sem

2023-2024 Ice Formation Environmental Effects Monitoring Study, Lower Churchill River 2021-87957 VC

REF # 193-003

20 YEARS

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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 2023-2024 ice season was the eleventh 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;
- Acquisition and interpretation of satellite imagery to document the freeze-up and break-up processes in each ice season; and
- Evaluation of long-term data series to determine any trends relative to the LCP project and the possible influence of climate change (analyses in the 2023-2024 ice season report only).

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. Review of images from this web camera was used to assist in planning acquisition of satellite images. Webcam images during the period from November 20, 2023, to December 18, 2023, and March 30 to April 24, 2024, were used to further document and describe the freeze-up and break-up processes, respectively. There were no images from December 21, 2023 (2:33 p.m.), to January 11, 2024 (3:01 p.m.) however the freeze up process had effectively been completed by December 15, 2023.

The timing of the freeze-up and break-up processes during the 2023-2024 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 15, 2023. The date of freeze-up was 15 days later than the long-term average (November 30), four days later than the freeze-up in 2022, and nine days later than the average for the last ten years 2014-2023 (December 6). This is the

third 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 19, 2024. The date of break-up was 25 days earlier the long-term average (May 14), ten days earlier than the break-up in 2023 (April 21), and 25 days earlier than the average for the last ten years, 2015 to 2024 (May 14). The break-up date in 2024 (April 19) was the earliest on record, and only the fifth in the month of April.

The total length of the ice-covered period or ice season was 126 days for the 2023-2024 ice season. Historically the ice season has ranged between 125 and 190 days, averaging 163.8 days since 1975-76 and 156.2 days over the last ten-year period (2014-2023). The ice season in 2023-2024 (126 days) was the second shortest on record only being less in 2010-11 (125 days).

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 2023-2024 (November 30, 2023), ice cover was fully formed (98.31%) above the Muskrat Falls dam (Site 7). Ice cover percentages at the lower site (1) was the next highest (9.11%) and ice cover at Site 1 accumulated the quickest reaching 89.7% on December 6, 2023. Site 2 achieved 89.7% ice cover by December 12, 2023. Sites 3 and 4 achieved 99.26% and 99.87% ice cover on December 15 and December 23, 2023, respectively. Increasing ice accumulation was largely continuous at most sites excepting Sites 3 and 6 where ice cover decreased from December 3 to December 6 (31.46% Site 4to 15.91%), 2023, and December 15 to December 23 (39.41% to 49.7%),2023, respectively. Site 5 was the last site to fully freeze-up with ice cover remaining below 10% until December 24, 2023, and then increasing rapidly from 16.41% on December 26, 2023, to 86.81% and then 98.98% from January 5 through January 12, 2024. Site 4, associated with the Blackrock Bridge and causeway, was mostly ice covered (97.58%) by December 23, 2023. This was similar to the 2022-2023 ice season, however, was in contrast to the 2020-2021 and 2021-2022 ice seasons where open water was still evident at the end of the freeze up period. Fast water at the narrowing of the bridge and causeway is thought to slow the freeze up process at this site.

The percent of ice cover decreased progressively from April 5 through May 3, 2024, with Site 5 the quickest to lose ice having only 11.0% ice cover on April 13, 2024. Sites 2, 3, 4 and 6 lost ice rapidly from April 13 to 20 with all sites having less than 10% ice cover by April 20. Site 7, below Muskrat Falls, was the last site to lose ice having 93.5% on April 22, 2024, and becoming being ice free by May 3, 2024, the last day of monitoring. Site 1 lost ice rapidly from April 17 (93.9%) to April 21 (4.87%), 2024. The loss of ice cover

was continuous at all sites over the break-up period with some minor evidence of ice accumulation or formation on April 21, 2024.

A total of 13 RADARSAT Constellation Mission (RCM) and seven 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 Appendices A (freeze-up) and B (Break-up).

Long-term mean monthly temperature data from the weather station in Happy Valley-Goose Bay was examined by linear regression to assess how much variance in temperature was explained from 1975 to 2024, with the passing of time a proxy for climate change. There was a weak trend towards increasing temperatures across most months however the trend was most pronounced during December (r^2=at 0.252, P<0.001). The pronounced warming trend during December may be an important contribution to a similar trend delaying of in freeze-up dates over time.

A more detailed analysis of available satellite imagery for from 2017-2018 to 2023-2024 ice seasons was used to evaluate the duration of three key life cycle events in the Lower Churchill ice season. There was a strong relationship between advancing years and the number of days that pass in each river ice life cycle. This trend was strongest during freeze-up (r^2=0.8802) followed by frozen (r^2=0.7789) and then break-up (r^2=0.6313). As the ice seasons passed, freeze-up events were extending (from 8 days in 2017/2018 to 43 days in 2023/2024), break-up events were extending (from 18 days in 2017/2018 to 30 days in 2023/2024), while the frozen period was shortening, particularly after 2019 (from 134 frozen days in 2017/2018 and 82 frozen days in 2023/2024).

The number of days the Mud Lake Ice Crossing was available for use by snowmobile has been documented by Mud Lake residents since 1975 and was examined as another measure of changing ice cover dynamics on the Churchill River. The number of days (duration) the ice crossing was available in each year from 1975 to 2023/24 ice season indicated a trend that the duration of the ice cover was reducing (r^2 = 0.225).

The influence of the Lower Churchill Project on ice season dynamics was examined by looking at freeze-up dates, break-up dates, and length of ice season before and after the Muskrat Falls reservoir was filled. Mud Lake residents had concerns the Project could affect timing of formation, duration and integrity of the Mud Lake ice crossing in late fall/early winter and in the spring when it is unsafe to cross the river by either boat or snowmobile. The reservoir was flooded in August of 2019, resulting in five years of data for the post-impoundment period and 45 years pre-impoundment. There was good evidence over this initial five year period that the Lower Churchill Project was delaying freeze-up, advancing break-up, and reducing the length of the ice season. NL Hydro collects ice measurements at several locations along, and in the vicinity of the Mud Lake crossing, on a biweekly basis. These data are provided to the NLDECC/WRMD for publishing on their webpage.

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 to Lake Melville (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 potentially 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.

Newfoundland and Labrador Hydro (NL Hydro, formerly Nalcor Energy for this project) has been observing ice processes in the Lower Churchill River since 2006 as part of baseline data collection and 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 NL Hydro to take appropriate precautions and develop mitigation measures to manage potential problems due to ice. NL Hydro 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, 2022-2023, and 2023-2024 ice seasons was contracted by the Muskrat Falls Corporation directly to SEM while NL Hydro retained overall management of the program. SEM has continued to partner with C-CORE on the acquisition and analysis of satellite imagery data.

This report presents the results of studies completed in the 2023-2024 ice season (Year 11) during the construction and operational phases of the LCP (SEM 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, and 2023). 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 2023-2024 ice season. A total of 13 RADARSAT Constellation Mission (RCM), and seven Sentinel-1 (S1) SAR images were analyzed during the freeze-up (November 30, 2023 to January 12, 2024) and break-up (Aril 3 to May 3, 2024) 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.

NL Hydro also requested that SEM conduct a trend analysis of the ice monitoring data to examine the effects of the LCP on the ice freeze-up and break-up processes and to determine if the predictions made during the environmental assessment process were supported by the monitoring data.

2.0 Materials and Methods

2.1 Objectives

The Ice Survey Program for the LCP has been focused on surveying ice freeze-up and break-up in the Lower Churchill River from Lake Melville to Muskrat Falls pre- and post-impoundment. The program during the 2023-2024 ice season was the eleventh survey in a continuation of previous monitoring during baseline and construction 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;

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

- In the 2023-2024 ice season, the ice monitoring data was further evaluated to determine any trends in the data relative to the LCP project and the possible influence of climate change.

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 13 RADARSAT Constellation Mission (RCM), and seven 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 2023-2024 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, timing of freeze-up and break up events.
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 during planning for timing of surveys and to document the freeze-up and break-up conditions. Images during the period from November 1, 2023, to January 31, 2024, and March 15 to May 15, 2023, were reviewed and 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 2023-2024 ice season were December 15, 2023 (first snowmobile crossing) and April 19, 2024 (first boat crossing).

2.5   Existing Conditions

River conditions during the 2023-2024 ice season were similar to the previous ice seasons from 2019-2020 to 2022-2023 with water impounded in the Muskrat Falls reservoir and the LCP fully operational. Water levels in the reservoir were maintained at full supply level throughout the 2023-2024 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 then 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.
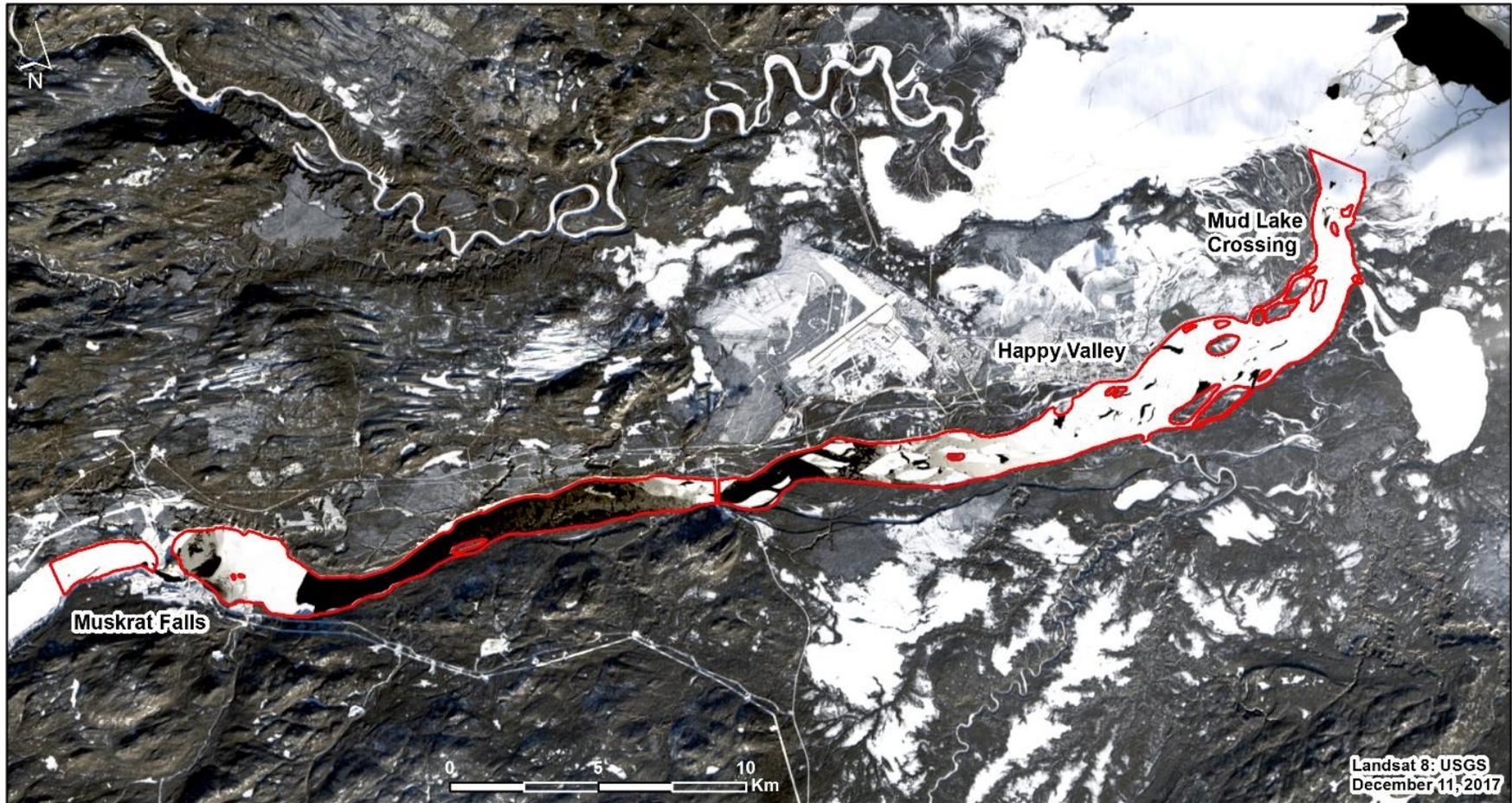
Figure 2.1   Section of the Lower Churchill River Monitored Between Muskrat Falls and Lake Melville.

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). The S1 constellation is currently down to one satellite due to an anomaly experienced on December 23, 2021, and a replacement satellite is expected to be launched in 2024. 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. RCM and S1 have similar spatial resolutions allowing them to be used together for this study. 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 2023-2024. 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 request for image tasking 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 acquired for this study. 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 2023-2024 Ice Season.

Satellite	Beam Mode	Spatial Resolution (m)	Image Width (km)	Number of Images
RCM	ScanSAR 30M	30	125	13
S1	Interferometric Wide	20	250	7

Table 2.3   Satellite Image Acquisition Schedule for the 2023-2024 Ice Season.

Date	Time (UTC)	Spatial Resolution (m)	Satellite	Event
November 30, 2023	10:13	20	S1	Freeze-up
December 3, 2023	10:21	30	RCM	Freeze-up
December 6, 2023	21:42	30	RCM	Freeze-up
December 12, 2023	10:13	20	S1	Freeze-up
December 15, 2023	21:49	30	RCM	Freeze-up
December 23, 2023	10:21	30	RCM	Freeze-up
December 24, 2023	10:13	20	S1	Freeze-up
December 26, 2023	10:14	30	RCM	Freeze-up
January 5, 2024	10:13	20	S1	Freeze-up
January 12, 2024	10:21	30	RCM	Freeze-up
April 3, 2024	10:21	20	S1	Break-up
April 5, 2024	10:21	30	RCM	Break-up
April 10, 2024	10:13	20	S1	Break-up
April 13, 2024	10:21	30	RCM	Break-up
April 17, 2024	10:21	30	RCM	Break-up
April 20, 2024	10:13	30	RCM	Break-up
April 21, 2024	10:21	30	RCM	Break-up
April 22, 2024	10:13	20	S1	Break-up
April 29, 2024	10:21	30	RCM	Break-up
May 3, 2024	10:21	30	RCM	Break-up
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.
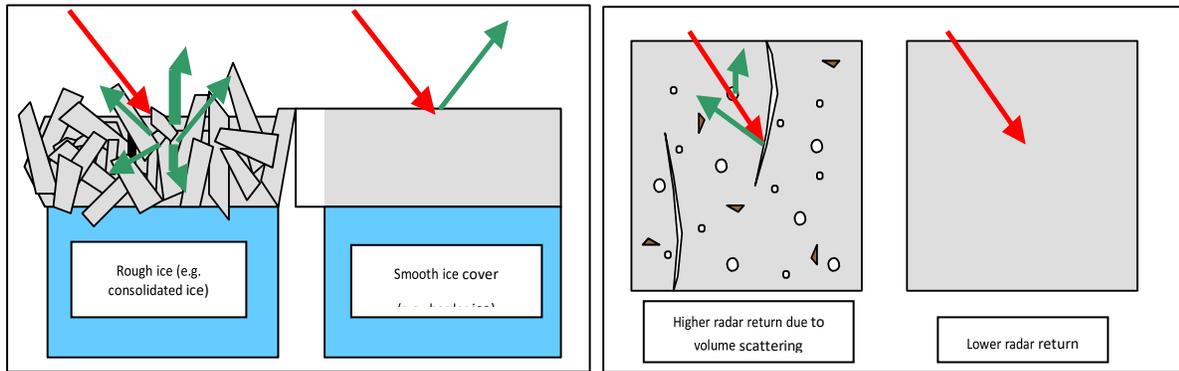
Figure 2.2   Conceptual River Ice Scattering Mechanisms (after Pelletier, Hicks and van der Sanden 2003).

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 12, 2023, 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 12, 2023, 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 6 and December 12, 2023, RCM images.
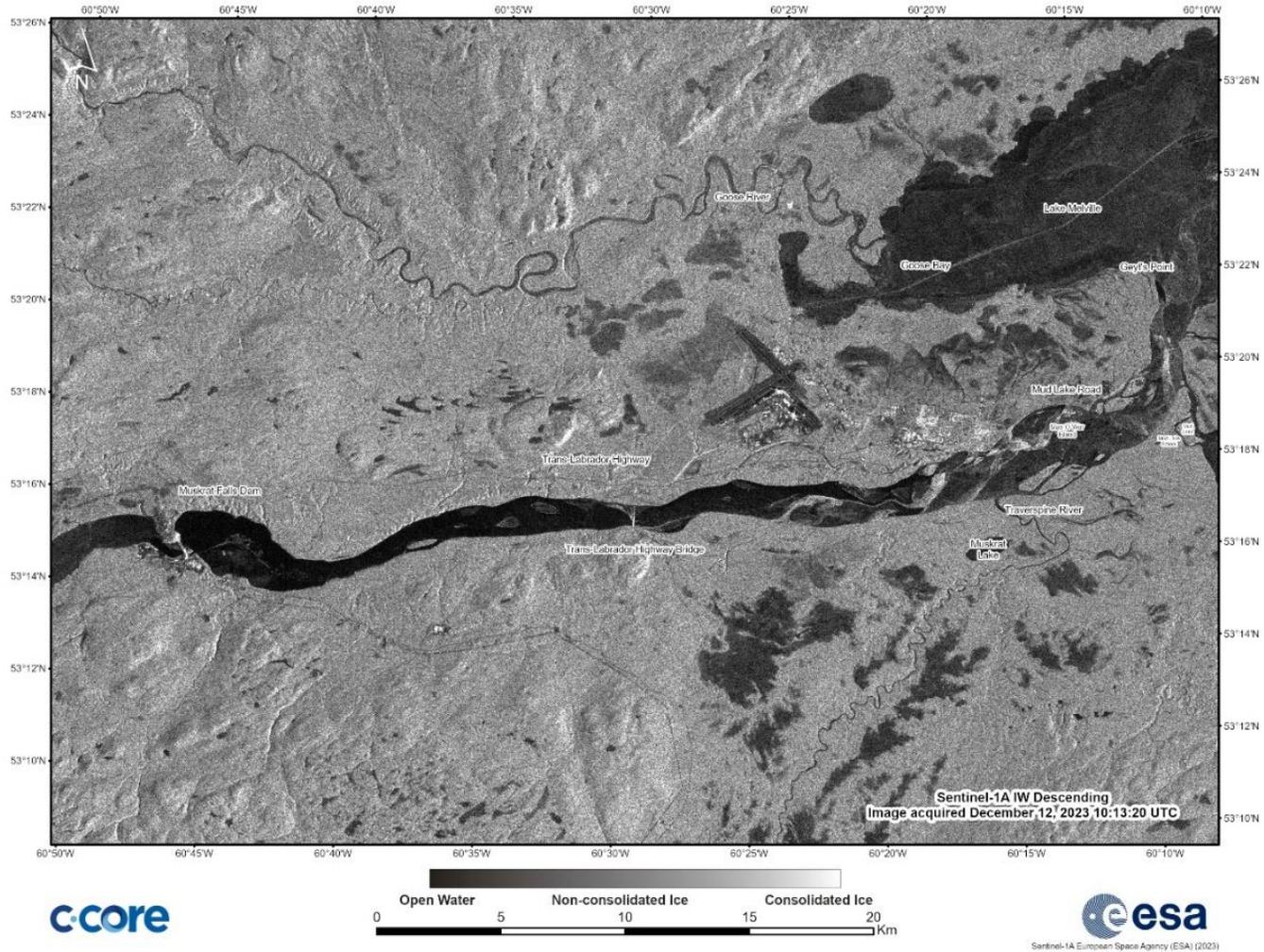
Figure 2.3   Ice Cover Product Created from the December 12, 2023, S1 Image.
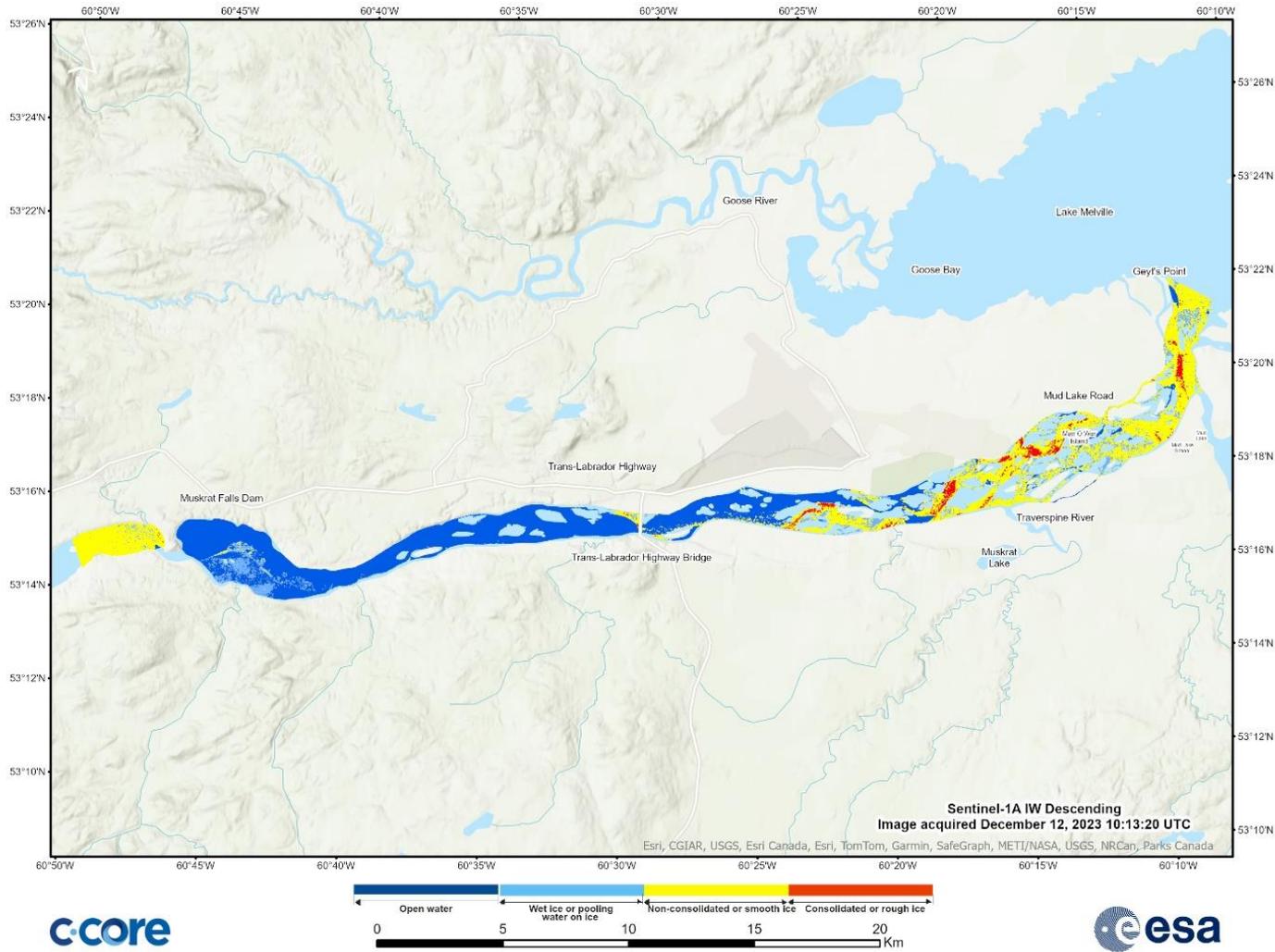
Figure 2.4   Ice Classification Product Created from the December 12, 2023, RCM Image.
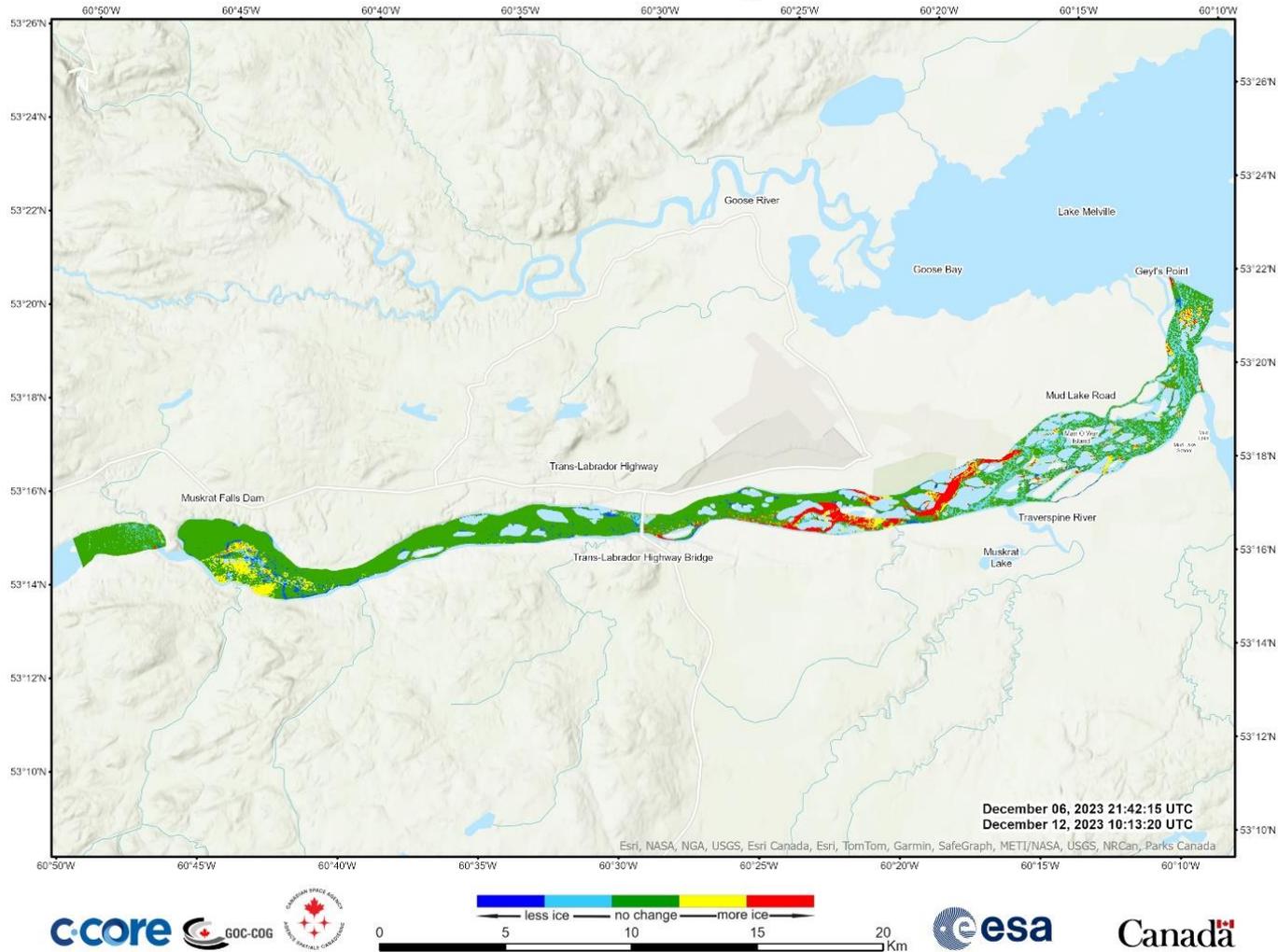
Figure 2.5   Change Detection Product Created from the December 6 and 12, 2023, Classifications.

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 seasons 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 2023-2024 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 2023-2024 to monitor and document the freeze-up and break-up processes. Images were subsequently provided by the NLDECC/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 12:00 p.m. each day. There were no images from December 21, 2023 (2:33 p.m.), to January 11, 2024 (3:01 p.m.), however, the freeze up process had effectively been completed by December 15, 2023.

The freeze-up sequence for the period from November 20, 2023, to December 18, 2023, is shown in Figures 3.1 and 3.2. Ice first started to form on November 25, 2023, and progressed through to December 2, 2023, when much of the river was ice covered. The river was fully frozen over on December 6, 2023. Surface water was apparent on the ice on December 8, 9 and 10, 2023, and had accumulated from a rainfall event. This surface water was fully frozen on December 15 and covered by snowfall. The ice bridge was considered formed on December 15, 2023, the date of the first snowmobile crossing for the 2023-2024 ice season (Jordan Hope, pers. comm.).

