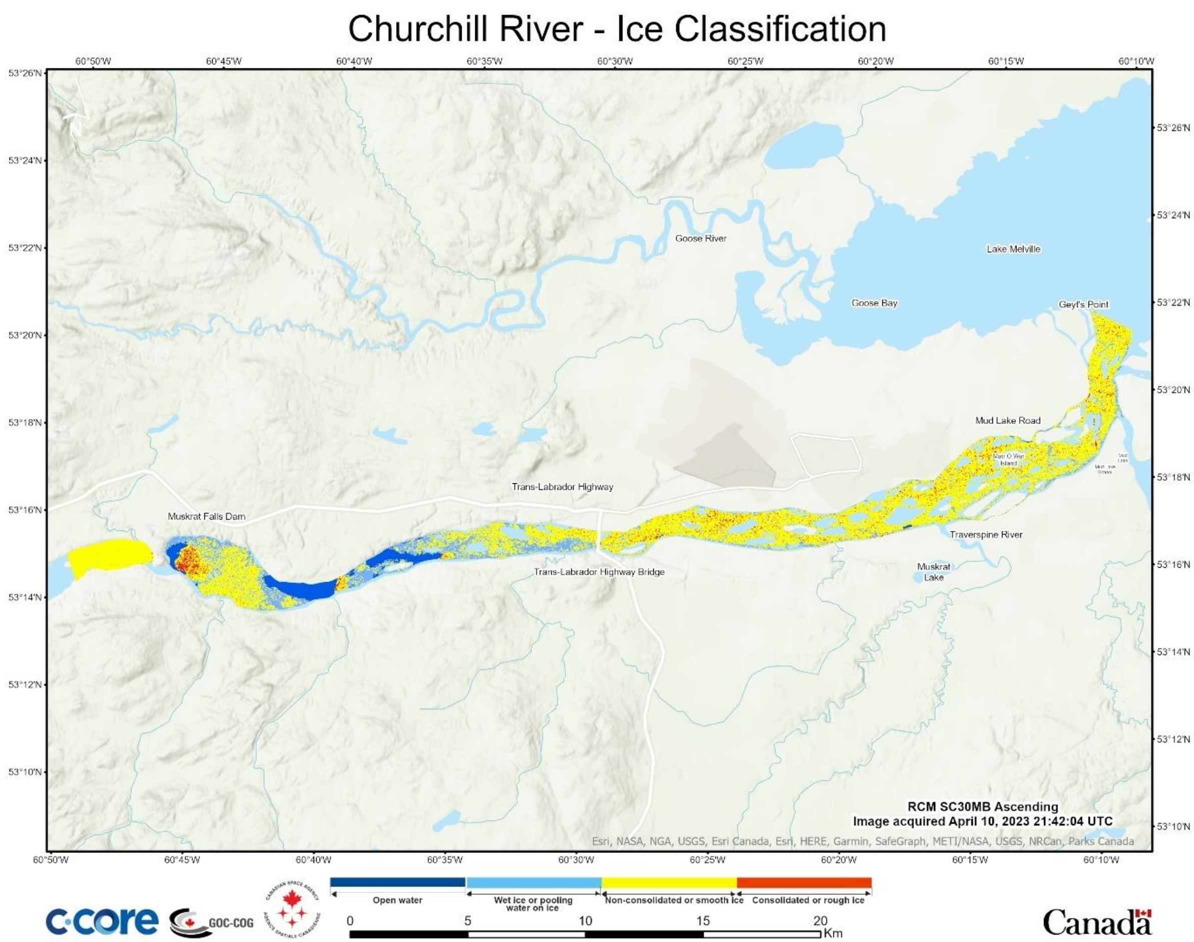

Figure 3.14 Ice Classification Product for April 10, 2023.

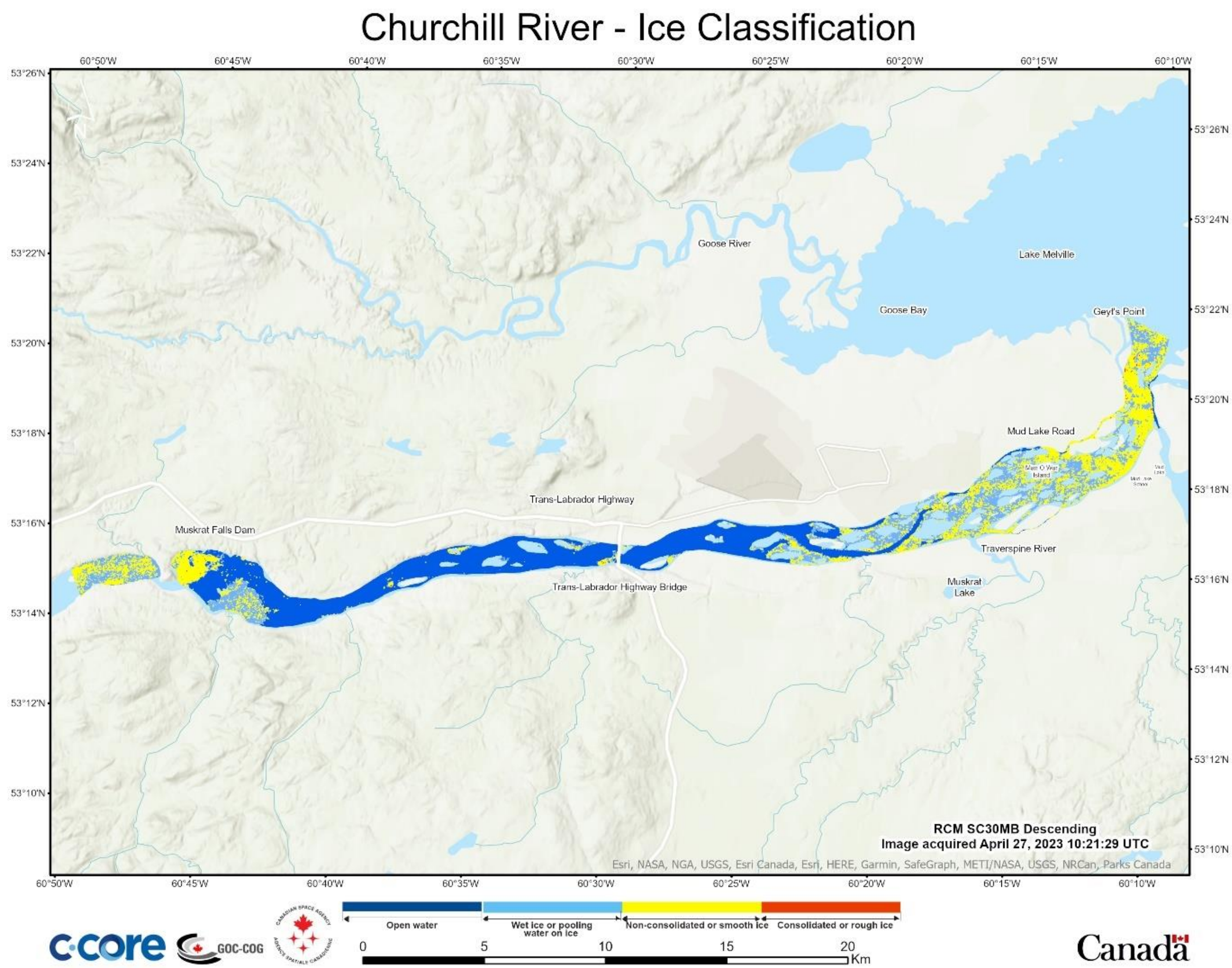

Figure 3.15 Ice Classification Product for April 27, 2023.

4.0 Conclusions and Recommendations

This report presents a summary of the activities for C-CORE's River Ice Monitoring Service for LCP in Labrador. During the 2022-2023 ice season, satellite images were used to monitor ice conditions between the Muskrat Falls Dam and Goose Bay. Images analyzed during freeze-up were acquired between December 7, 2022, and January 9, 2023. Images covering the break-up period were collected from March 26 to May 4, 2023. A total of 20 satellite images were processed to generate and deliver 58 ice information products.

Ice floe concentration analysis was performed on 20 classified satellite images acquired during the freeze-up and break-up periods. The results provided open water and ice cover area concentrations.

Satellite image collection for the 2022-2023 ice season was very successful with acquisition of all 20 required images during ice freeze-up and break-up over the river at the required temporal frequencies. Freely available RCM and S1 SAR combined to provide the 20 images this season to maximize cost efficiency. The continued surveillance over consecutive years is valuable for understanding trends in the ice conditions, ice development and break-up as well as their variability from year to year.

It is recommended to continue to use RCM and S1 SAR images for seasonal monitoring during the period between freeze-up and break-up events due to the high quality of freely available images. With S1B officially lost, S1C is currently being built as a replacement with an expected launch sometime in 2023. The loss of S1B did not affect ice monitoring of the Churchill River due to frequent RCM coverage. Other sources of freely available imagery include the optical satellite missions Sentinel-2 and Landsat, which serve to significantly enhance the day-time spatial and temporal coverage during cloud-free conditions. All systematically acquired, freely available satellite scenes are archived. Relevant archival scenes can be selected on-demand and processed to examine ice cover development within a given season as well as across multiple seasons.

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Appendix A

Lower Churchill Freeze-Up Satellite Imagery

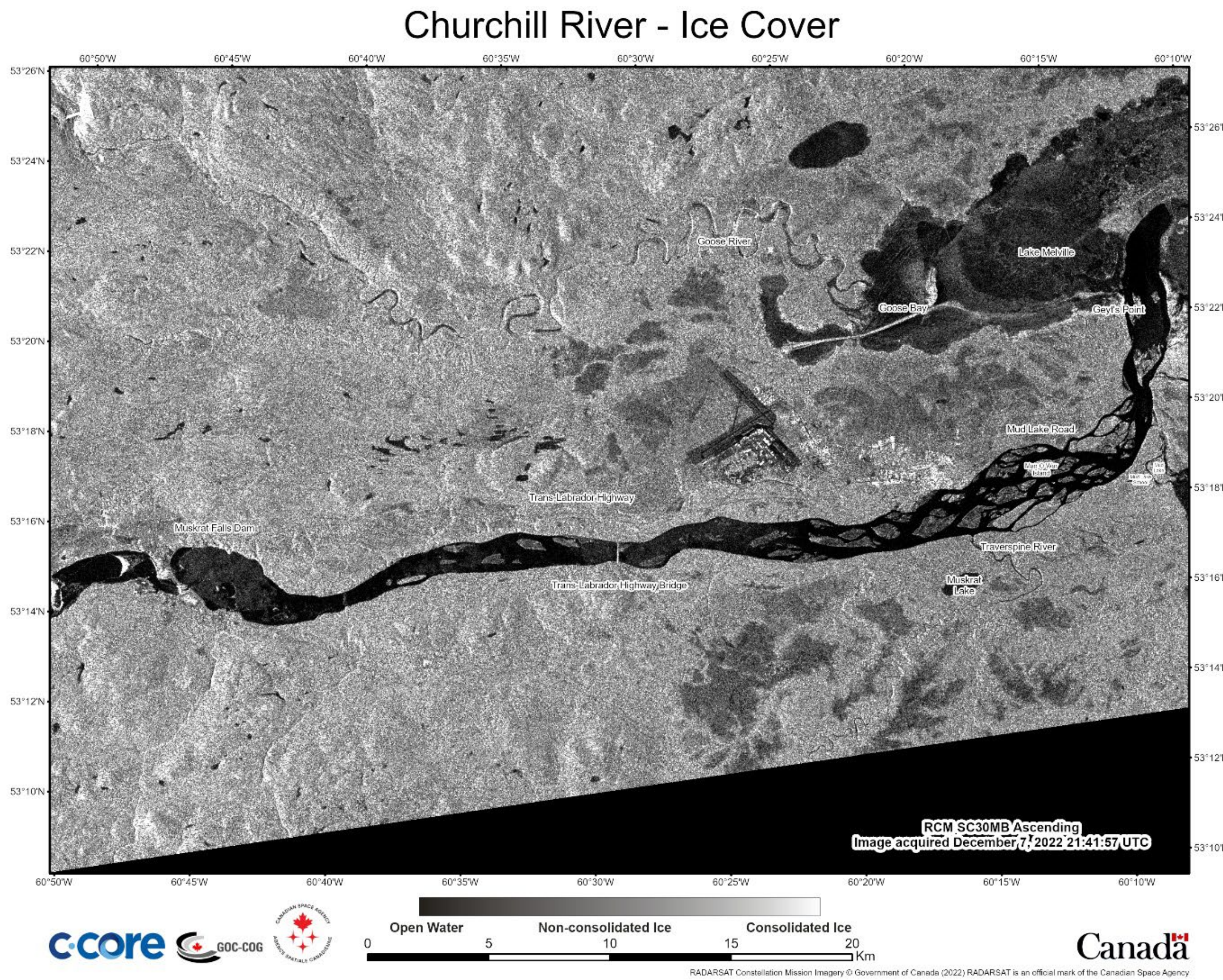

Figure A-1: Ice Cover – December 7, 2022.

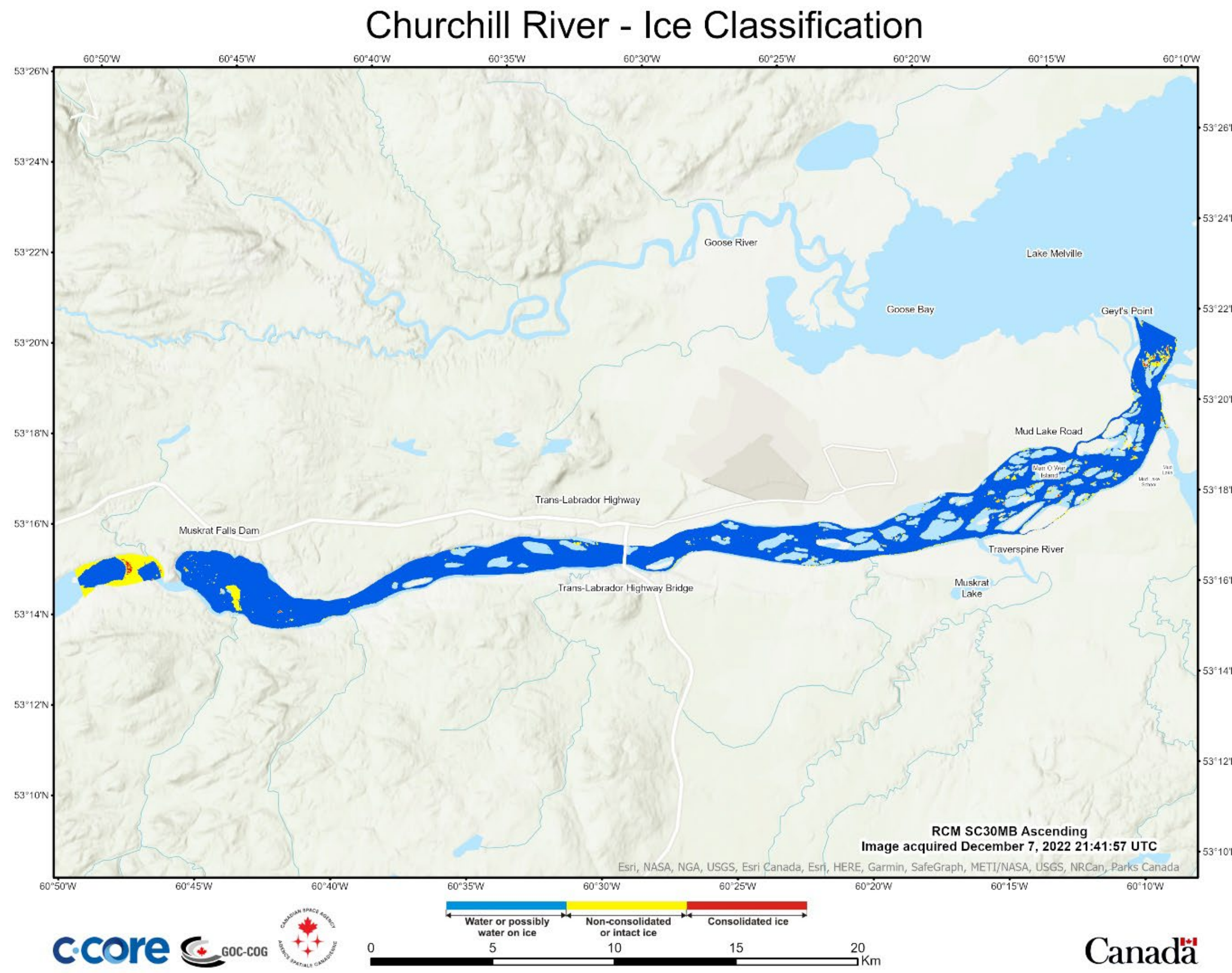

Figure A-2: Ice Classification – December 7, 2022.

Figure A-3: Ice Cover – December 12, 2022.

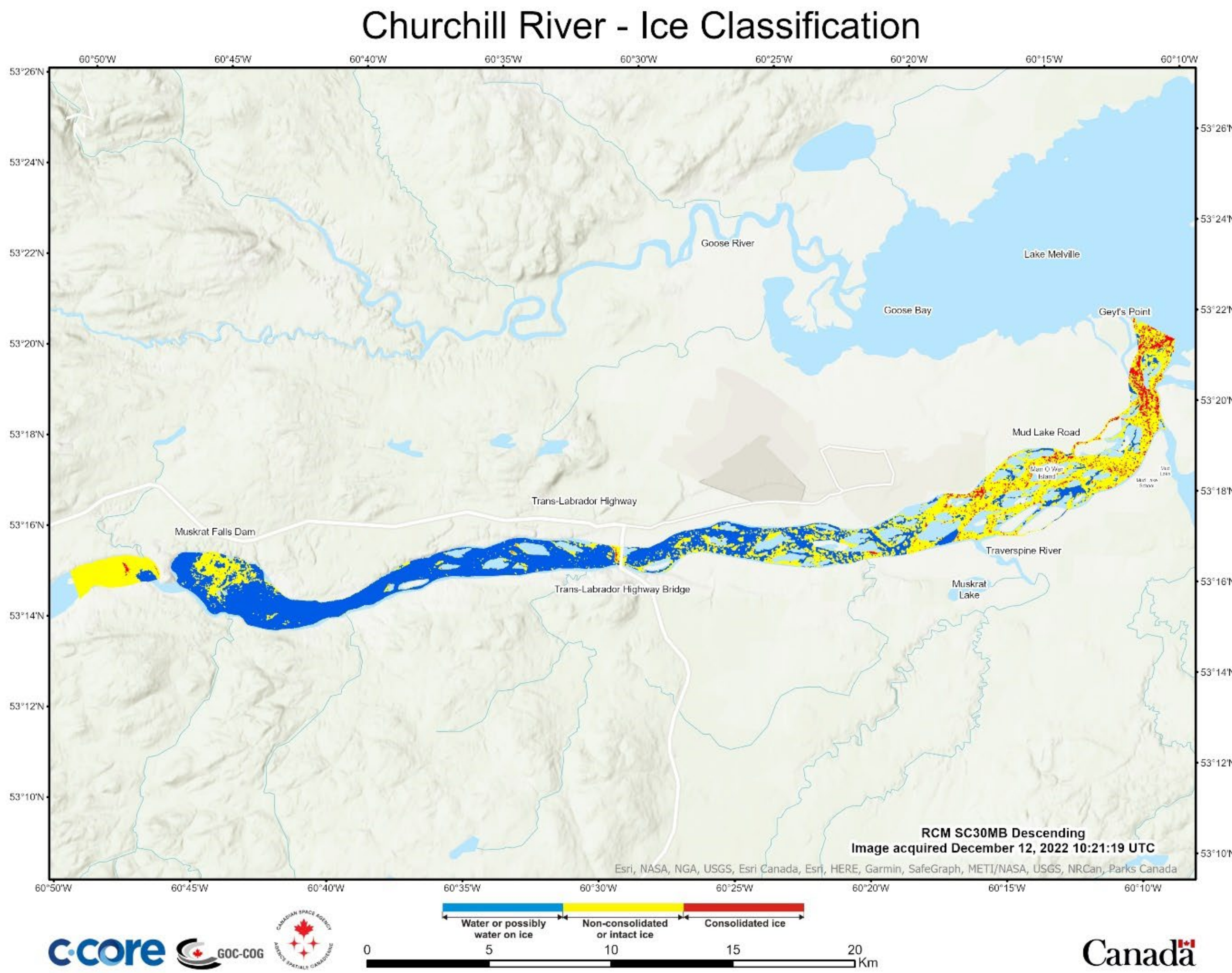

Figure A-4: Ice Classification – December 12, 2022.

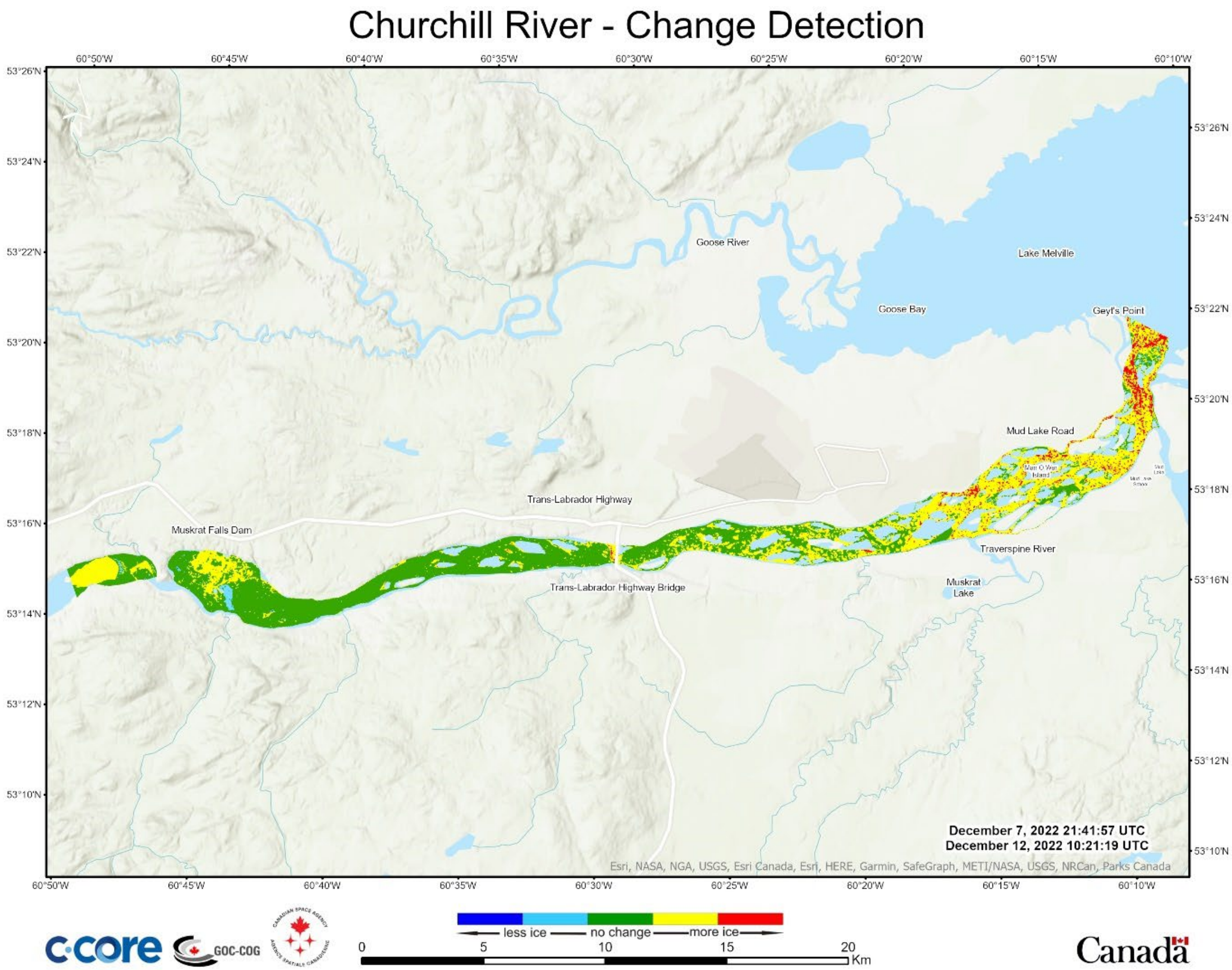

Figure A-5: Change Detection – December 7 and 12, 2022.

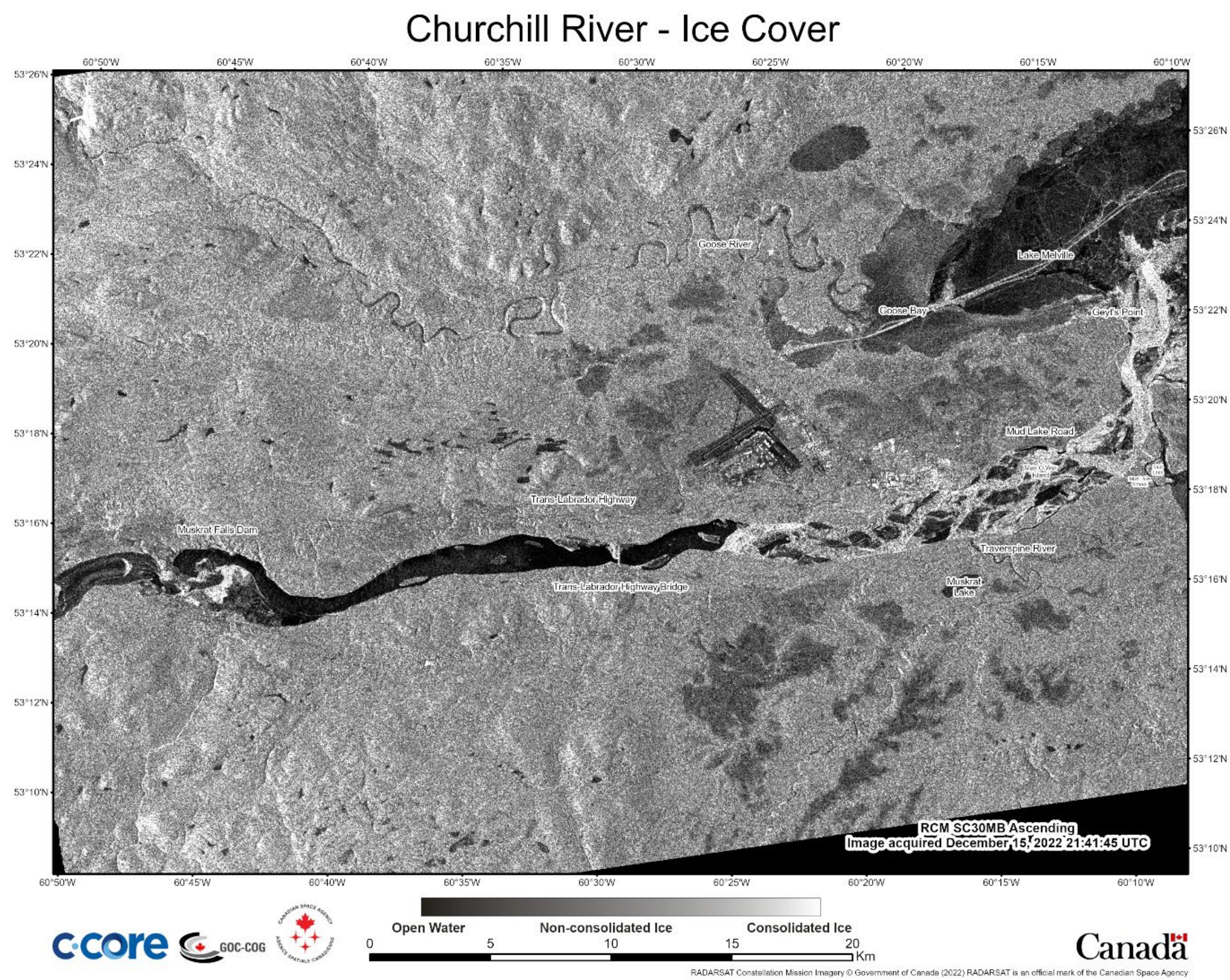

Figure A-6: Ice Cover – December 15, 2022.

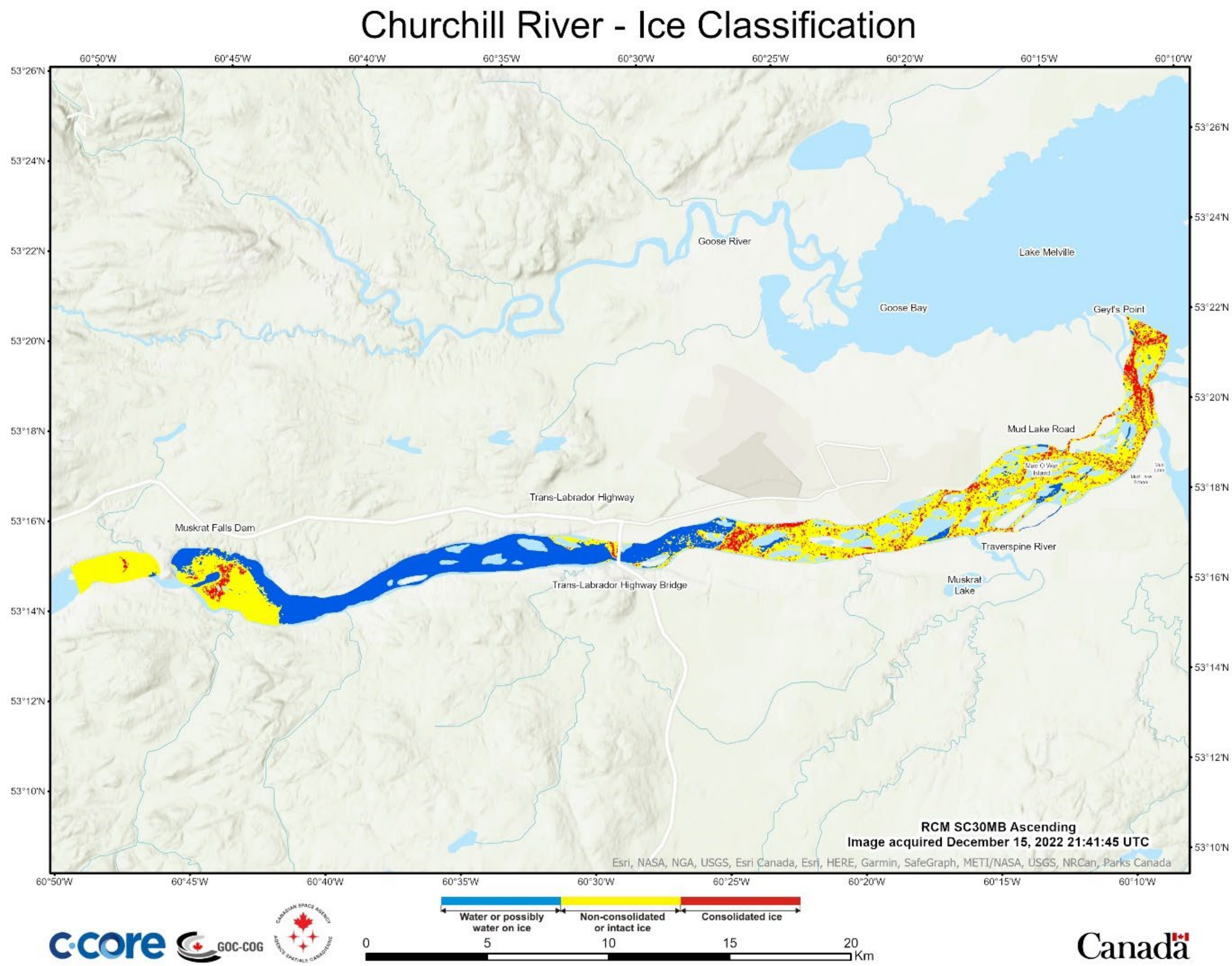

Figure A-7: Ice Classification – December 15, 2022.

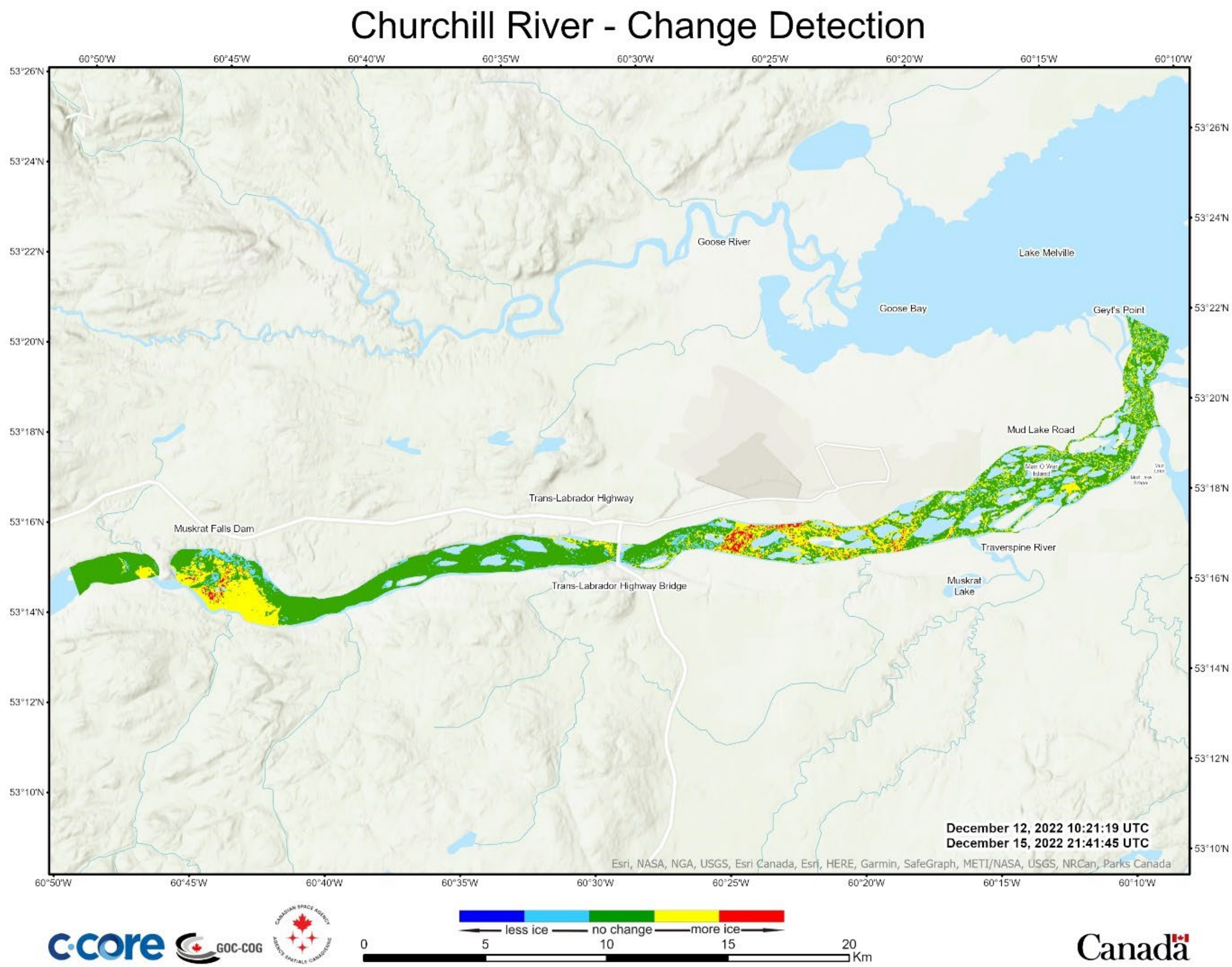

Figure A-8: Change Detection - December 12 and 15, 2022.

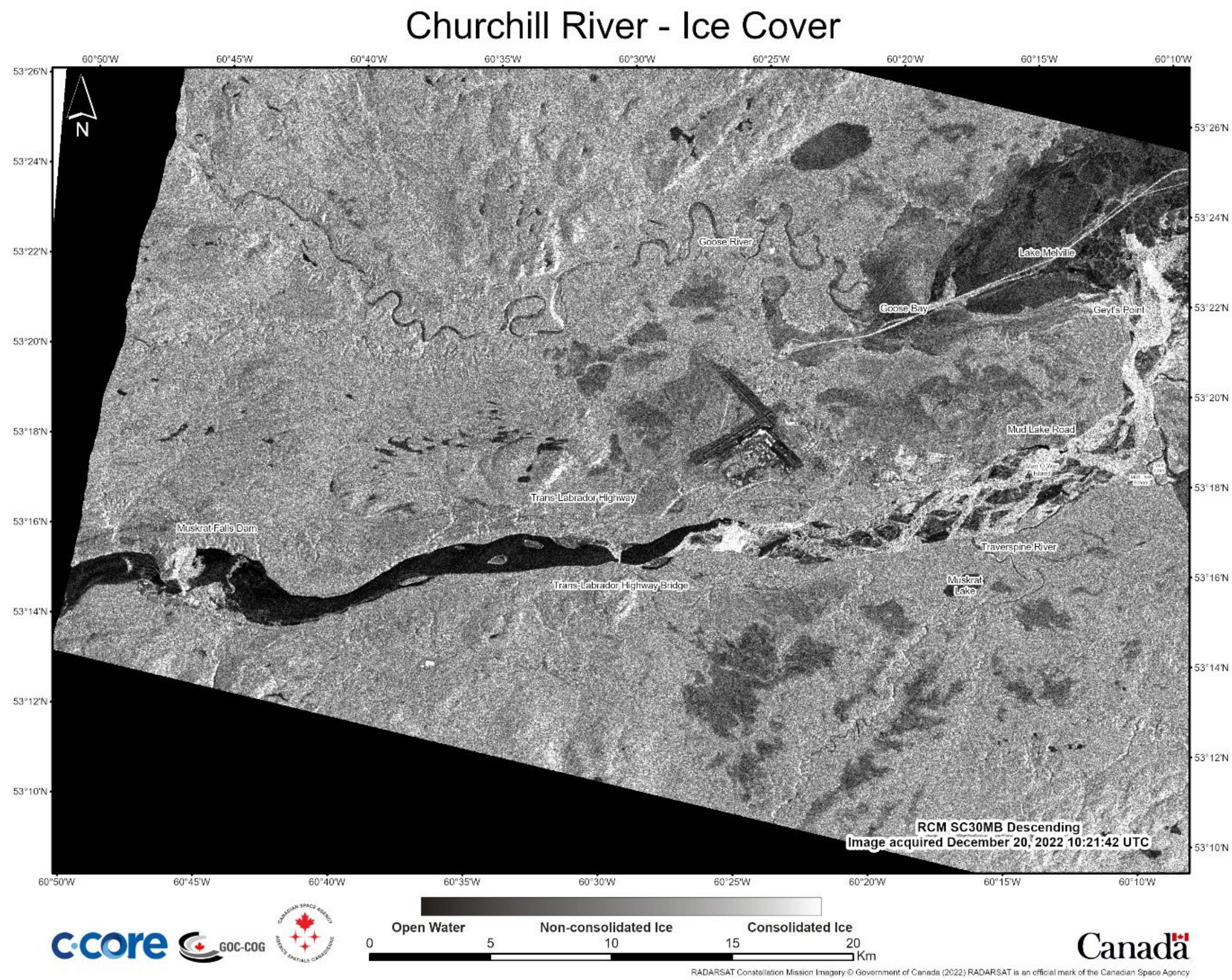

Figure A-9: Ice Cover – December 20, 2022.

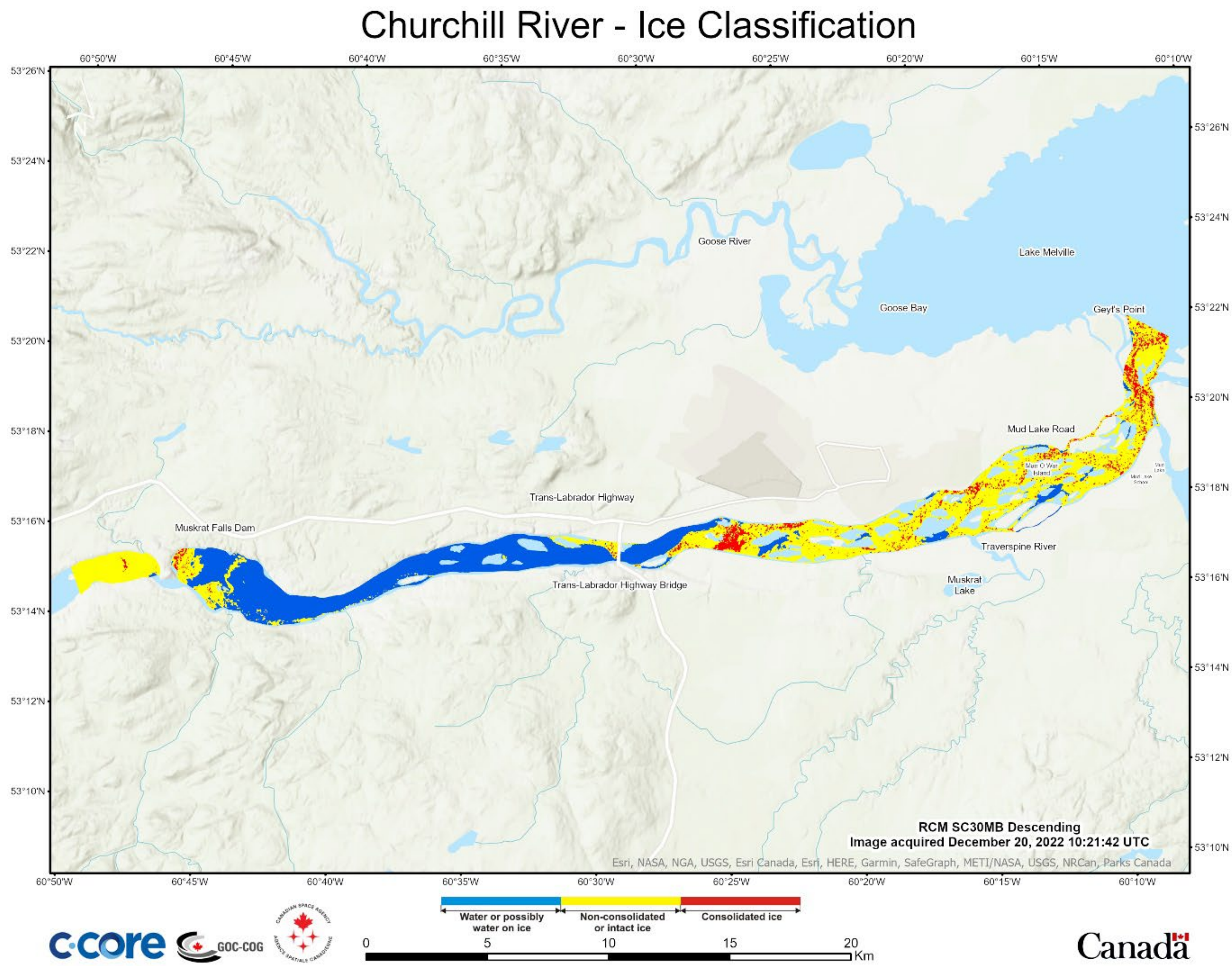

Figure A-10: Ice Classification – December 20, 2022.

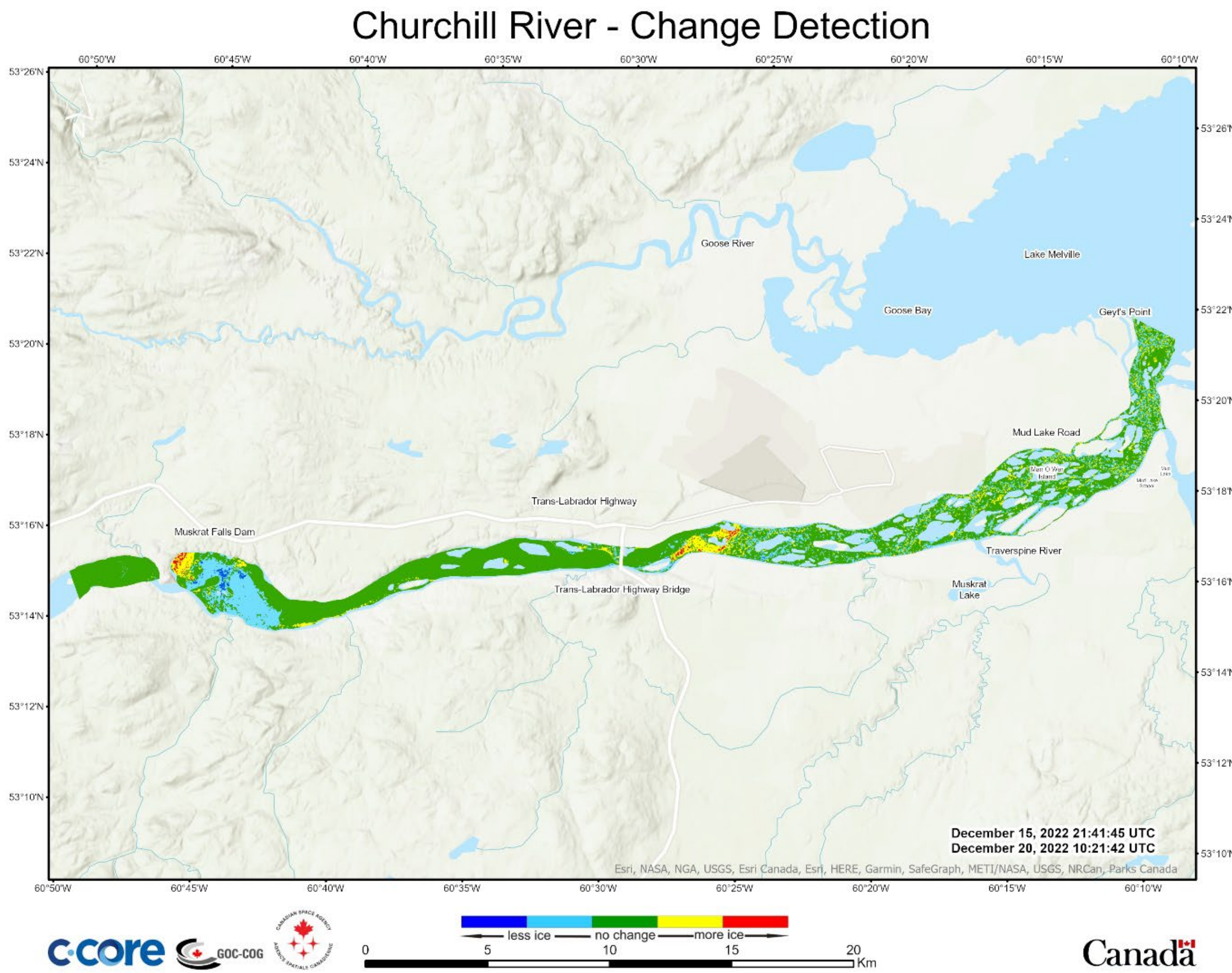

Figure A-11: Change Detection – December 15 and 20, 2022.

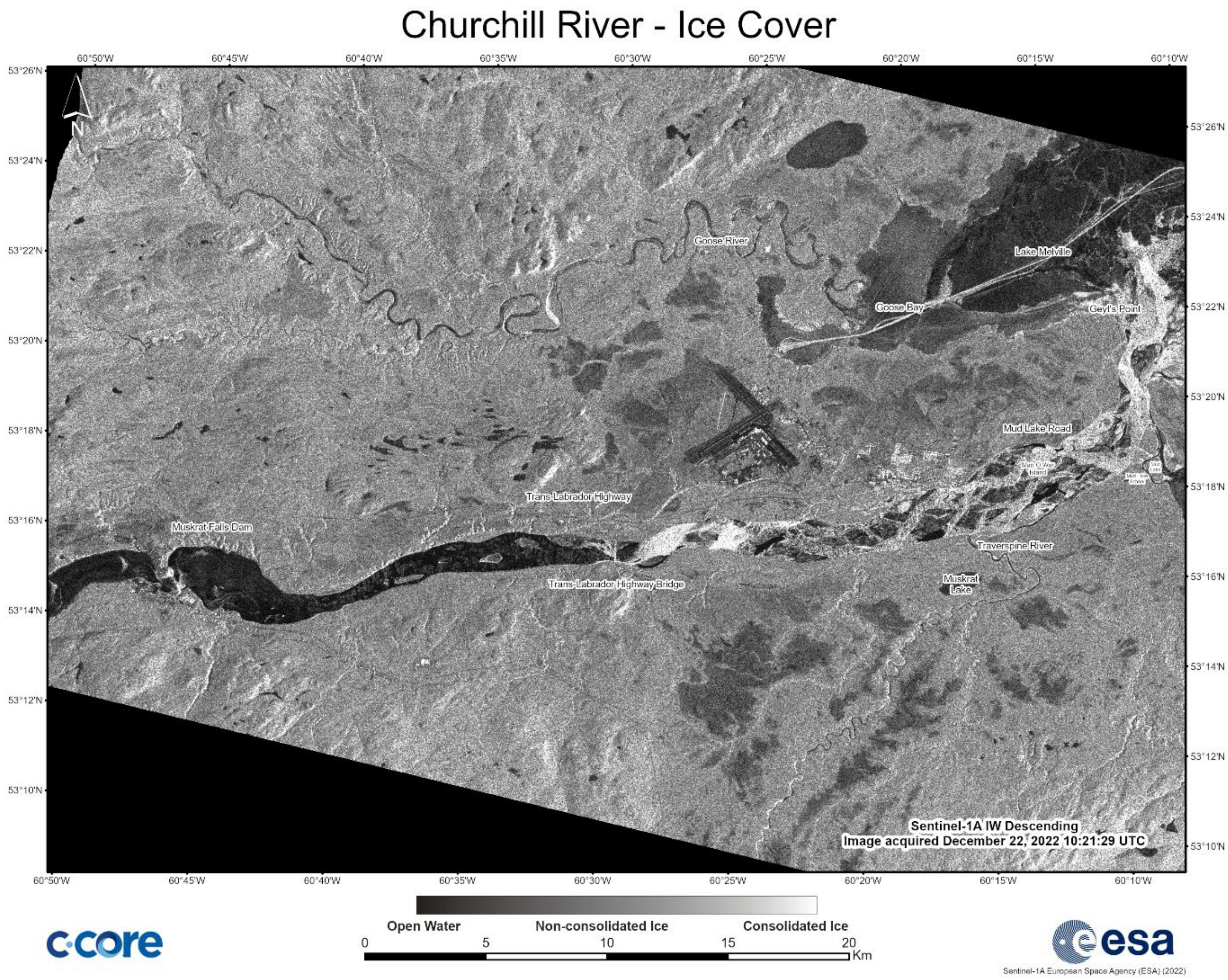

Figure A-12: Ice Cover – December 22, 2022.

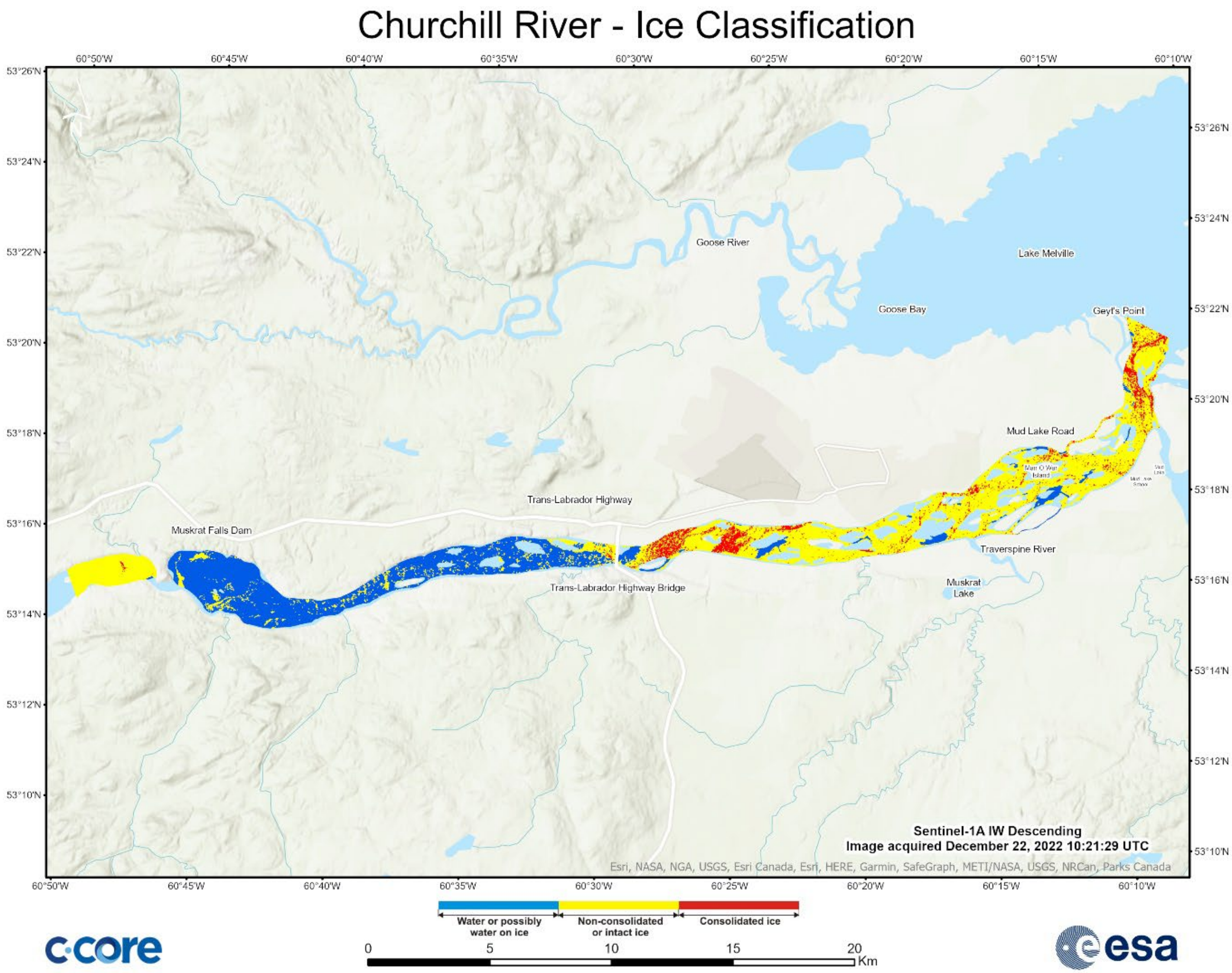

Figure A-13: Ice Classification – December 22, 2022.