The break-up sequence for the period from March 30 to April 24, 2024, is shown in Figures 3.3 and 3.4. The images from March 30 through April 10, 2024, document the period pre-break-up where the river was still frozen over completely with some melting occurring on the southern shore of the river. Melting of the snow cover was apparent starting April 13 through 19, 2024, and significant melting was first apparent on April 20 through 22, 2024. The ice then rapidly broke up and the river was ice free on April 23, 2024. The date of first crossing by boat was April 19, 2024 (Jordan Hope, pers. comm.). The duration of the major break-up was 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 and 2023 (four to five days, SEM 2022 and 2023).
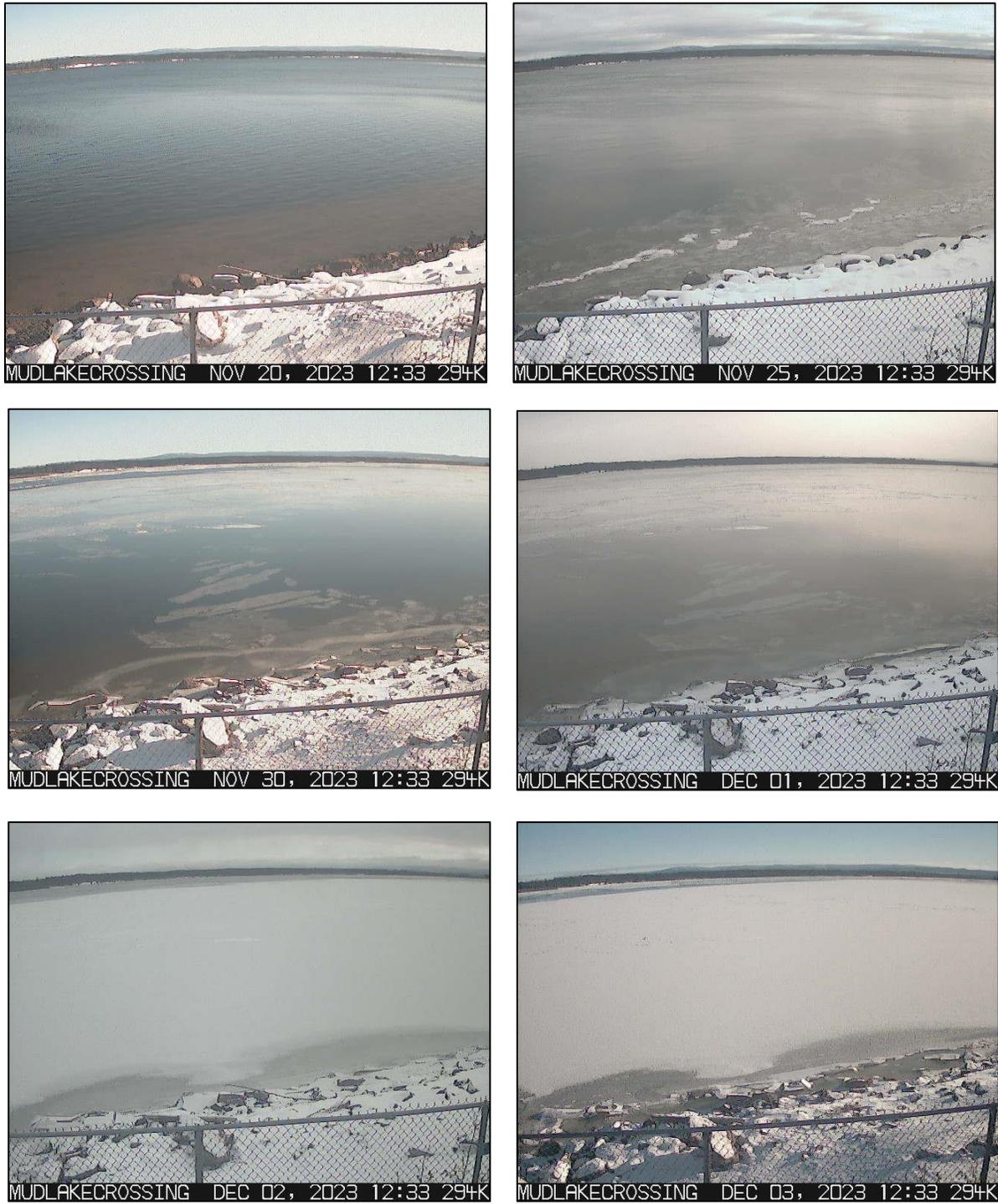
Figure 3.1   Mud Lake Web Camera Images During the Freeze-Up Process, November 20 to December 3, 2023.
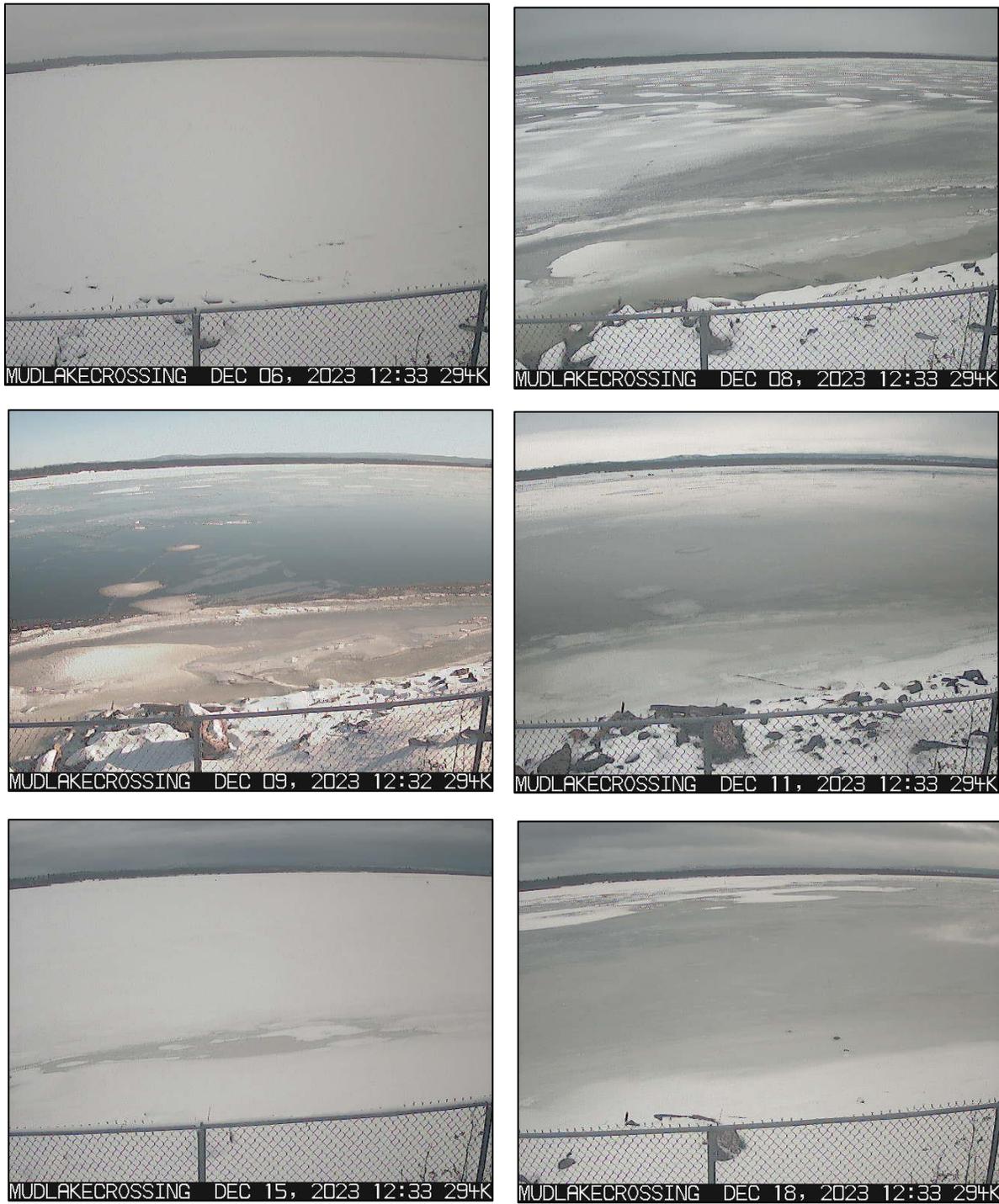
Figure 3.2   Mud Lake Web Camera Images During the Freeze-Up Process, December 6 to 18, 2023.
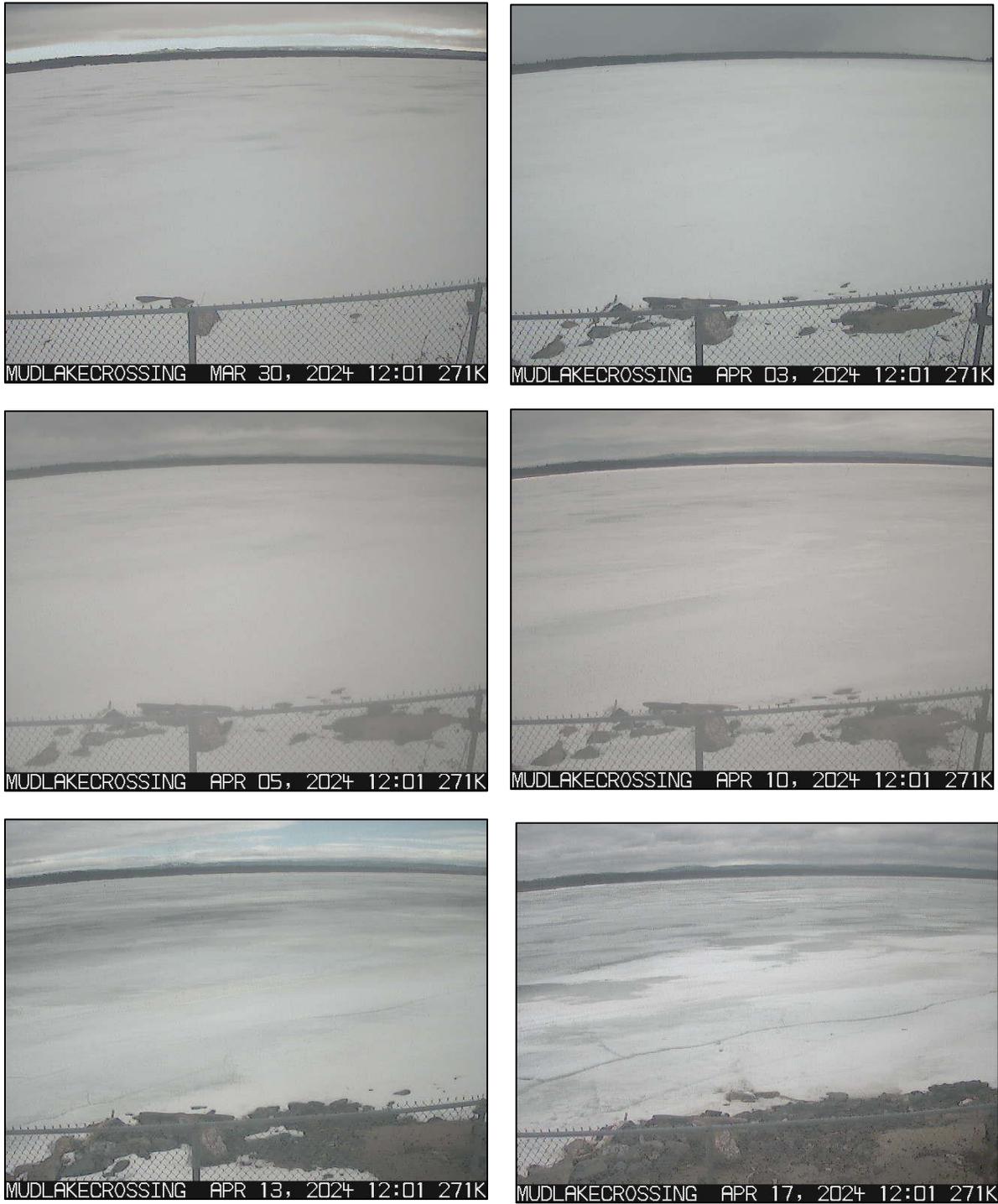
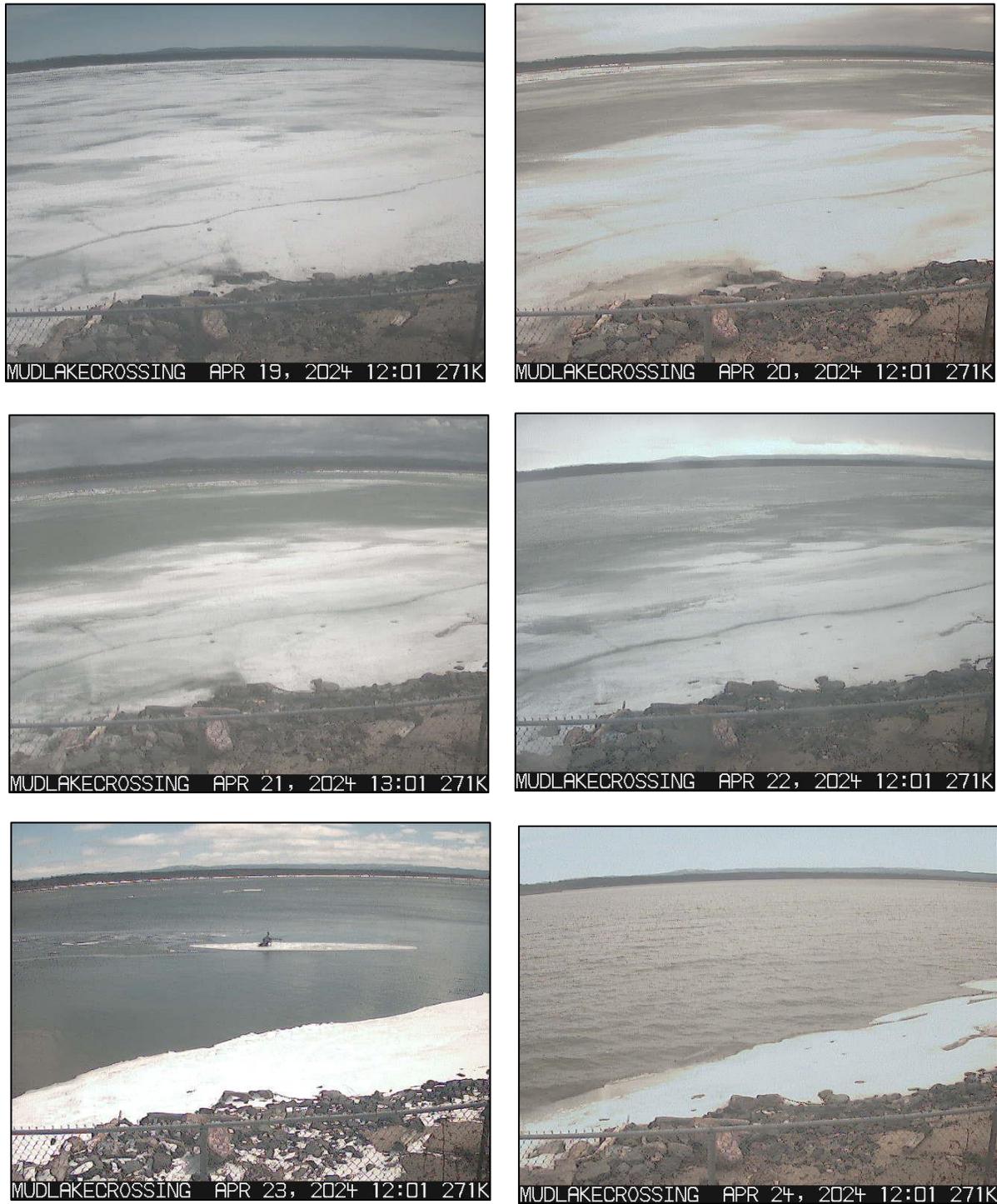**Figure 3.3   Mud Lake Web Camera Images During the Break-Up Process, March 30 to April 17, 2024.**

Figure 3.4   Mud Lake Web Camera Images During the Break-Up Process, April 19 to 24, 2024.

3.2 Timing of Freeze-Up and Break-Up

The timing of the freeze-up and break-up processes during the 2023-2024 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 15, 2023. The date of freeze-up was 15 days later than the long-term average (November 30), four days later than the freeze-up in 2022, and nine days later than the average for the last ten years 2014-2023 (December 6). This is the third 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 19, 2024. The date of break-up was 25 days earlier the long-term average (May 14), ten days earlier than the break-up in 2023 (April 21), and 25 days earlier than the average for the last ten years, 2015 to 2024 (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 2021 being the second latest freeze-up date over the last ten years (December 15). Since 2000, freeze-up has occurred in December in 18 of 24 years. The freeze-up date in 2022 was tied as the second 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
1987	28-Nov-87	23-Apr-87

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)
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	15-Dec-2023	29-Apr-23
2024	TBD	19-Apr-24
Long Term Average	30-Nov	14-May
Average 2012 – 2021 (Last 10 Years)	6-Dec	14-May

The average date of break-up over the last ten years (May 14) has the same as the long-term average (May 14), however the break-up in 2024 was considerably earlier than these averages. The break-up date in 2024 (April 19) was the earliest on record, and only the fifth 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 2023 (December 15) and break-up date in 2024 (April 19) resulted in total ice-covered period of 126 days for the 2023-2024 ice season. Historically the ice season has ranged between 125 and 190 days, averaging 163.8 days since 1975-76 and 156.2 days over the last ten-year period (2014-2023). The ice season in 2023-2043 (126 days) was the second shortest on record only being less in 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
1996-97	175
1997-98	170
1998-99	161
1999-2000	169
2000-01	171

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

Ice Season	Duration (Days)
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
2023-24	126
Long Term Average	163.8
Last 10 Year Average	156.2
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; November 30, December 3, 6, 12, 15, 23, 24, 26, 29, 2023, and January 5 and 12, 2024. The site numbers correspond to the numbered sections in Figure 2.6.

At the start of the monitoring period in 2023-2024 (November 30, 2023), ice cover was fully formed (98.31%) above the Muskrat Falls dam (Site 7). Ice cover percentages at the lower site (1) was the next highest (9.11%) and ice cover at Site 1 accumulated the quickest reaching 89.7% on December 6, 2023. Site 2 achieved 89.7% ice cover by December 12, 2023. Sites 3 and 4 achieved 99.26% and 99.87% on December 15 and December 23, 2023, respectively. Increasing ice accumulation was largely continuous at most sites excepting Sites 3 where ice cover noticeably decreased from December 3 to December 6 (31.46% Site 4to 15.91%), 2023. Site 5 was the last site to fully freeze-up with ice cover remaining below 10% until December 24, 2023, and then increasing rapidly from 16.41% on December 26, 2023, to 86.81% and then 98.98% from January 5 through January 12, 2024. Site 4, associated with the Blackrock Bridge and causeway, was mostly ice covered (97.58%) by December 23, 2023. This was similar to the 2022-2023 ice season, however, was in contrast to the 2020-2021 and 2021-2022 ice seasons where open water was still evident at the end of the freeze up period. Fast water at the narrowing of the bridge and causeway is thought to slow the freeze up process at this site.

Table 3.3   **Ice Cover and Open Water Percent Coverage for the Freeze-Up Period in 2023-2024.**

Site	30-Nov-23 Water (%)	Ice (%)	03-Dec-23 Water (%)	Ice (%)	06-Dec-23 Water (%)	Ice (%)	12-Dec-22 Water (%)	Ice (%)	15-Dec-22 Water (%)	Ice (%)
1	90.89	9.11	45.02	54.98	10.3	89.7	4.46	95.54	5.11	94.89
2	97.47	2.53	59.44	40.56	42.85	57.15	10.06	89.94	7.01	92.99
3	98.68	1.32	68.54	31.46	84.09	15.91	39.3	60.7	0.74	99.26
4	98.55	1.45	83.53	16.47	79.89	20.11	82.17	17.83	51.61	48.39
5	100	0	92.22	7.78	95.49	4.51	98.25	1.75	96.98	3.02
6	100	0	93.15	6.85	88.18	11.82	76.03	23.97	60.59	39.41
7	1.69	98.31	0.86	99.14	0.55	99.45	0.64	99.36	99.14	0.86
Mean	83.90	16.10	63.25	36.75	57.34	42.66	44.42	55.58	45.88	54.12
Std. Dev.	36.38	36.38	32.69	32.69	39.32	39.32	40.91	40.91	42.64	42.64

Site	23-Dec-22 Water (%)	Ice (%)	24-Dec-22 Water (%)	Ice (%)	26-Dec-22 Water (%)	Ice (%)	05-Jan-23 Water (%)	Ice (%)	12-Jan-23 Water (%)	Ice (%)
1	2.39	97.61	2.82	97.18	2.08	97.92	3.27	96.73	2.21	97.79
2	5.55	94.45	8.46	91.54	3.61	96.39	5.21	94.79	3.82	96.18
3	0.13	99.87	0.29	99.71	0.2	99.8	0.31	99.69	0.24	99.76
4	2.42	97.58	2.9	97.1	2.01	97.99	2.28	97.72	1.59	98.41
5	90.29	9.71	97.28	2.72	83.59	16.41	13.19	86.81	1.02	98.98
6	50.3	49.7	60.54	39.46	60.91	39.09	6.47	93.53	4.48	95.52
7	0.66	99.34	0.69	99.31	0.45	99.55	0.03	99.97	0.03	99.97
Mean	21.68	78.32	24.71	75.29	21.84	78.16	4.39	95.61	1.91	98.09
Std. Dev.	35.20	35.20	38.61	38.61	35.07	35.07	4.54	4.54	1.71	1.71
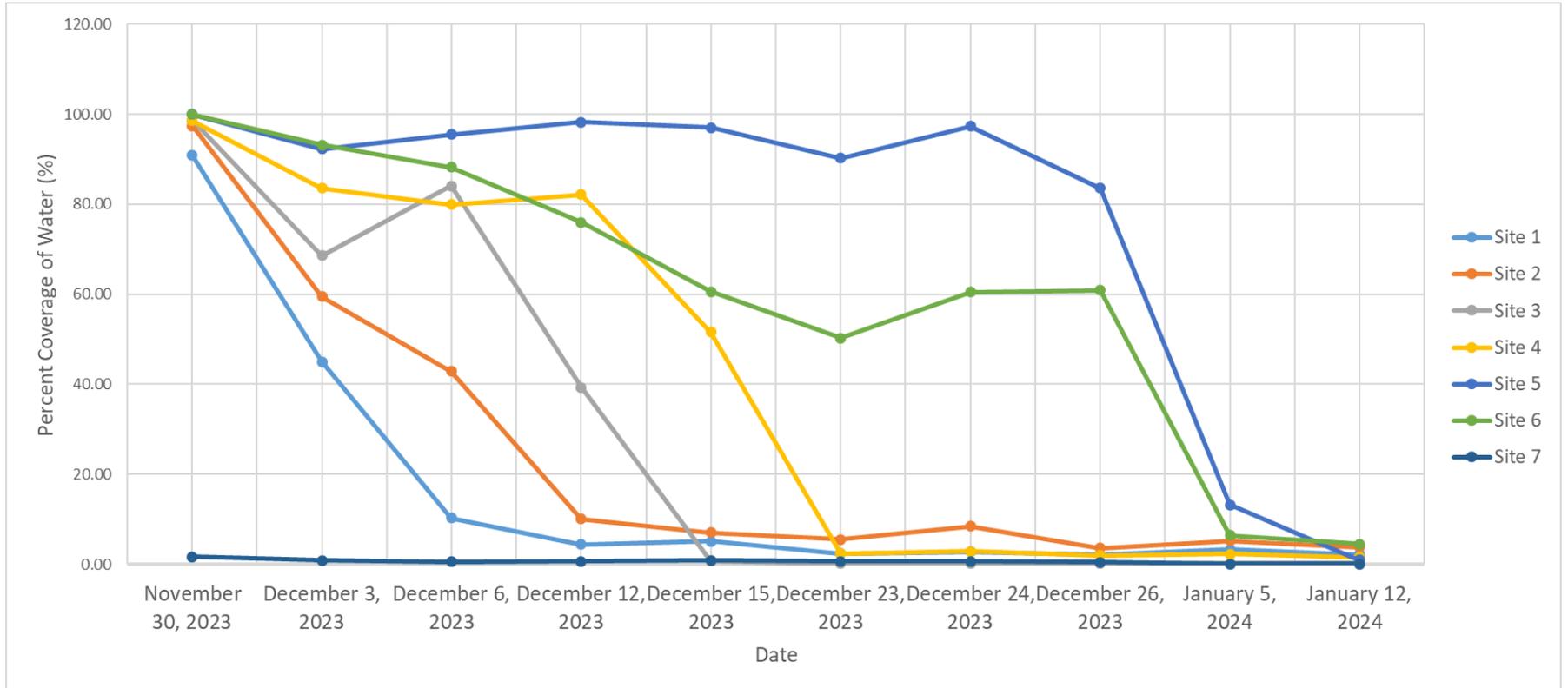
Figure 3.5   Open Water Percent Coverage for Freeze-Up in 2023-2024.
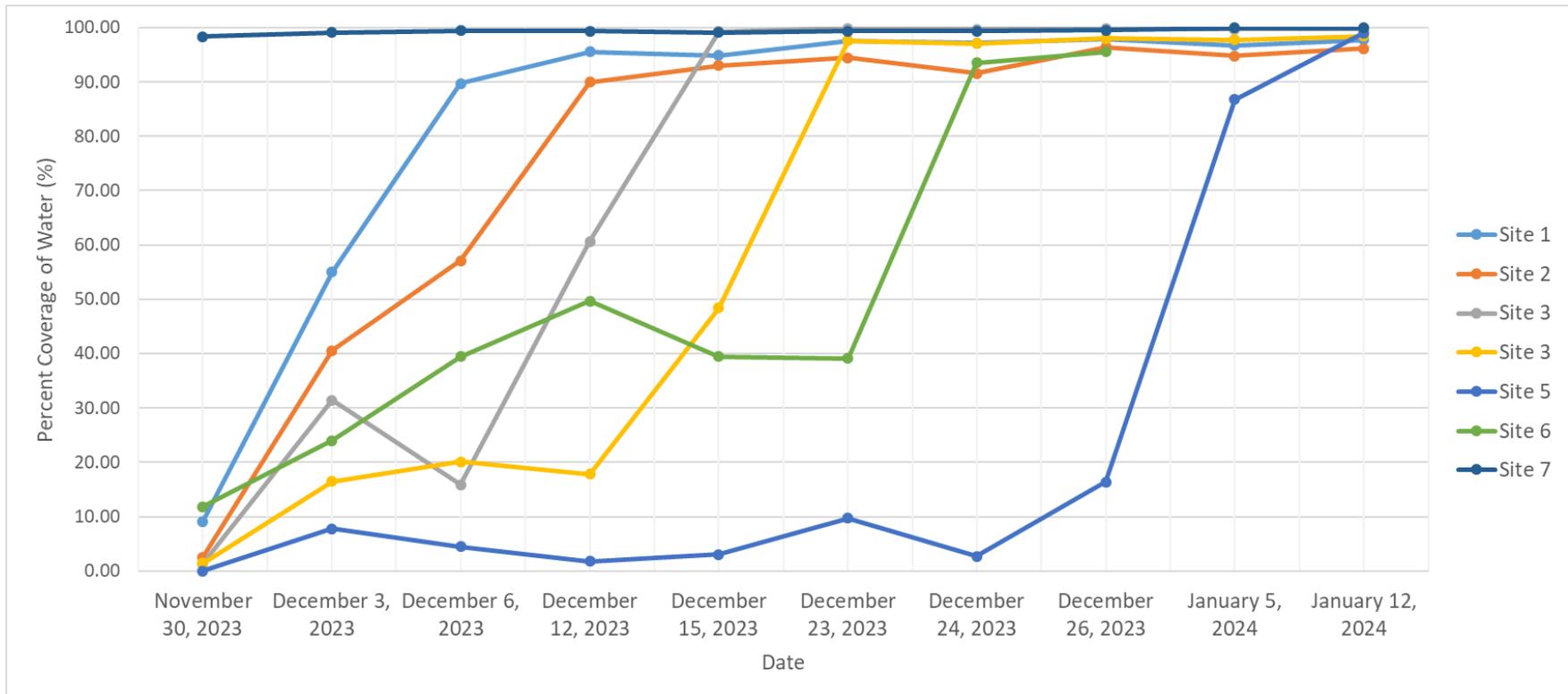
Figure 3.6   Ice Cover Percent Coverage for Freeze-Up in 2023-2024.

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: April 3, 5, 10, 13, 17, 20, 21, 22, 29, and May 3, 2024. The site numbers correspond to the numbered sections in Figure 2.6.

The percent of ice cover decreased progressively from April 5 through May 3, 2024, with Site 5 the quickest to lose ice with having only 11.0% ice cover on April 13, 2024. Site 2, 3, 4 and 6 lost ice rapidly from April 13 to 20 with all site having less than 10% ice cover by April 20. Site 7, below Muskrat Falls, was the last site to lose ice having 93.5% on April 22, 2024, and becoming being ice free by May 3, 2024, the last day of monitoring. Site 1 lost ice rapidly from April 17 (93.9%) to April 21 (4.87%), 2024. The loss of ice cover was continuous at all sites over the break-up period with some minor evidence of ice accumulation or formation on April 21, 2024.

Table 3.4   Ice Cover and Open Water Percent Coverage for the Break-Up Period in 2024.

Site	03-Apr-24		05-Apr-24		10-Apr-24		13-Apr-24		17-Apr-24	
	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)
1	0.03	99.97	0.05	99.95	0.17	99.83	0.03	99.97	6.1	93.9
2	1.97	98.03	2.34	97.66	2.48	97.52	2.53	97.47	3.74	96.26
3	0	100	0	100	0	100	0	100	18.29	81.71
4	0.44	99.56	0.2	99.8	0.23	99.77	0.52	99.48	90	10
5	6.37	93.63	6.5	93.5	38.91	61.09	89	11	95.3	4.7
6	4.74	95.26	6.09	93.91	10.12	89.88	15.02	84.98	62.38	37.62
7	0	100	0	100	0	100	0	100	0.04	99.96
Mean	1.94	98.06	2.17	97.83	7.42	92.58	15.30	84.70	39.41	60.59
Std. Dev.	2.61	2.61	2.94	2.94	14.36	14.36	32.95	32.95	42.01	42.01

Table 3.4   Ice Cover and Open Water Percent Coverage for the Break-Up Period in 2024. (Cont'd)

Site	20-Apr-24		21-Apr-24		22-Apr-24		29-Apr-24		03-May-24	
	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)	Water (%)	Ice (%)
1	38.81	61.19	95.13	4.87	97.82	2.18	100	0	100	0
2	93.84	6.16	93.77	6.23	96.85	3.15	100	0	100	0
3	98.96	1.04	98.07	1.93	99	1	100	0	100	0
4	97.78	2.22	96.72	3.28	97.78	2.22	100	0	100	0
5	100	0	97.79	2.21	100	0	100	0	100	0
6	67.17	32.83	97.85	2.15	97.83	2.17	100	0	100	0
7	0.6	99.4	3.57	96.43	6.5	93.5	29.94	70.06	100	0
Mean	71.02	28.98	83.27	16.73	85.11	14.89	89.99	10.01	100.00	0.00
Std. Dev.	38.45	38.45	35.18	35.18	34.68	34.68	26.48	26.48	0.00	0.00
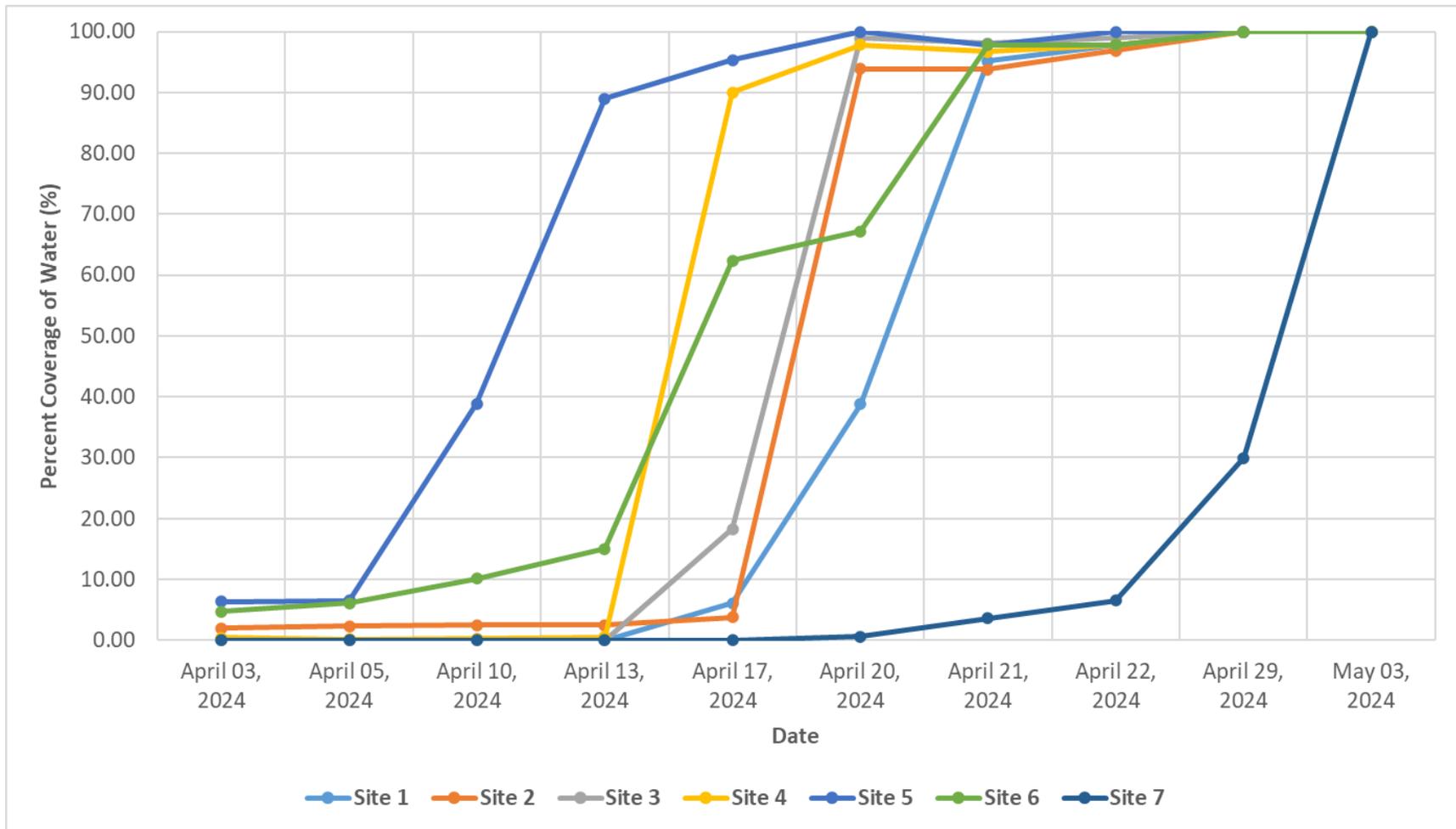
Figure 3.7   Open Water Percent Coverage for Break-Up In 2024.
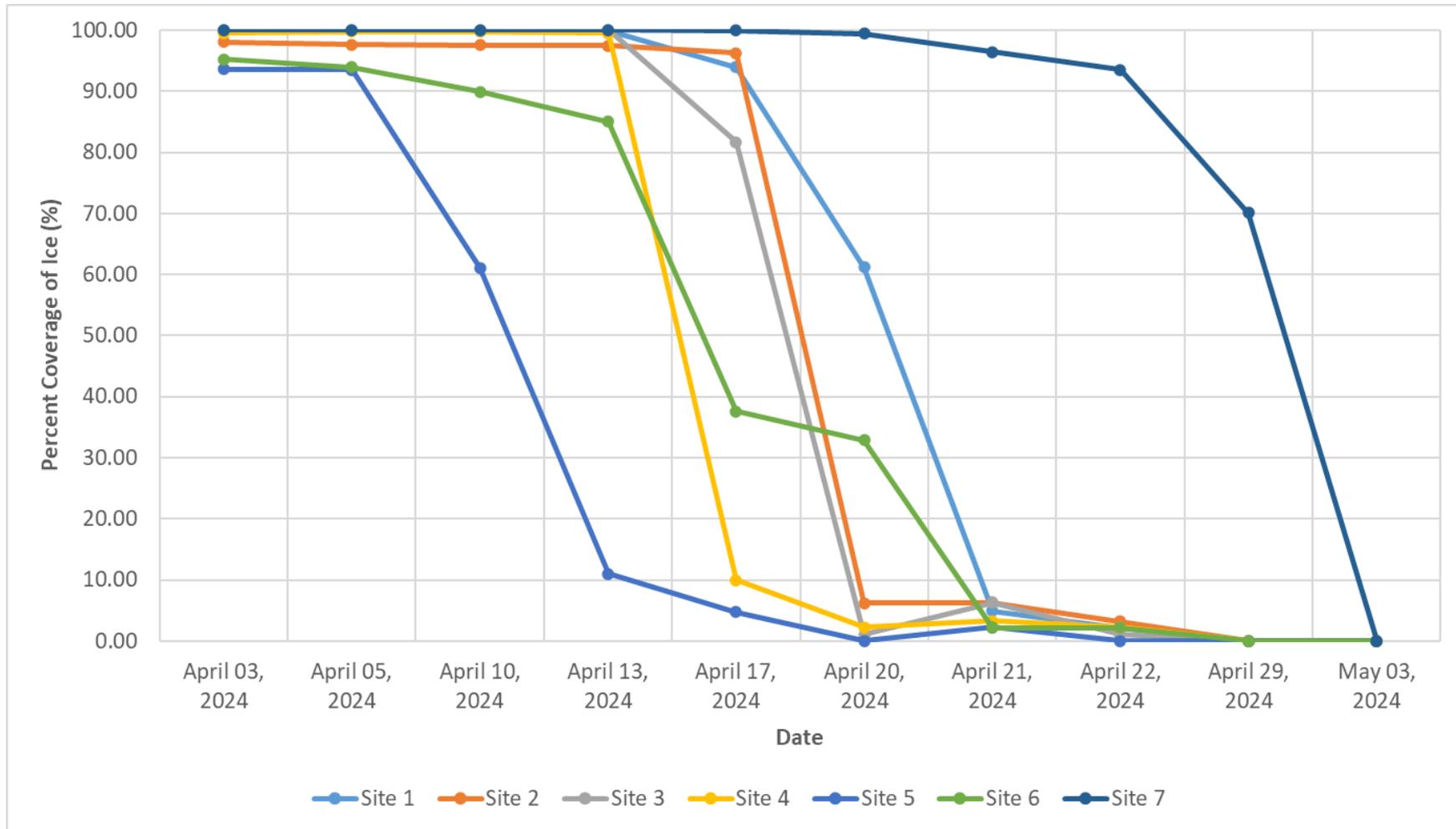
Figure 3.8   Ice Cover Percent Coverage for Break-Up in 2024.