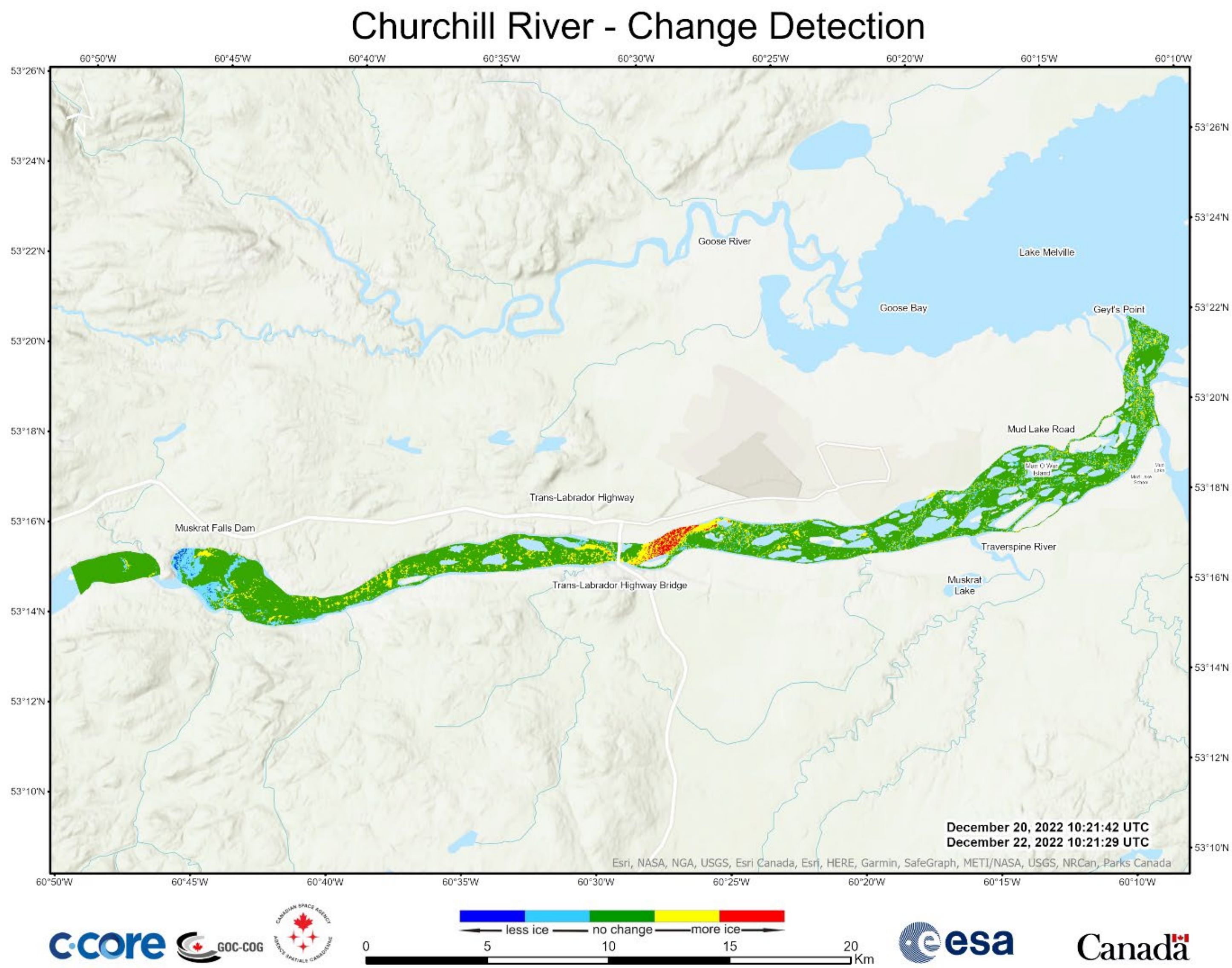

Figure A-14: Change Detection – December 20 and 22, 2022.

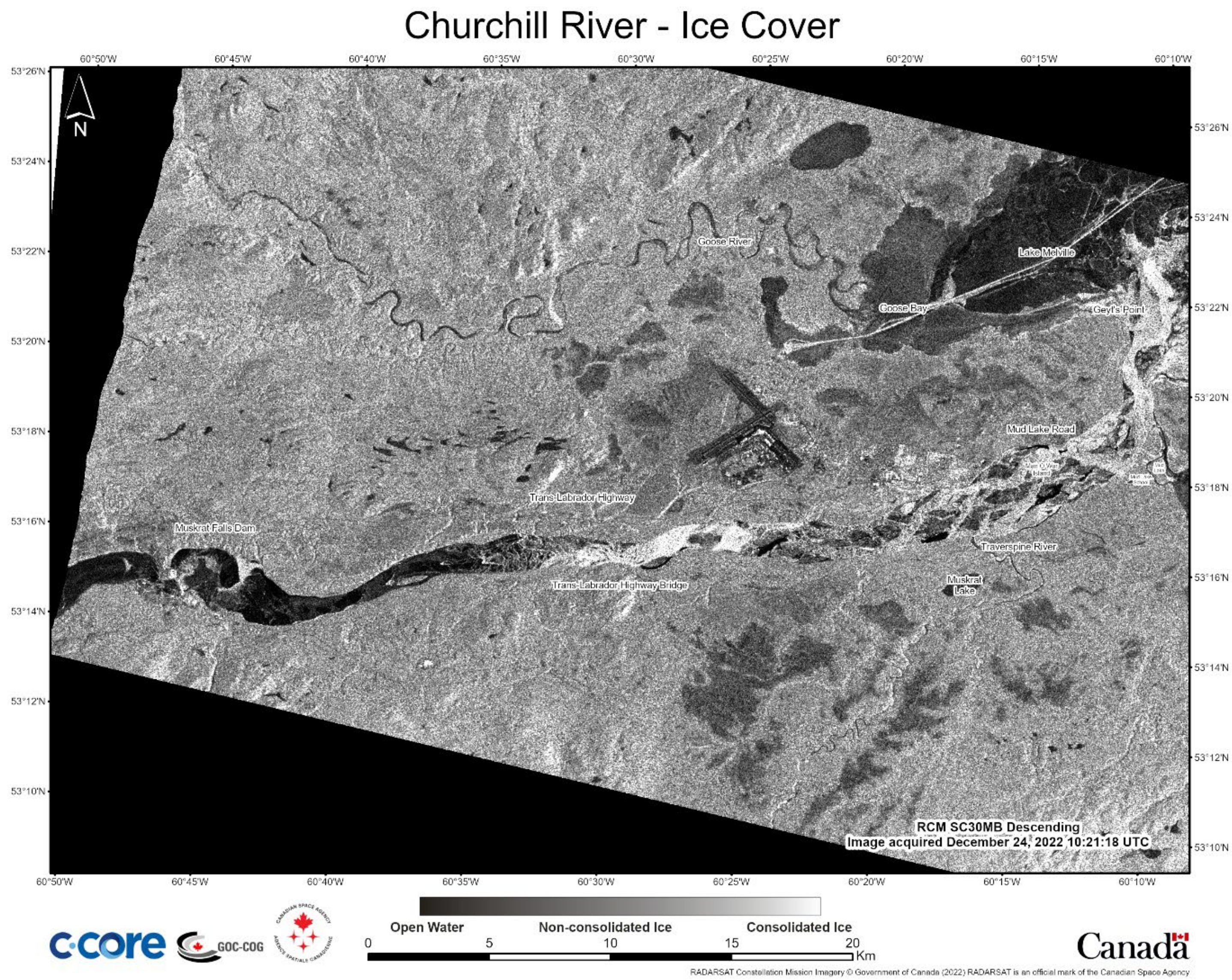

Figure A-15: Ice Cover – December 24, 2022.

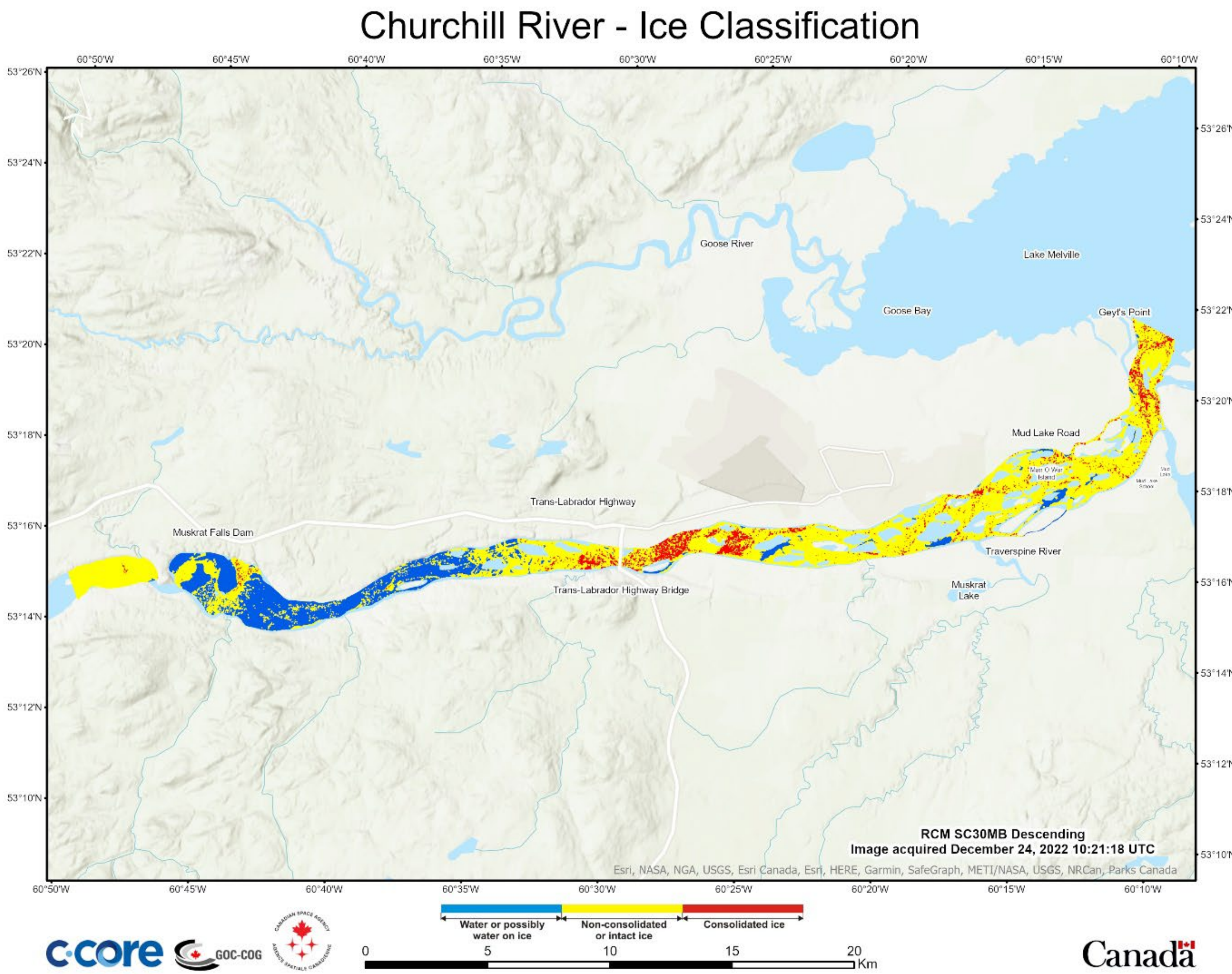

Figure A-16: Ice Classification – December 24, 2022.

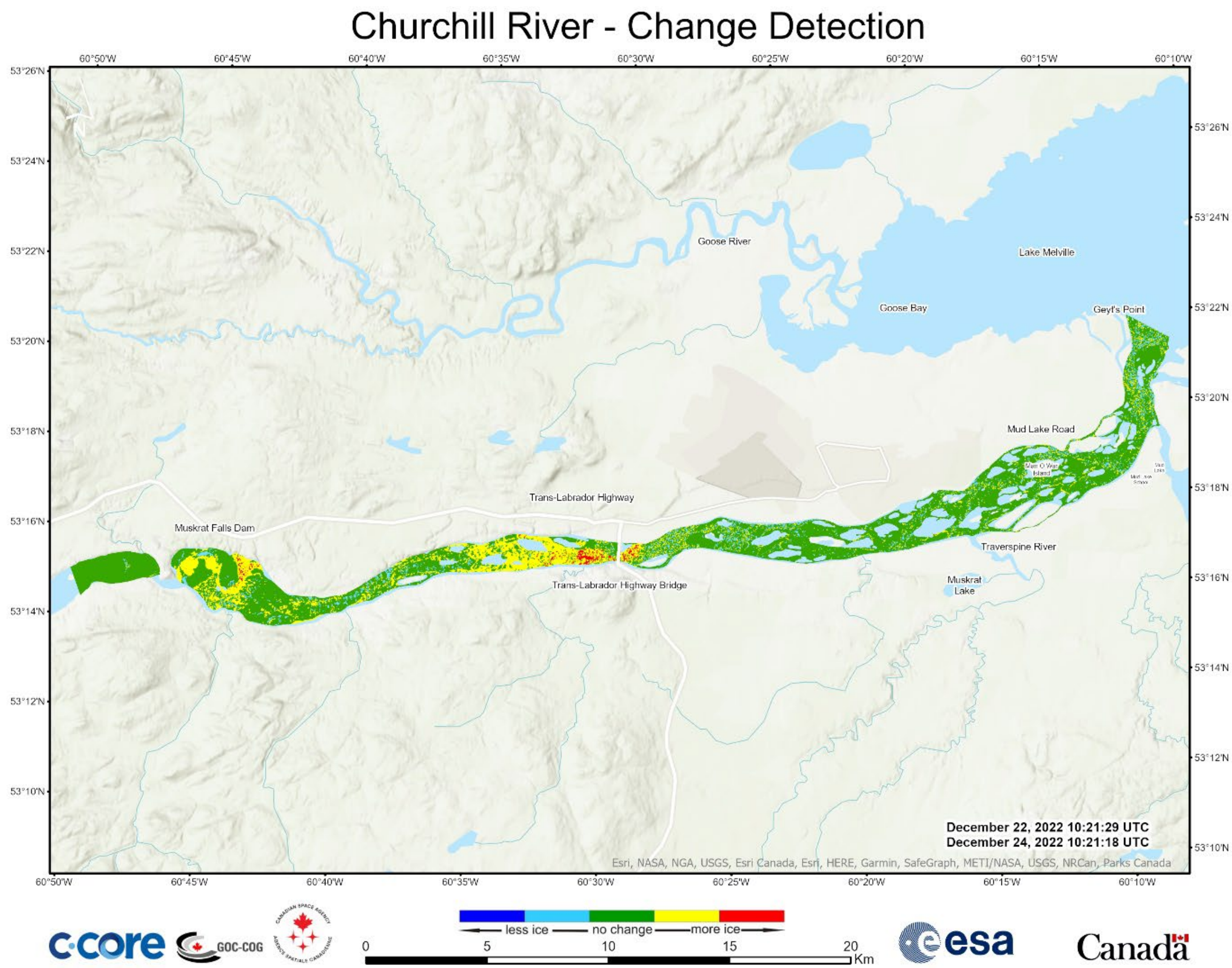

Figure A-17: Change Detection –December 22 and 24, 2022.

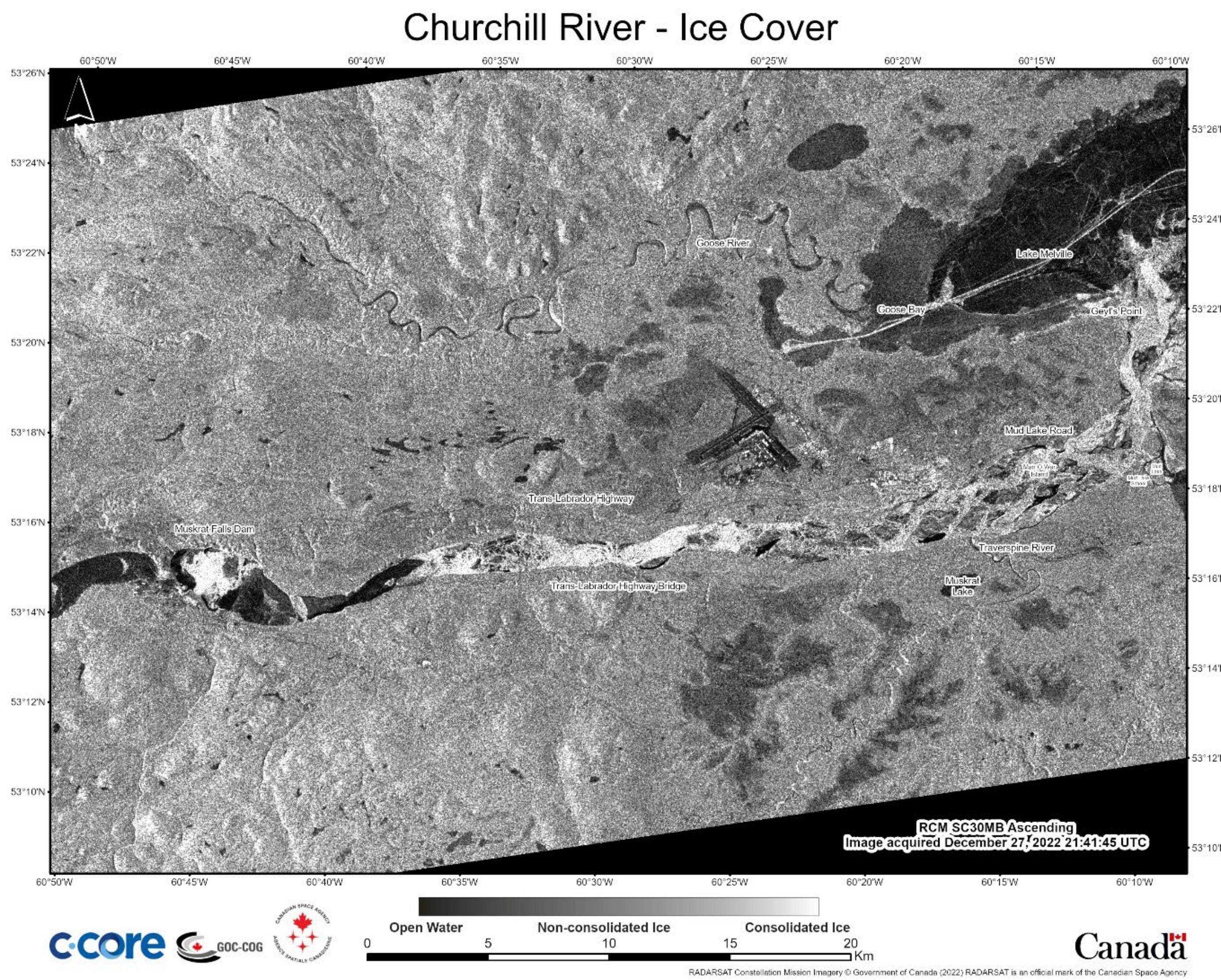

Figure A-18: Ice Cover – December 27, 2022.

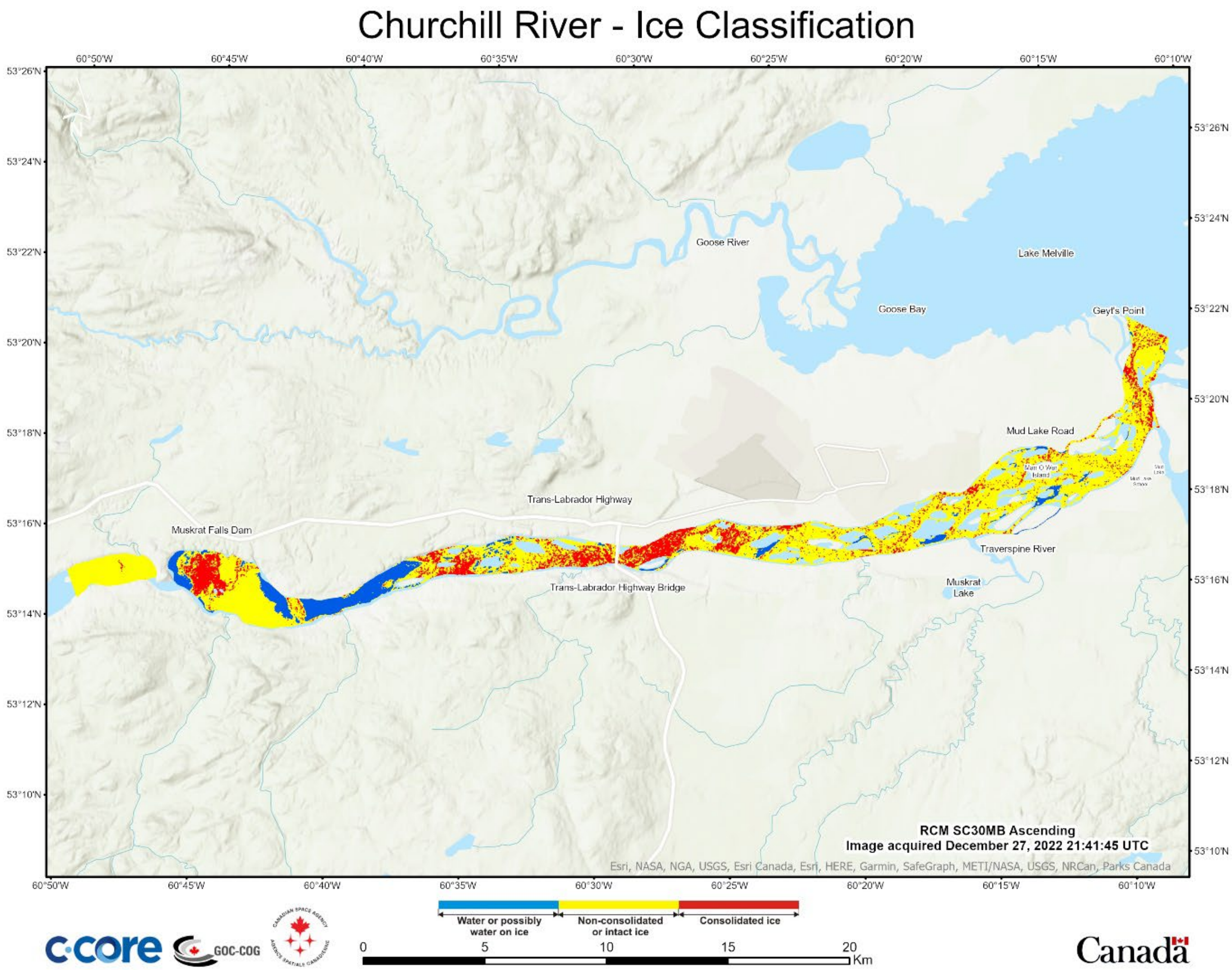

Figure A-19: Ice Classification – December 27, 2022.

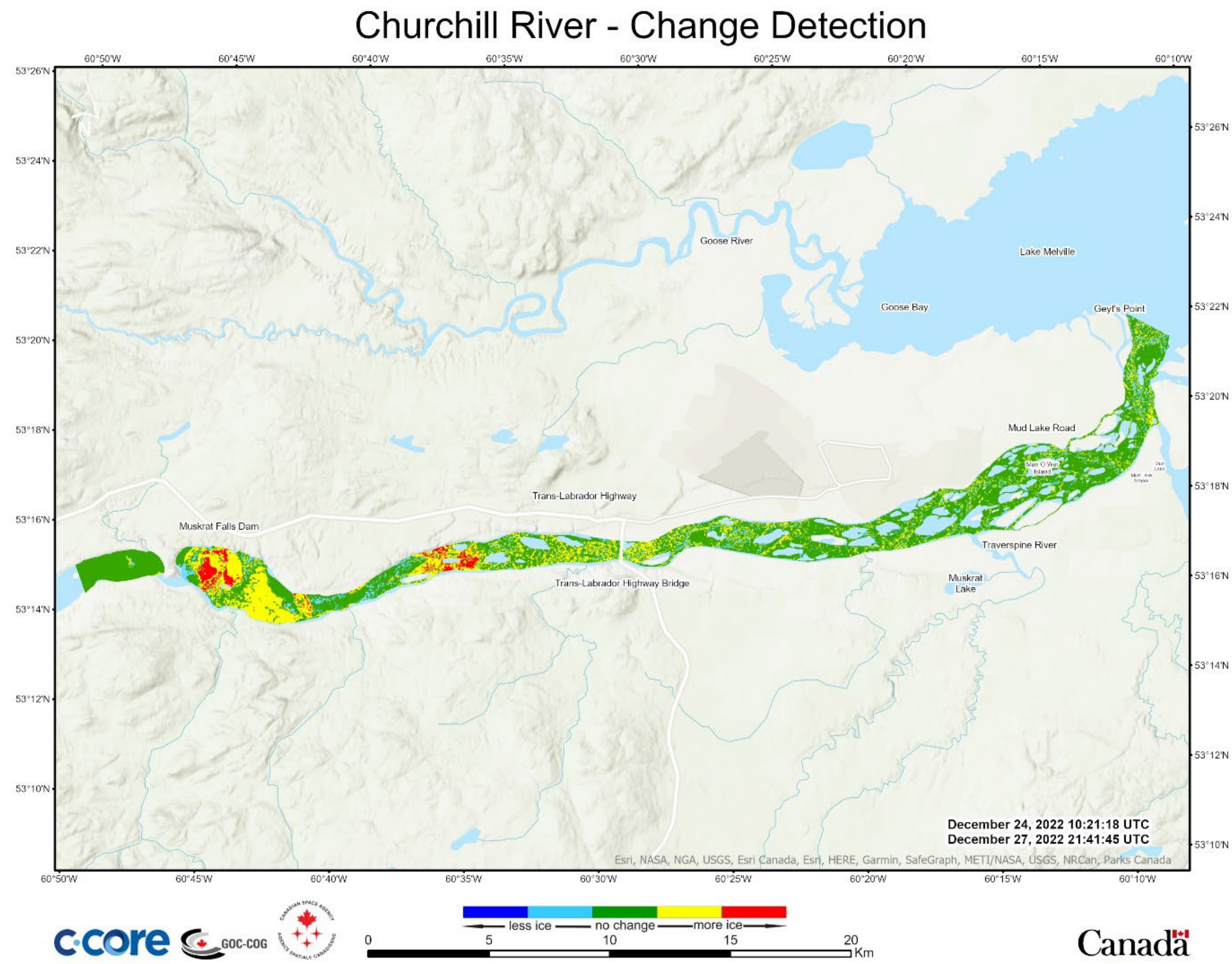

Figure A-20: Change Detection – December 24 and 27, 2022.

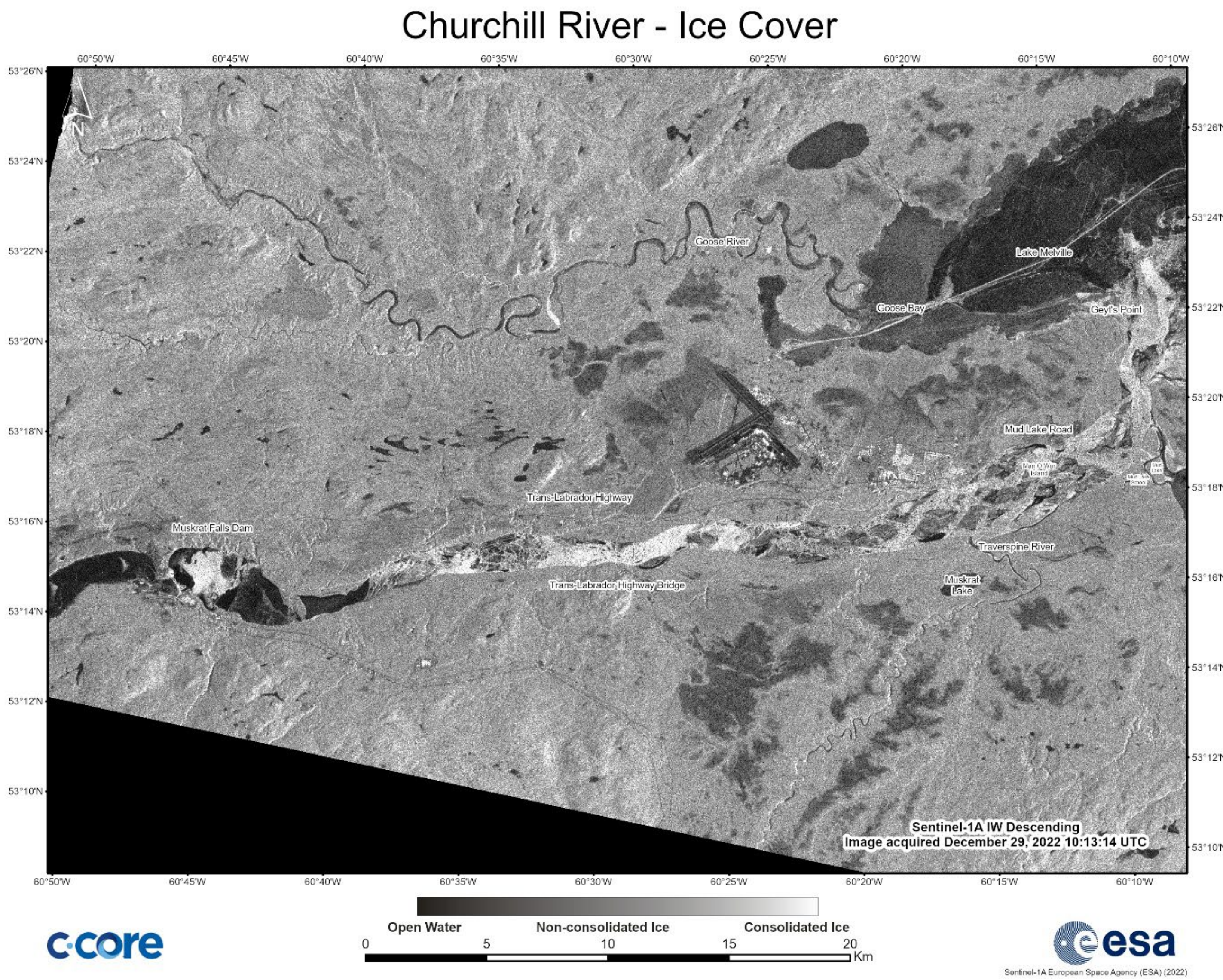

Figure A-21: Ice Cover – December 29, 2022

Churchill River - Ice Classification

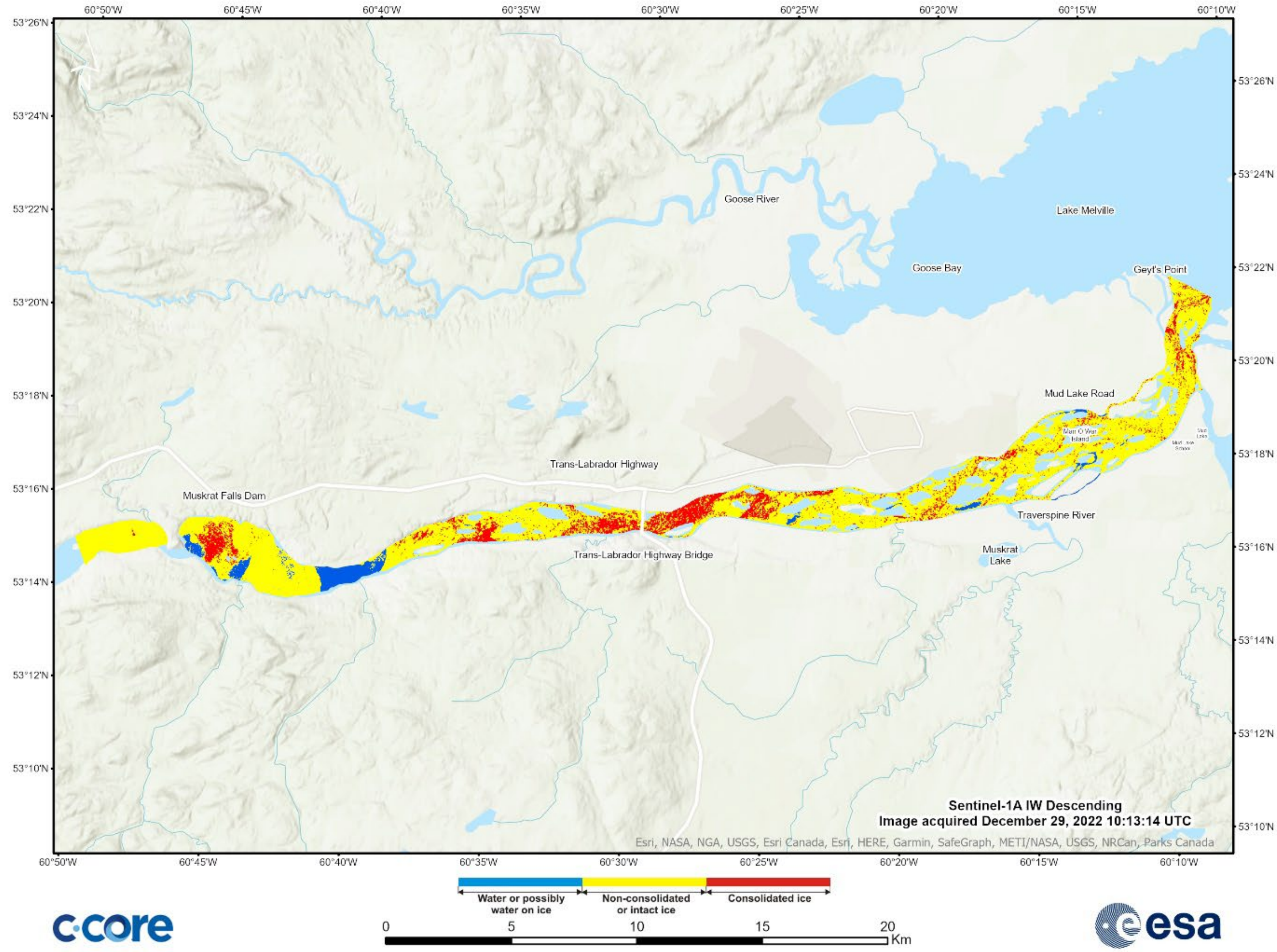

Figure A-22: Ice Classification – December 29, 2022.

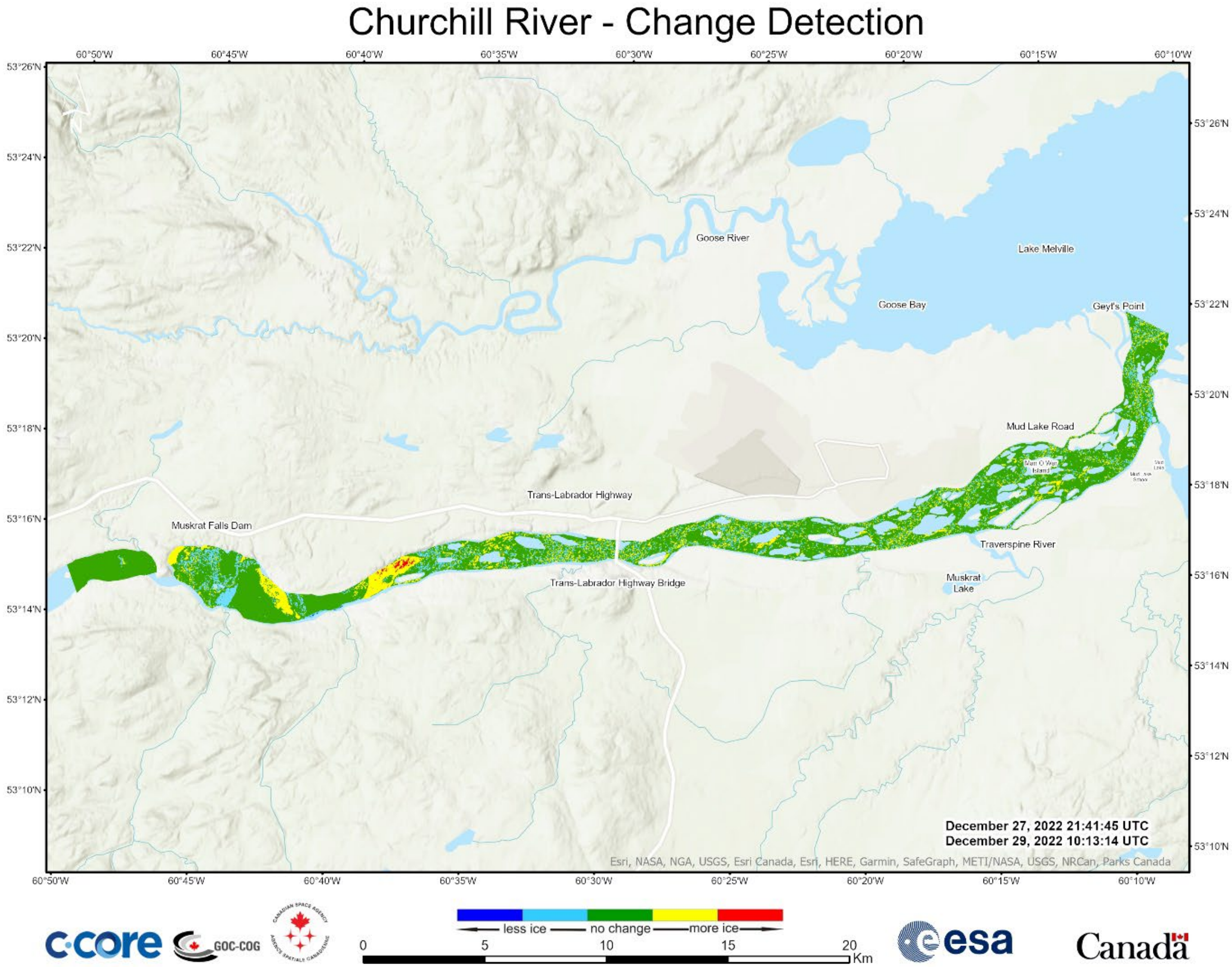

Figure A-23: Change Detection – December 27 and 29, 2022.

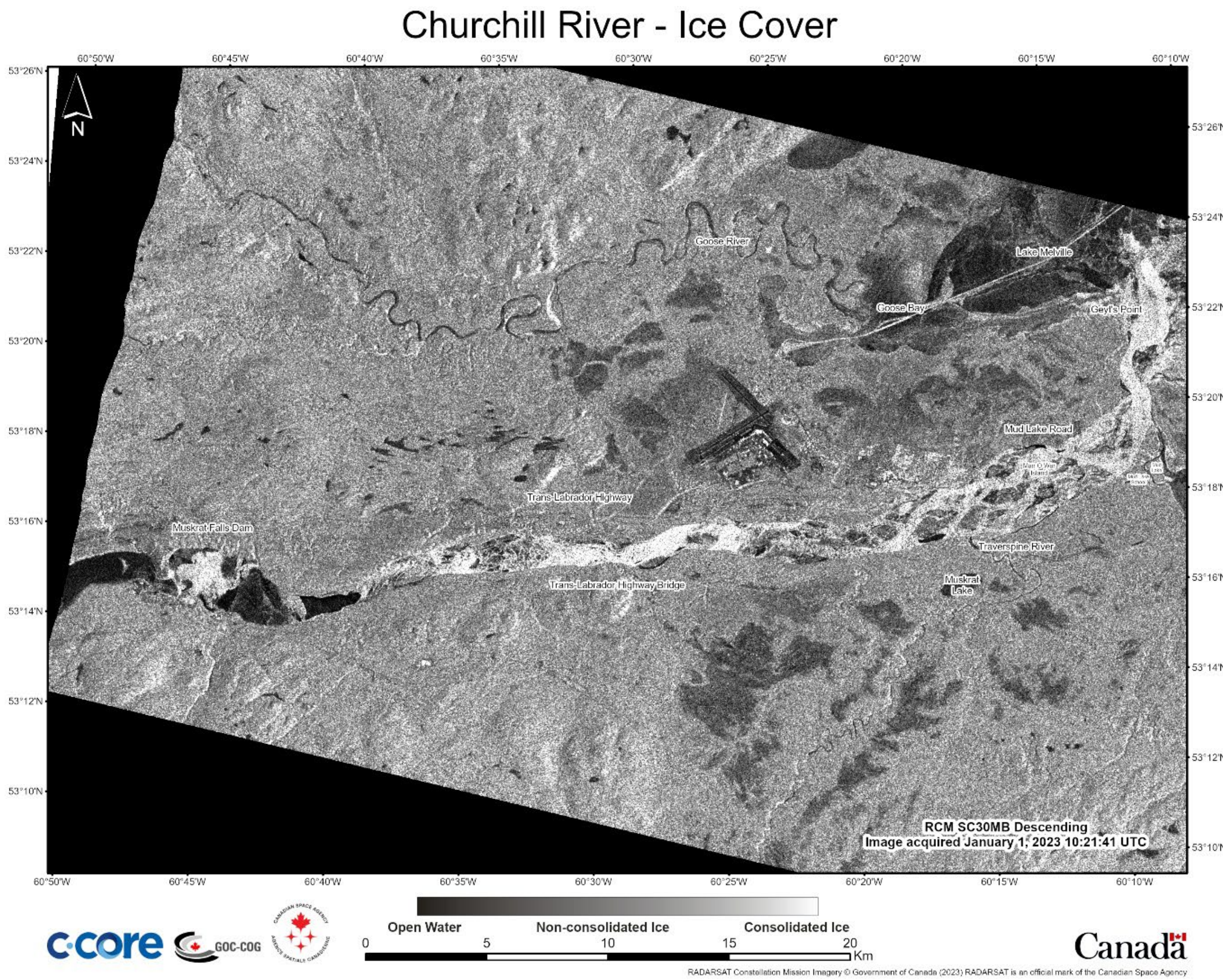

Figure A-24: Ice Cover – January 1, 2023.

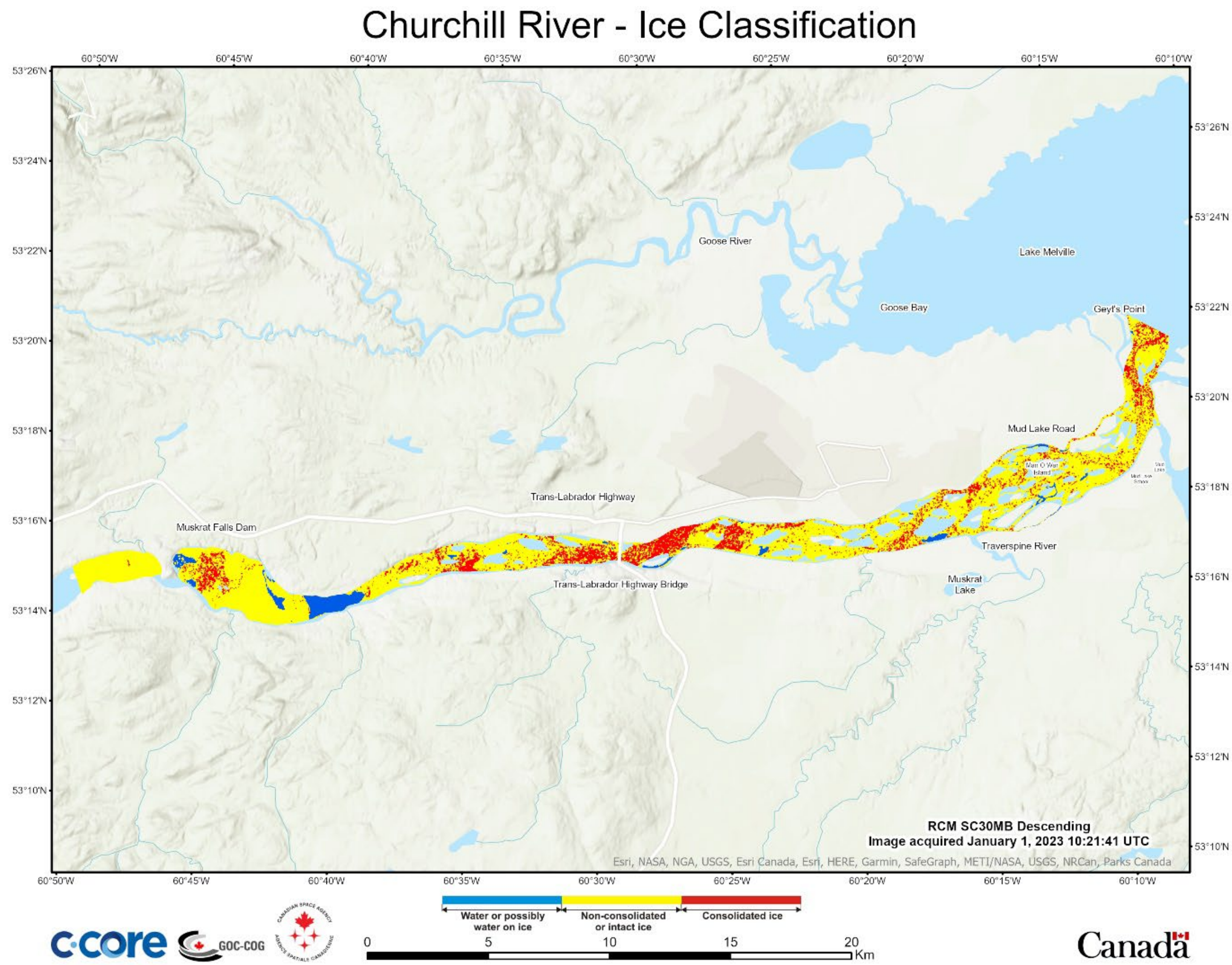

Figure A-25: Ice Classification – January 1, 2023.

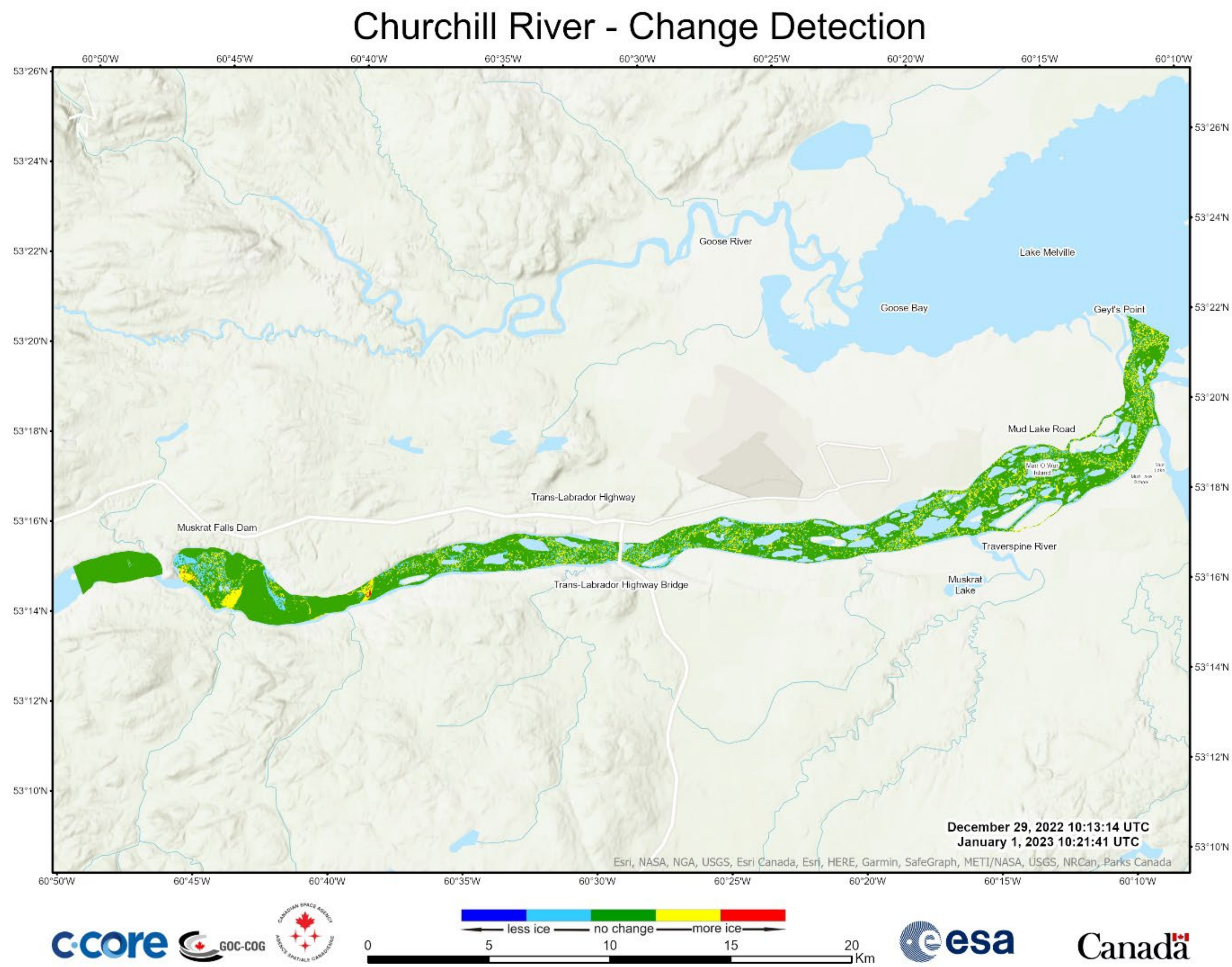

Figure A-26: Change Detection – December 29, 2022 and January 1, 2023.

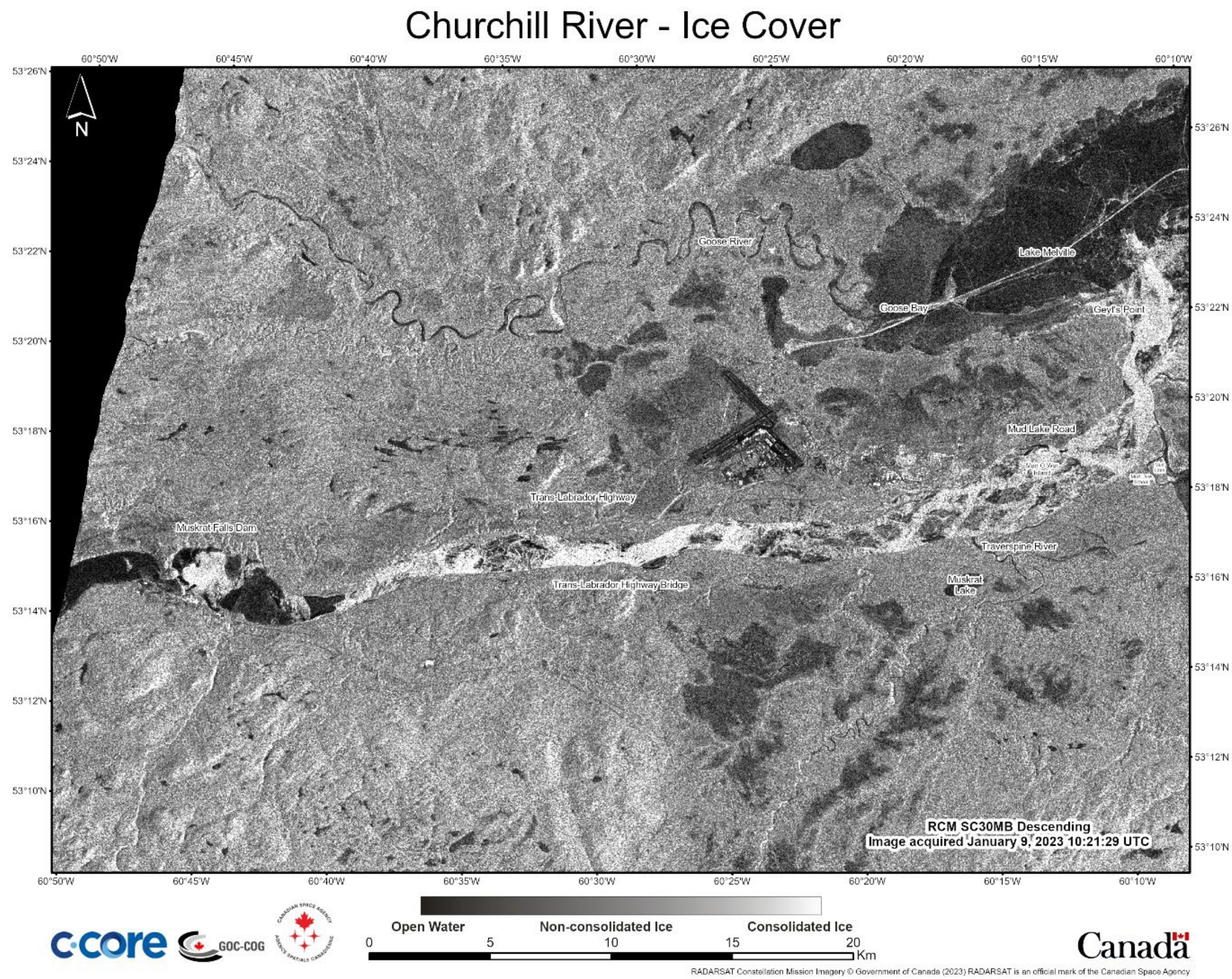

Figure A-27: Ice Cover – January 9, 2023.

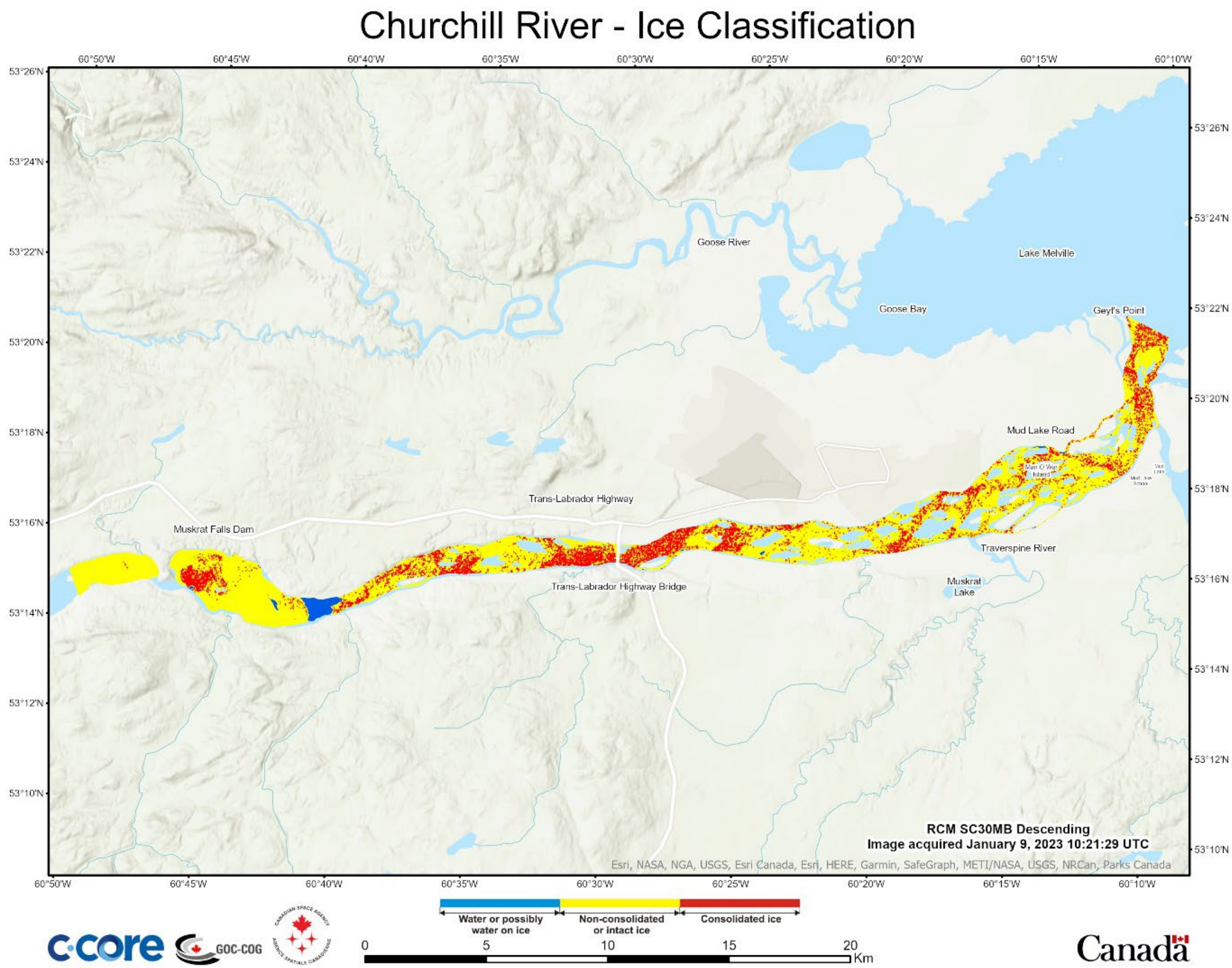

Figure A-28: Ice Classification – January 9, 2023.