3.4 Satellite Image Analyses

The following sections document the results of the Lower Churchill River freeze-up and break-up monitoring for the 2023-2024 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 3.9), 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.
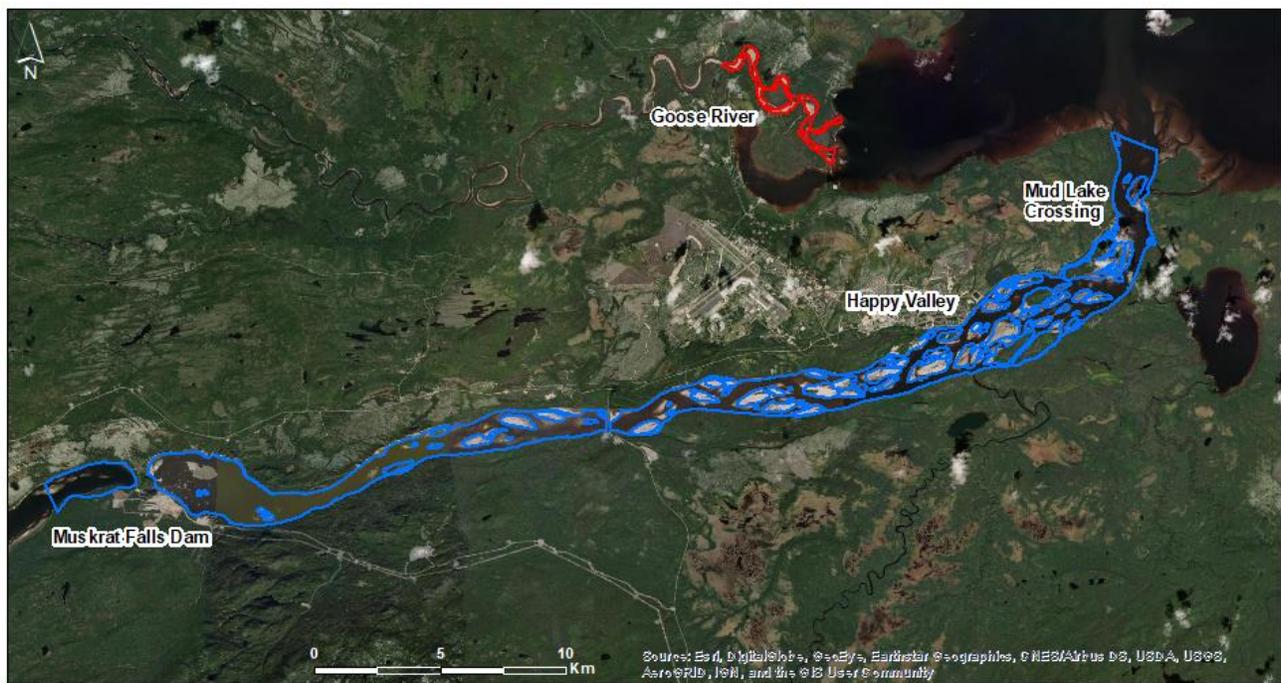
Figure 3.9   Goose River (Red) is Located North of the Churchill River (Blue).

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 November 30, 2023, and January 12, 2024. 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 November 30, 2023, where no change detection was produced because it was the first image in the series. Figure 3.10 shows the maximum and minimum temperatures, as recorded by Environment and Climate Change Canada for Goose Bay, Labrador, between November 1, 2023, and January 31, 2024. Minimum temperatures were below freezing for the most part during this period with daily maximum temperatures often above the freezing mark up to 12°C on December 19, 2023. Little to no rain fell during this period totaling 3.6 mm. There was a total of 156.9 cm of snowfall during this period including four days where more than 10 cm fell.

Table 3.5   Freeze-up Monitoring Dates for the Last Seven 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
2023-2024	November 30, 2023	January 12, 2024

During the early stages of freeze-up, ice accumulated at the mouth of the Churchill River due to ice buildup in Goose Bay and on the borders of sandbars and islands. Ice also formed on the river above the Muskrat Falls hydroelectric dam. Figures 3.11 and 3.12 shows the ice classification for November 30, 2023, and January 12, 2024, respectively. Over the next seven 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 37 days until the entire section of river was ice covered. One area remained open about 6 km downstream of the dam and a few areas remained open throughout the winter.
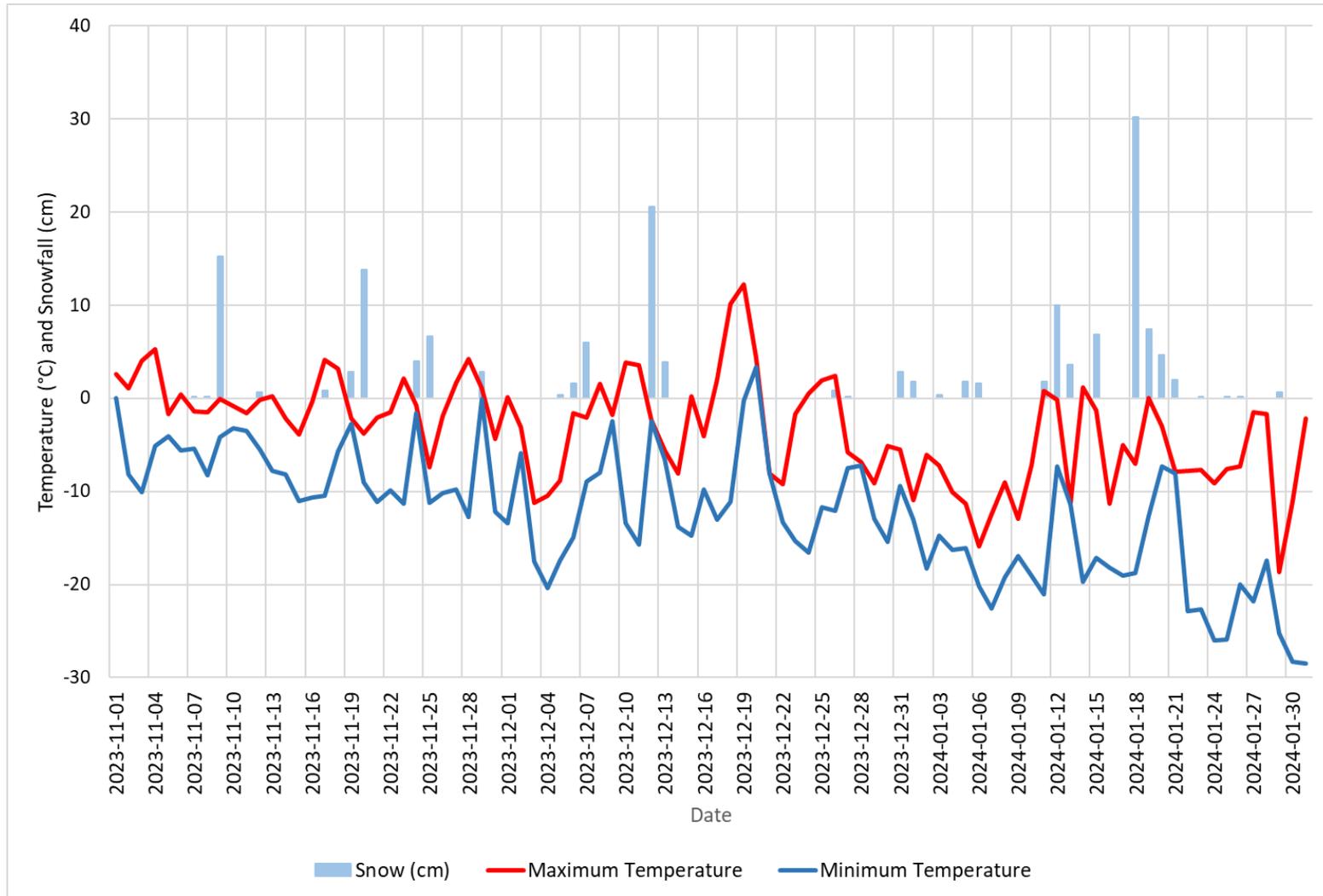
Figure 3.10   Maximum (red) and Minimum (blue) Daily Temperatures for Happy Valley – Goose Bay, Labrador with Snowfall Amounts During Freeze-up from November 1, 2023, to January 31, 2024.
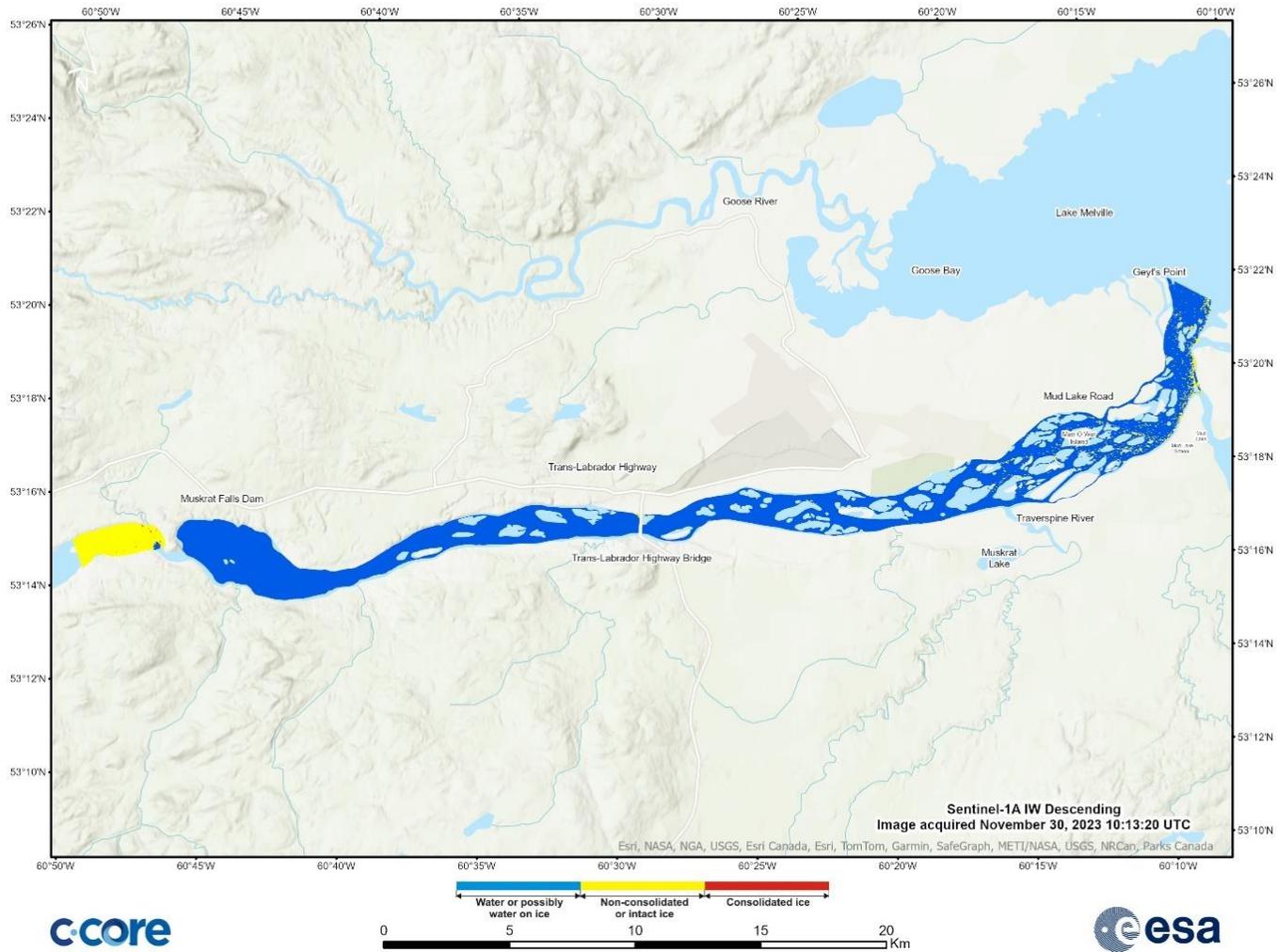
Figure 3.11   Ice Classification Product for November 30, 2023.
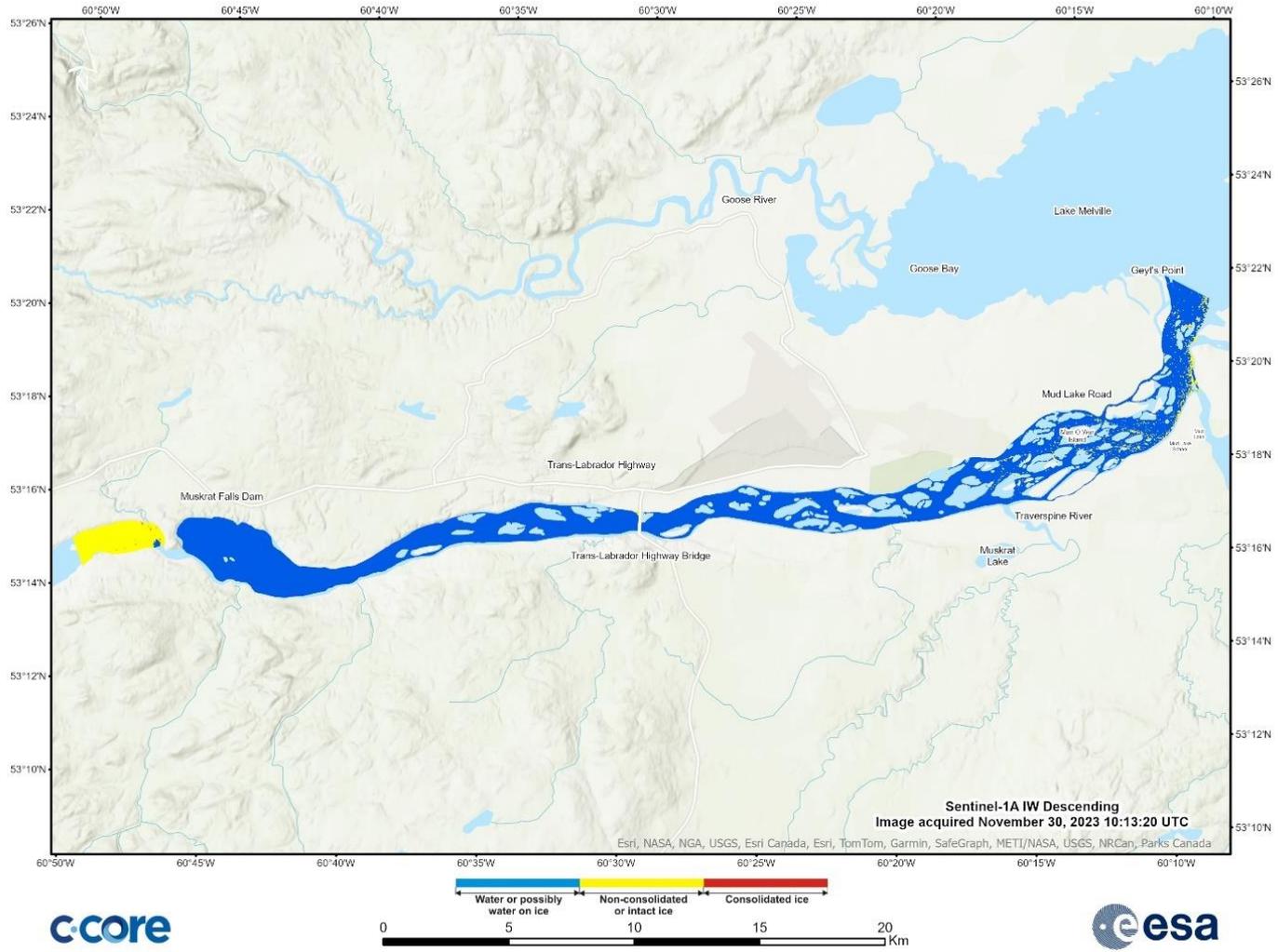
Figure 3.12   Ice Classification Product for January 12, 2024.

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 3, and May 3, 2024. Table 3.6 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 April 3, 2024, where no change detection was produced because it was the first image in the series. Figure 3.13 shows the maximum and minimum temperatures and precipitation from March 1 to May 31, 2023, as recorded by Environment and Climate Change Canada for Goose Bay, Labrador. Beginning on March 10, maximum daily temperatures were consistently above freezing and continued until the river was free of ice on May 3, 2024. Daytime low temperatures were below freezing during most of the period until the beginning of May.

The first signs of ice cover deterioration were found with the April 3, 2024 image (Figure 3.14) where open areas of water appeared downstream of the dam. With the break-up analysis, a third ice class was used to represent areas of pooling water on the ice cover. The open water and ice covered pooling areas continued to grow through April as warm temperatures continued. Pooling water continued to increase on the ice surface as air temperatures warmed in April. By April 17, 2024 (Figure 3.15), the upper half of the monitored section of the Churchill River was ice free. The ice cover continues to shrink downstream until May 3 (Figure 3.16), when the river was ice free including the section above the dam in the reservoir.

Table 3.6   **Break-up Monitoring Dates for the Last Seven 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
2023-2024	April 3, 2024	May 3, 2024
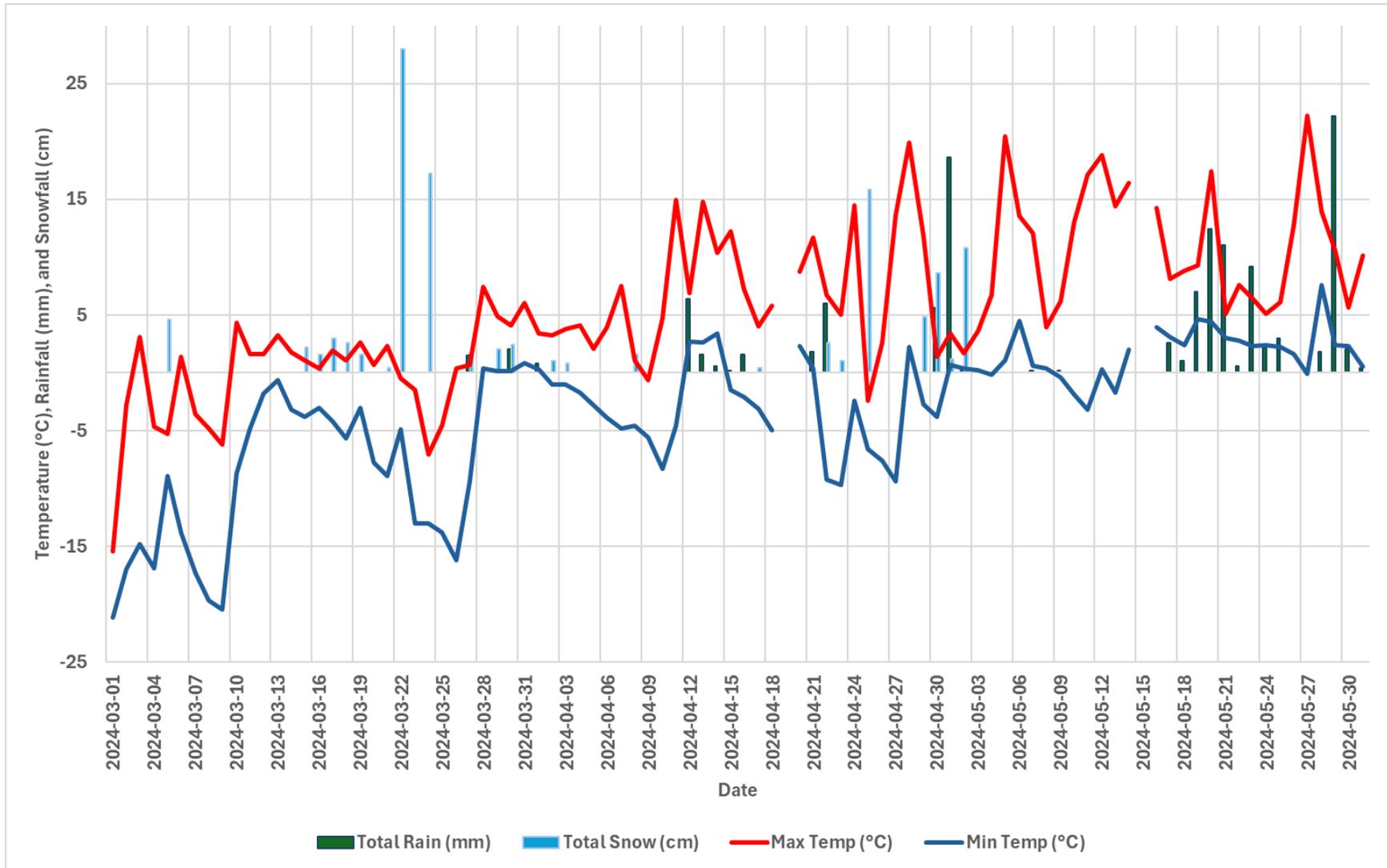
Figure 3.13   Maximum (red) and Minimum (blue) Daily Temperatures for Happy Valley – Goose Bay, Labrador with Precipitation Amounts and Types During Break-up from March 1 to May 31, 2024.
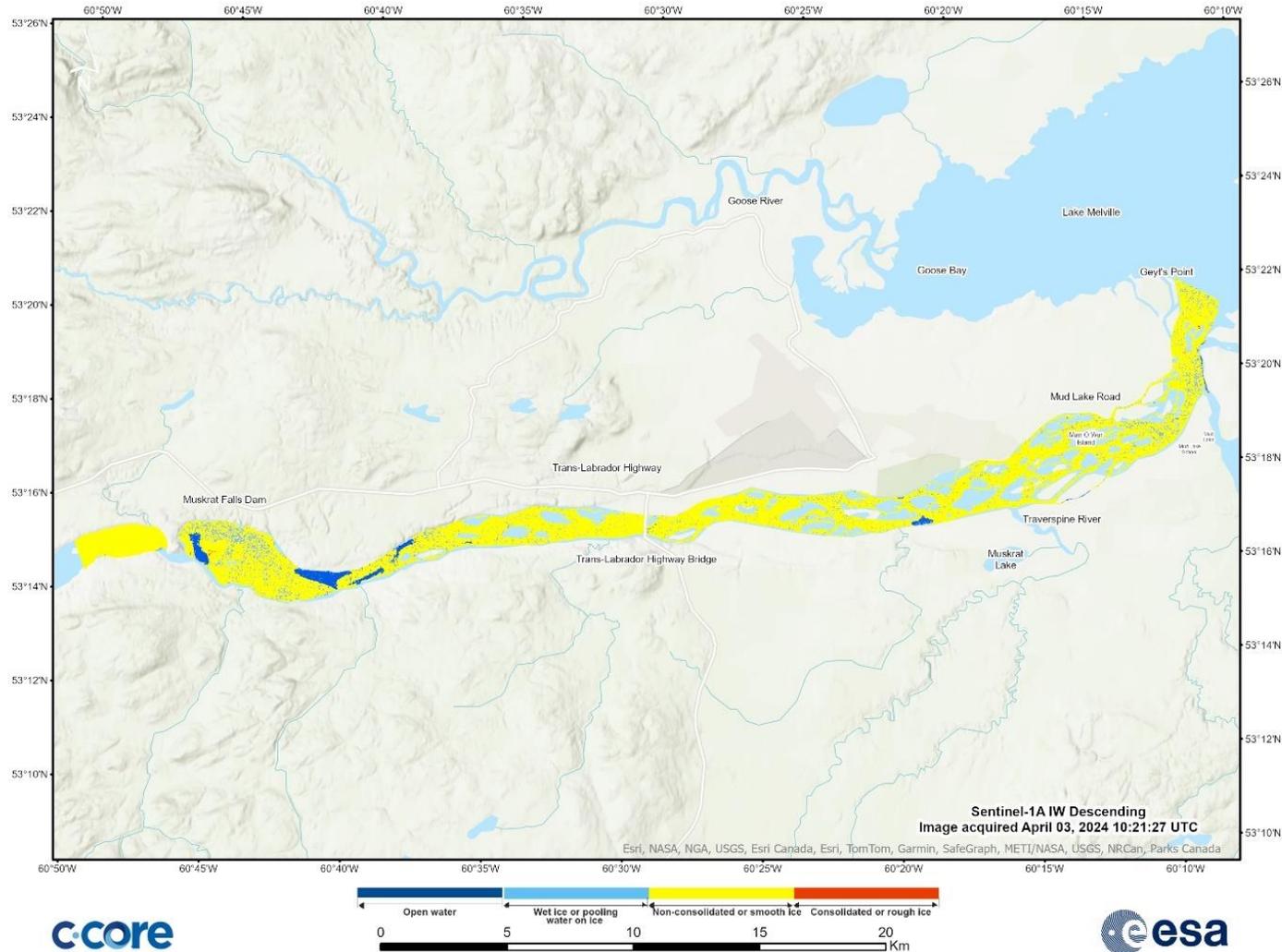
Figure 3.14   Ice Classification Product for April 3, 2024.
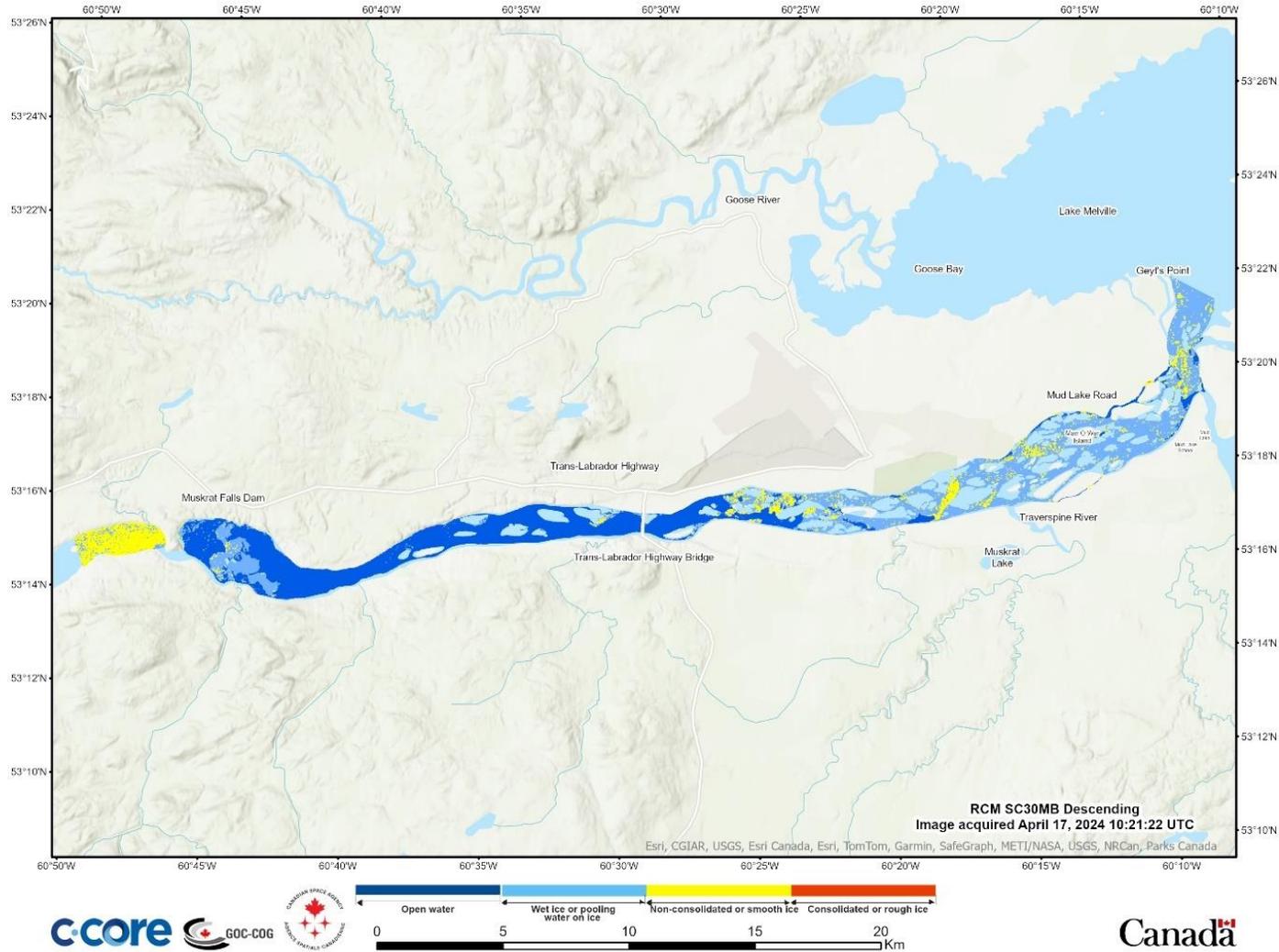
Figure 3.15   Ice Classification Product for April 17, 2024.
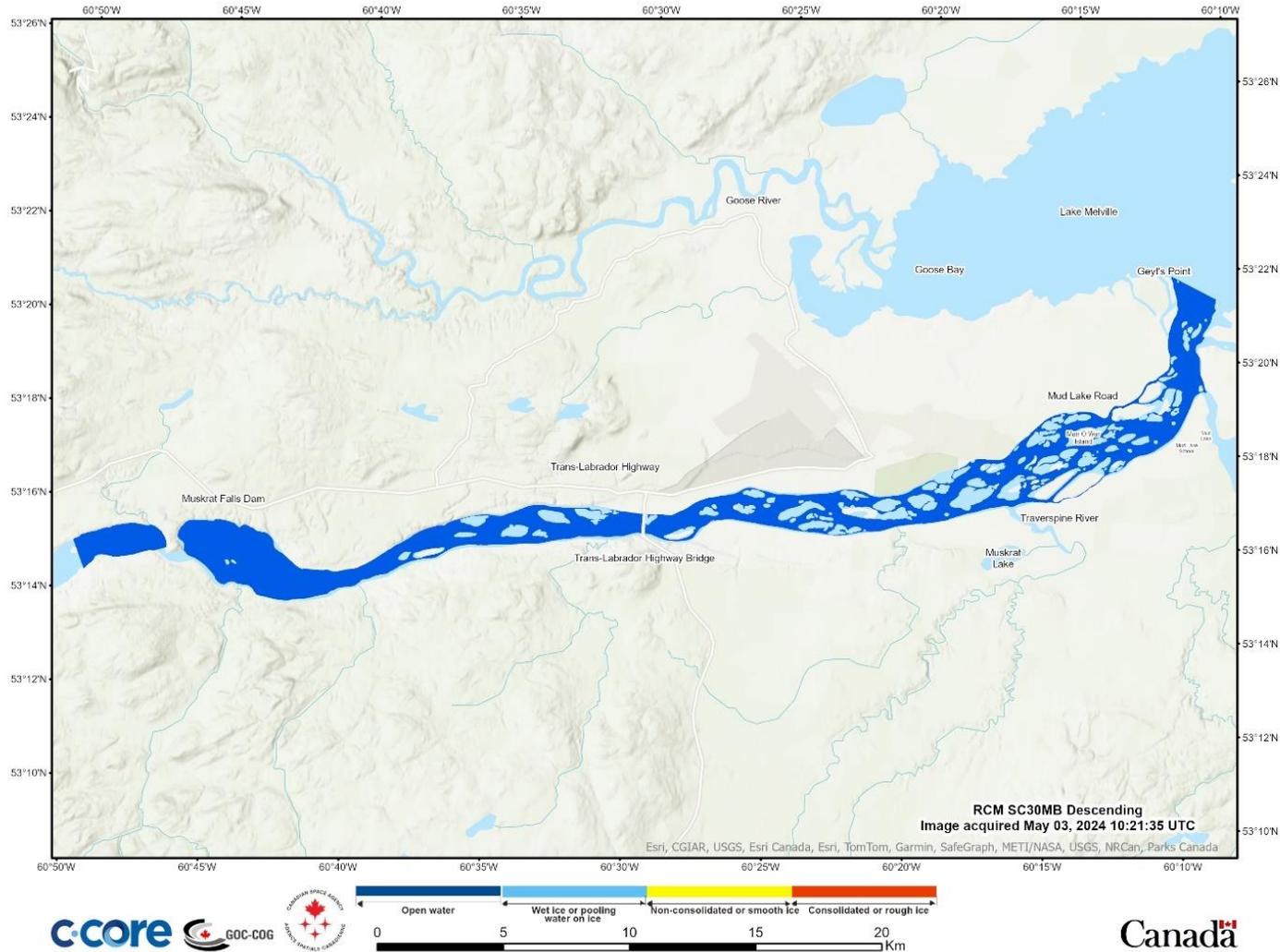
Figure 3.16   Ice Classification Product for May 3, 2024.