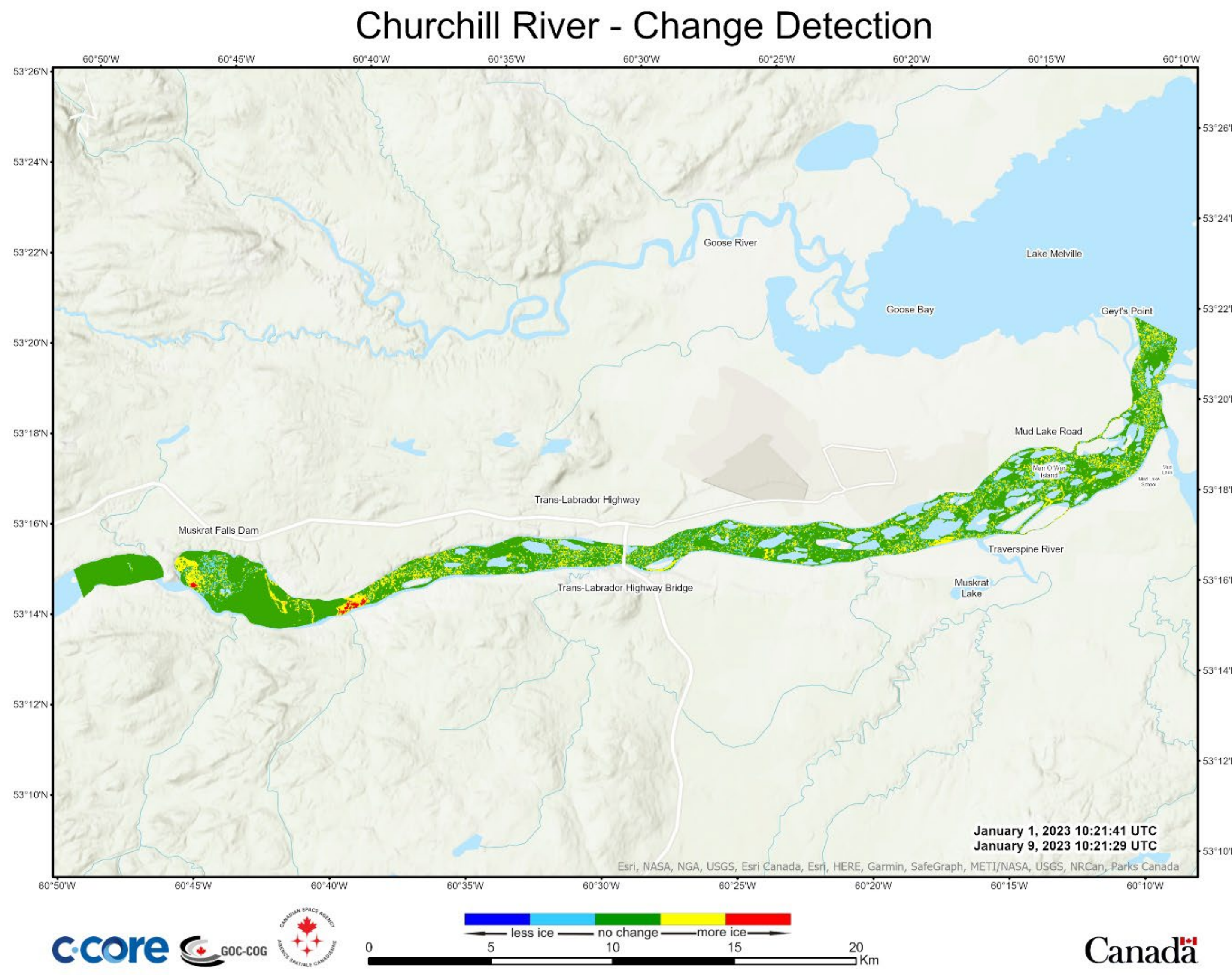

Figure A-29: Change Detection – January 1 and January 9, 2023.

Appendix B

Lower Churchill Break-Up Satellite Imagery

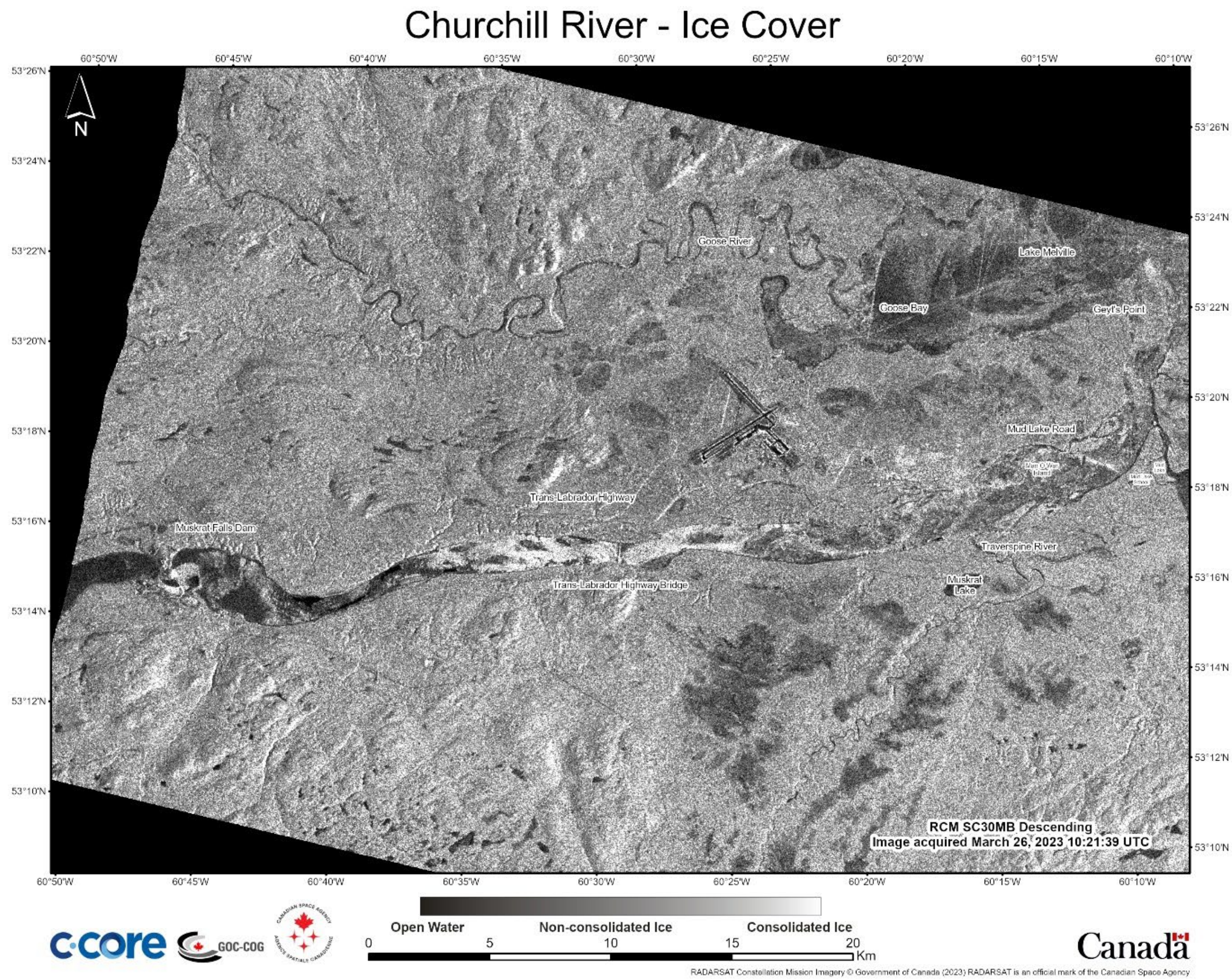

Figure B-1: Ice Cover – March 26, 2023.

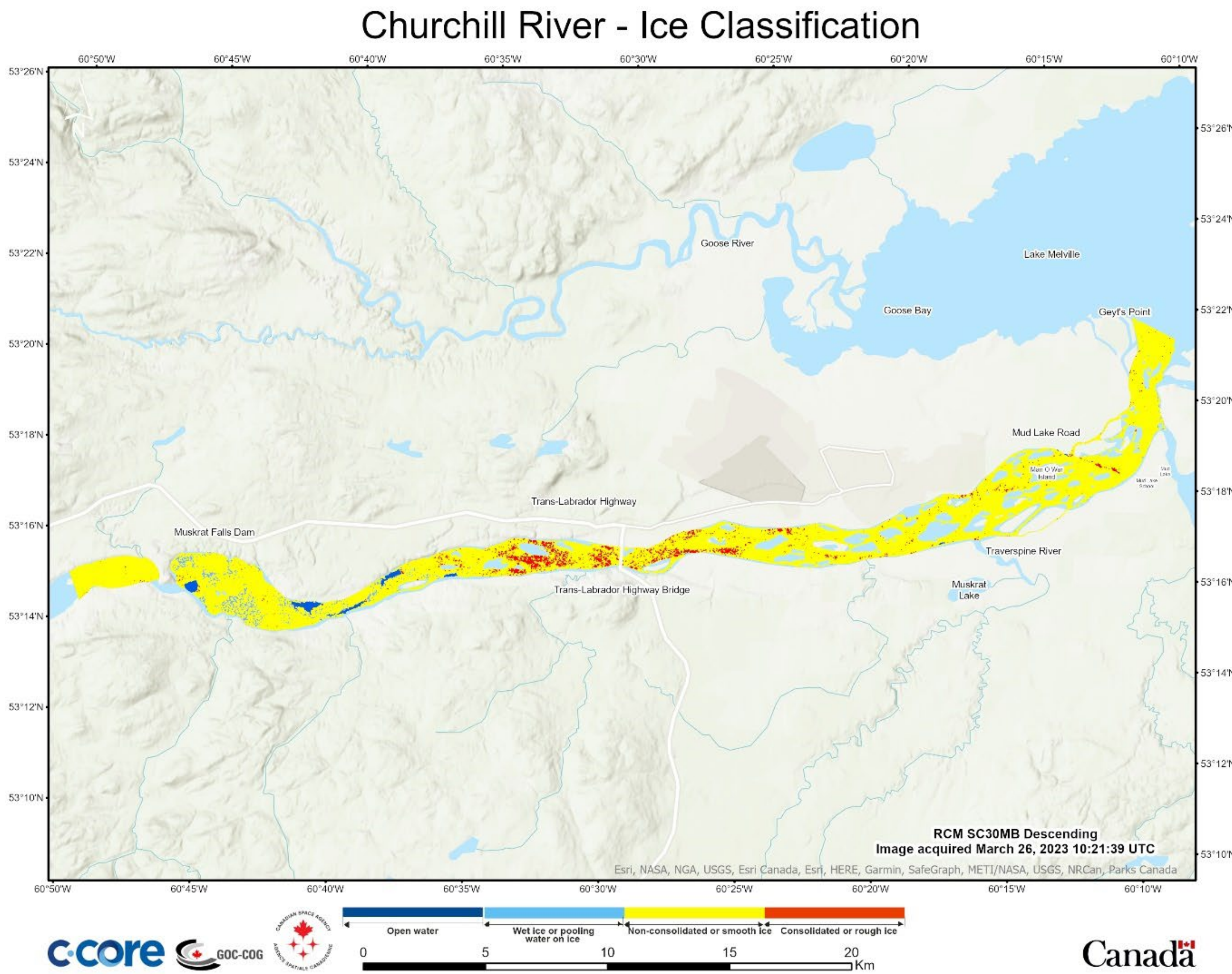

Figure B-2: Ice Classification – March 26, 2023.

Figure B-3: Ice Cover – April 4, 2023.

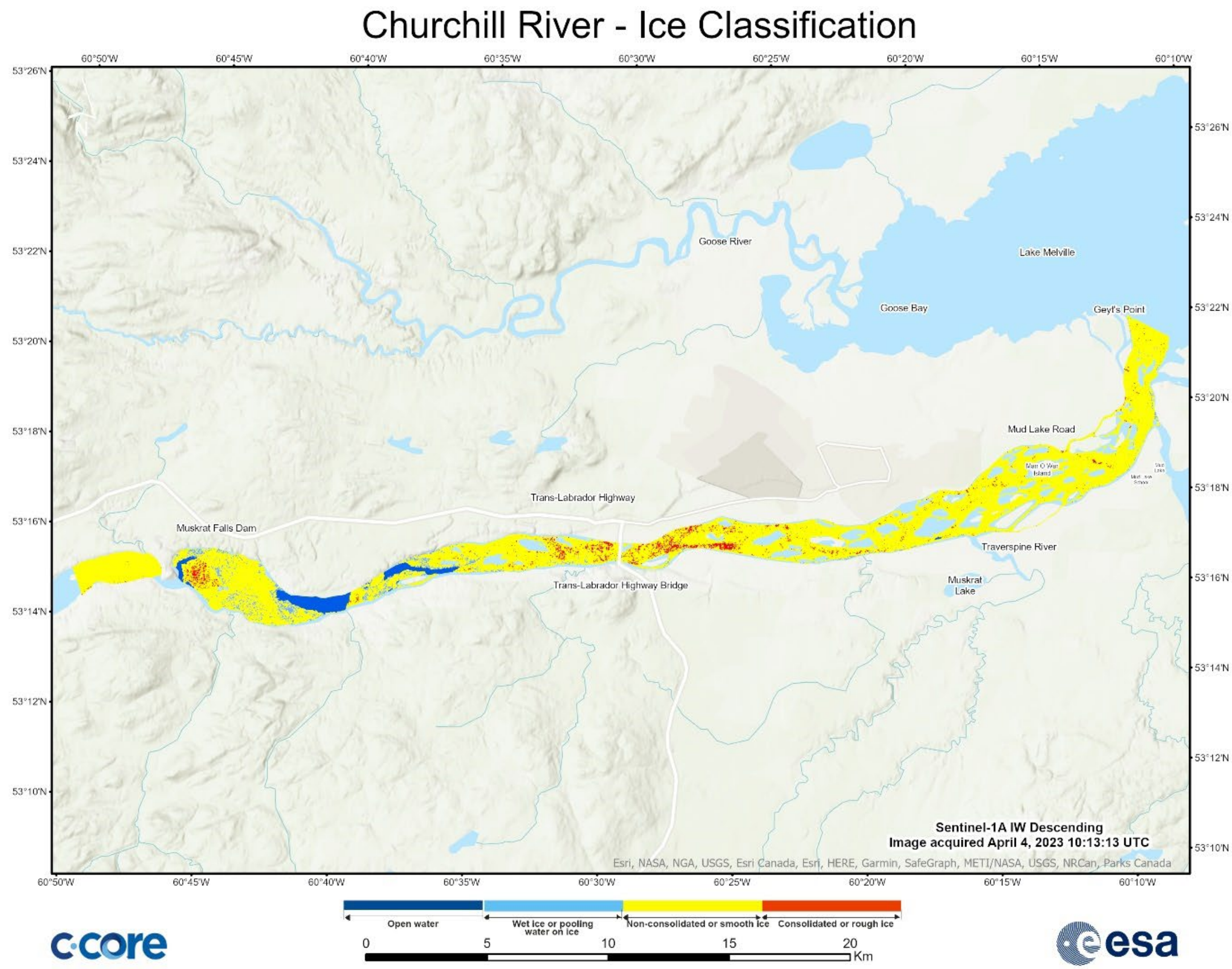

Figure B-4: Ice Classification – April 4, 2023.

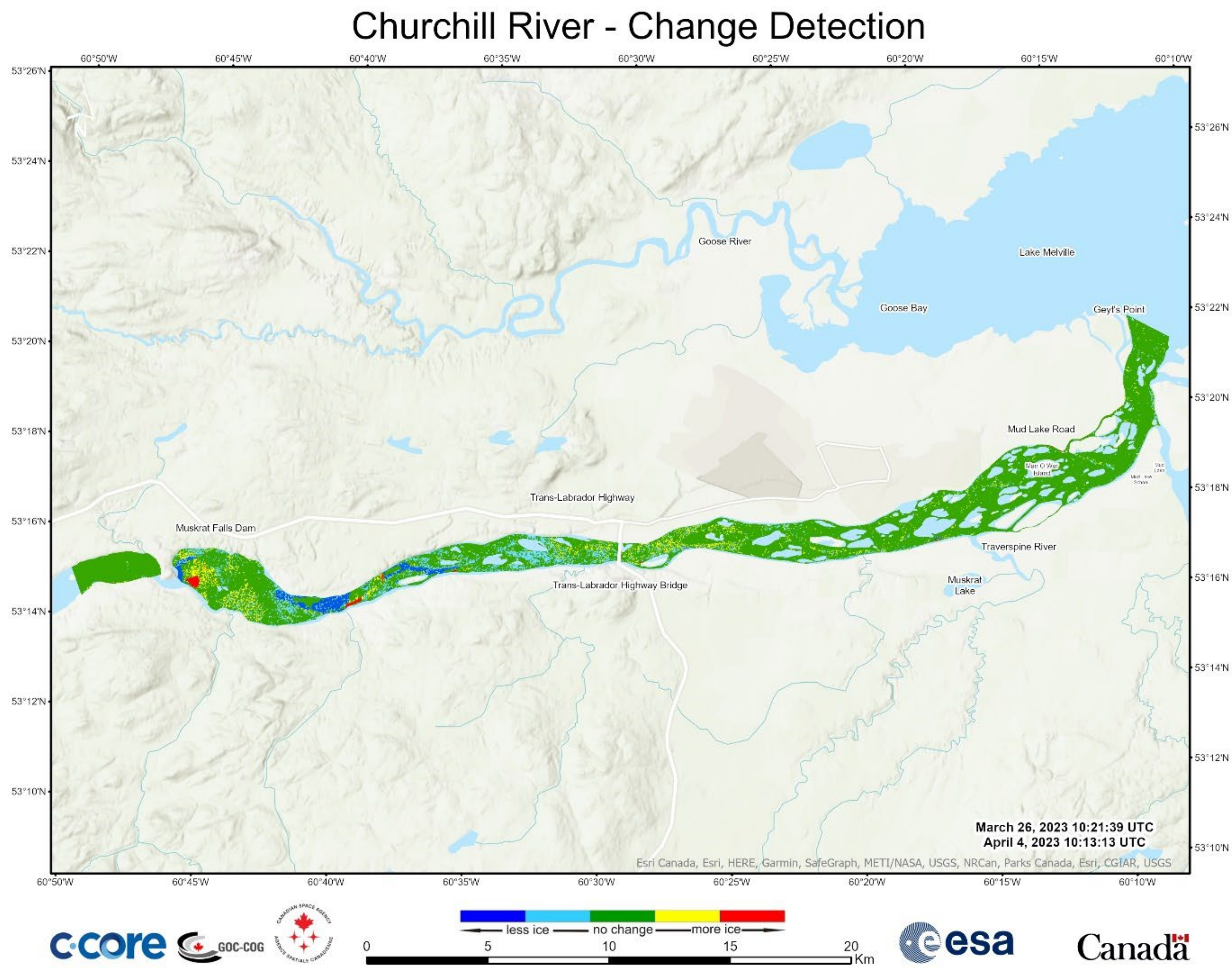

Figure B-5: Change Detection – March 26 and April 4, 2023.

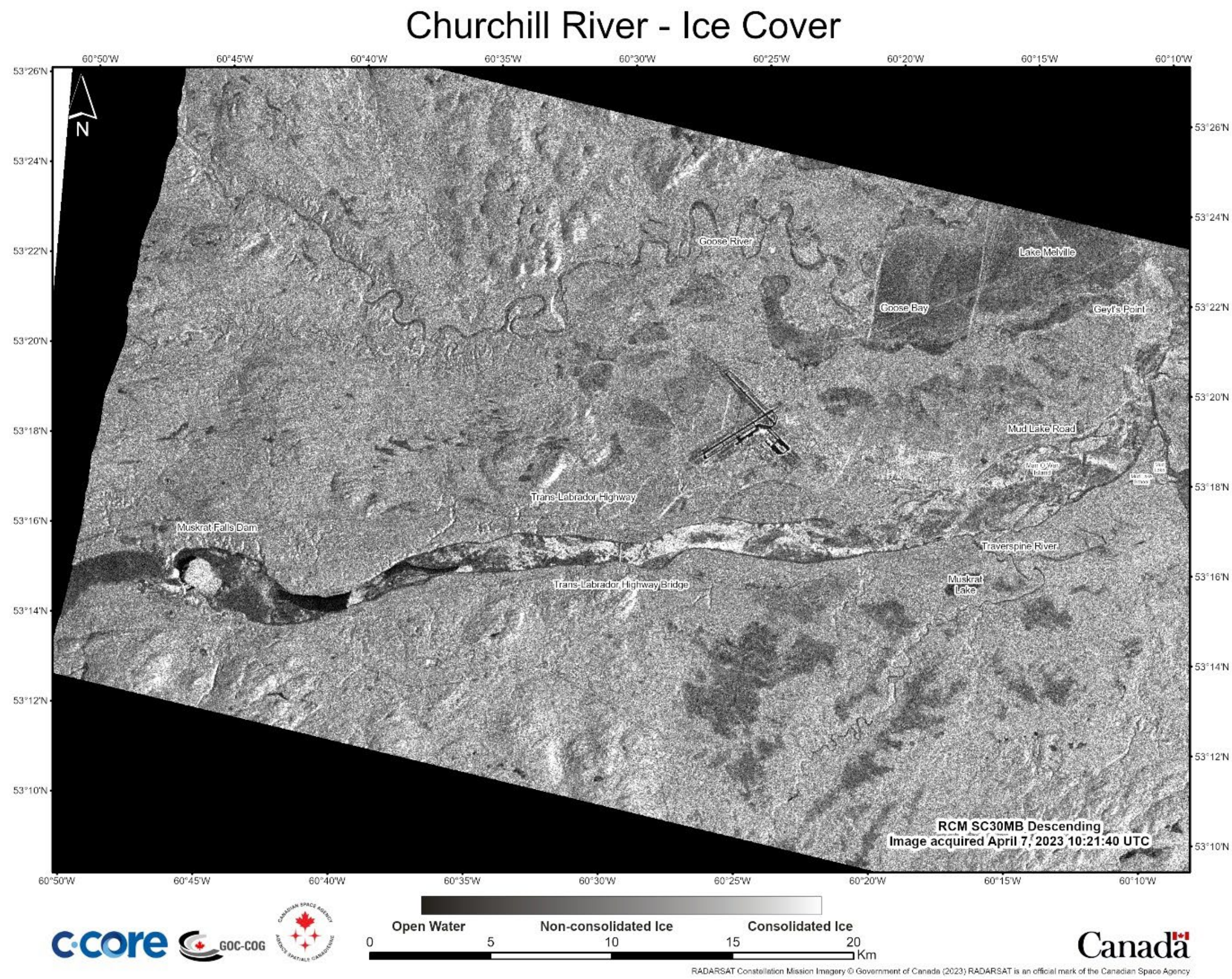

Figure B-6: Ice Cover – April 7, 2023.

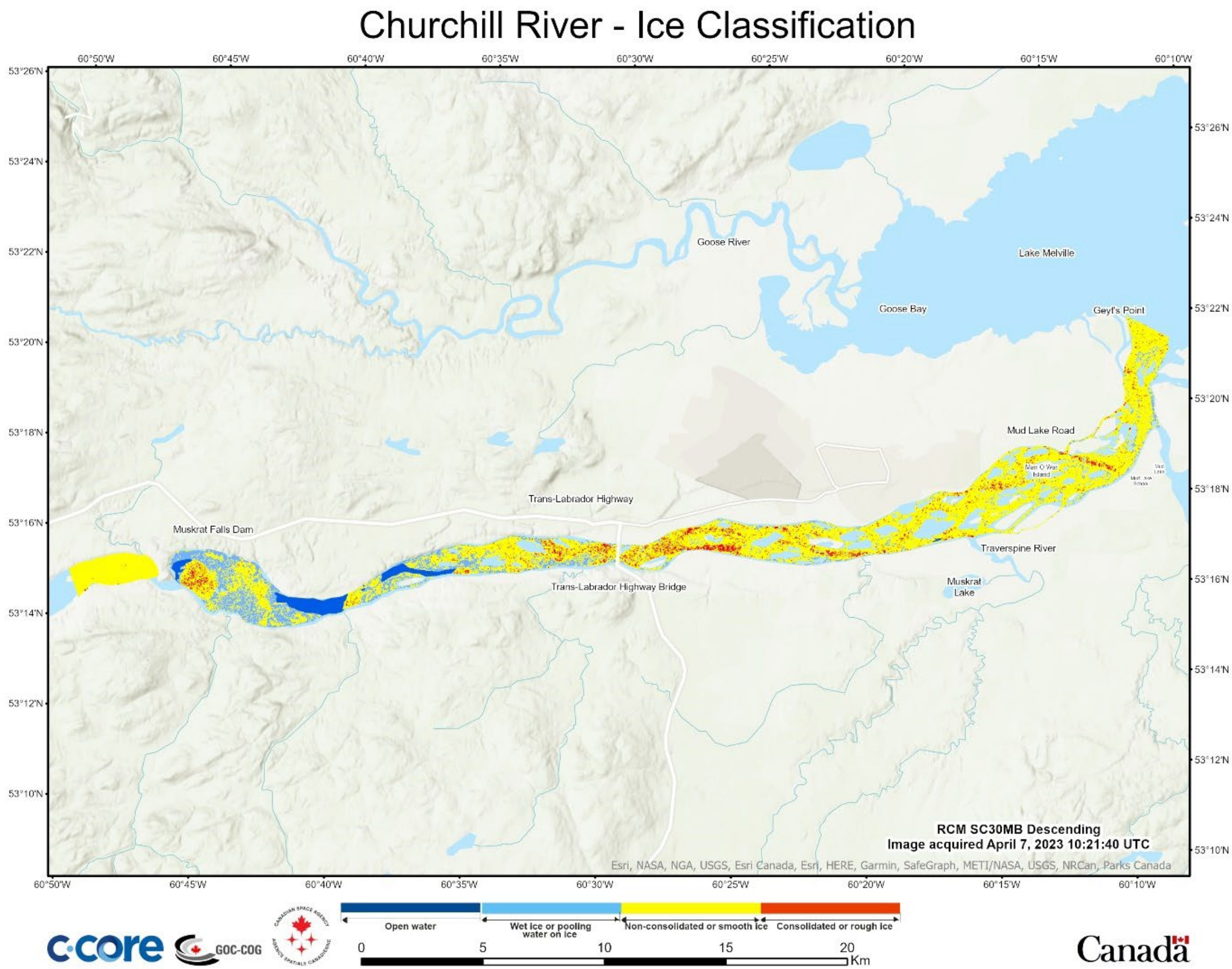

Figure B-7: Ice Classification – April 7, 2023.

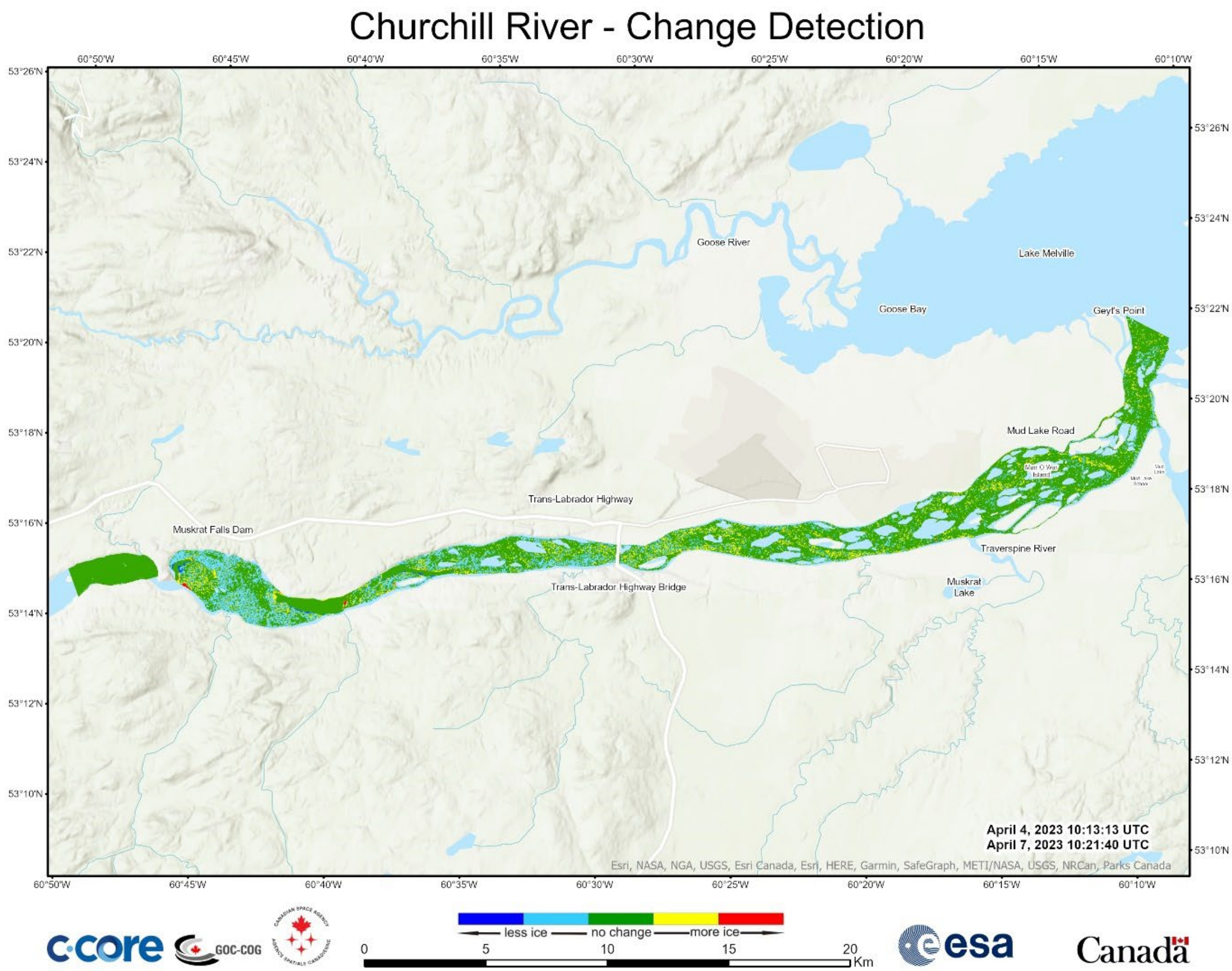

Figure B-8: Change Detection – April 4 and April 7, 2023.