3.5 Trend Analysis – Lower Churchill River Ice Formation and Break-Up

An analysis was performed to determine if there were trends in data highlighting changes in ice formation and break-up on the Churchill River. Data were further assessed to determine if there was any influence of Lower Churchill Project on ice season dynamics. Three datasets were used as listed below:

- Climate data dating back to 1975 collected from the weather station located at the Goose Bay Airport (Happy Valley Goose Bay Station, Location: 53°24'23.099" N, 60°33'38.099" W);
- Freeze-up and break-up start and end dates generated from more detailed analyses of satellite data for 2017 to 2024; and
- Freeze-up and break-up dates as provided by Mud Lake Residents from 1975 to 2024 (Table 3.1) which generated data on duration of the ice season (Table 3.2).

3.5.1 Climate Data

Historical climate data recorded at the Goose Bay Airport was used dating back to 1975 with a focus on the winter months (November to May). The weather station (ID 8501915) is located at 53°19'00.000" N, 60°25'00.000" W which is approximately 4.1 km from the river mouthy at an elevation of 48.8 m above sea level.

Examination of temperature trends over time may reveal information that can help explain changes in river ice freeze-up and break-up patterns and help inform on future predictions, particularly given current global warming trends due to climate change. According to a recent report (Environment and Climate Change Canada 2023) average yearly temperatures across Canada have increased overall compared to a 1961-1990 baseline, and warming trends are most pronounced during winter months, and less so during spring and summer. These trends are partially reflected in Figure 3.17, which displays monthly average air temperatures measured from the Goose Bay Airport during the months relevant to the Churchill River ice season (November to May). A linear regression for each month was used to assess how much variance in temperature was explained from 1975 to 2024, with the passing of time used as a proxy for climate change. The December r^2 value is the highest at 0.252 (P<0.001), meaning ~25% of the variance in temperature can be explained by the passing of time.
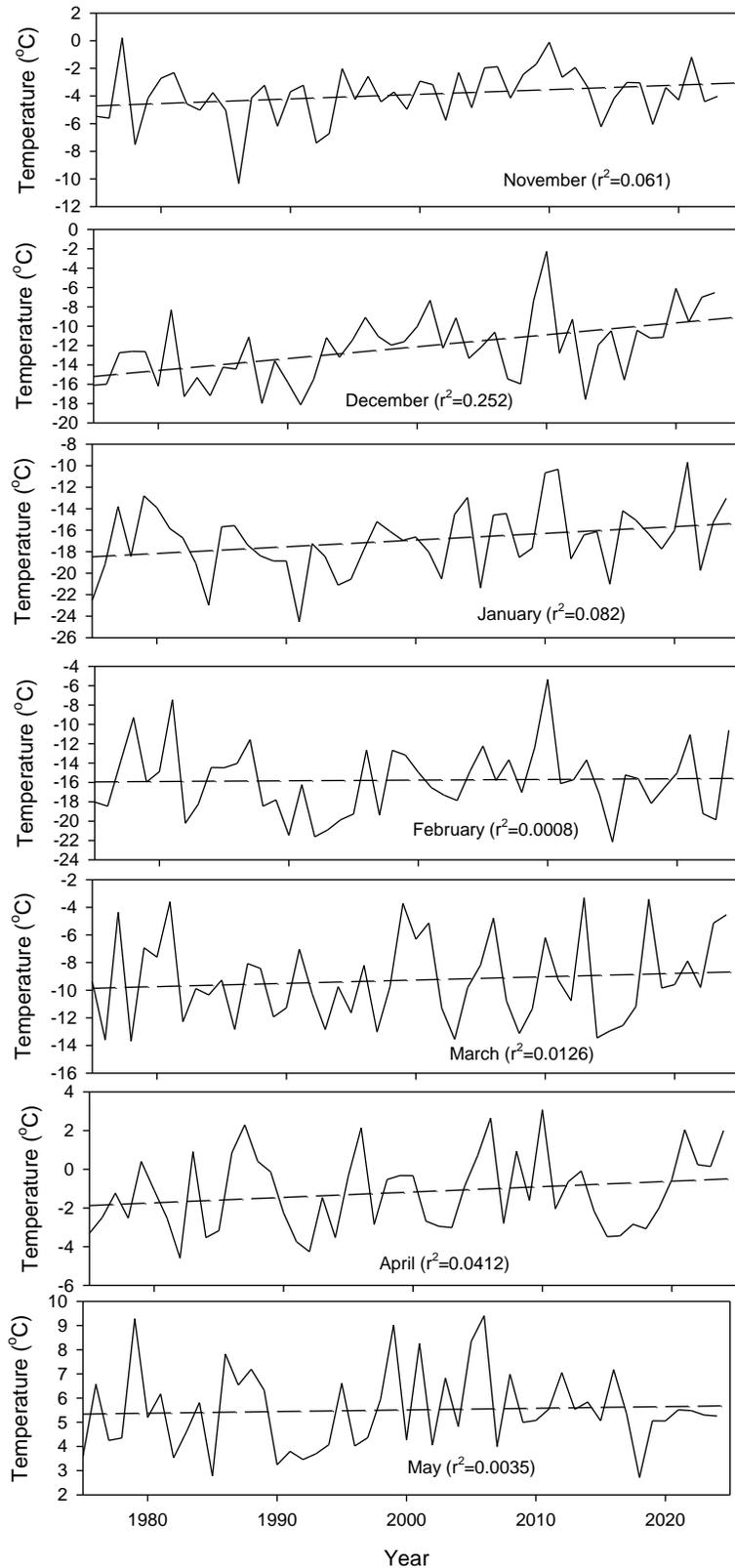
Figure 3.17   Average Monthly Temperatures for the River Ice Season from 1975 to 2024.

Figure 3.17 reveals a weak trend towards increasing temperatures over time across most months however the trend is most pronounced during December, an important month for freeze-up timing in the Churchill River. Average temperature is one characteristic among an ensemble of variables impacting the overall life cycle of the Churchill River ice season, there are potential implications on the timing of break-up and freeze-up. The pronounced warming trend during December may indicate an important contribution to a similar trend in freeze-up dates to be discussed (to follow).

3.5.2   Churchill River Ice Life Cycle

A more detailed analysis of available satellite imagery for the 2017-2018 to the recent 2023-2024 ice seasons has been used to evaluate the duration of three key life cycle events in the Lower Churchill ice season. Though a small number of years have been examined, the timing and duration of freeze-up and break-up events reveals trends in the Churchill River ice life cycle and can provide some context for what can be expected in years to come. Figure reveals patterns in the number of days that pass during freeze-up, break-up, and the time between the end of freeze-up and the start of break-up, here referred to as frozen. It is important to note in this figure that we are examining the freeze-up and break-up events, i.e. the number of days that pass from the start to the end of these events, and not the specific dates associated with the first snowmobile crossing after freeze-up and first boat crossing after break-up. The freeze-up event is from when ice is first observed in the river to when the ice cover extent is not changing anymore. The break-up event is from when there is new open water after several days of above freezing temperatures and the satellite detect melting snow cover until the river is completely ice free.

The reported r^2 values reveal a strong relationship between advancing years and the number of days that pass during each portion of the river ice life cycle. This trend is strongest during freeze-up (r^2=0.8802) followed by frozen (r^2=0.7789) and then break-up (r^2=0.6313). As ice seasons pass, freeze-up events are extending (from 8 days in 2017/2018 to 43 days in 2023/2024), break-up events are extending (from 18 days in 2017/2018 to 30 days in 2023/2024), while the frozen period is shortening, particularly after 2019 (from 134 frozen days in 2017/2018 and 82 frozen days in 2023/2024).

Figure 3.19 reveals a weak trend toward later start dates for freeze-up, moving further into December. This trend is much stronger for the timing of freeze-up end which has moved from mid-December in 2017/2018 to mid-January in 2013/2024. The opposite can be seen during break-up timing. There is a strong trend towards earlier break-up start and end dates. During the 2017-2018 season, break-up started near the end of April and ended near the middle of May and during the 2013-2014 season, break-up started near the end of March and ended near the start of May. In summary, freeze-up is starting later and ending later over time, and break-up is starting earlier and ending earlier over time.

These trends over the most recent seven years indicate that the length of time during freeze-up and break-up is increasing, i.e. from 8 days 43 days for freeze up and 18 to 30 days for break-up, and the frozen time between freeze-up end and break-up start is shortening, i.e. from 134 to 82 days. Trends also reveal that the timing of freeze--up start and freeze-up end is happening later in the winter, and the timing of break-up start and break-up end is happening earlier in the spring. These trends are likely being influenced in part by temperature trends reported in Figure 3.17. Other factors include trends in extreme weather events (storms and significant precipitation), changes in maximum and minimum temperature patterns, changes in water levels, sand bars, etc. These trends may also manifest differently across different segments of the river. Further consideration should be given to the small size of the dataset available here (only 7-yearly data points) and the number of images used for processing, images not used for processing, and dates where images are not available to confirm ice presence. However, these results reflect those reports for other waterbodies across the Northern Hemisphere (Newton and Mullan 2021).
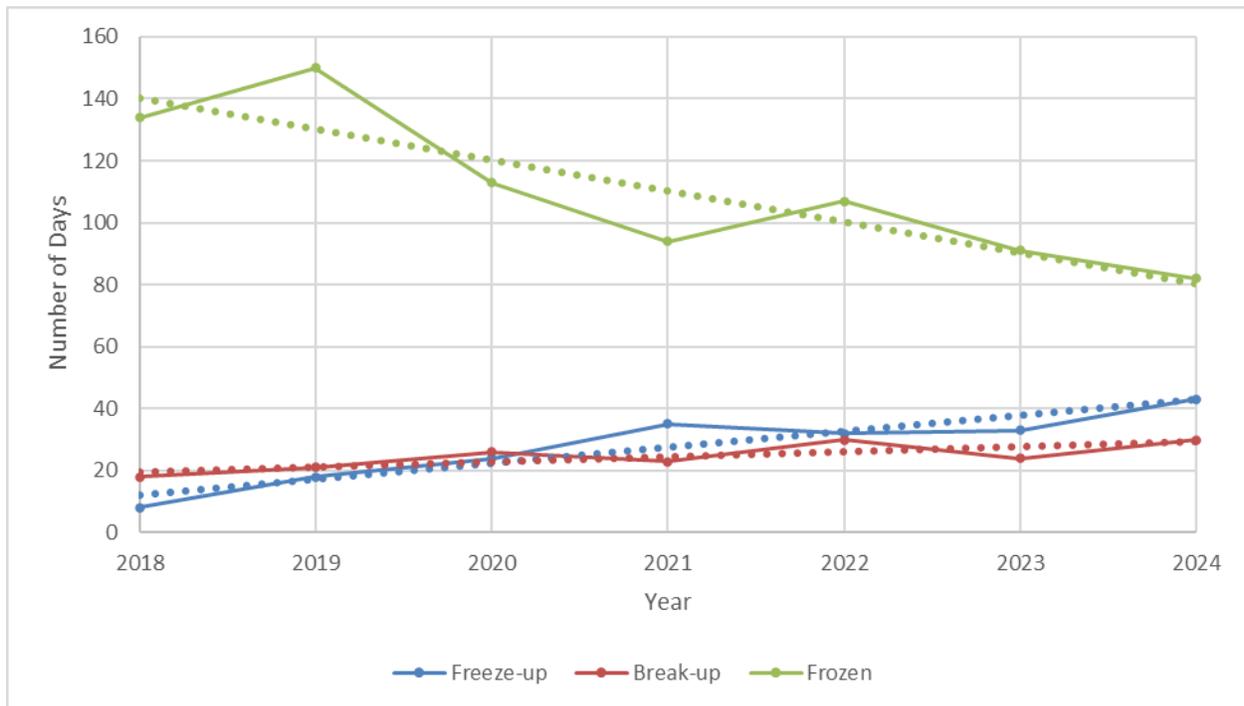
Figure 3.18   The Total Number of Days that Pass During the Three Churchill River Life Cycle Events from 2017-2018 to 2023-2024. Dotted Lines are Linear Regression Trend Lines.
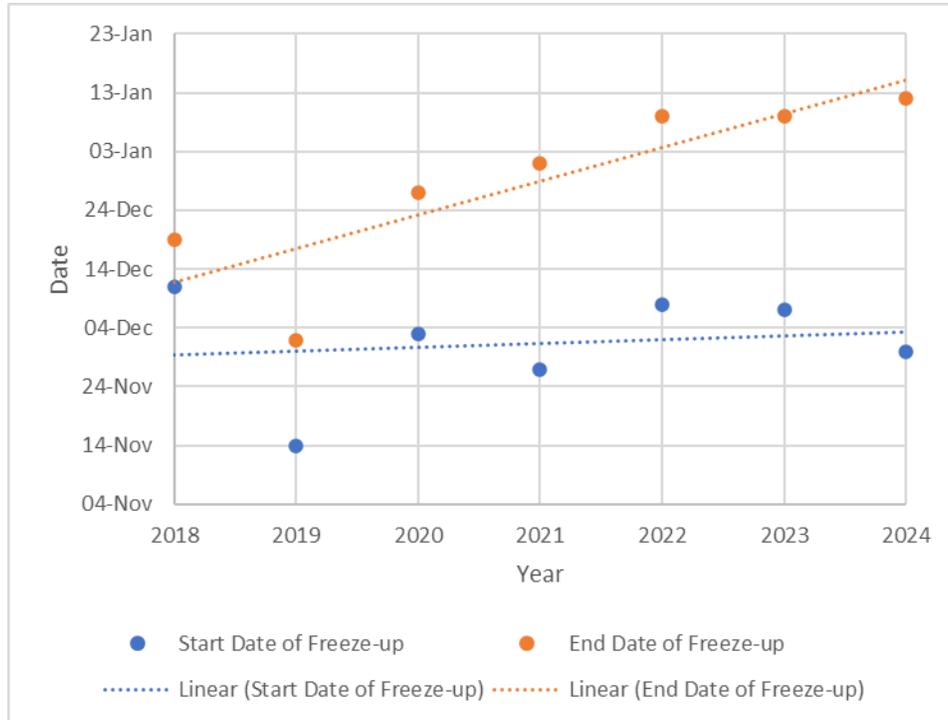
Figure 3.19   Dates of the Beginning of Freeze-up (R^2 = 0.7232) and End of Freeze-up (R^2 = 0.0234).
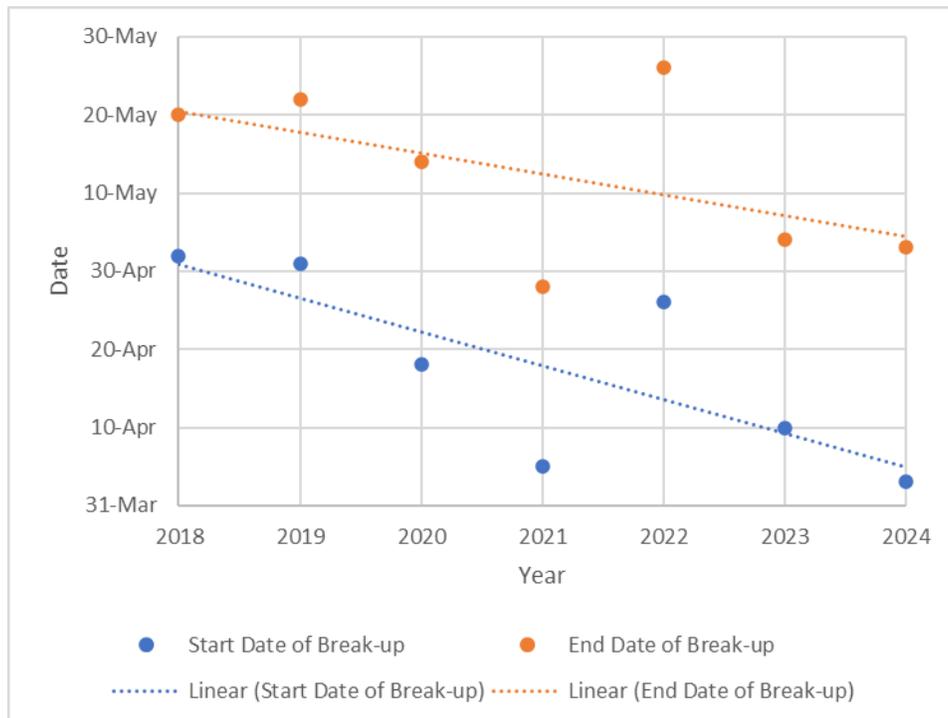
Figure 3.20   Dates of the Beginning of Break-up (R^2 = 0.5896) and End of Break-up (R^2= 0.2855).

3.5.3 Mud Lake Ice Crossing Duration

The number of days the Mud Lake Ice Crossing was available for use by snowmobile has been documented by Mud Lake residents since 1975, and is examined as a third measure of determining if the ice cover has been changing on the Churchill River. The crossing is located near Happy Valley–Goose Bay, on the north side of the river, and the community of Mud Lake on the south side of the river, connecting the two communities. Mud Lake residents depend on this crossing to travel to Happy Valley–Goose Bay during the winter months. Figure 3.21 shows the number of days (duration) the ice crossing was available in each year from 1975 to 2023/24 ice season. Duration is defined as the date of first crossing by snowmobile to the last day of crossing before the ice becomes unsafe to cross. Figure 3.21 indicates there is a trend indicating the duration of the ice cover is reducing (r^2 = 0.1506).
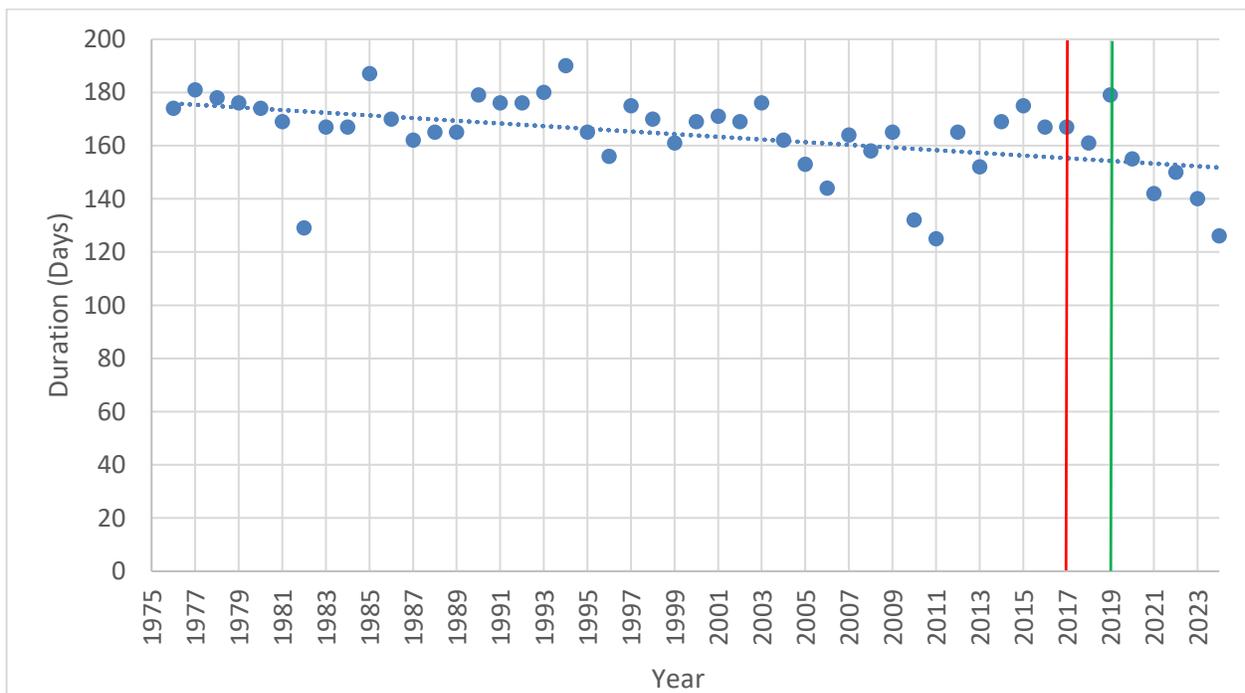
Figure 3.21   The Total Number of Days the Mud Lake Crossing was Used by Snowmobile on the Churchill River Each Season Since 1975. Red reference line - year of head pond formation, Green reference line – year of full impoundment.

3.5.4 Influence of the Lower Churchill Project

The possible influence of the Lower Churchill Project on ice season dynamics has been examined by looking at the long-term record for freeze-up dates, break-up dates, and length of ice season before and

after the Muskrat Falls reservoir was filled. The reservoir above the dam was flooded in August of 2019, resulting in five years of data for freeze-up. break-up, and ice season length post-impoundment and 45 years pre-impoundment. The large difference in sample size required that a one-way Analysis of Variance (ANOVA) be used to compare the pre- and post-impoundment data. In all three analyses, a Kruskal-Wallis One Way Analysis of Variance on Ranks test was used as the normality test failed due to difference in sample sizes.

The average freeze-up date for the pre-impoundment period was November 30, and post-impoundment was December 8, with freeze-up being delayed by an average of eight days post-impoundment. This difference was not statistically significant at P<0.05 (P=0.064).

The average break-up date for the pre-impoundment period was May 16 and post-impoundment was April 30, with break-up being advanced by an average of 16 days post-impoundment. This difference was not statistically significant at P<0.05 (P=0.052).

The average length of the ice season for the pre-impoundment period was 166.25 days and post-impoundment was 142.6 days, with the ice season being shortened by an average of 23.65 days post-impoundment. This difference is not surprising given the above trends in delay of freeze-up and advancing of the break-up. This difference was statistically significant at P<0.05 (P=0.002).

The above analyses provide good evidence as to the influence the Lower Churchill Project on the ice season dynamics in the Lower Churchill River below Muskrat Falls in delaying freeze-up, advancing break-up, and reducing the ice season. While the differences in freeze-up and break-up dates pre- and post impoundment were not statistically significant they were close to being statistically significant. The difference in the length of the ice season was highly statistically significant.

Hatch (2008) indicated that after construction of the Lower Churchill Project elimination of open water area upstream of Muskrat Falls and the effect of seasonal heat storage in the Muskrat Falls reservoir, there would be a delay in the formation of the ice bridge at Mud Lake in the order of two weeks, depending upon climatic conditions in any given year. Initial monitoring has indicated a delay in freeze up of eight days on average which is consistent with the analysis by Hatch. Mud Lake residents have indicated it takes from four to seven days for the ice bridge to strengthen at freeze-up until it is safe to cross by snowmobile. Hatch indicated that this process will take about the same time post-Project and concluded that the period of time during which it will be unsafe to cross the river in late fall/ early winter will be unchanged from the pre-Project condition.

Hatch further indicated that the hydraulic regime will be similar pre- and post-project, the mechanism for spring break-up is expected to be unchanged. Thermal analysis indicated that warm-up of the water in the

spring will occur approximately one week later on average; delaying the break-up by one week. However, the initial five years of monitoring post-impoundment has indicated the break-up has advanced by an average of 16 days.

4.0 Conclusions and Recommendations

This report is the final report presenting a summary of the ice monitoring for the Lower Churchill River Hydroelectric Project in Labrador. During the 2023-2024 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 November 30, 2023, and January 12, 2024. Images covering the break-up period were collected from April 3 to May 3, 2024. 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 2023-2024 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 images this season to maximize cost efficiency.

Average temperature trend analysis indicates slightly warming winters during the past 50 years. An analysis of the ice season life cycles from 2027/18 to 2023/24 indicates that the length of time during the freeze-up process and break-up process is increasing, and the frozen time between freeze-up end and break-up start is shortening. There is also a long-term trend indicating the number of days that the Mud Lake ice crossing is open is reducing.

The influence of the Muskrat Falls Hydroelectric dam on the ice cover dynamics was analyzed and there is good evidence as to the influence the Lower Churchill Project below Muskrat Falls in delaying freeze-up, advancing break-up, and reducing the ice season.

NL Hydro continues to collect ice measurements at several locations along, and in the vicinity of the Mud Lake crossing on a biweekly basis. This data is provided to the NLDECC/WRMD for publishing on their webpage (Churchill River Early Flood Warning and Alert System - Environment and Climate Change).