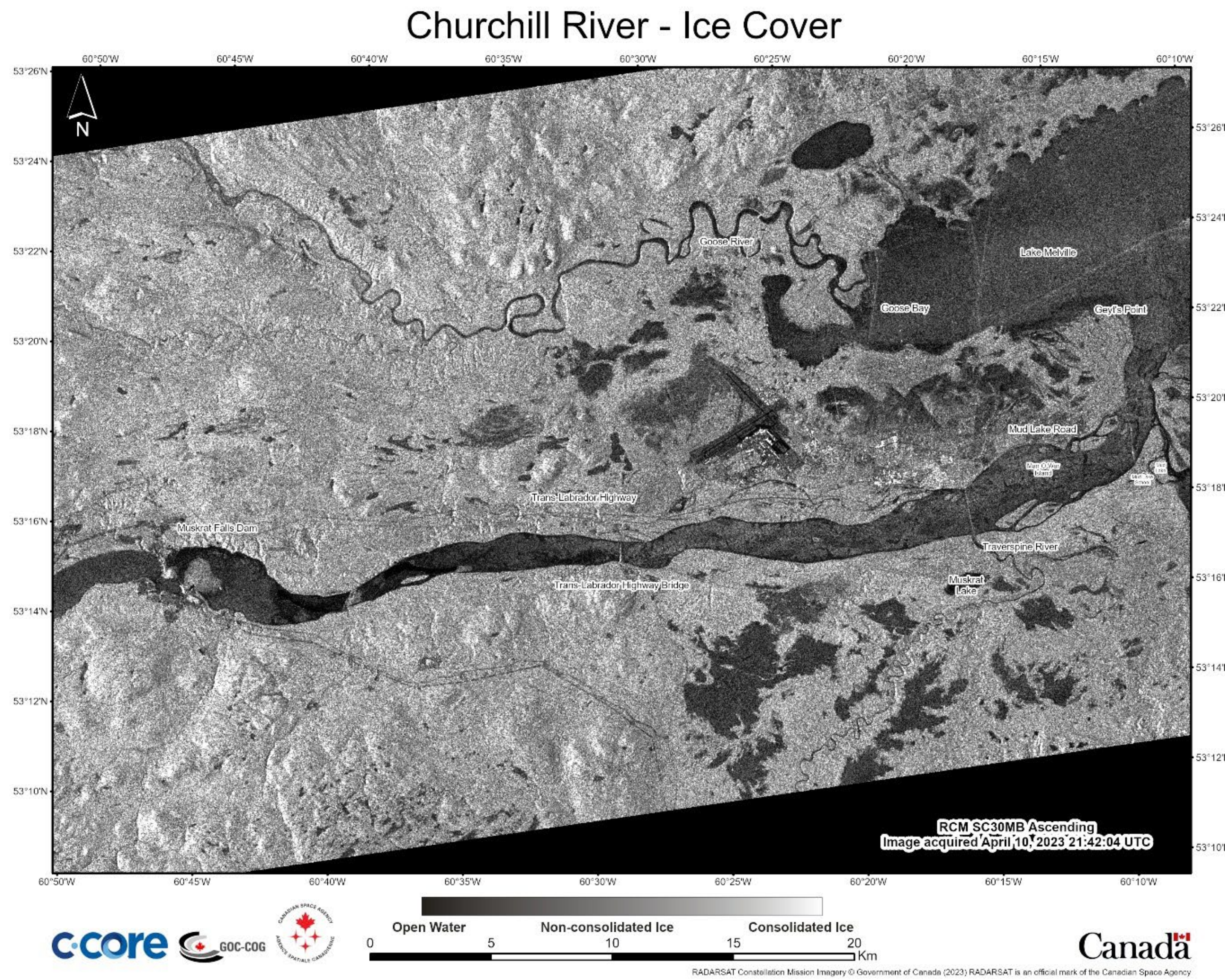

Figure B-9: Ice Cover – April 10, 2023.

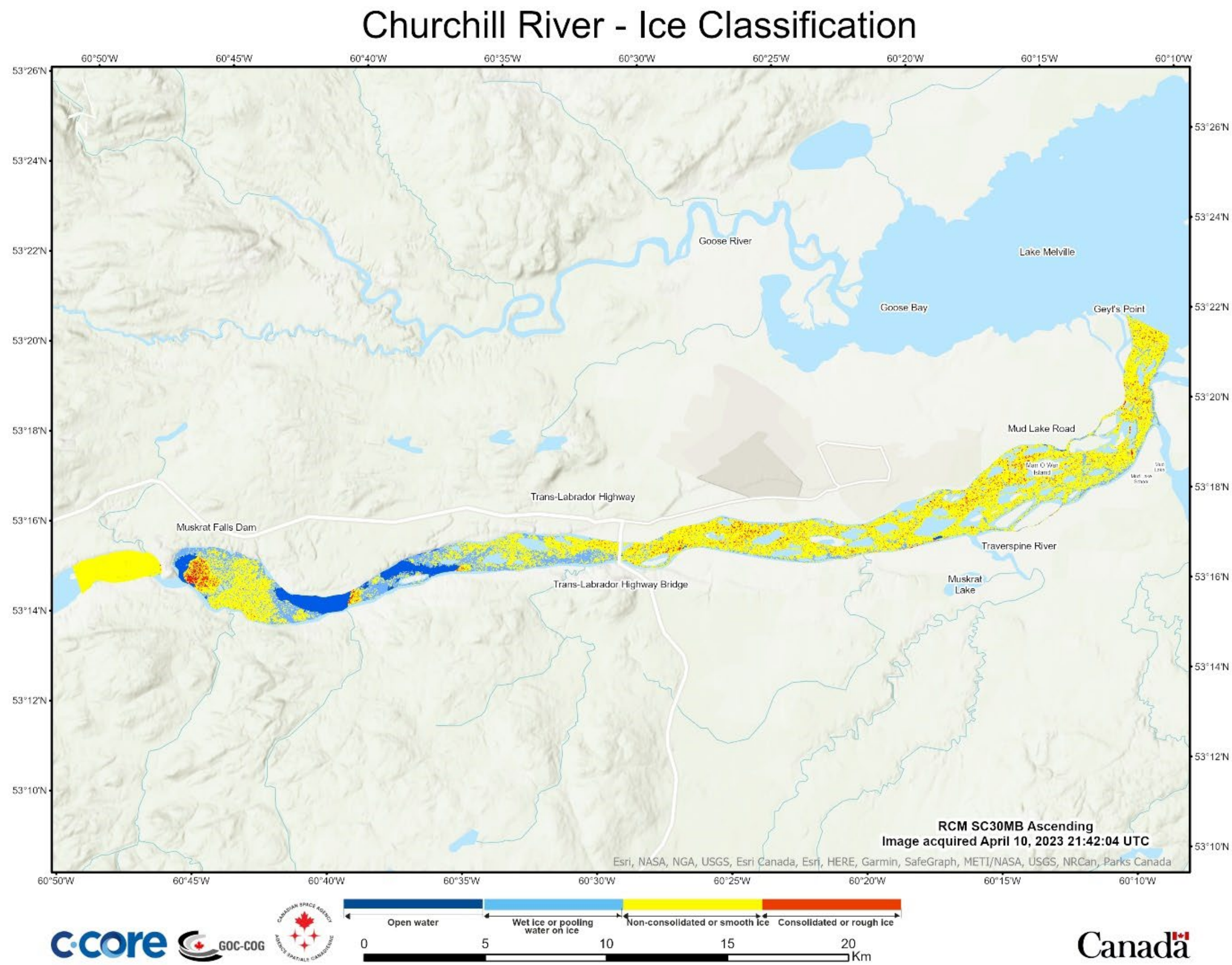

Figure B-10: Ice Classification – April 10, 2023.

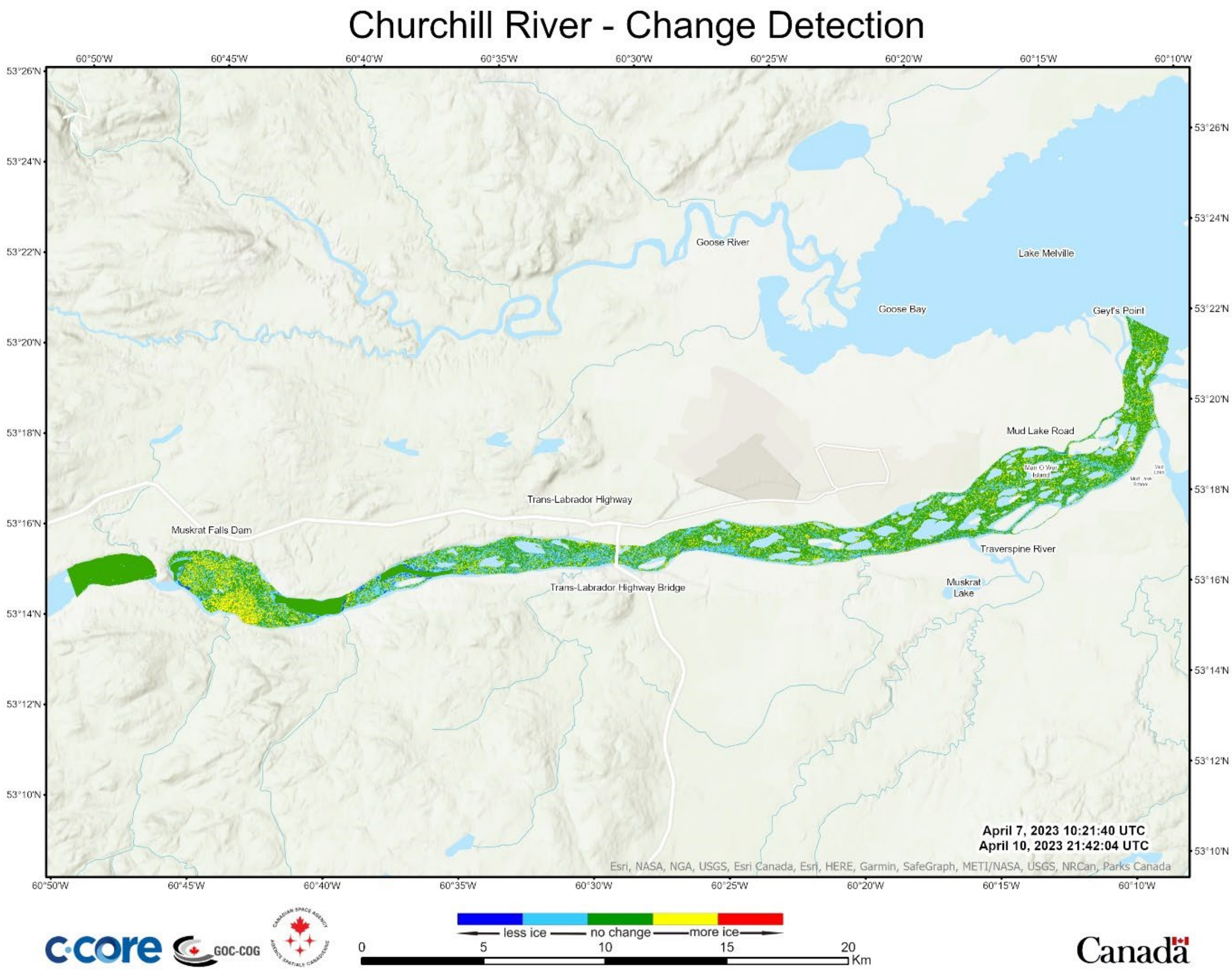

Figure B-11: Change Detection –April 7 and 10, 2023.

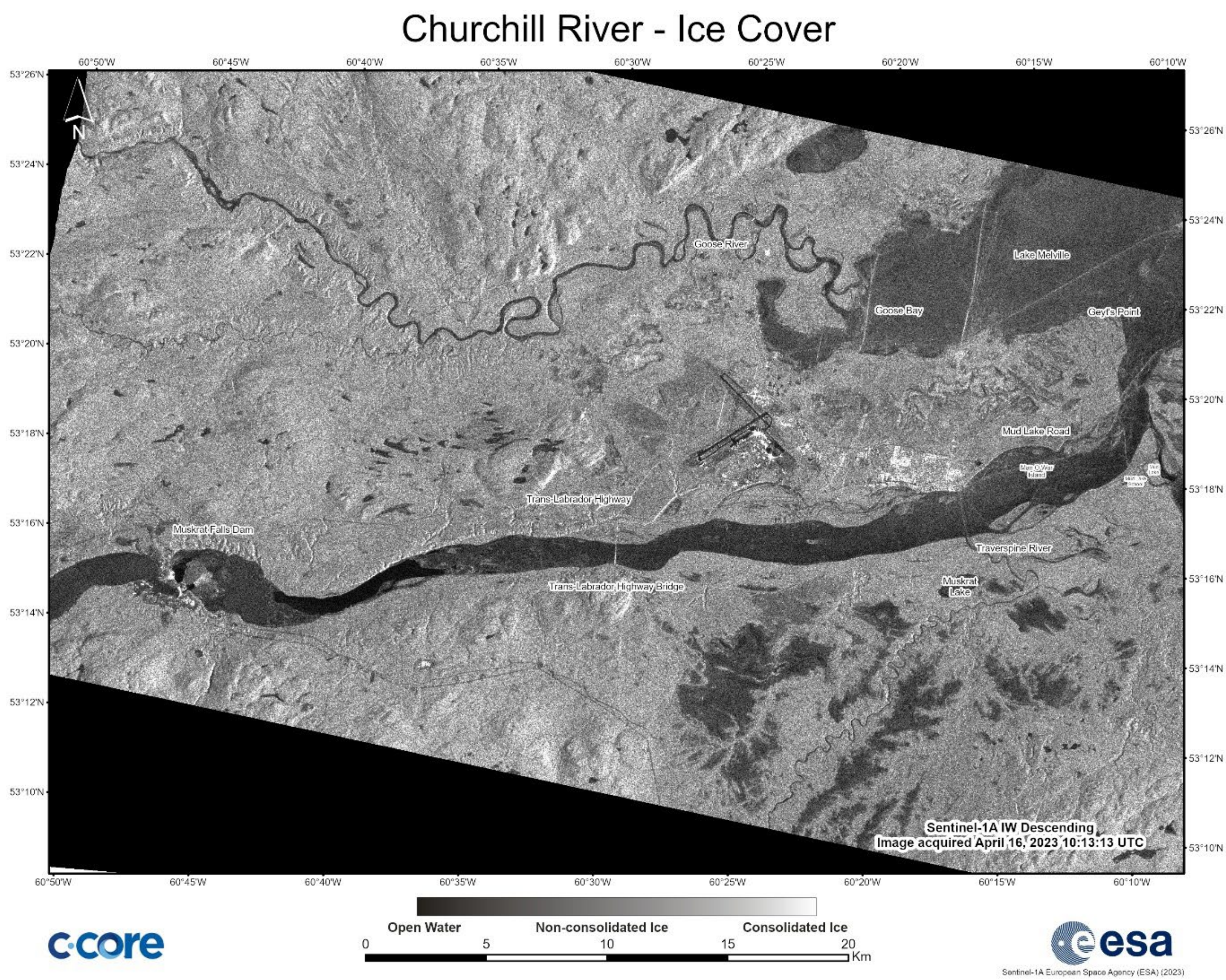

Figure B-12: Ice Cover – April 16, 2023.

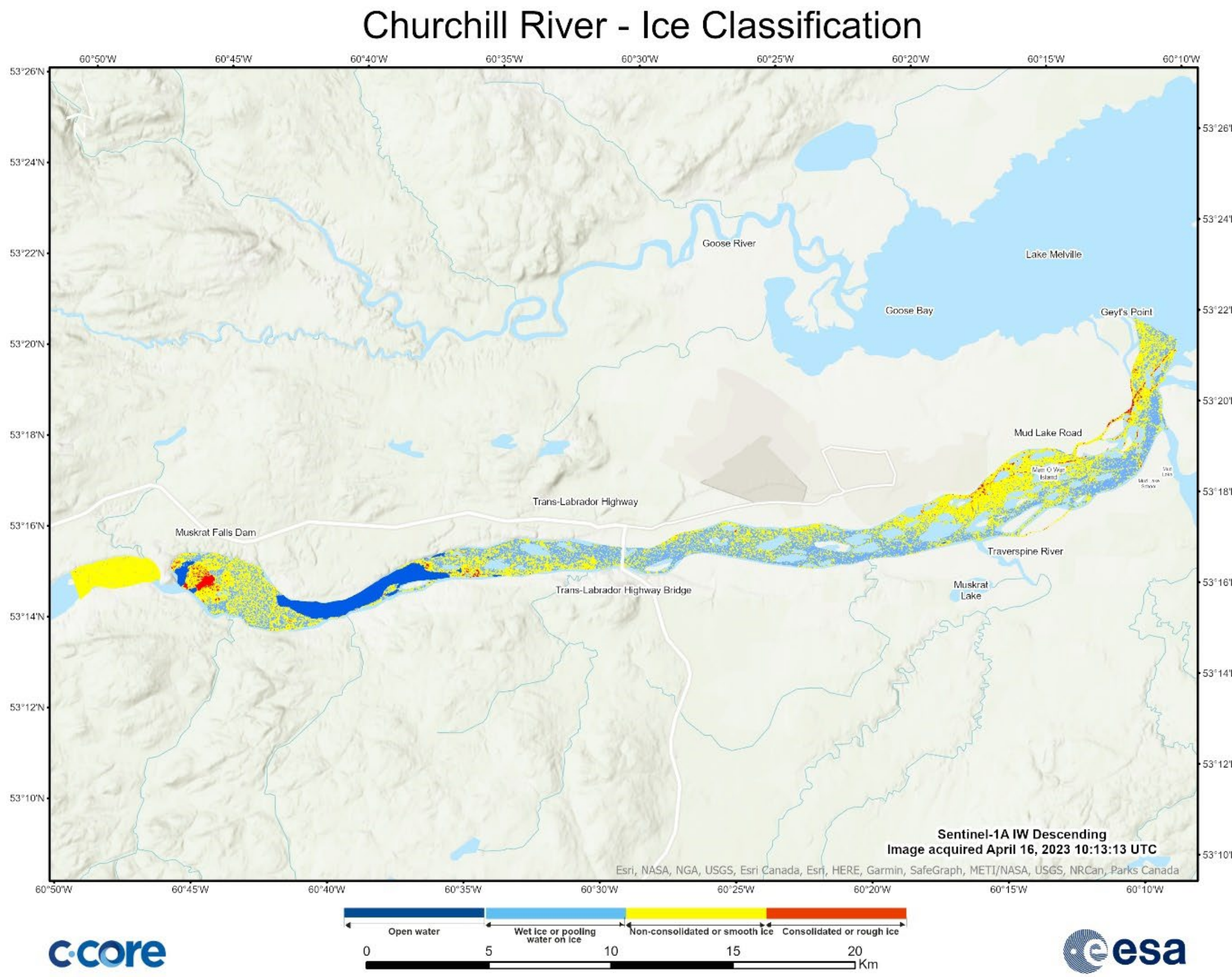

Figure B-13: Ice Classification – April 16, 2023.

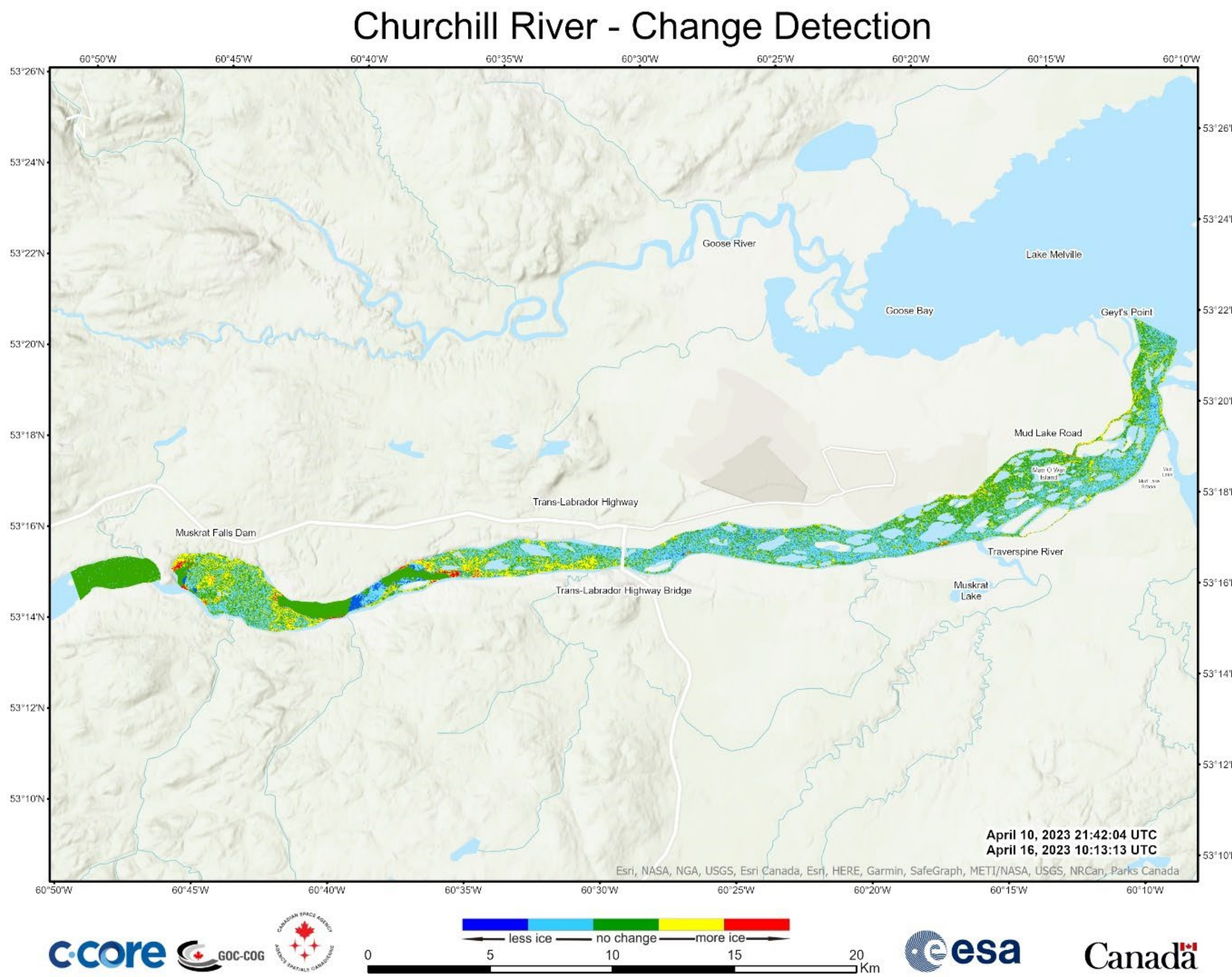

Figure B-14: Change Detection – April 10 and 16, 2023.

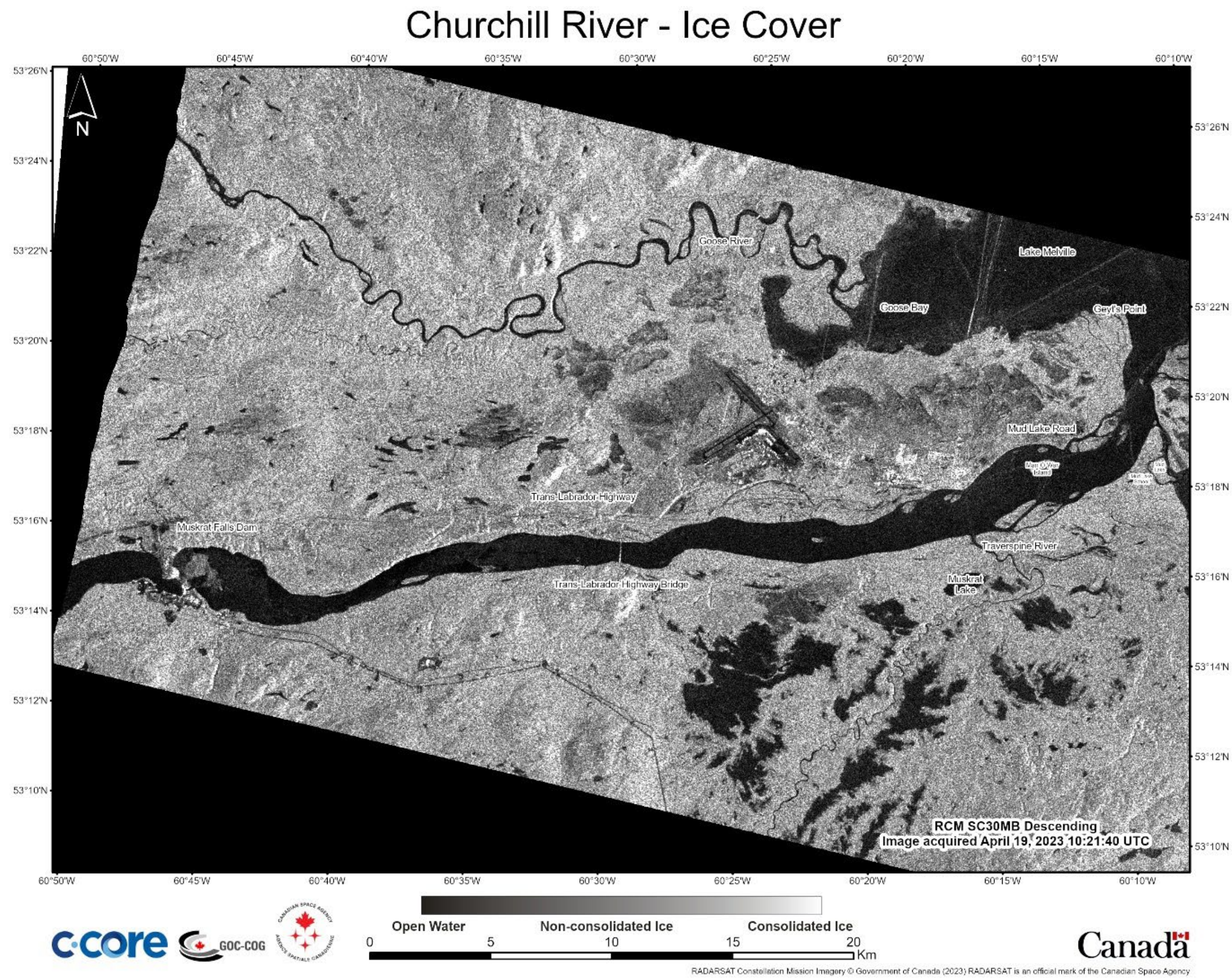

Figure B-15: Ice Cover – April 19, 2023.