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Appendix A

Lower Churchill Freeze-Up Satellite Imagery

Figure A-1: Ice Cover – November 30, 2023.
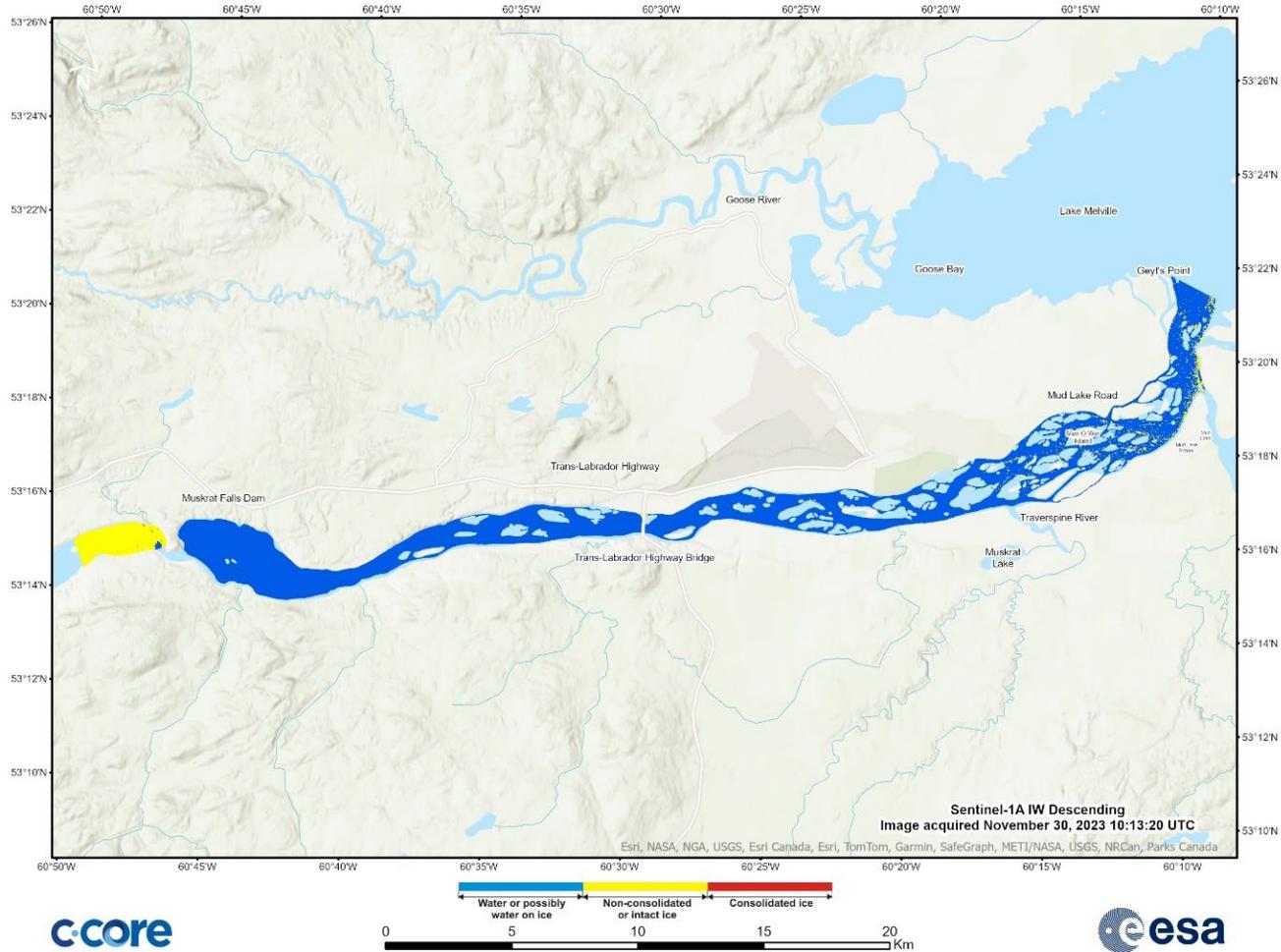
Figure A-2: Ice Classification – November 30, 2023.
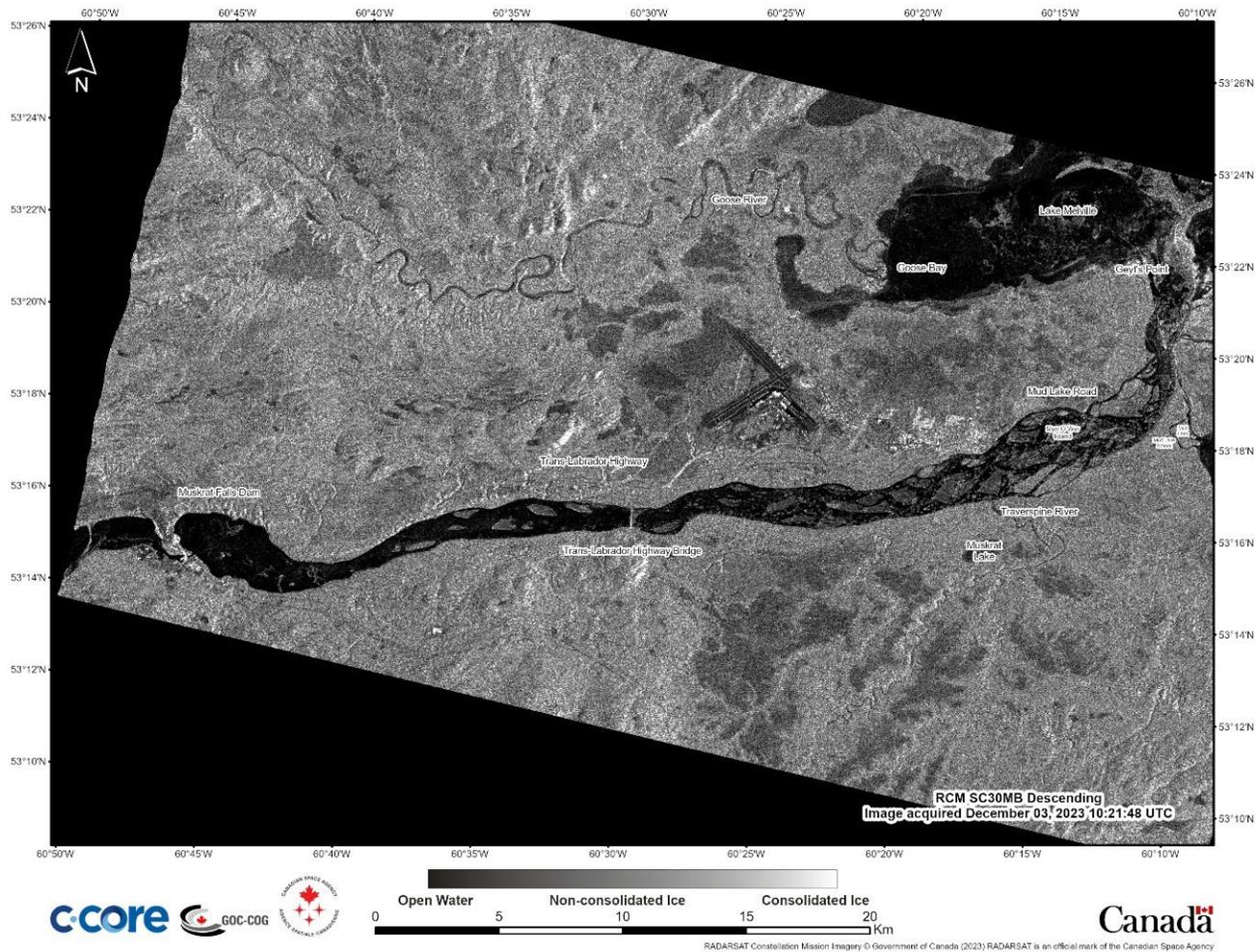
Figure A-3: Ice Cover – December 3, 2023.
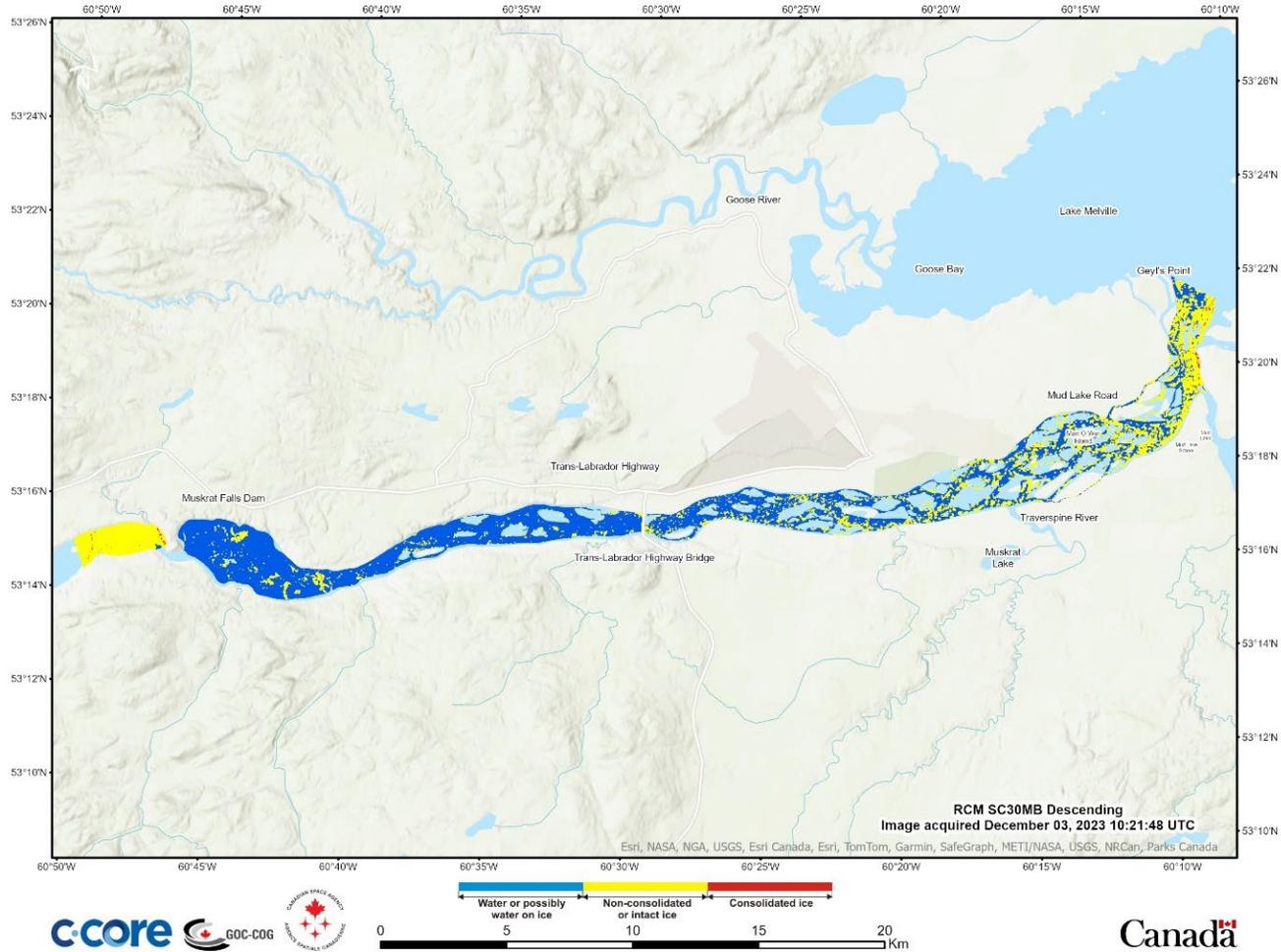
Figure A-4: Ice Classification – December 3, 2023.
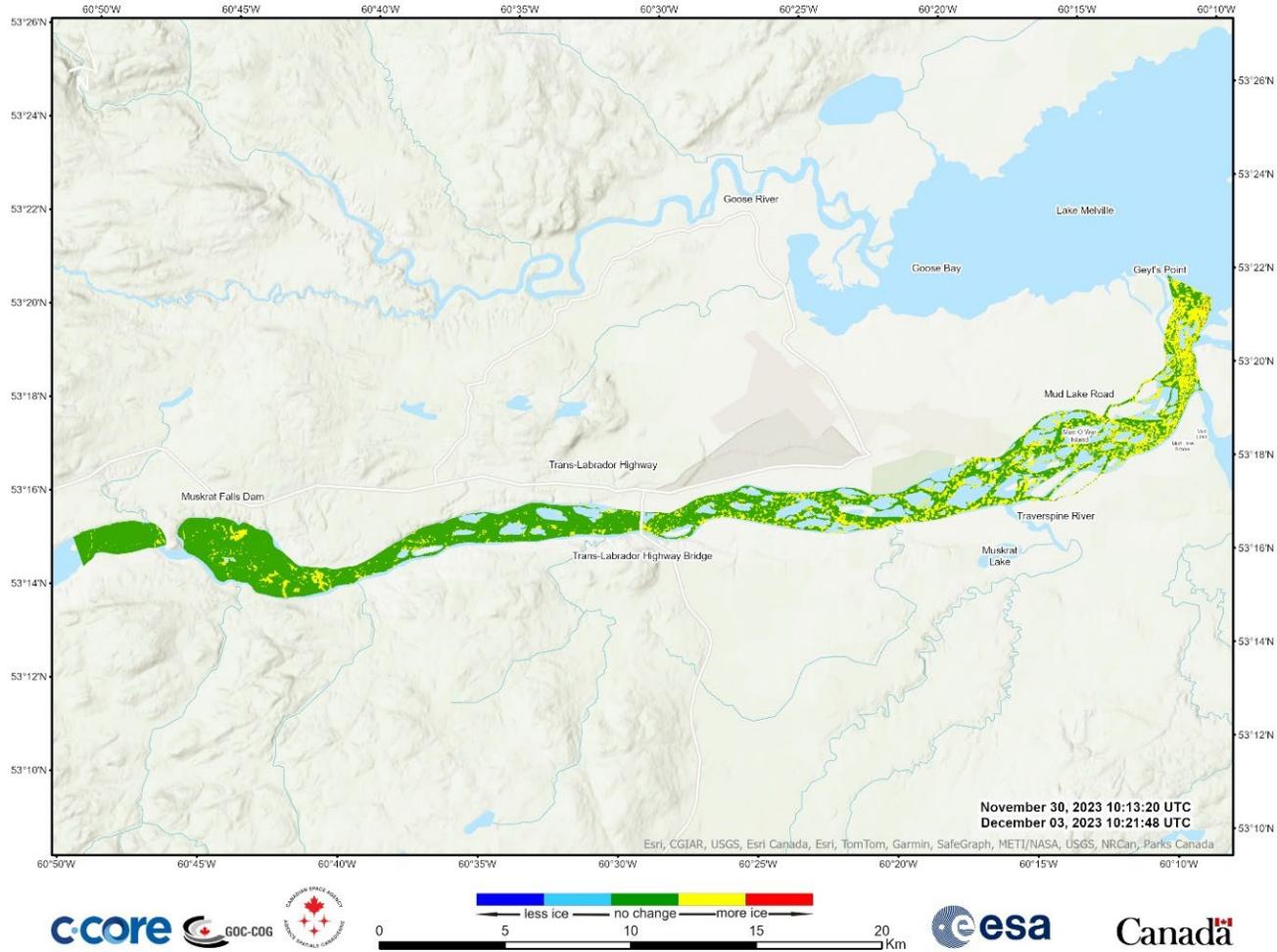
Figure A-5:   Change Detection – November 30 and December 3, 2023.
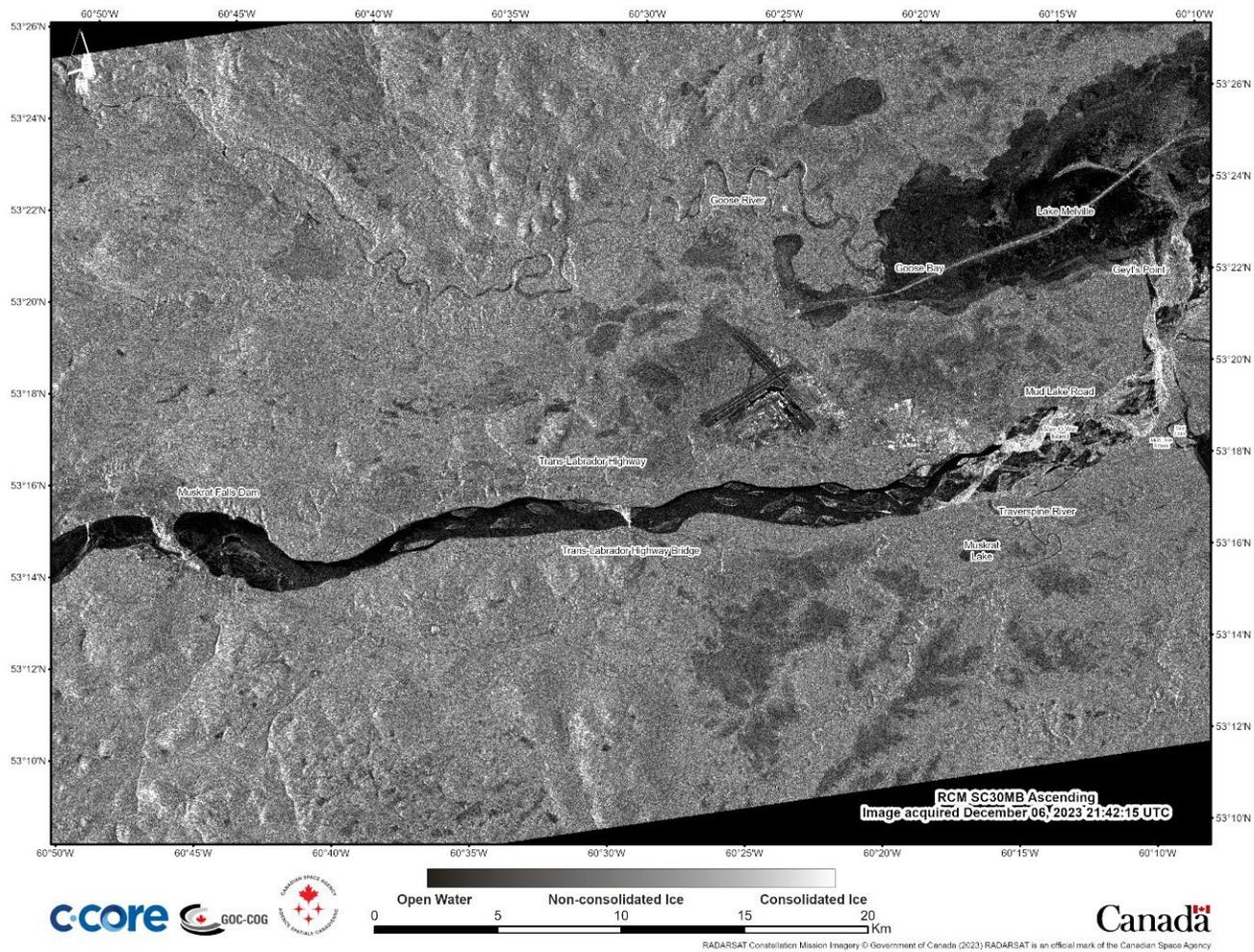
Figure A-6: Ice Cover – December 6, 2023.
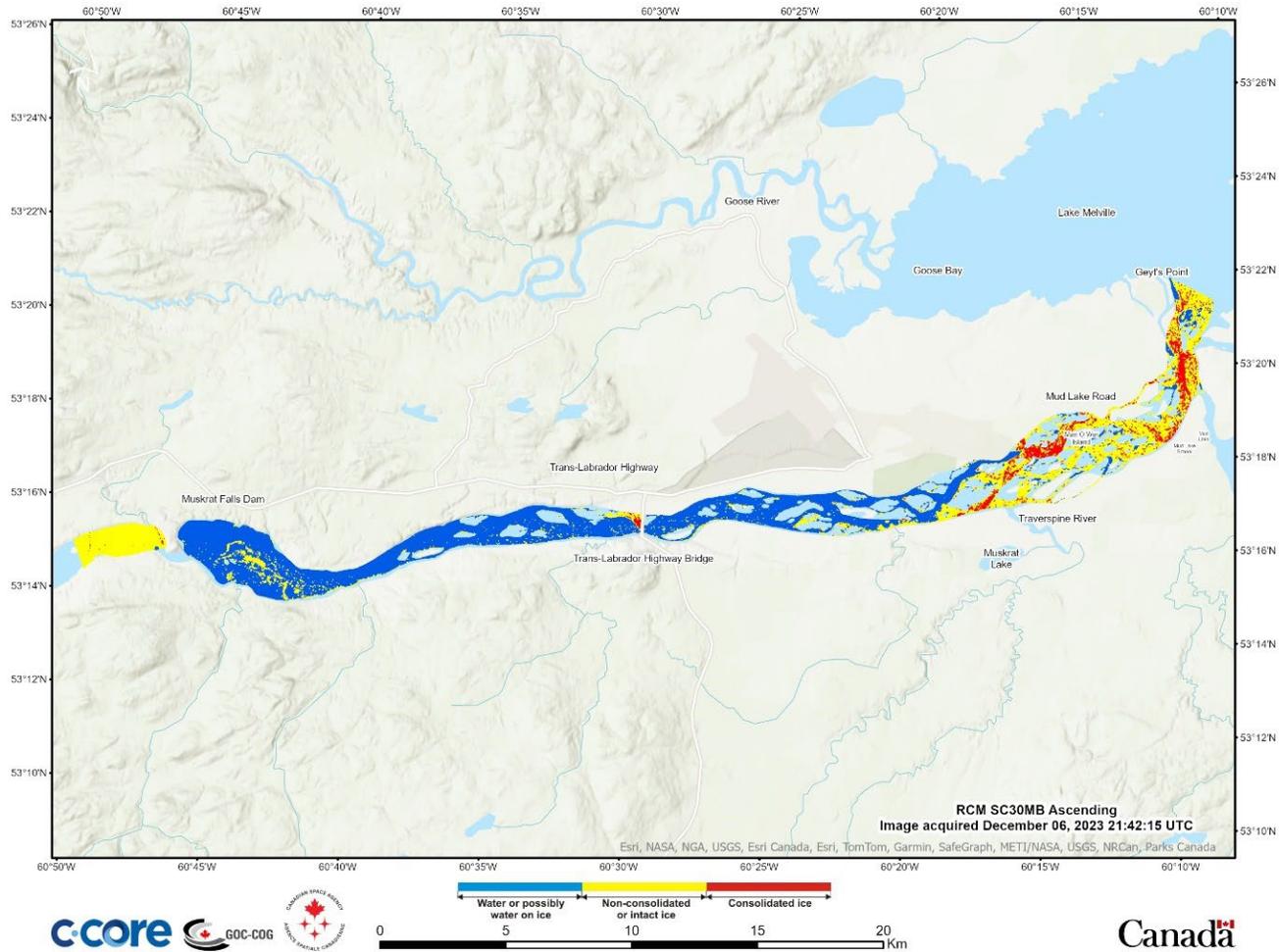
Figure A-7: Ice Classification – December 6, 2023.

Figure A-8: Change Detection - December 3 and 6, 2023.

Figure A-9: Ice Cover – December 12, 2023.

Figure A-10: Ice Classification – December 12, 2023.

Figure A-11: Change Detection – December 6 and 12, 2023.