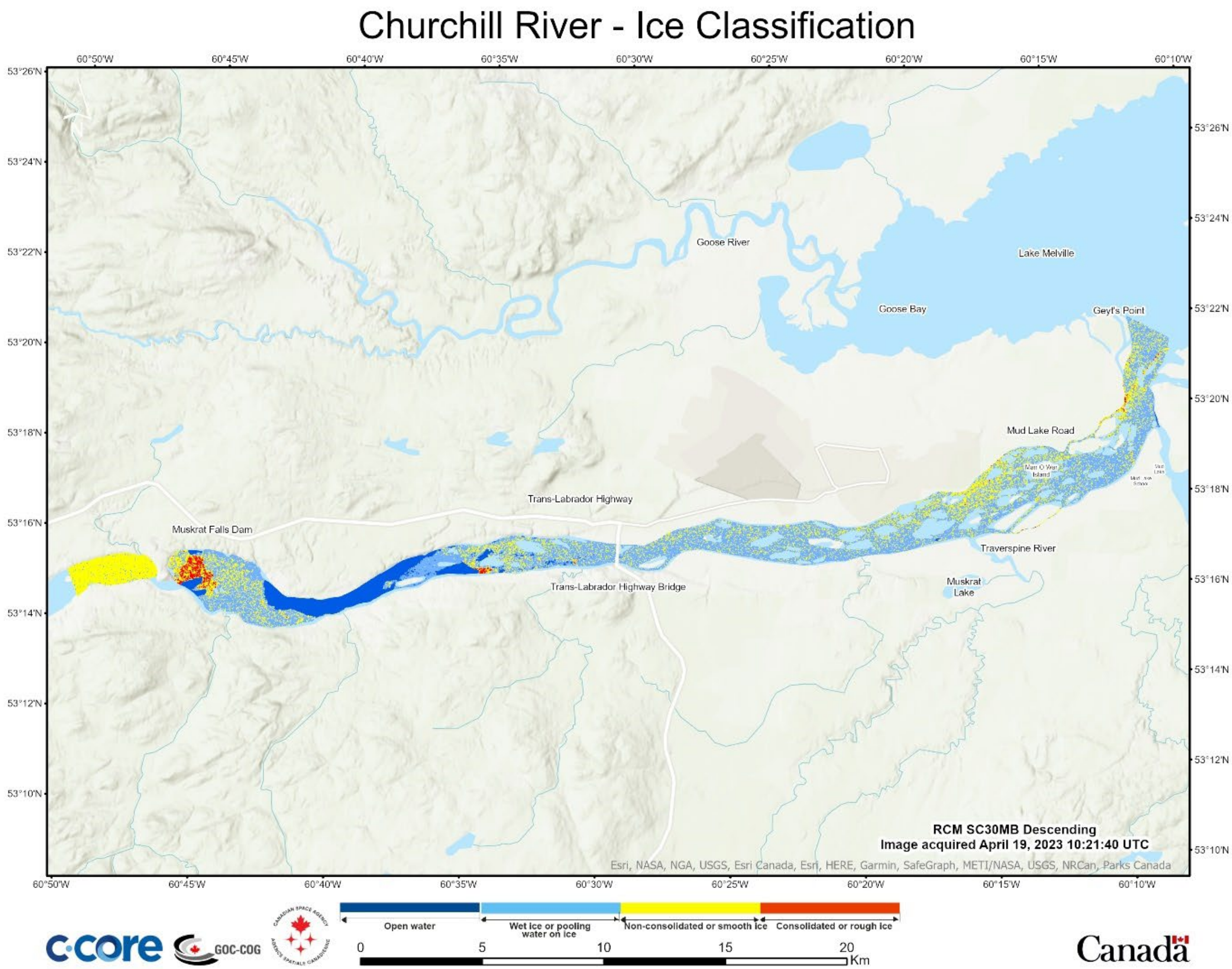

Figure B-16: Ice Classification – April 19, 2023.

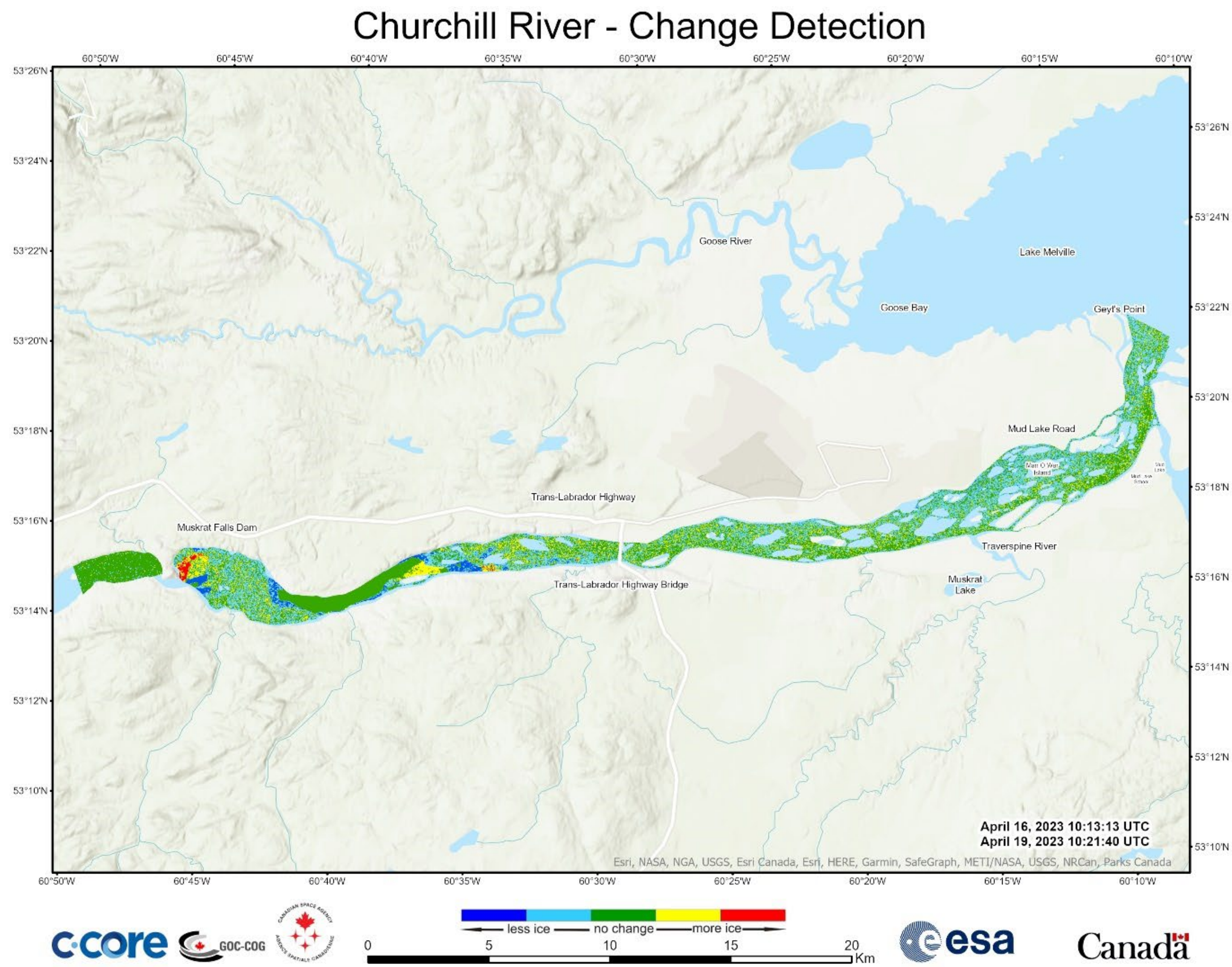

Figure B-17: Change Detection – April 16 and 19, 2023.

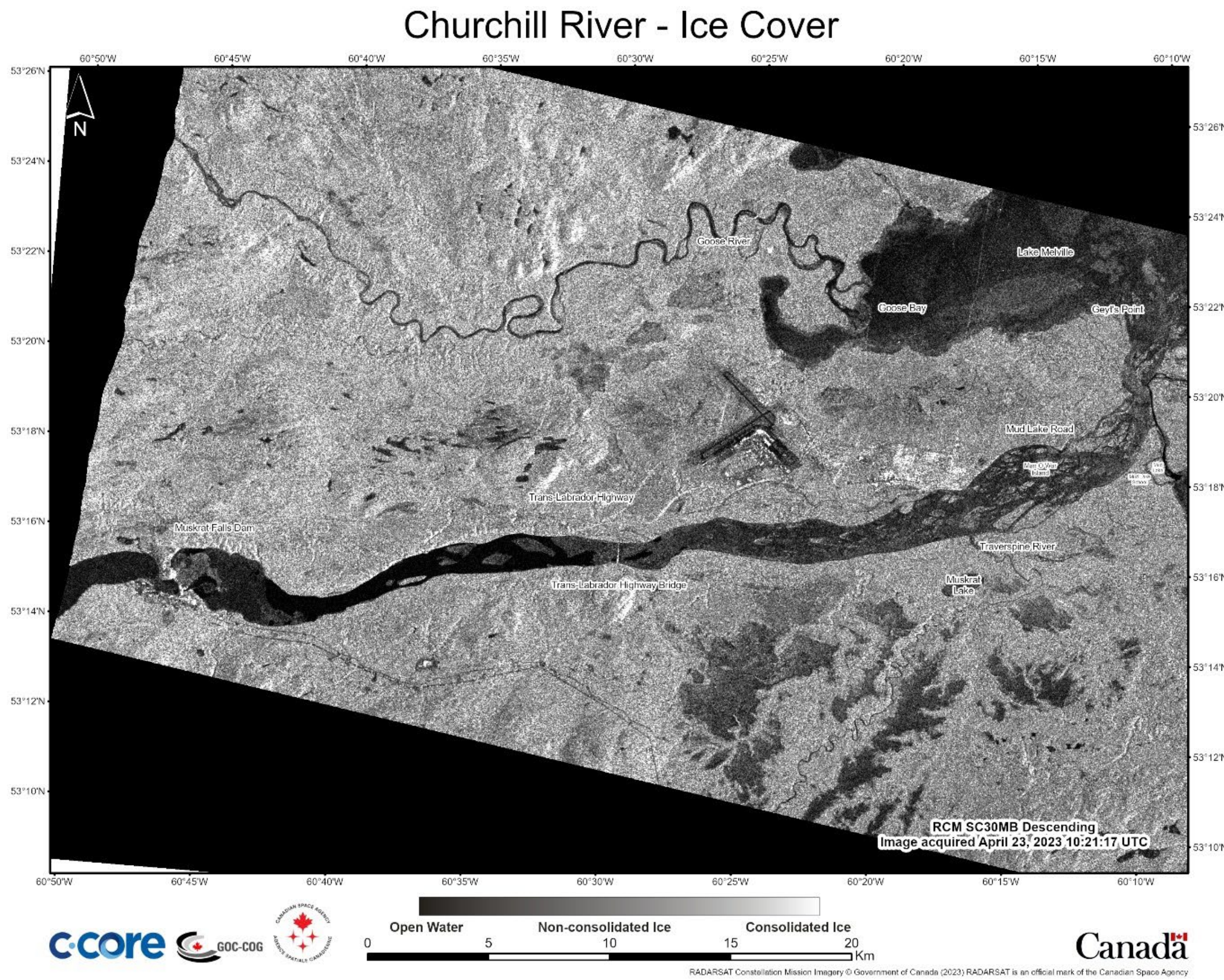

Figure B-18: Ice Cover – April 23, 2023.

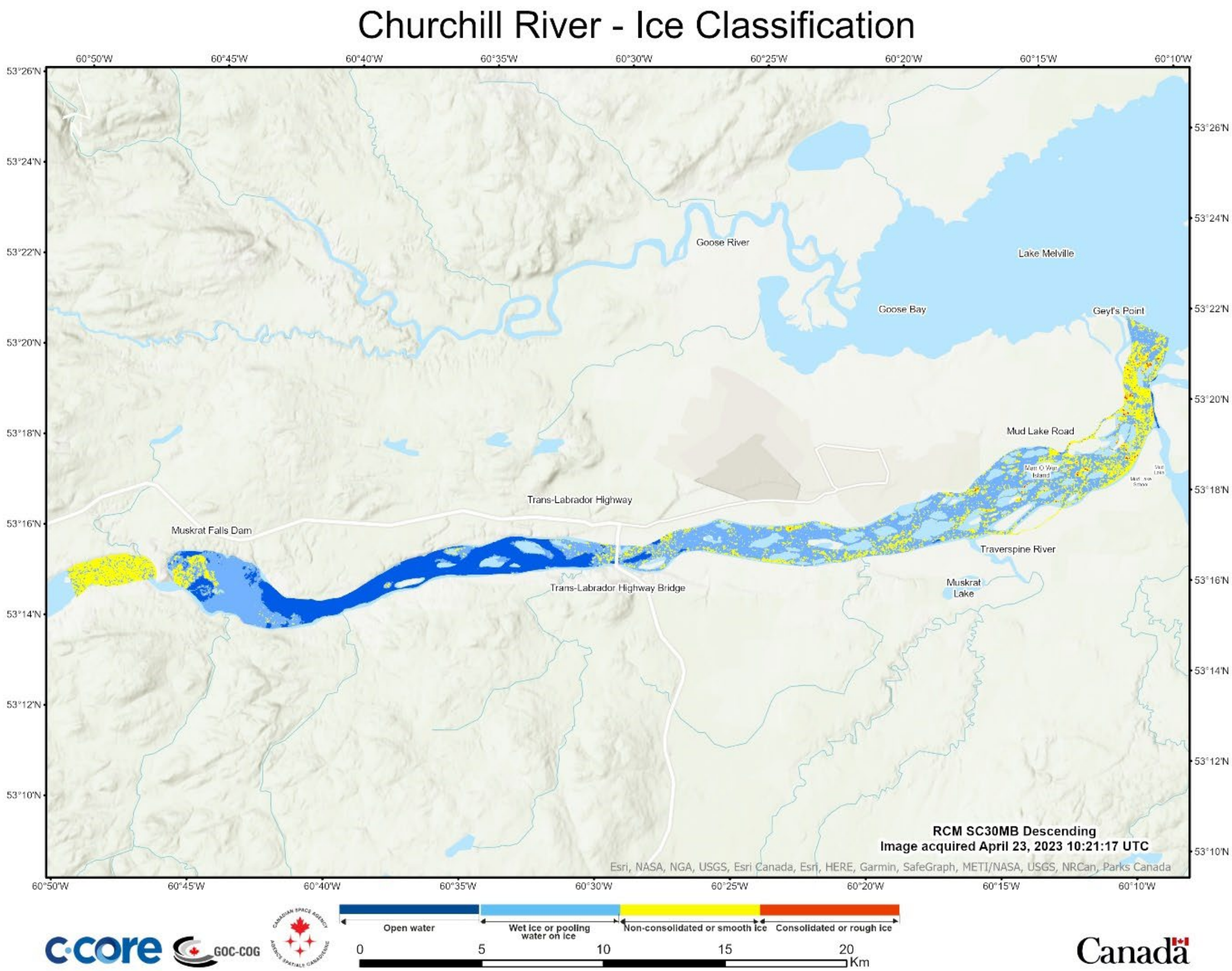

Figure B-19: Ice Classification – April 23, 2023.

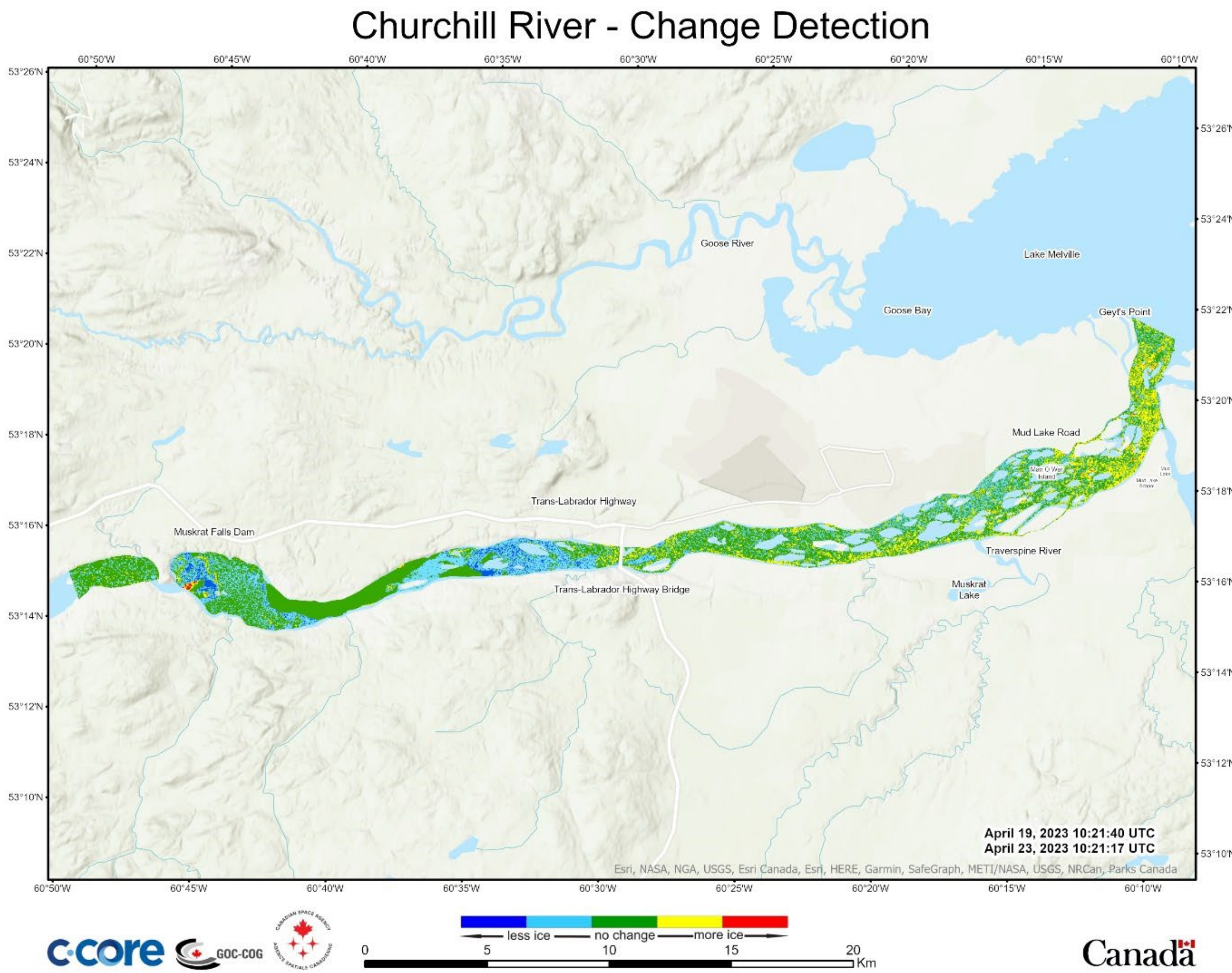

Figure B-20 Change Detection – April 19 and 23, 2023.

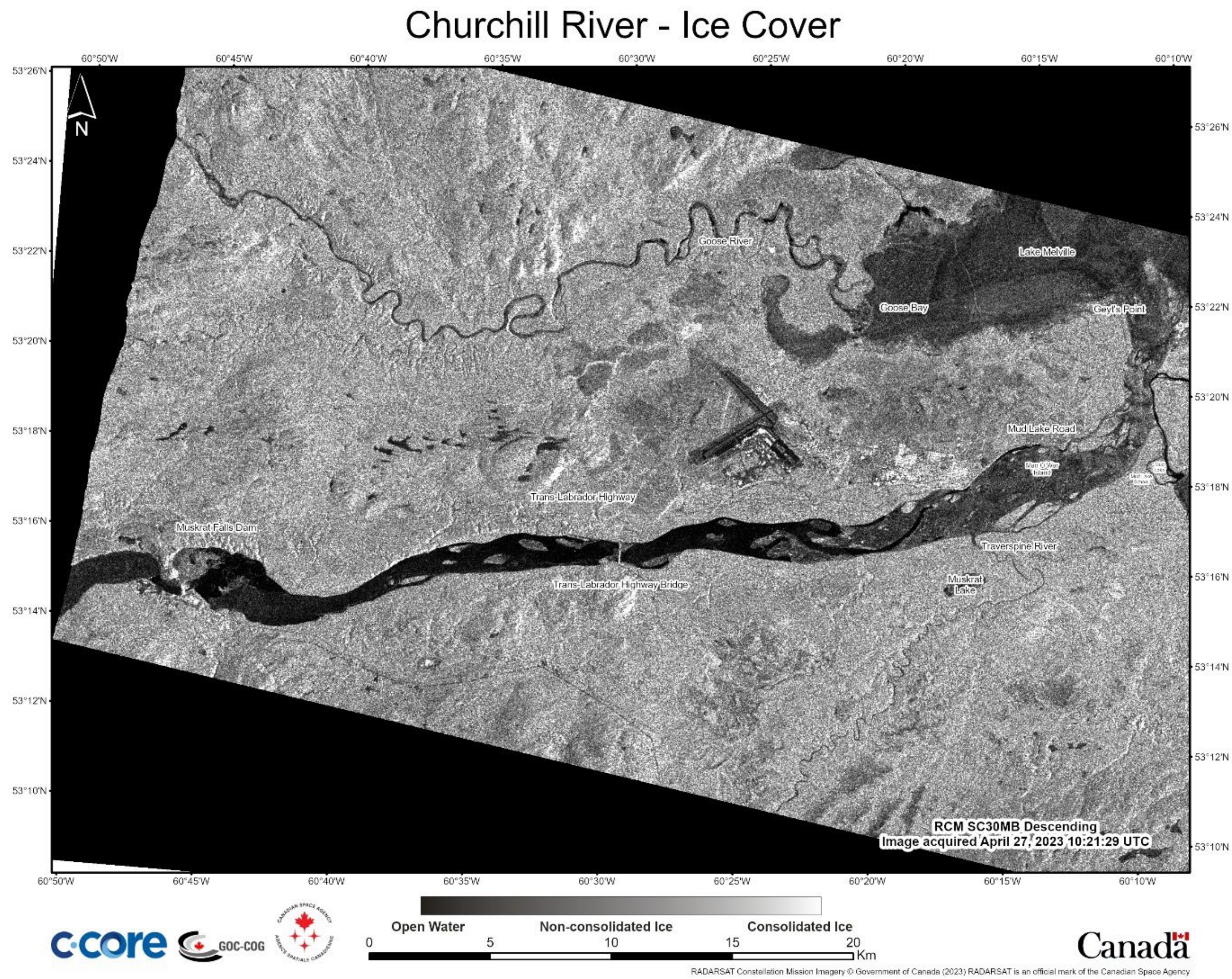

Figure B-21: Ice Cover – April 27, 2023.

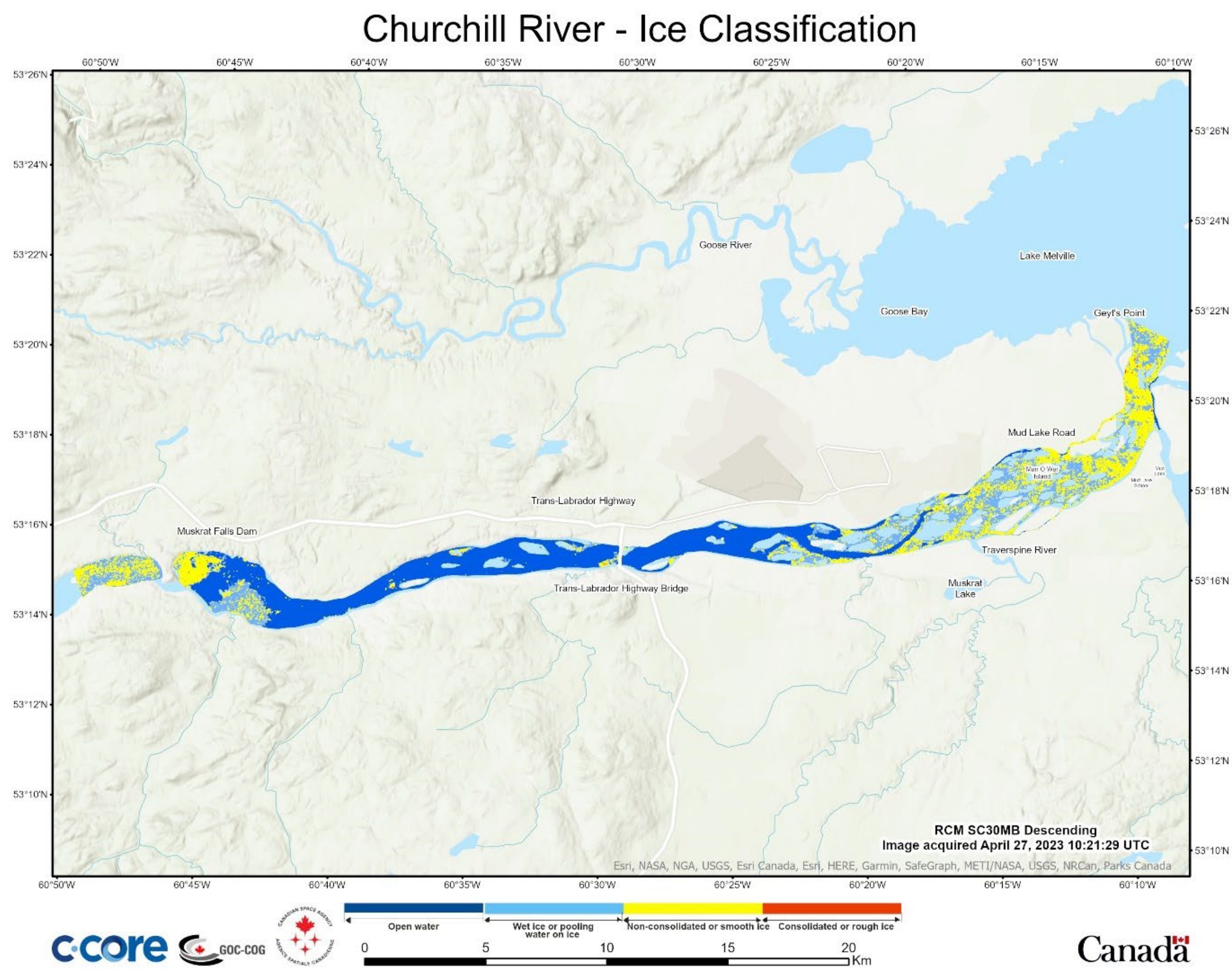

Figure B-22: Ice Classification – April 27, 2023.

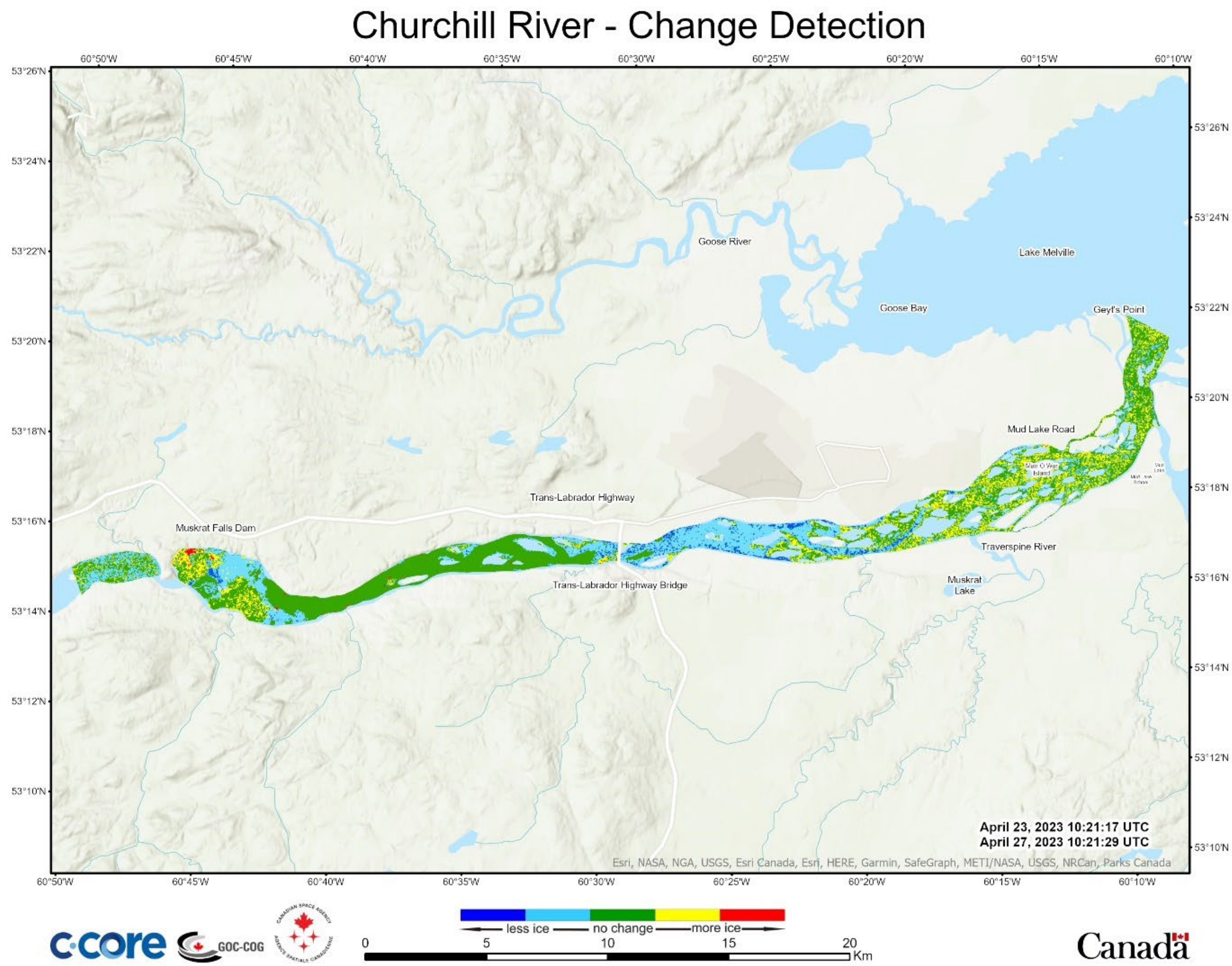

Figure B-23: Change Detection – April 23 and 27, 2023.