Churchill River - Ice Cover
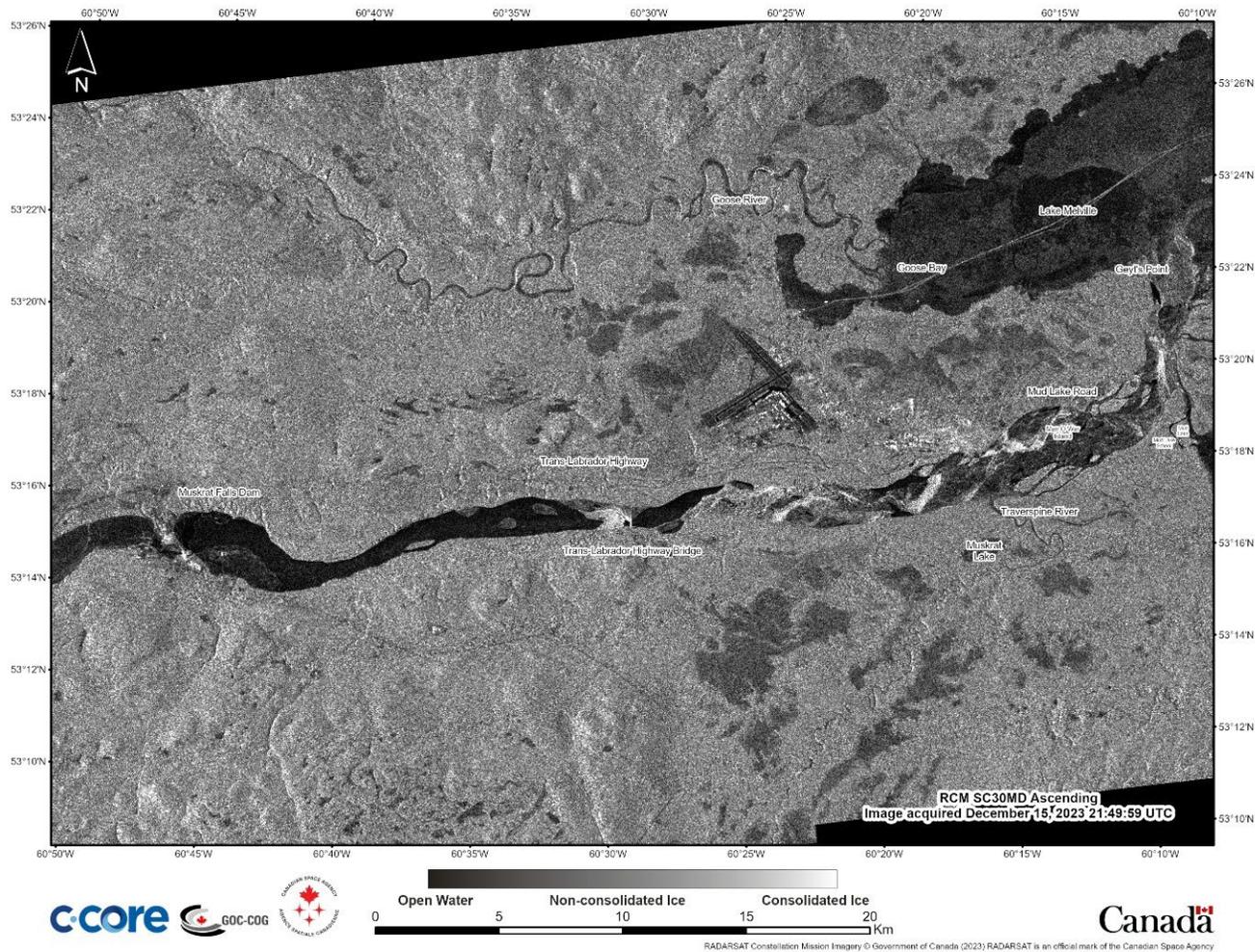
Figure A-12: Ice Cover – December 15, 2023.
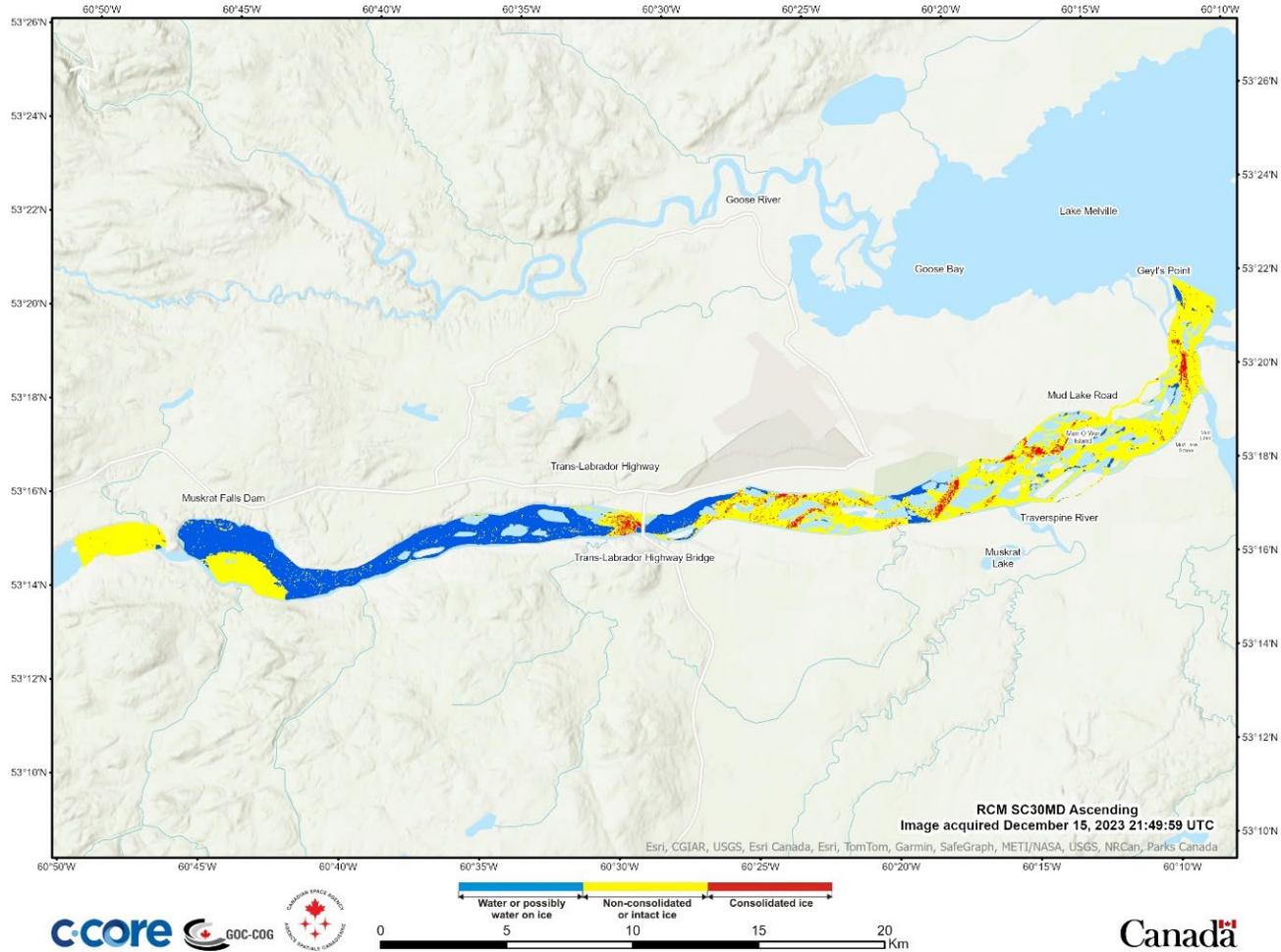
Figure A-13: Ice Classification – December 15, 2023.
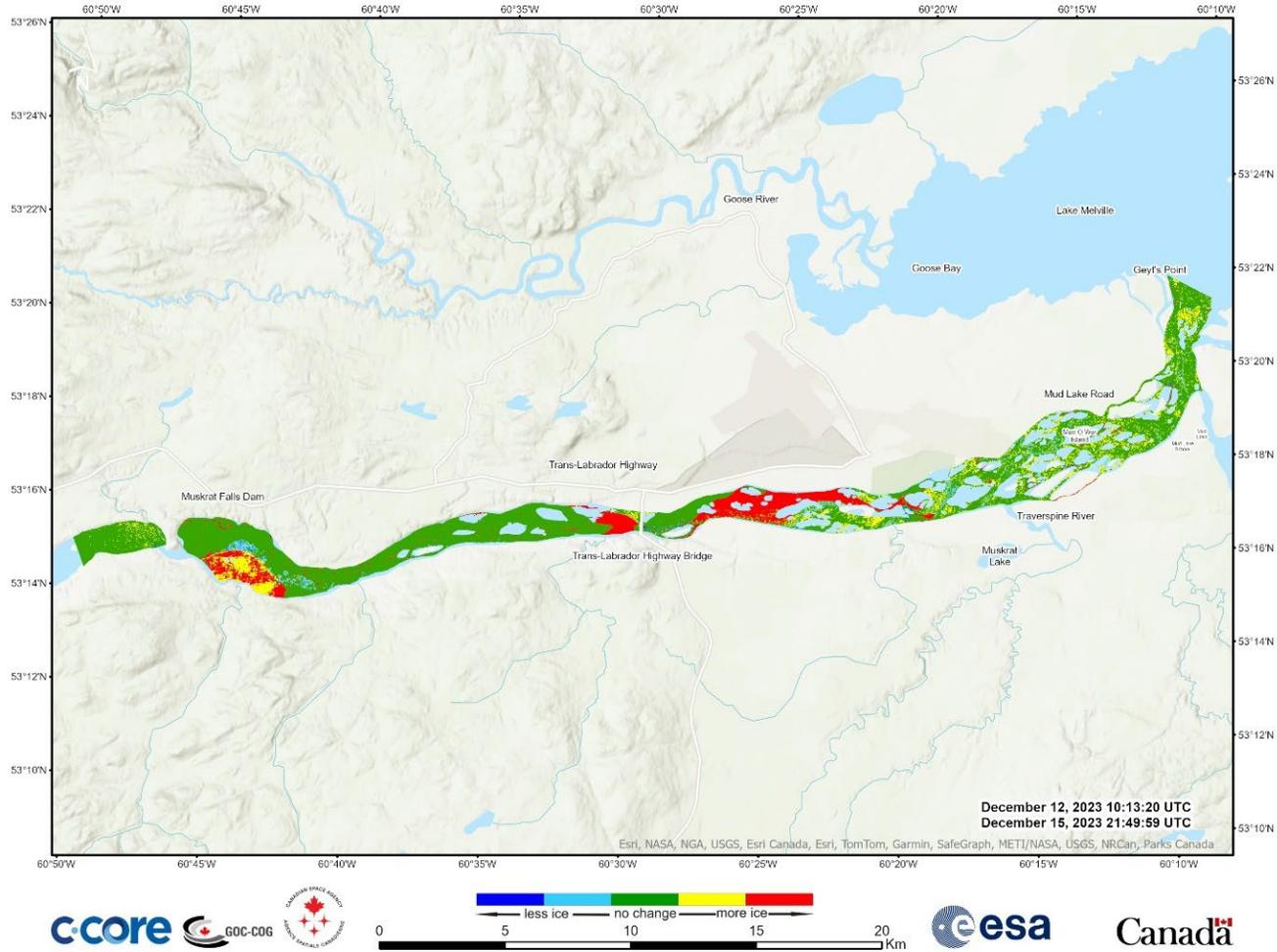
Figure A-14: Change Detection – December 12 and 15, 2023.
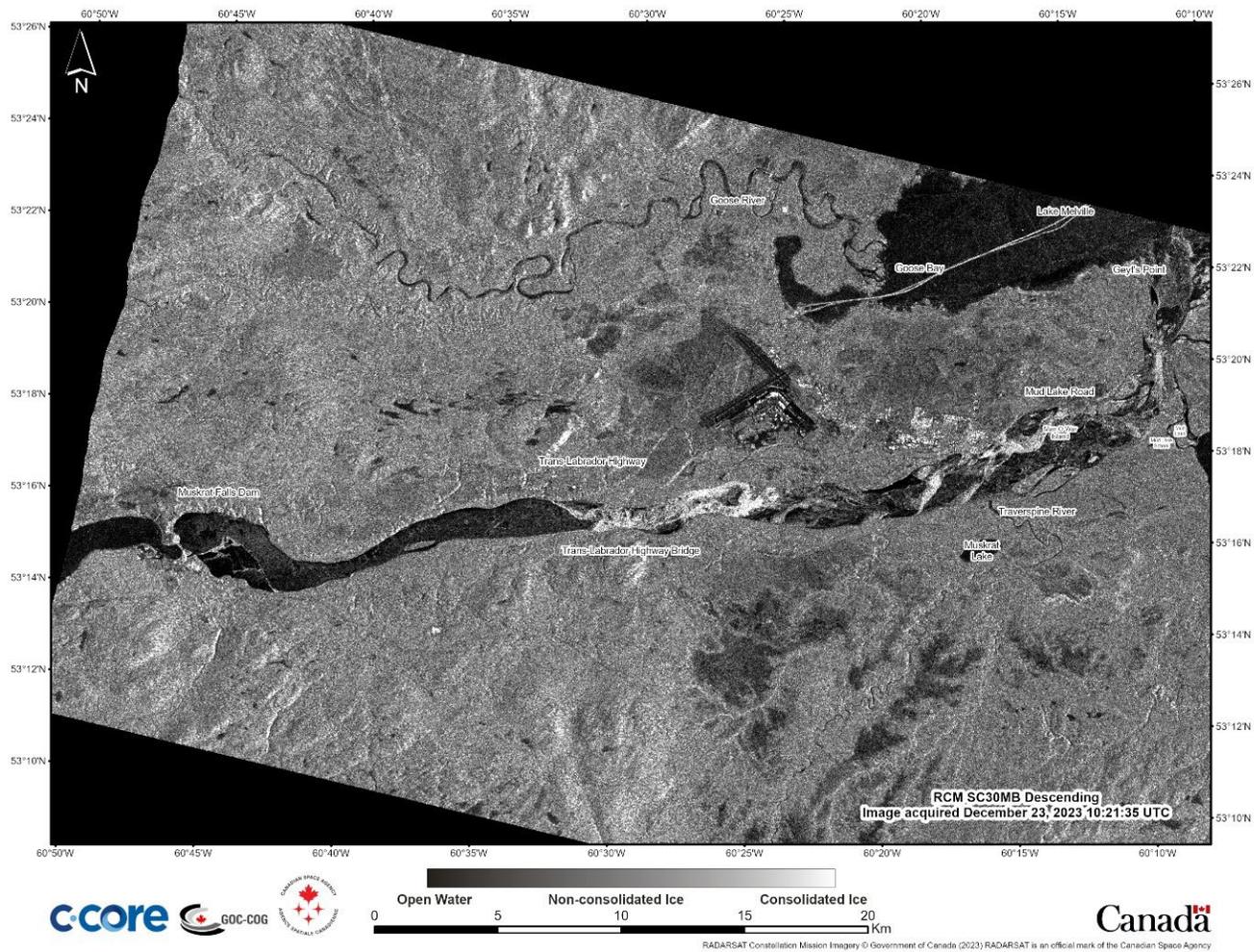
Figure A-15: Ice Cover – December 23, 2023.
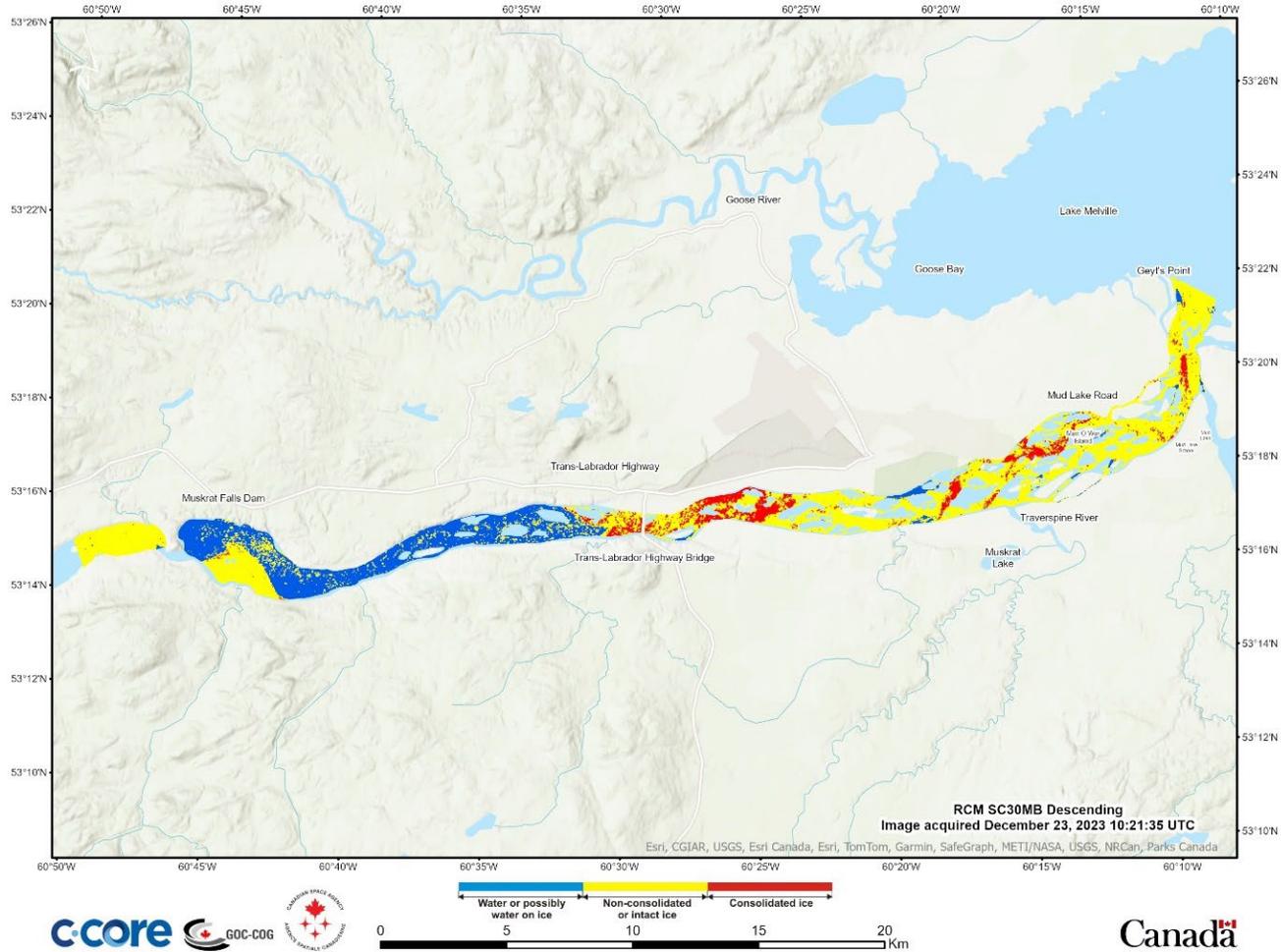
Figure A-16: Ice Classification – December 23, 2023.
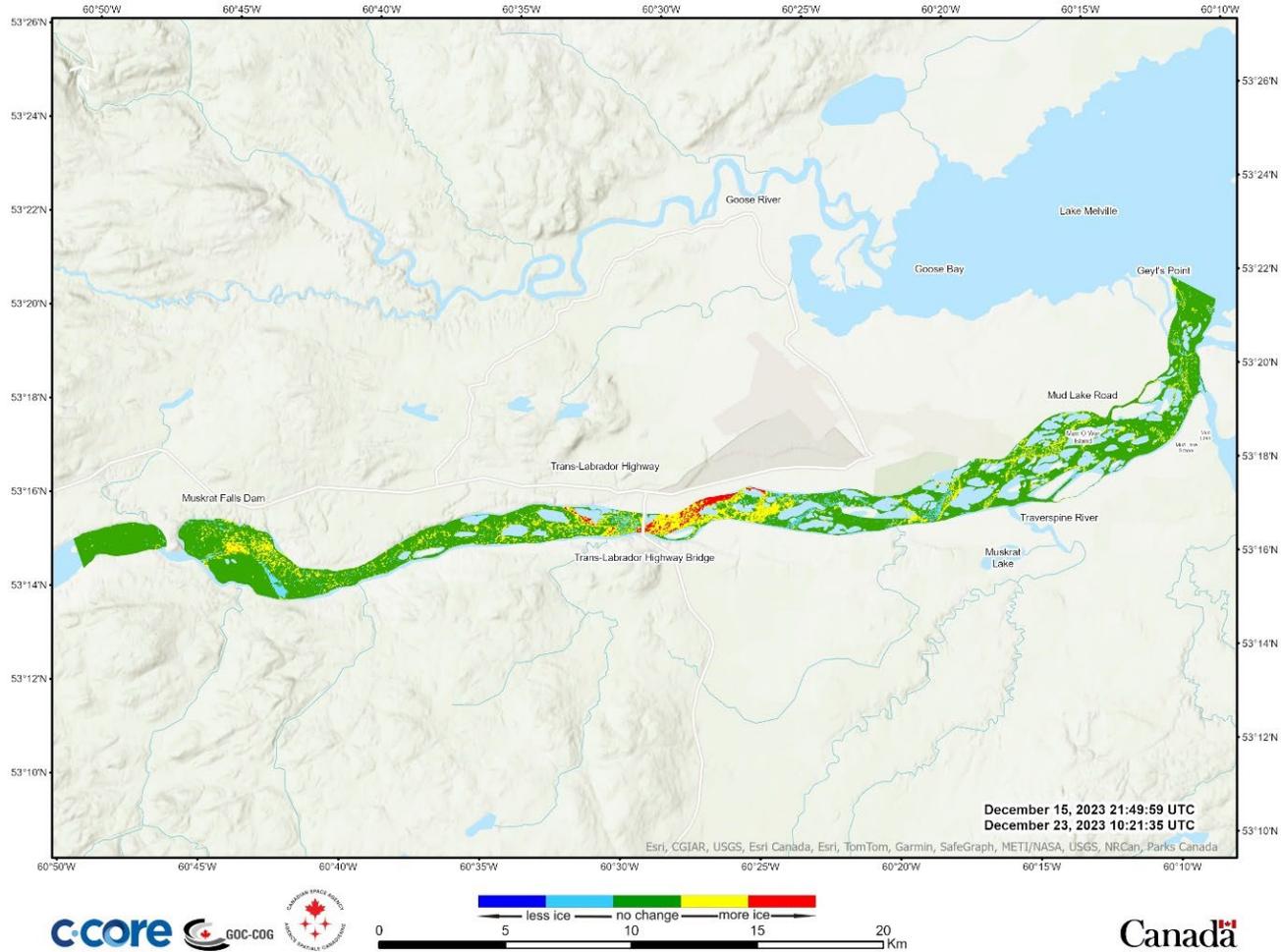
Figure A-17: Change Detection – December 15 and 23, 2023.
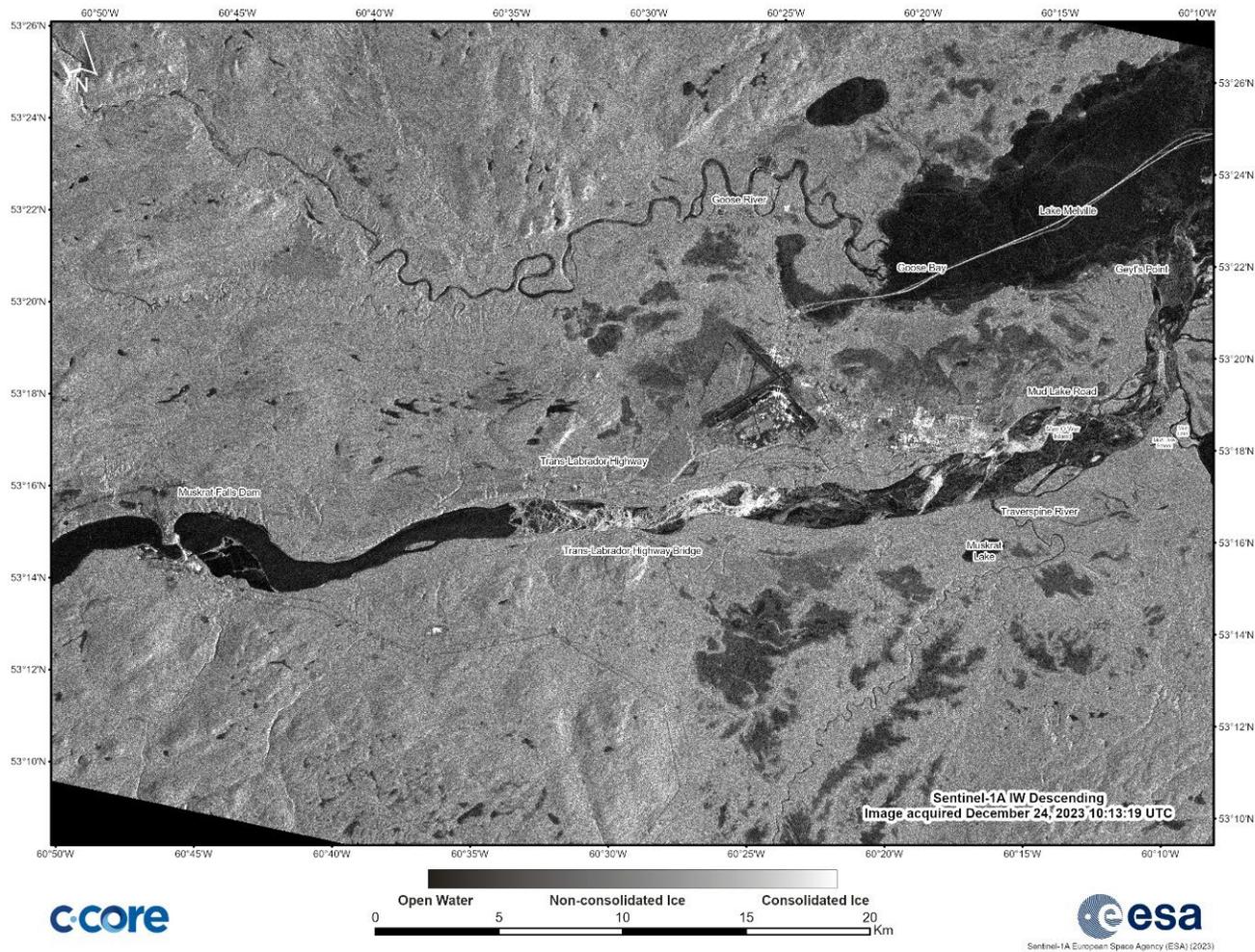
Figure A-18: Ice Cover – December 24, 2023.
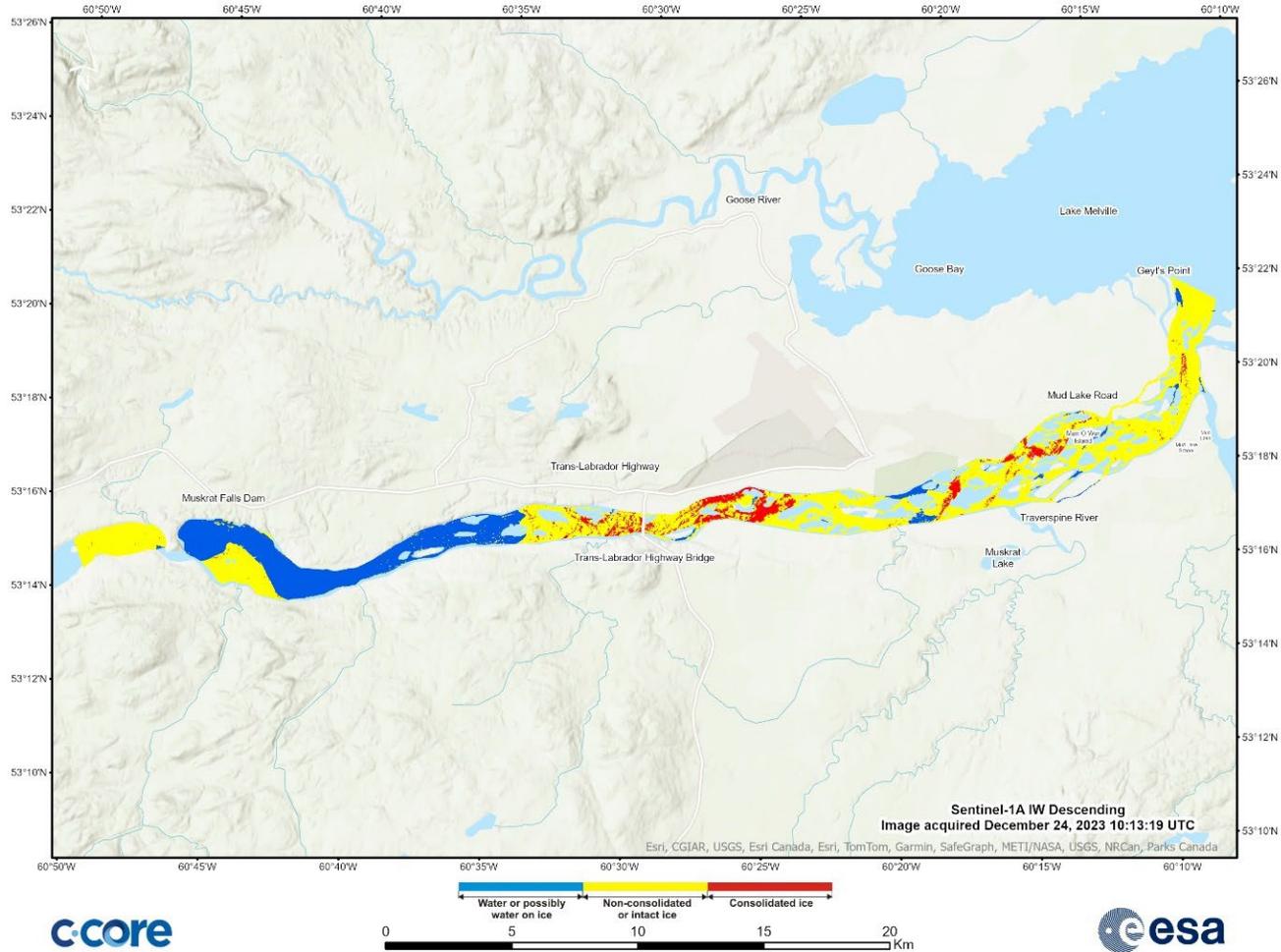
Figure A-19: Ice Classification – December 24, 2023.
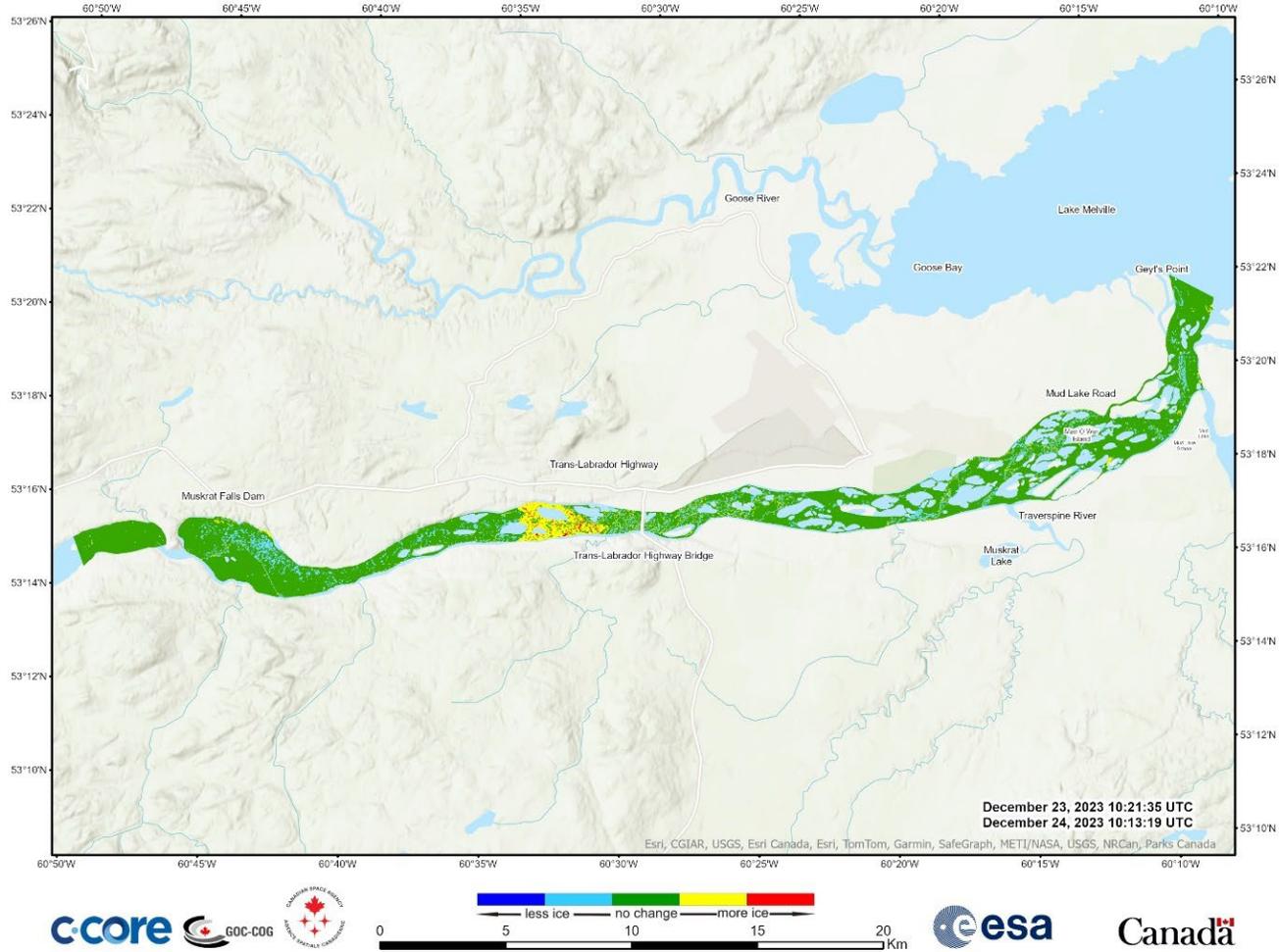
Figure A-20: Change Detection – December 23 and 24, 2023.
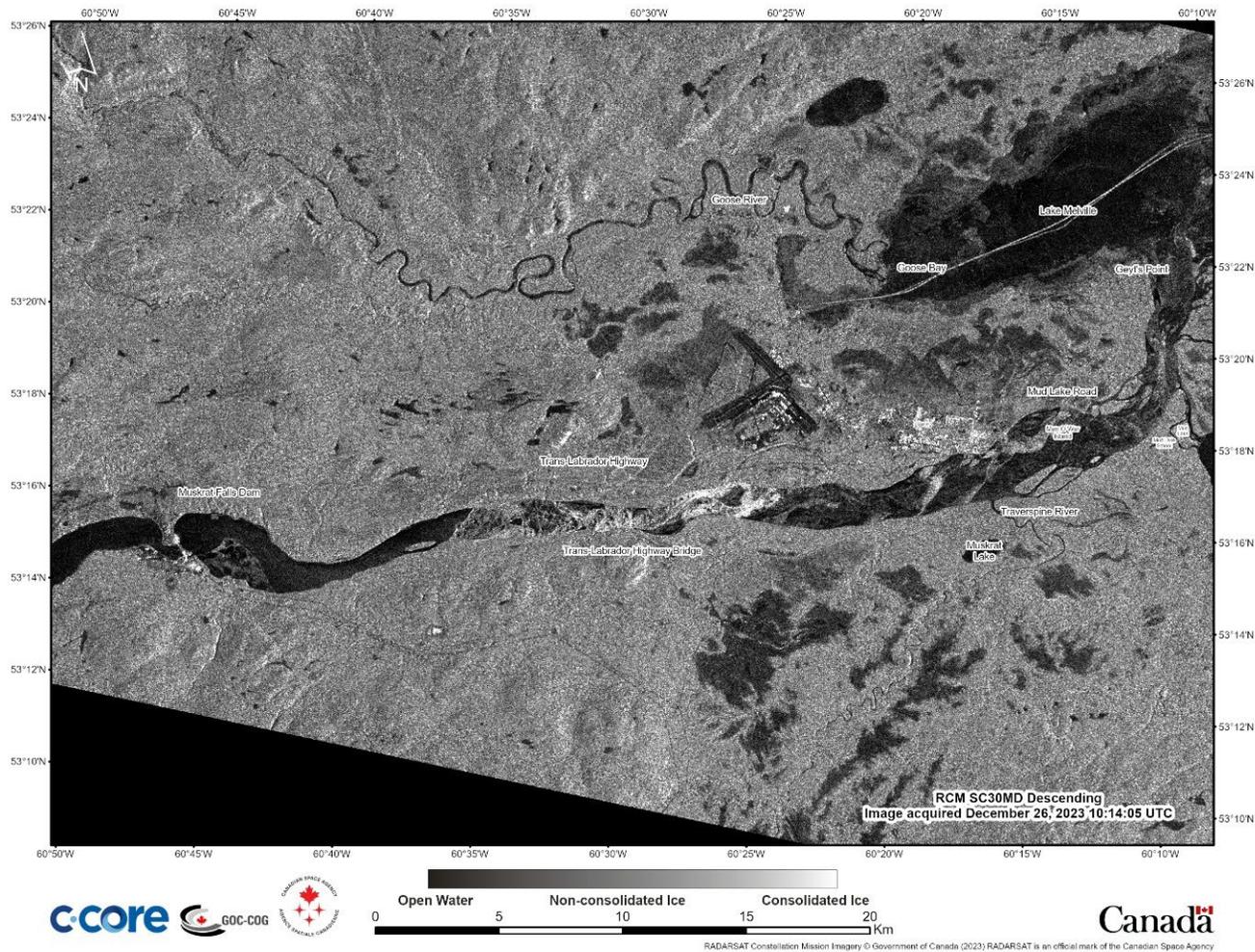
Figure A-21: Ice Cover – December 26, 2023.
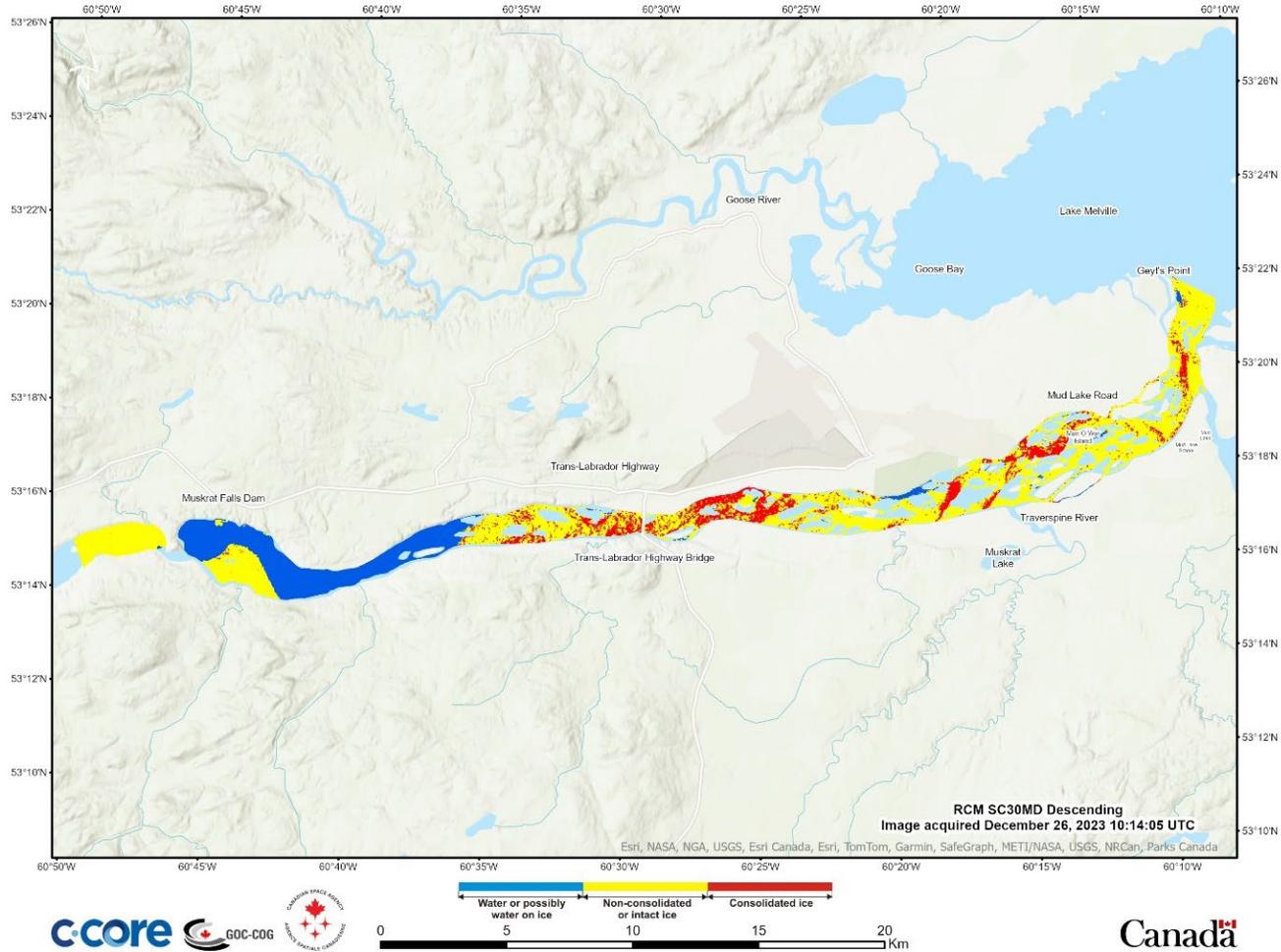
Figure A-22: Ice Classification – December 26, 2023.
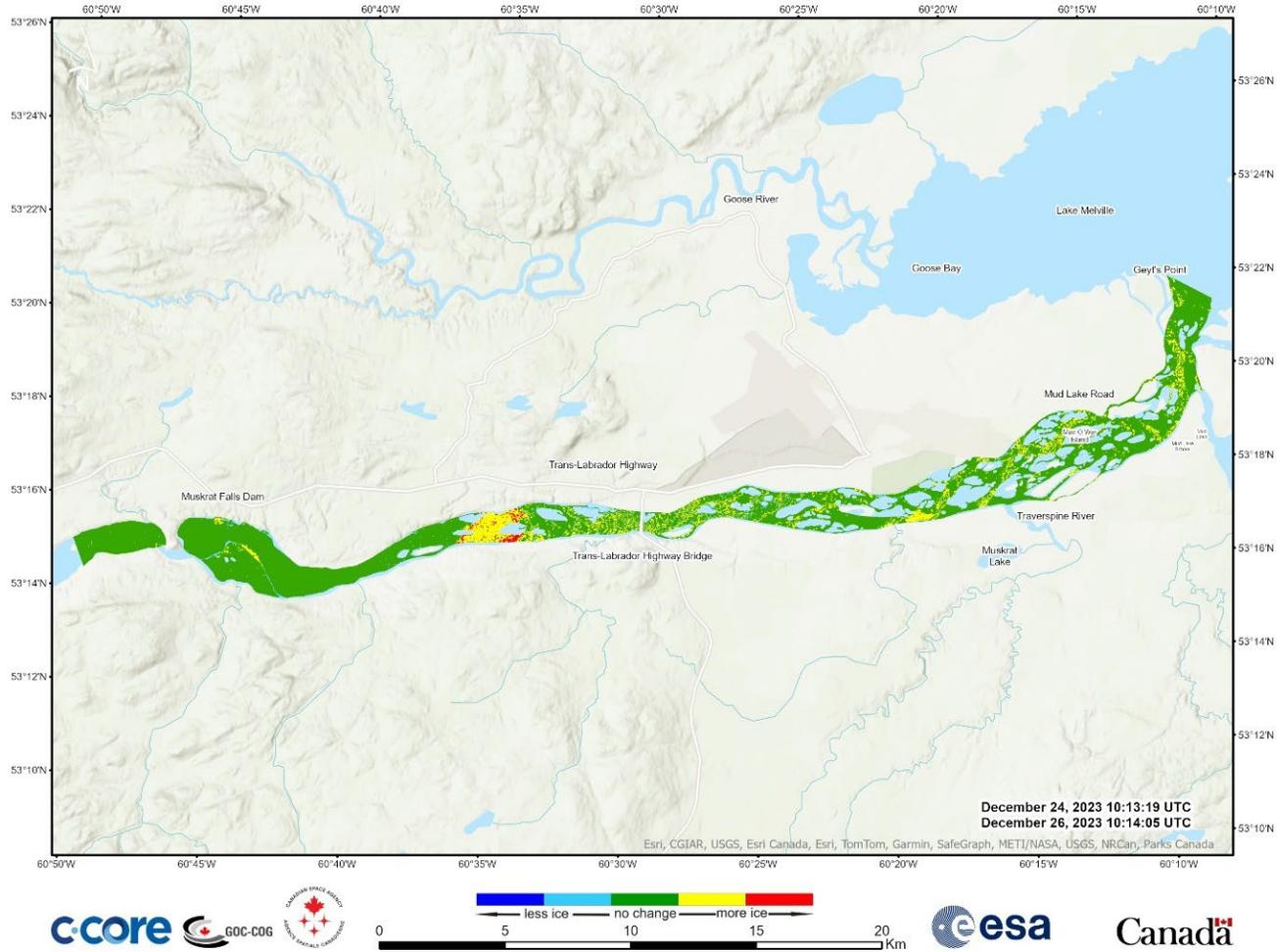
Figure A-23: Change Detection – December 24 and 26, 2023.
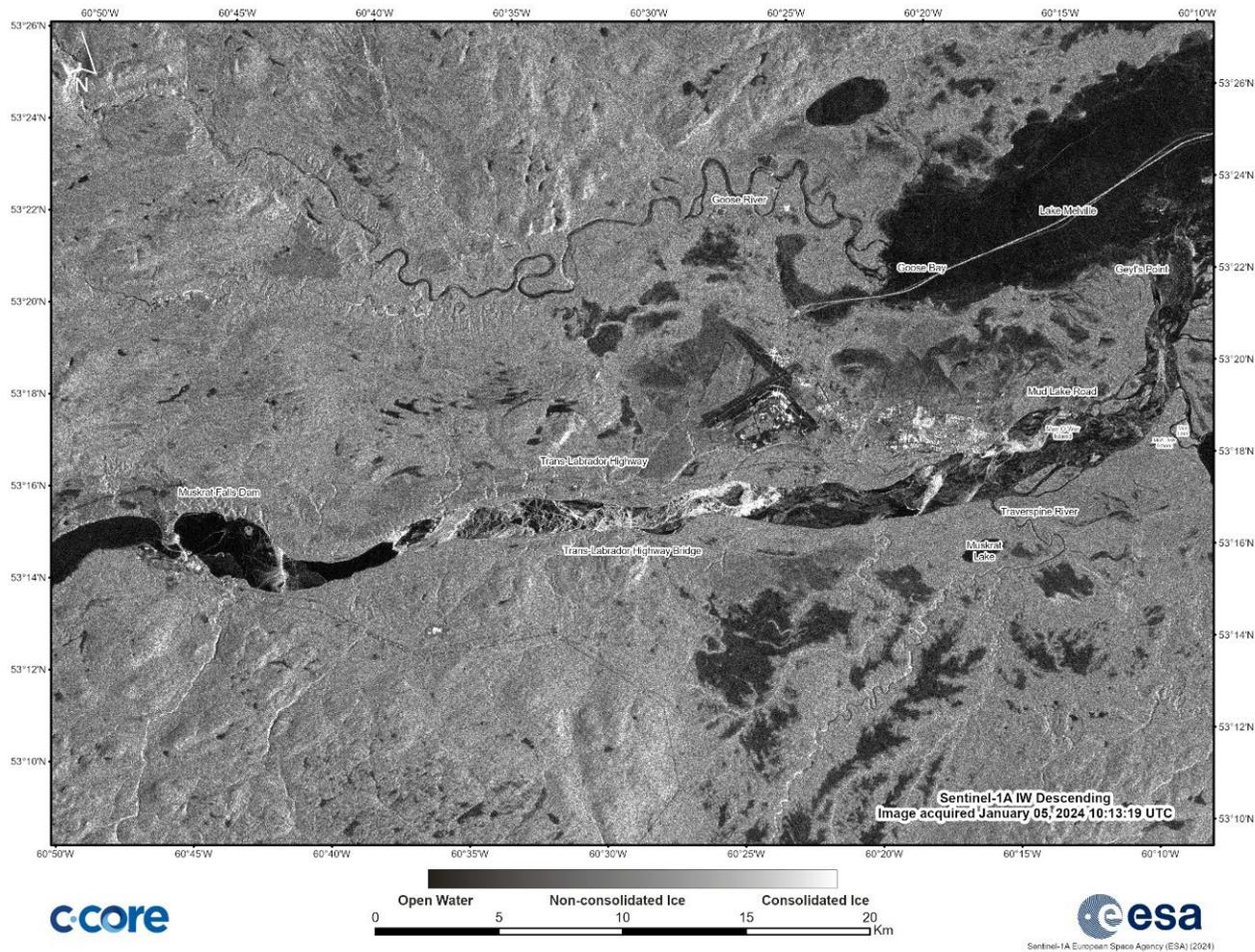
Figure A-24: Ice Cover – January 5, 2024.
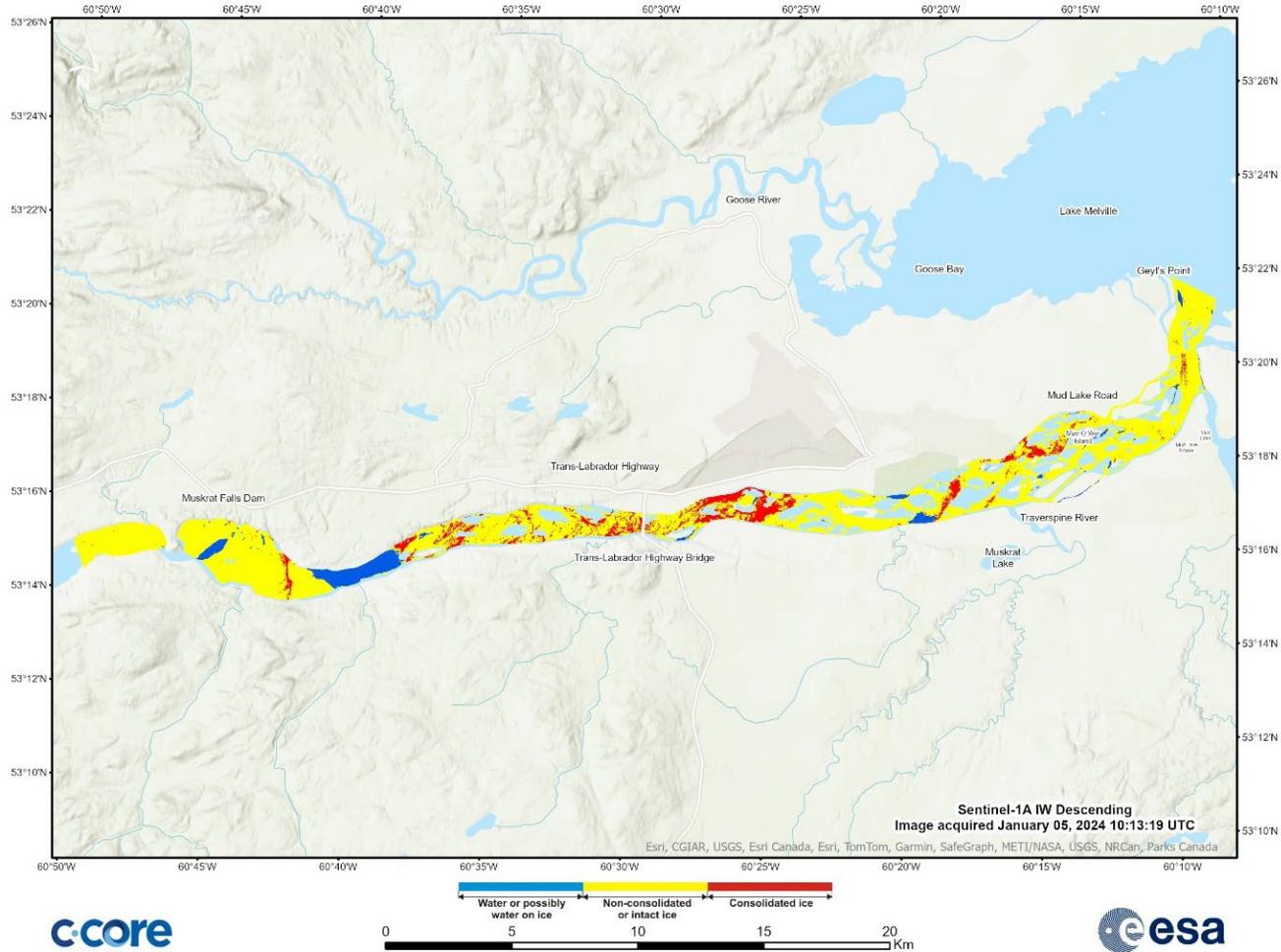
Figure A-25: Ice Classification – January 5, 2024.
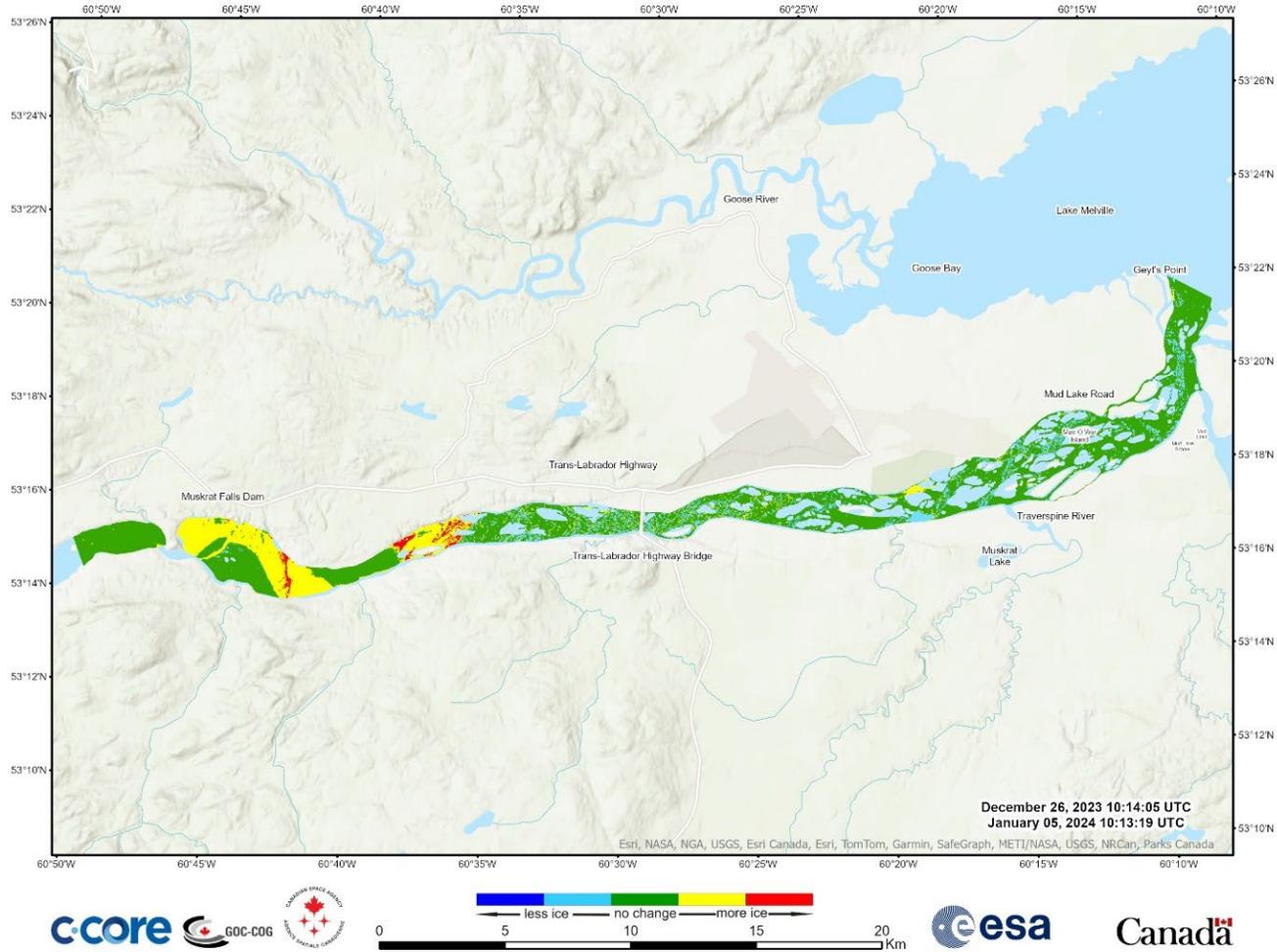
Figure A-26: Change Detection – December 26, 2023 and January 5, 2024.
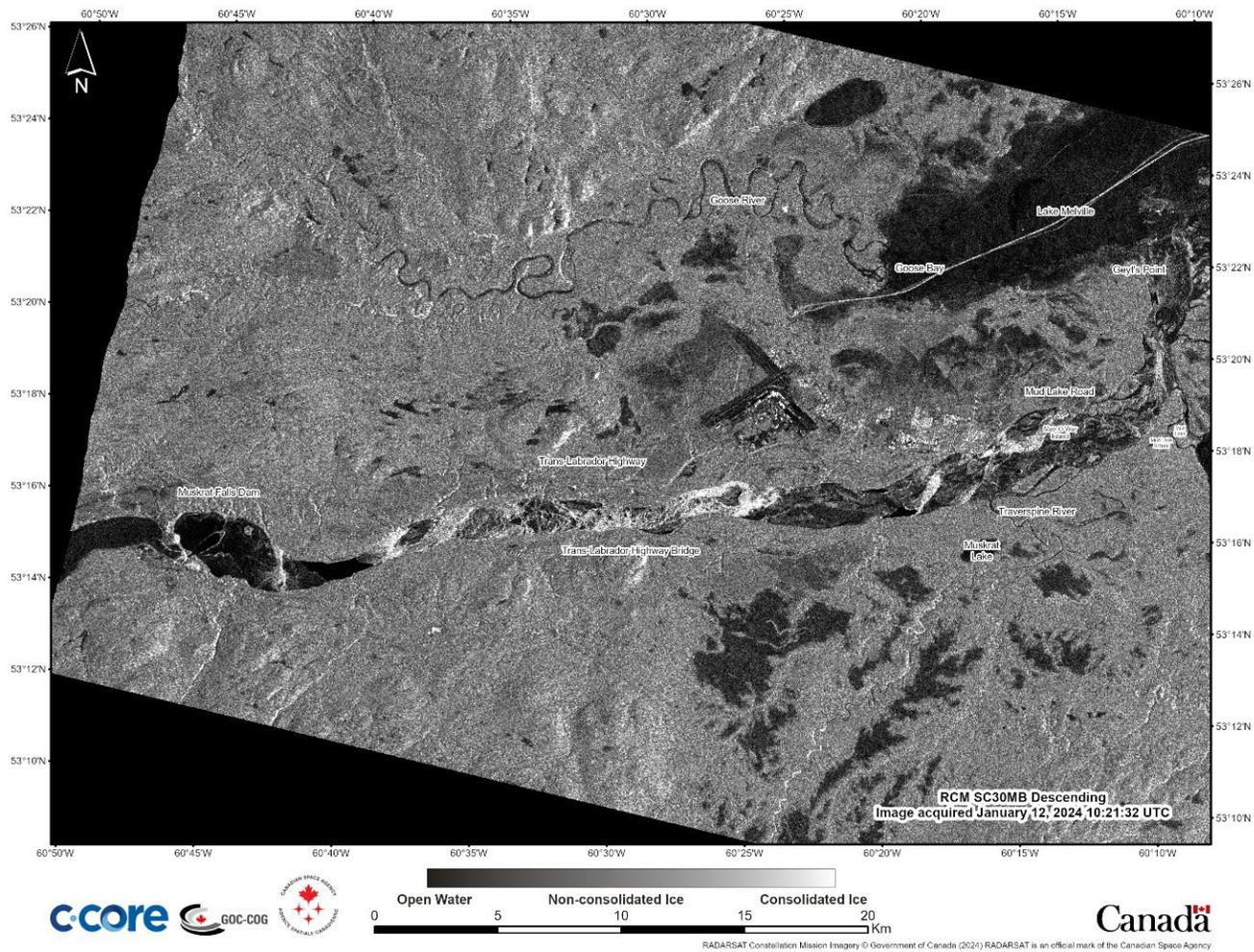
Figure A-27: Ice Cover – January 12, 2024.
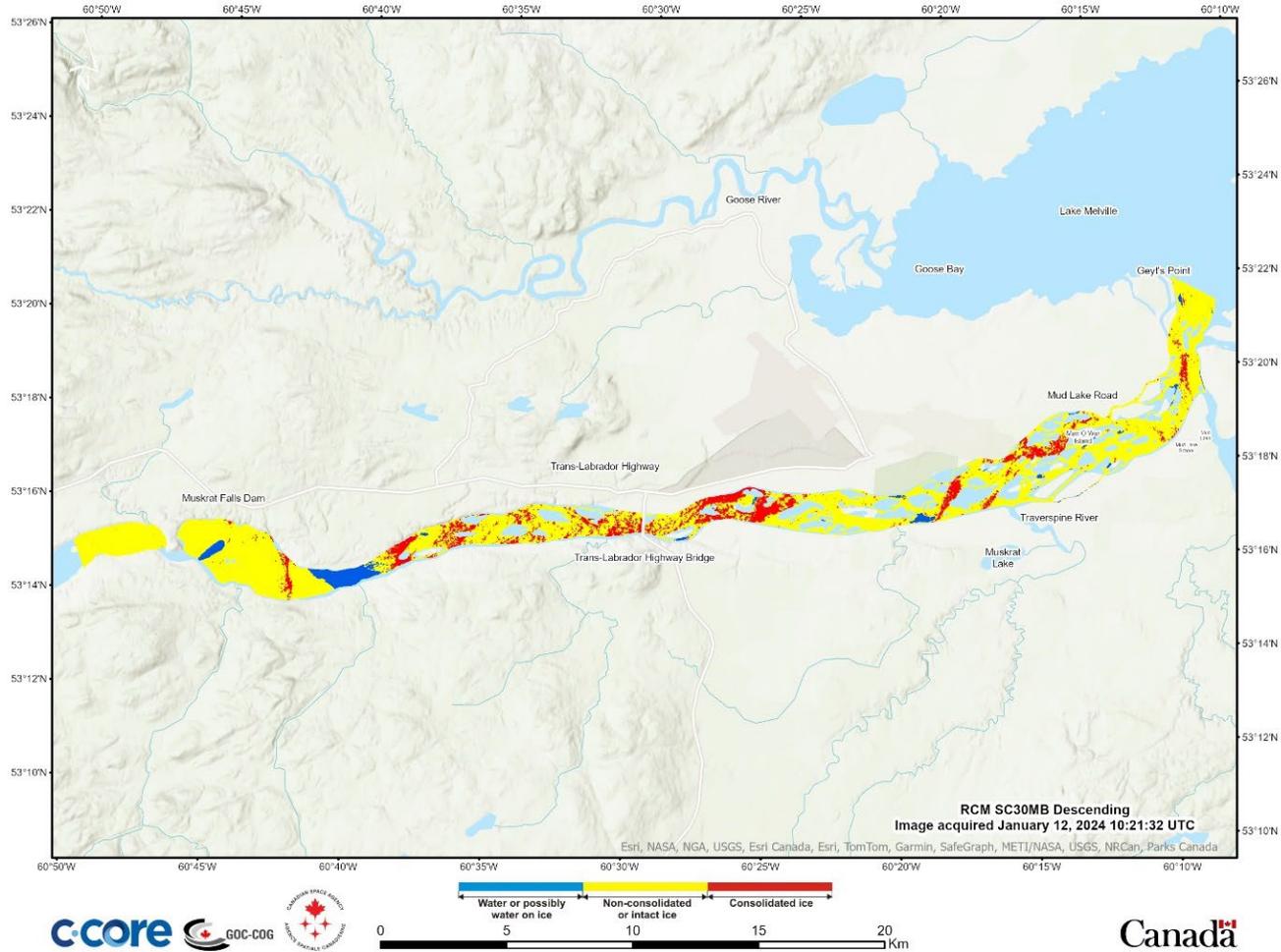
Figure A-28: Ice Classification – January 12, 2024.
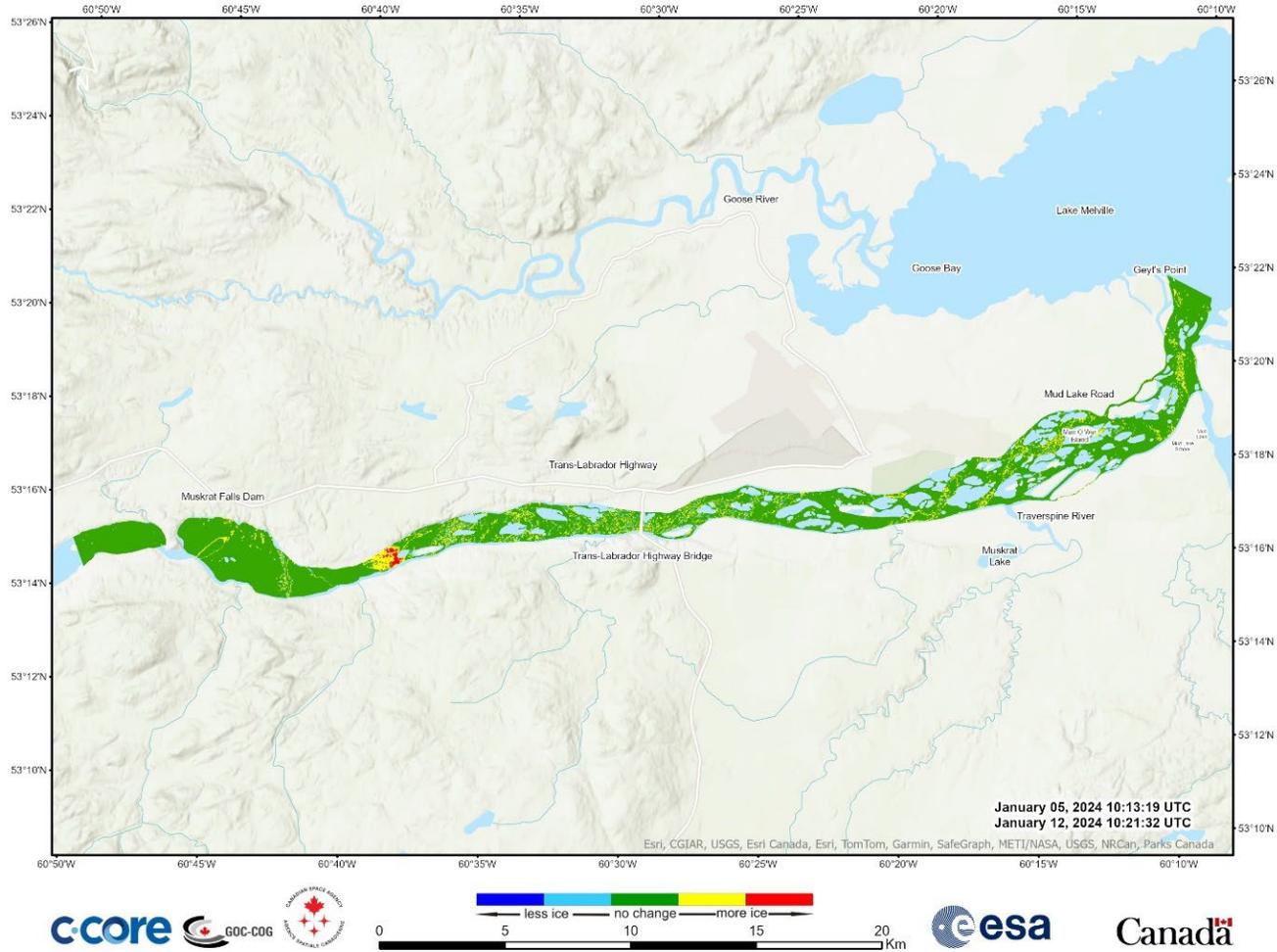
Figure A-29: Change Detection – January 6 and January 12, 2024.