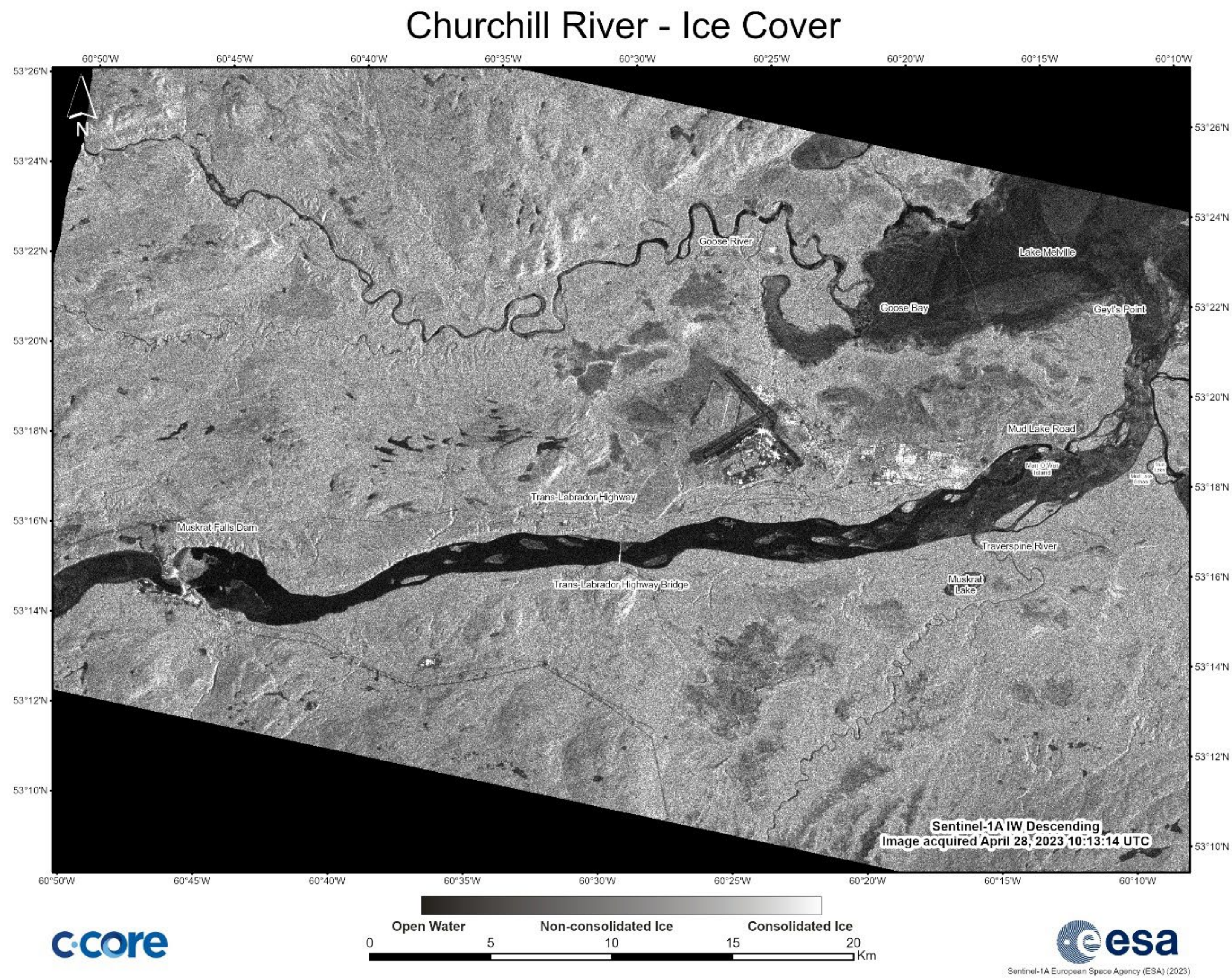

Figure B-24: Ice Cover – April 28, 2023.

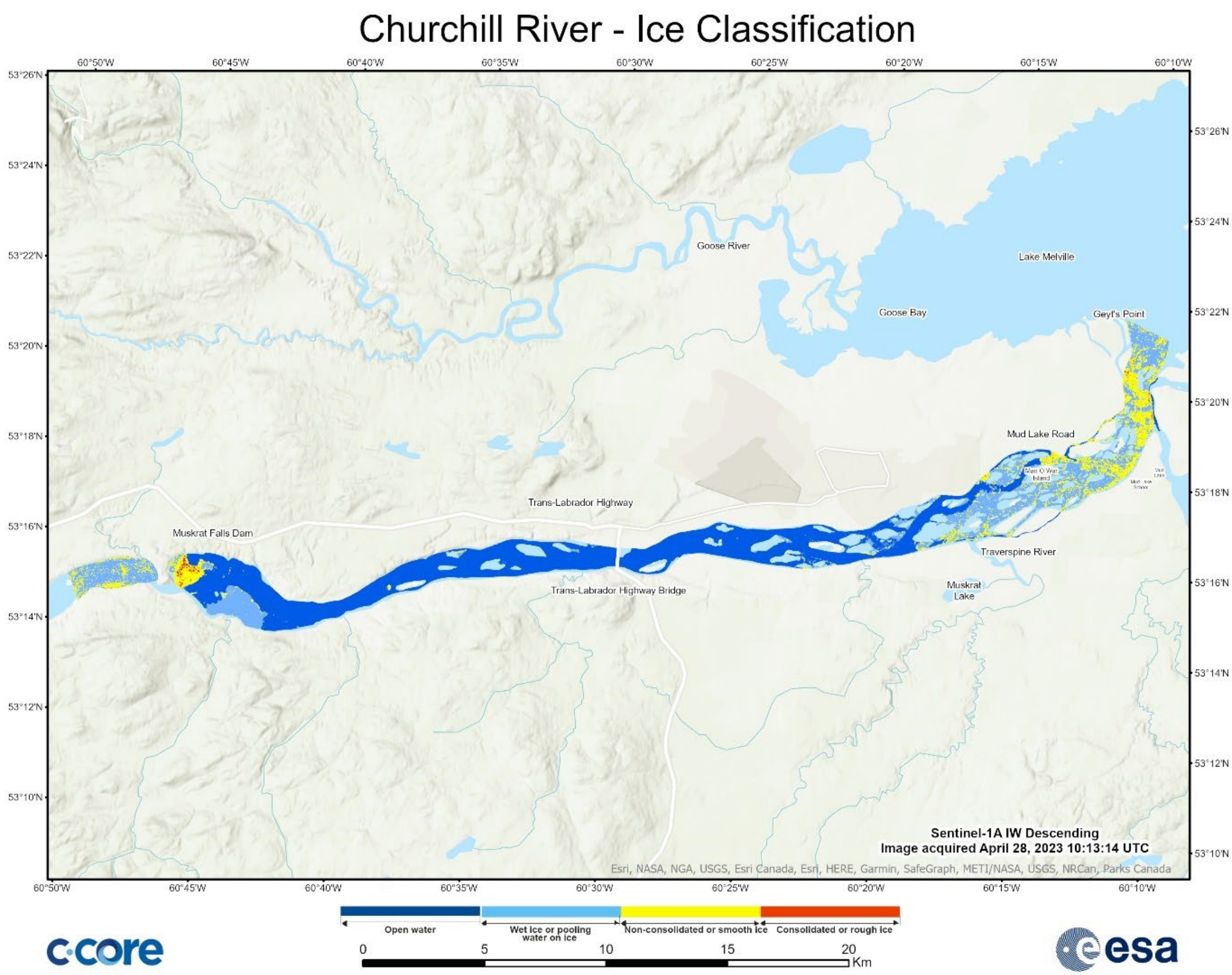

Figure B-25: Ice Classification – April 28, 2023.

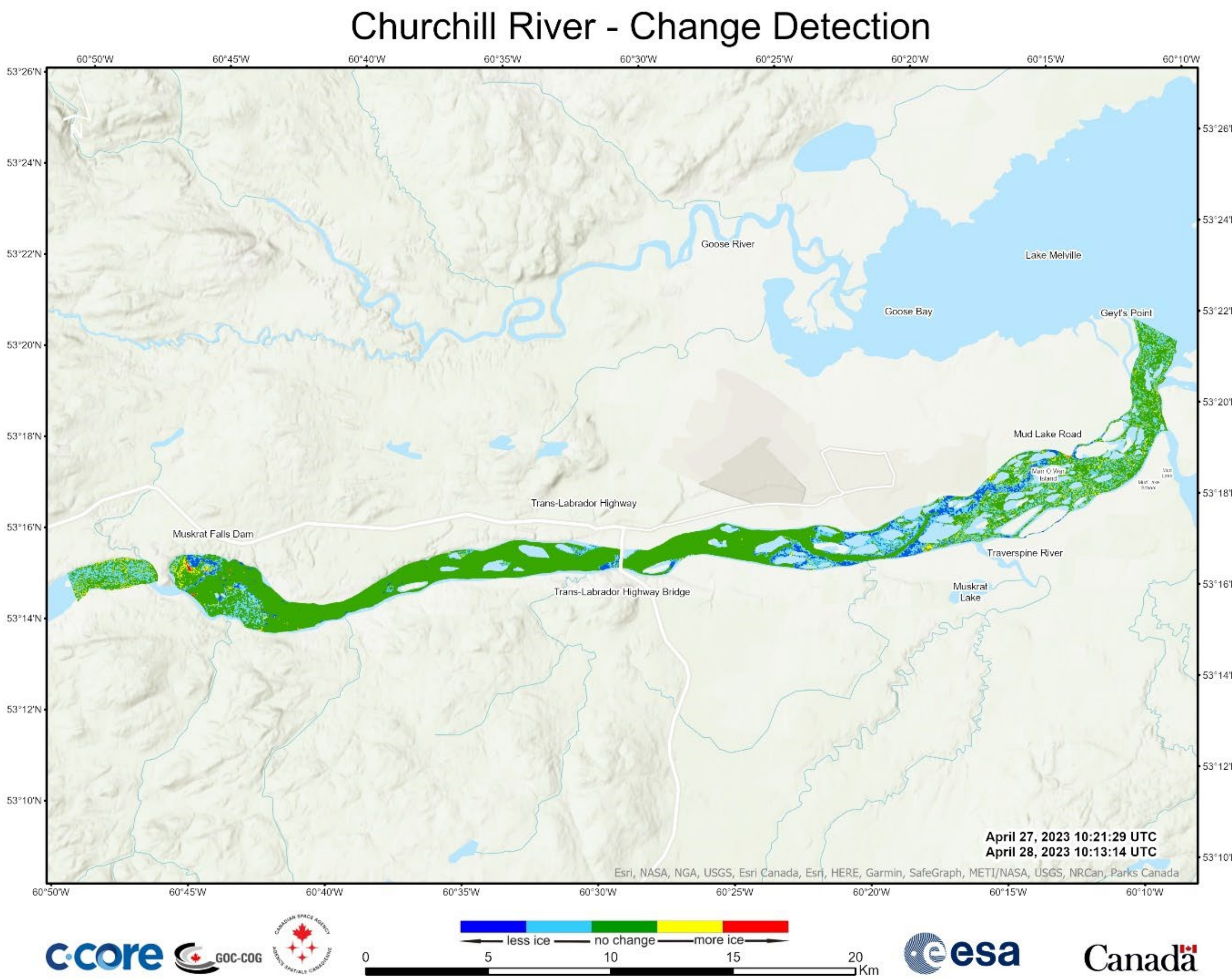

Figure B-26: Change Detection – April 27 and 28, 2023.

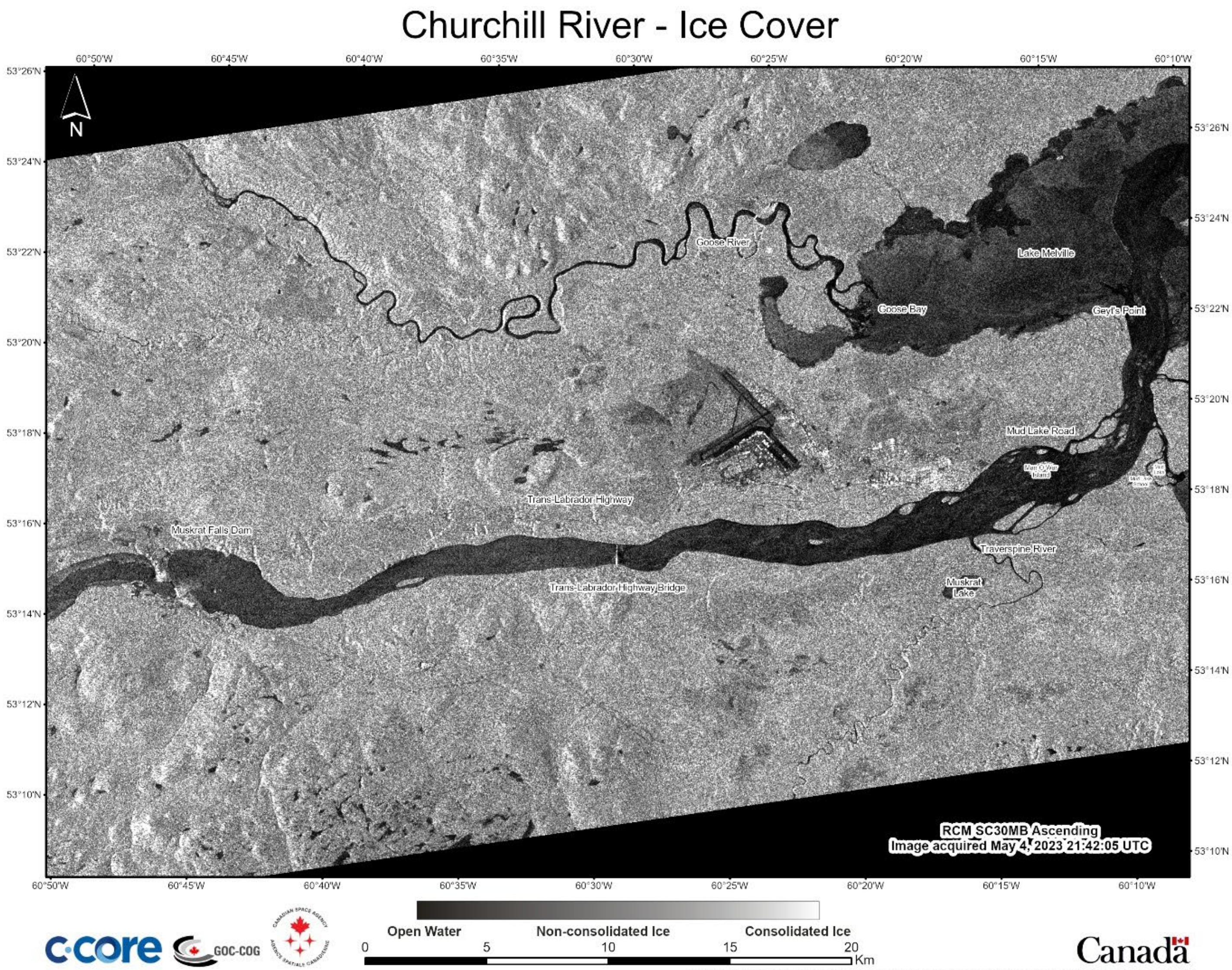

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Figure B-27: Ice Cover – May 4, 2023.

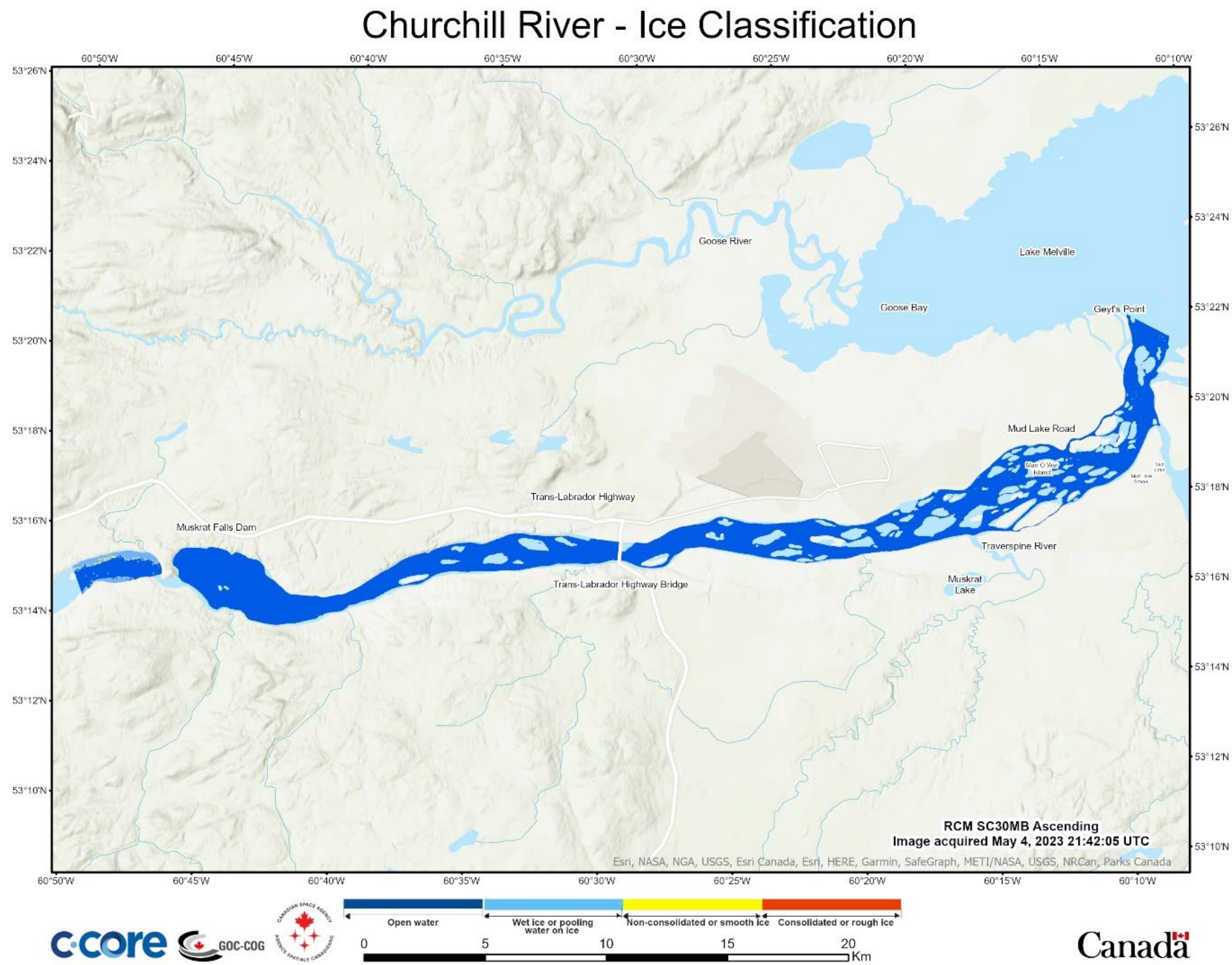


Figure B-28: Ice Classification – May 4, 2023.

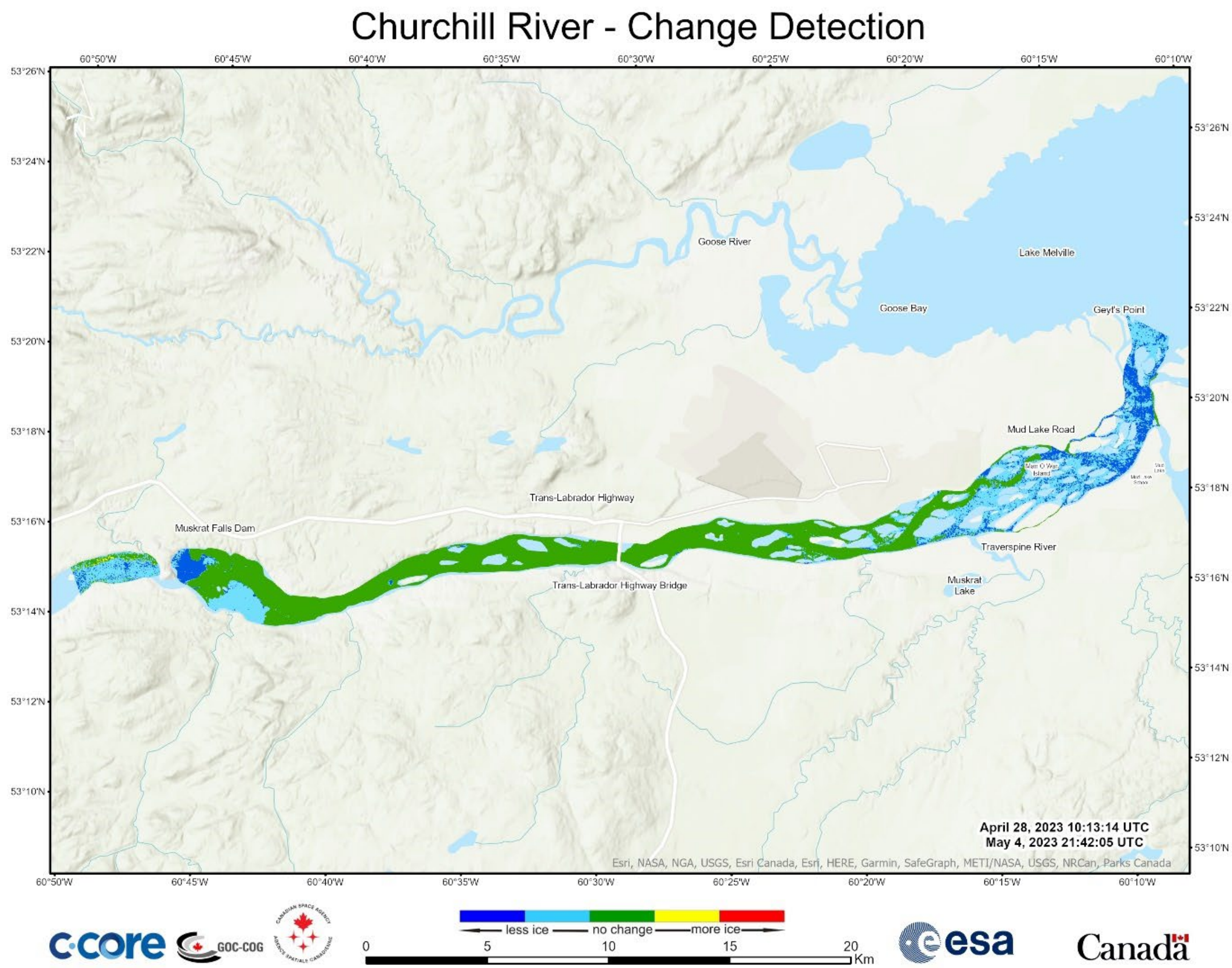
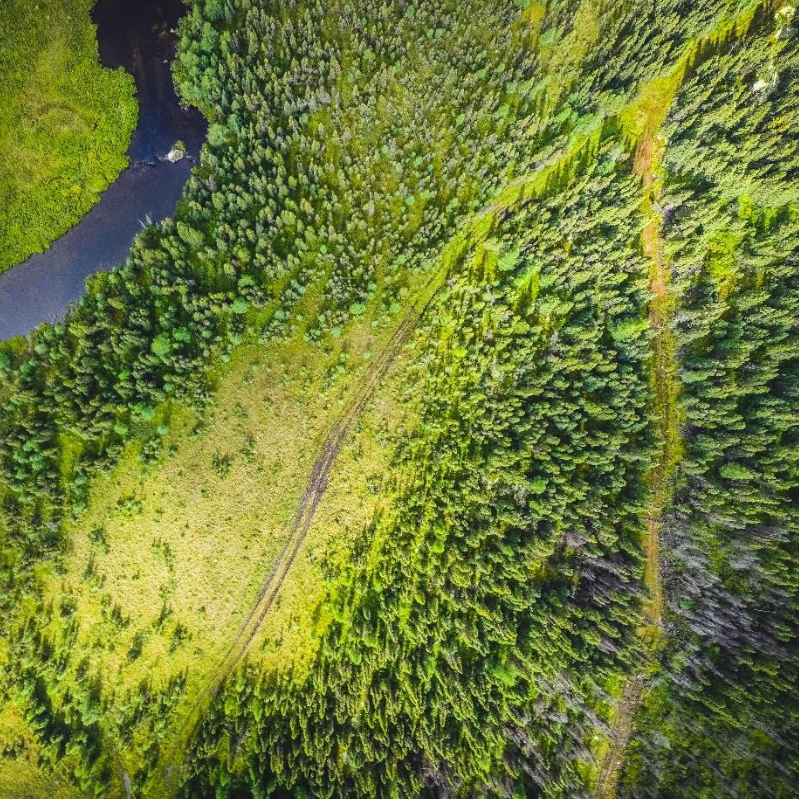
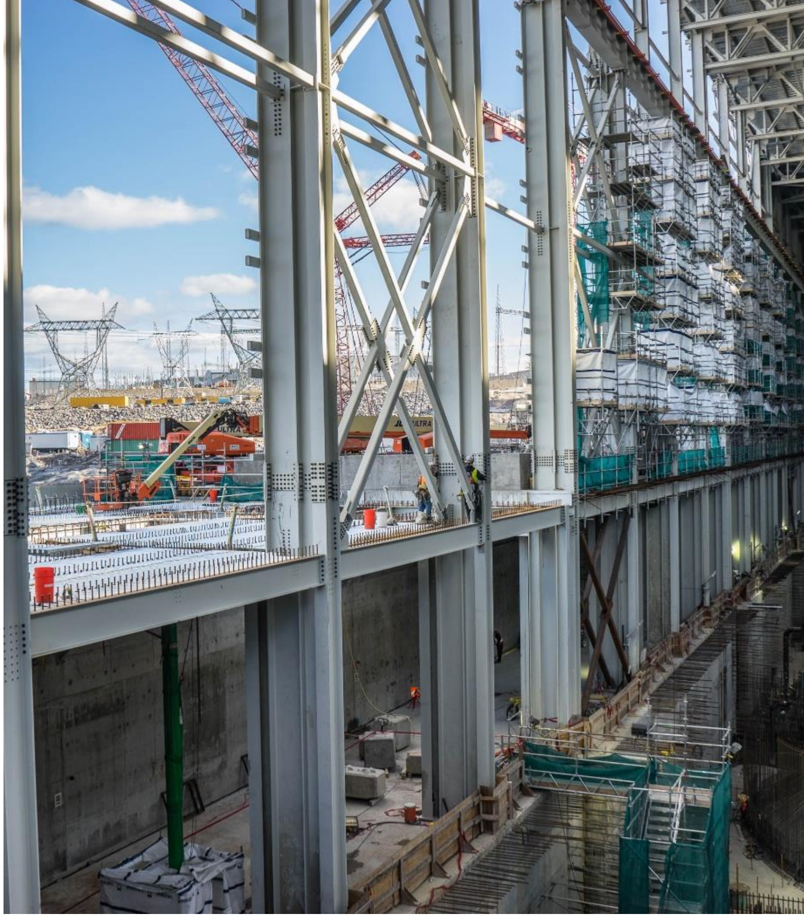


Figure B-29: Change Detection – April 28 and May 4, 2023.





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