Appendix B

Lower Churchill Break-Up Satellite Imagery

Churchill River - Ice Cover
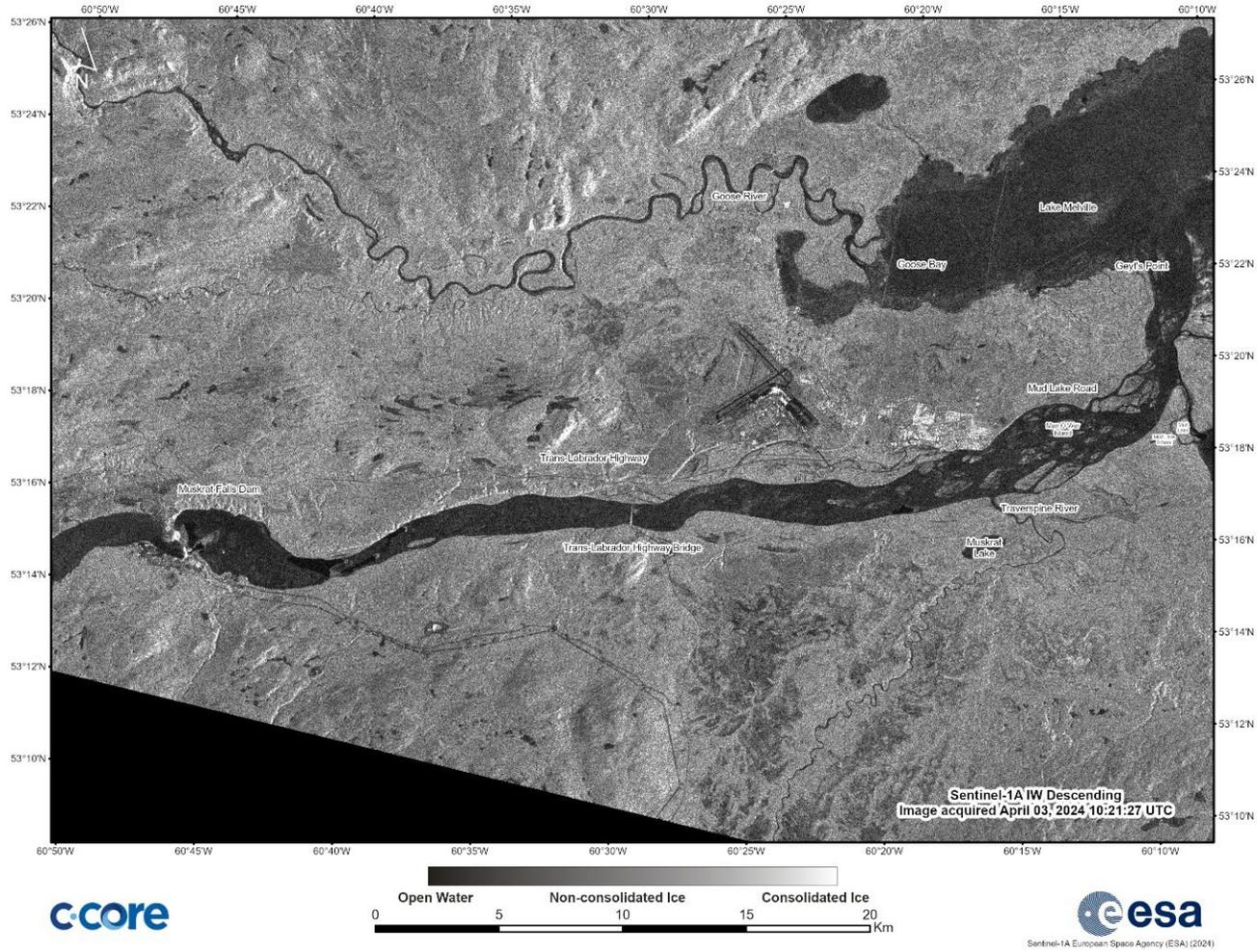
Figure B-1: Ice Cover – April 3, 2024.
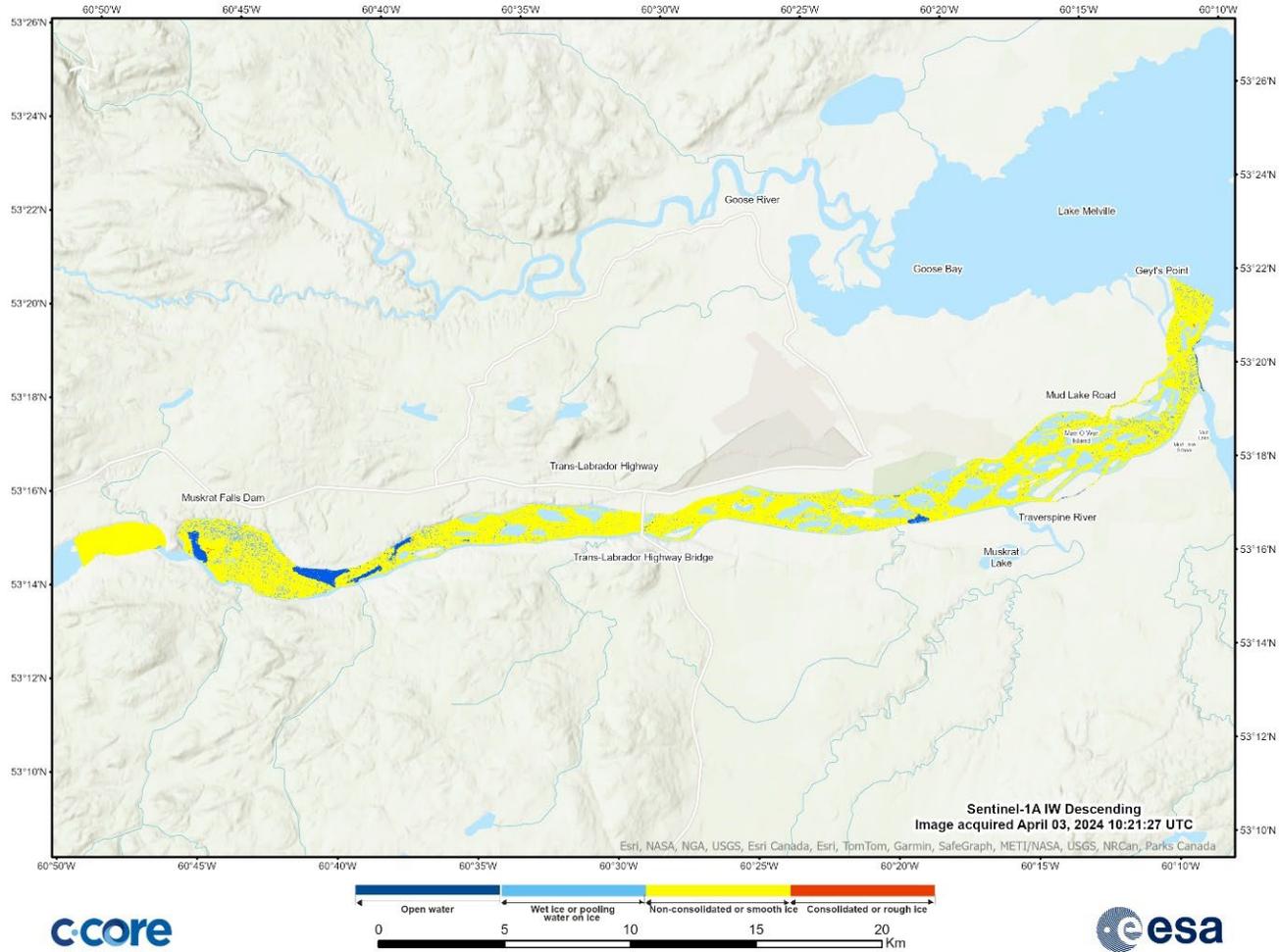
Figure B-2: Ice Classification – April 3, 2024.
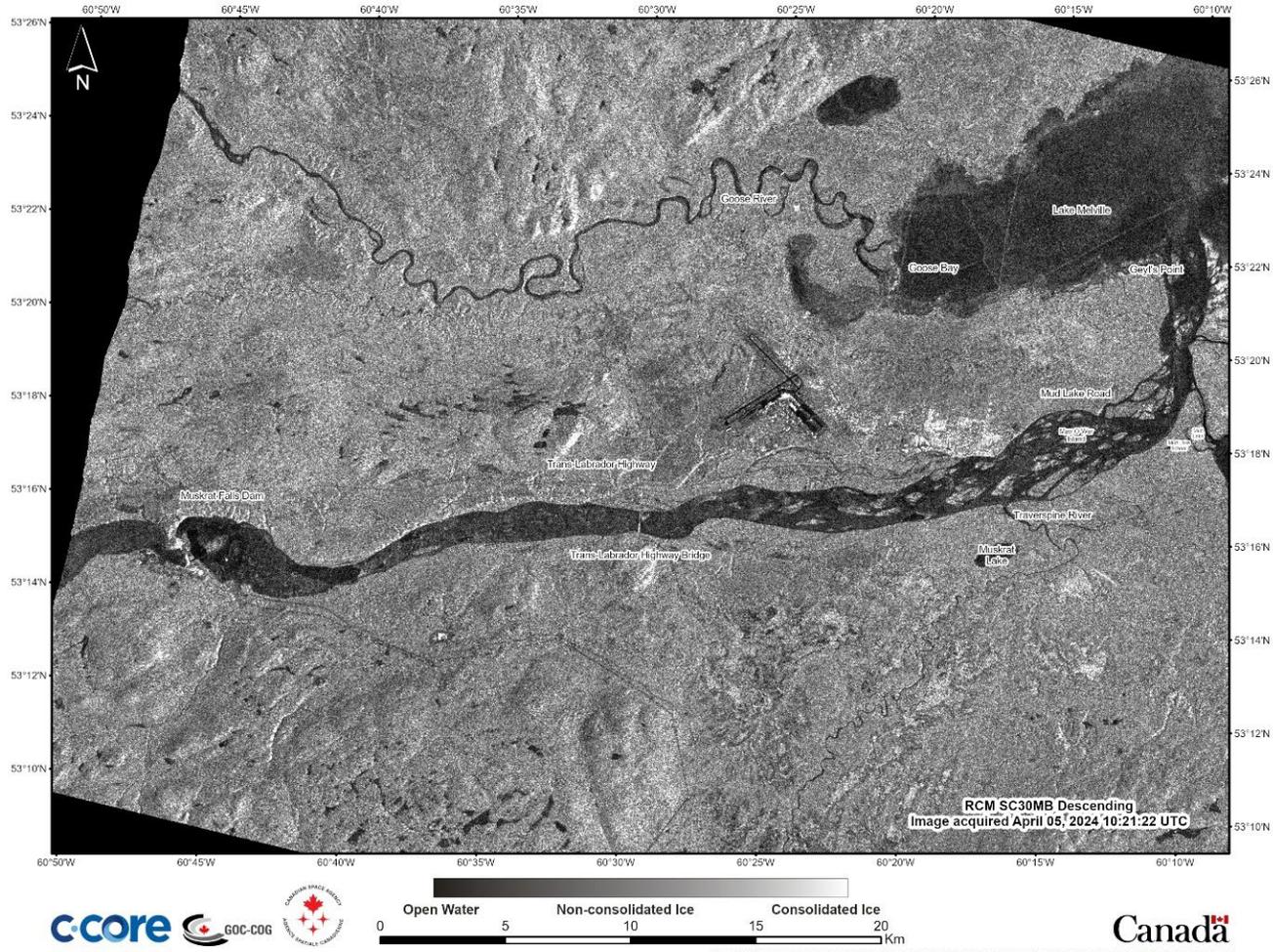
Figure B-3: Ice Cover – April 5, 2024.
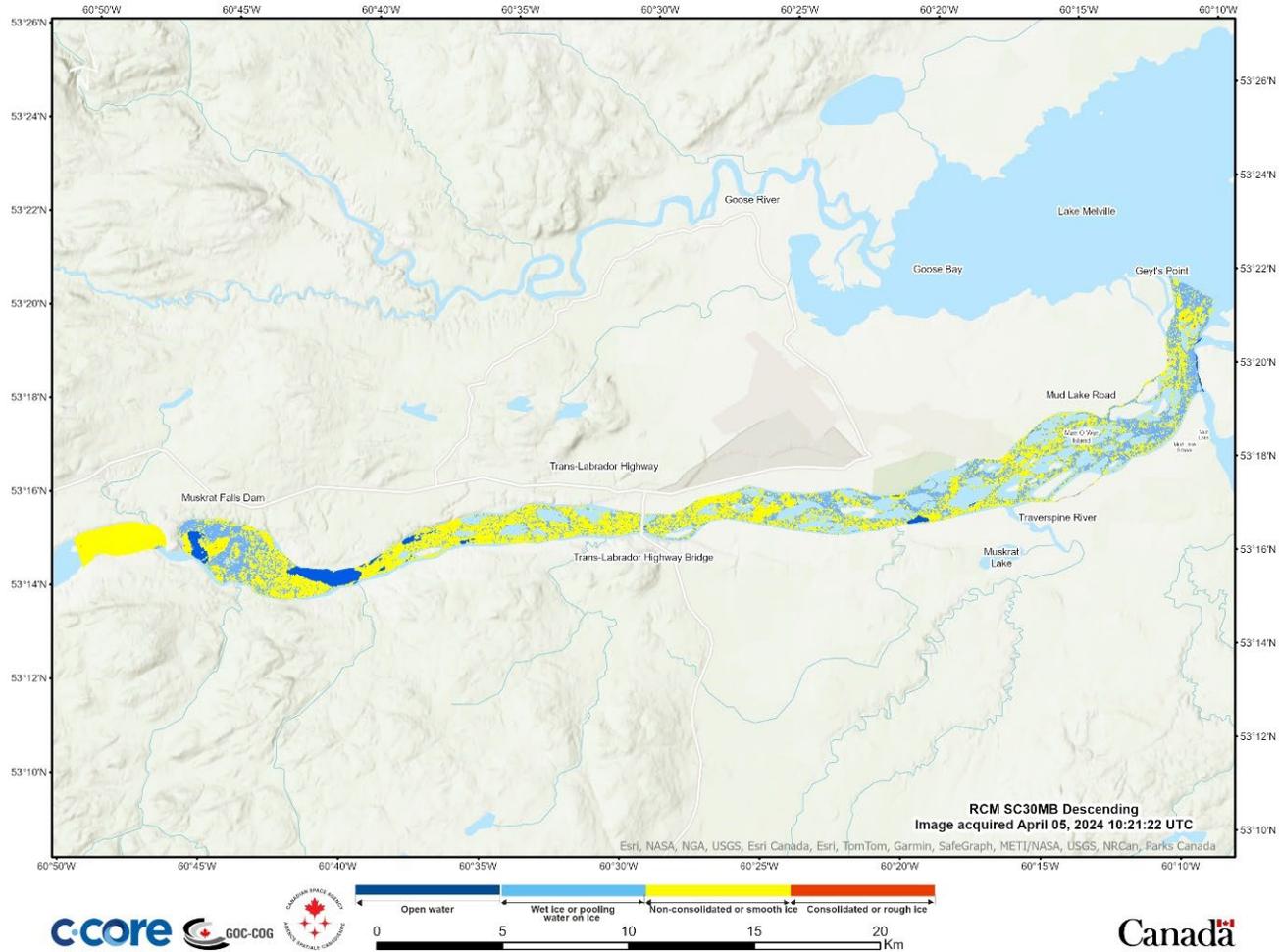
Figure B-4: Ice Classification – April 5, 2024.
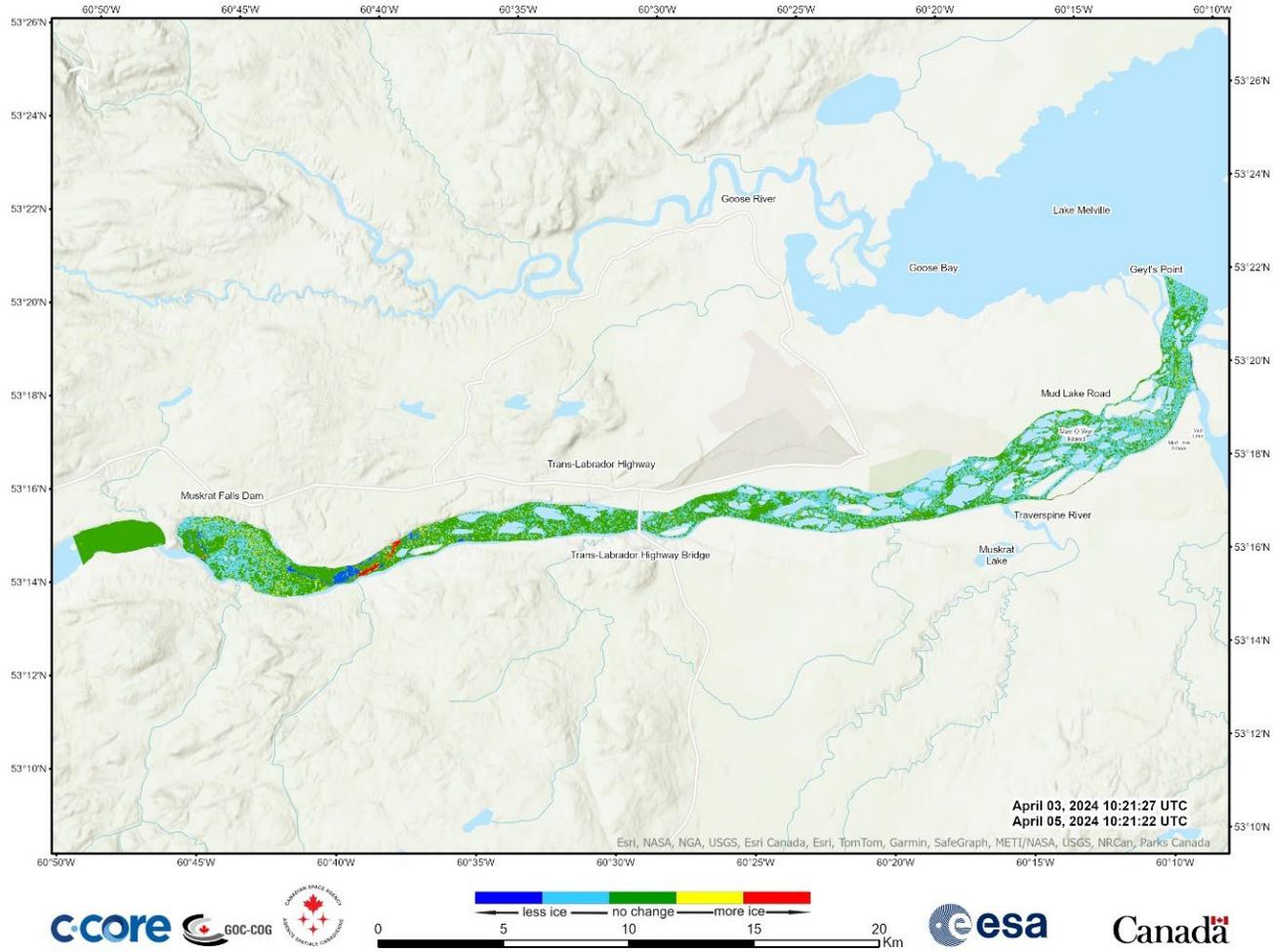
Figure B-5: Change Detection –April 3 and 5, 2024.
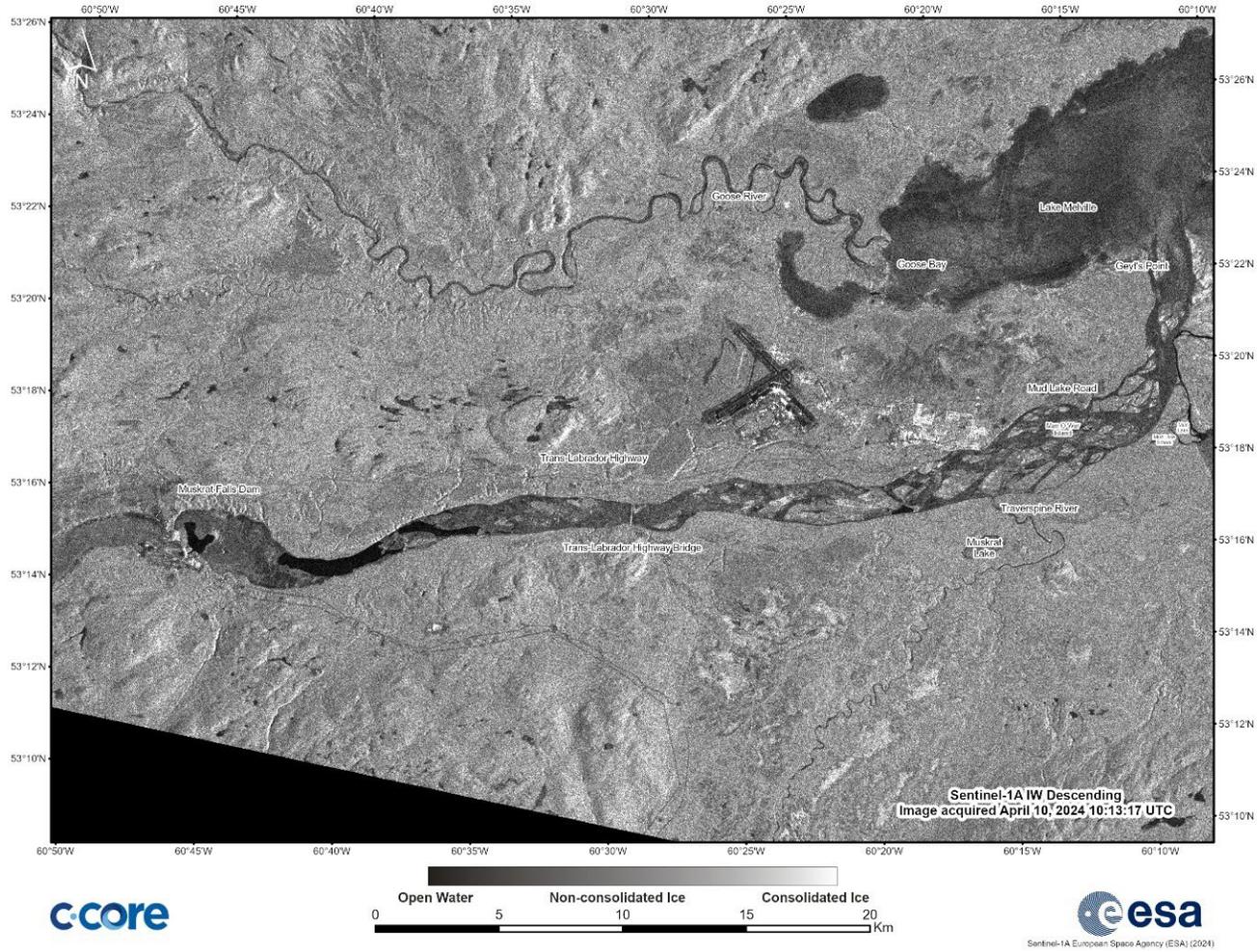
Figure B-6: Ice Cover – April 10, 2024.
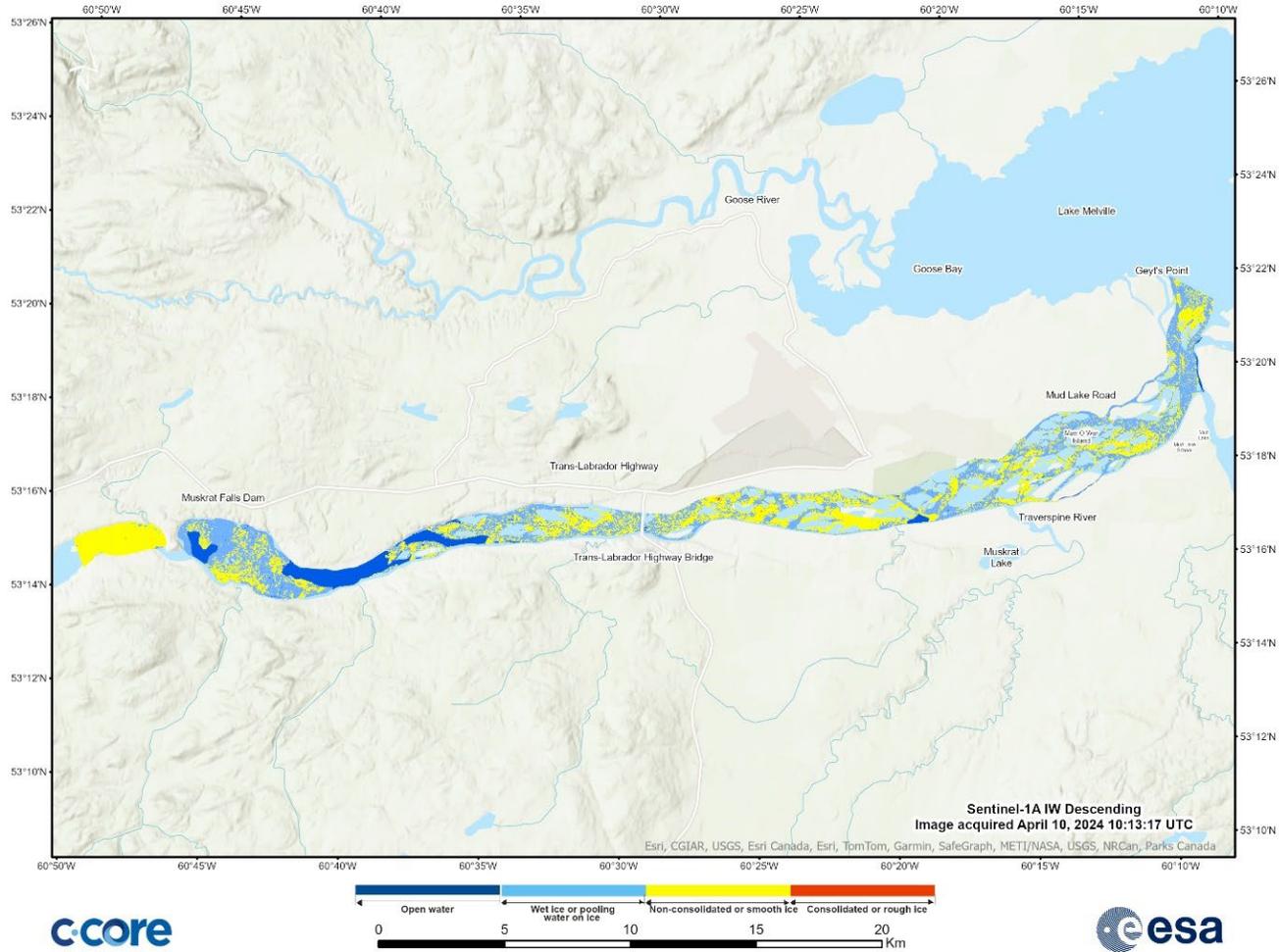
Figure B-7: Ice Classification – April 10, 2024.
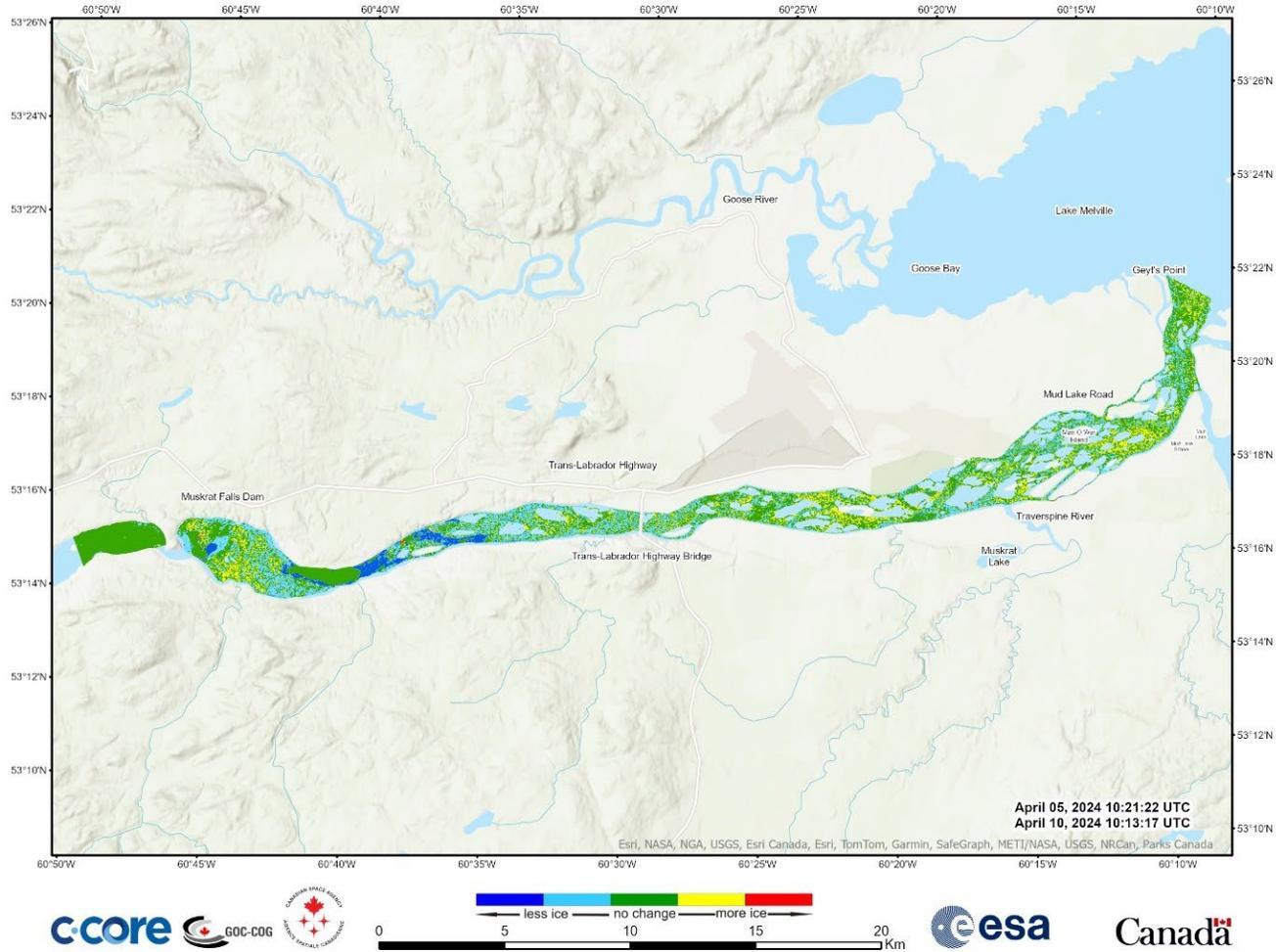
Figure B-8: Change Detection – April 5 and 10, 2024.
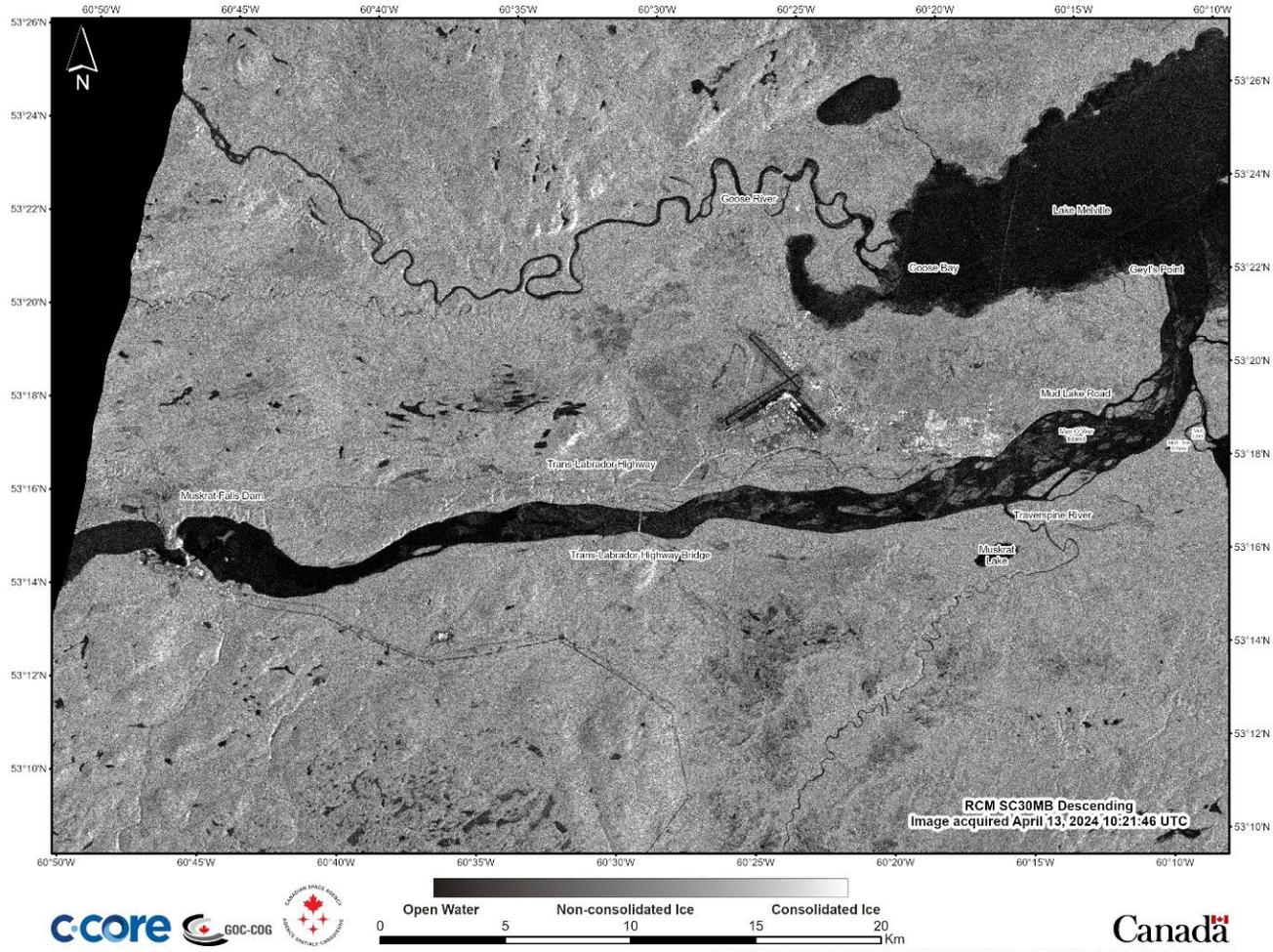
Figure B-9: Ice Cover – April 13, 2024.

Figure B-10: Ice Classification – April 13, 2024.

Figure B-11: Change Detection –April 10 and 13, 2024.

Churchill River - Ice Cover
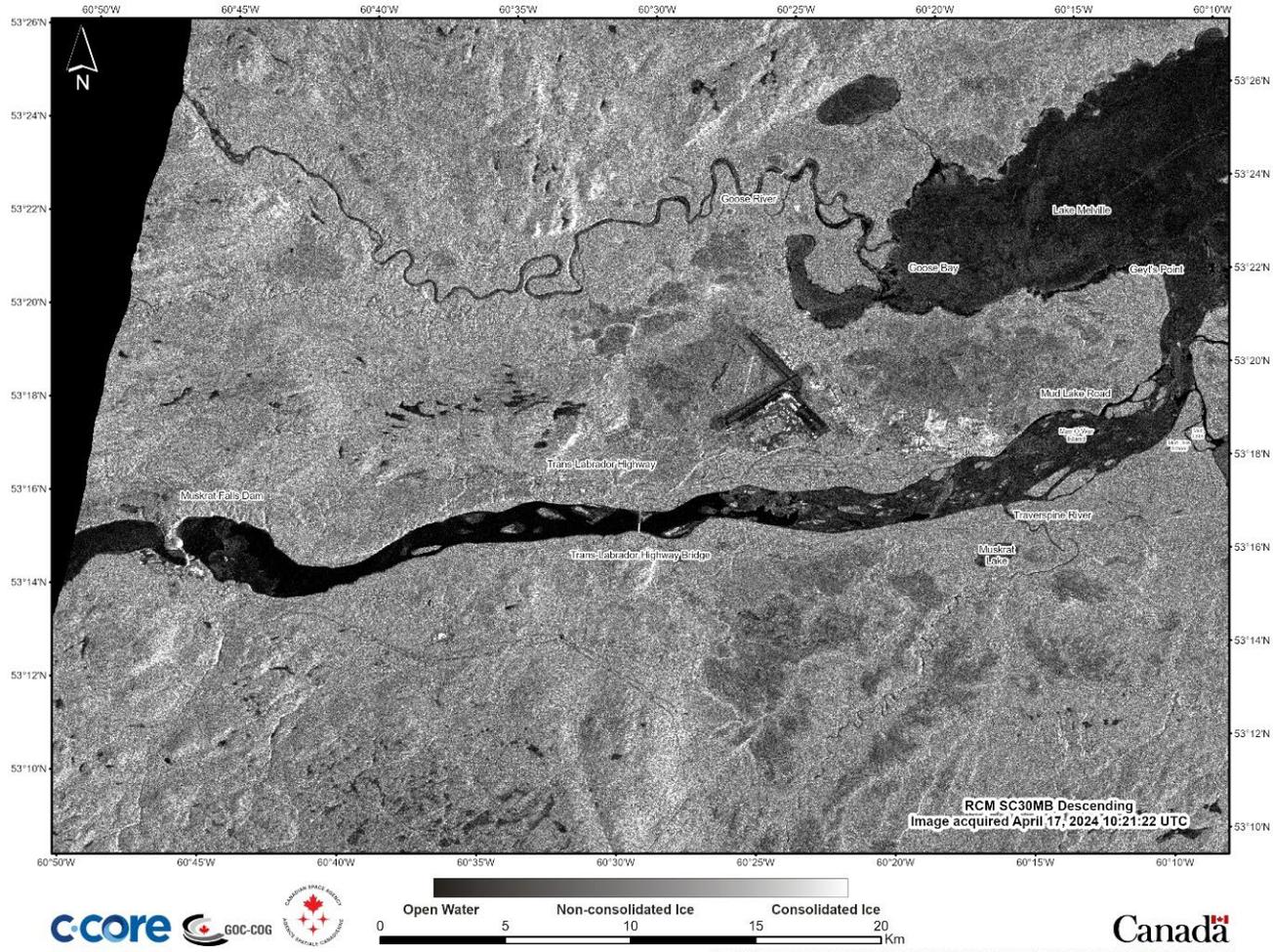
Figure B-12: Ice Cover – April 17, 2024.

Figure B-13: Ice Classification – April 17, 2024.

Figure B-14: Change Detection – April 13 and 17, 2024.

Churchill River - Ice Cover
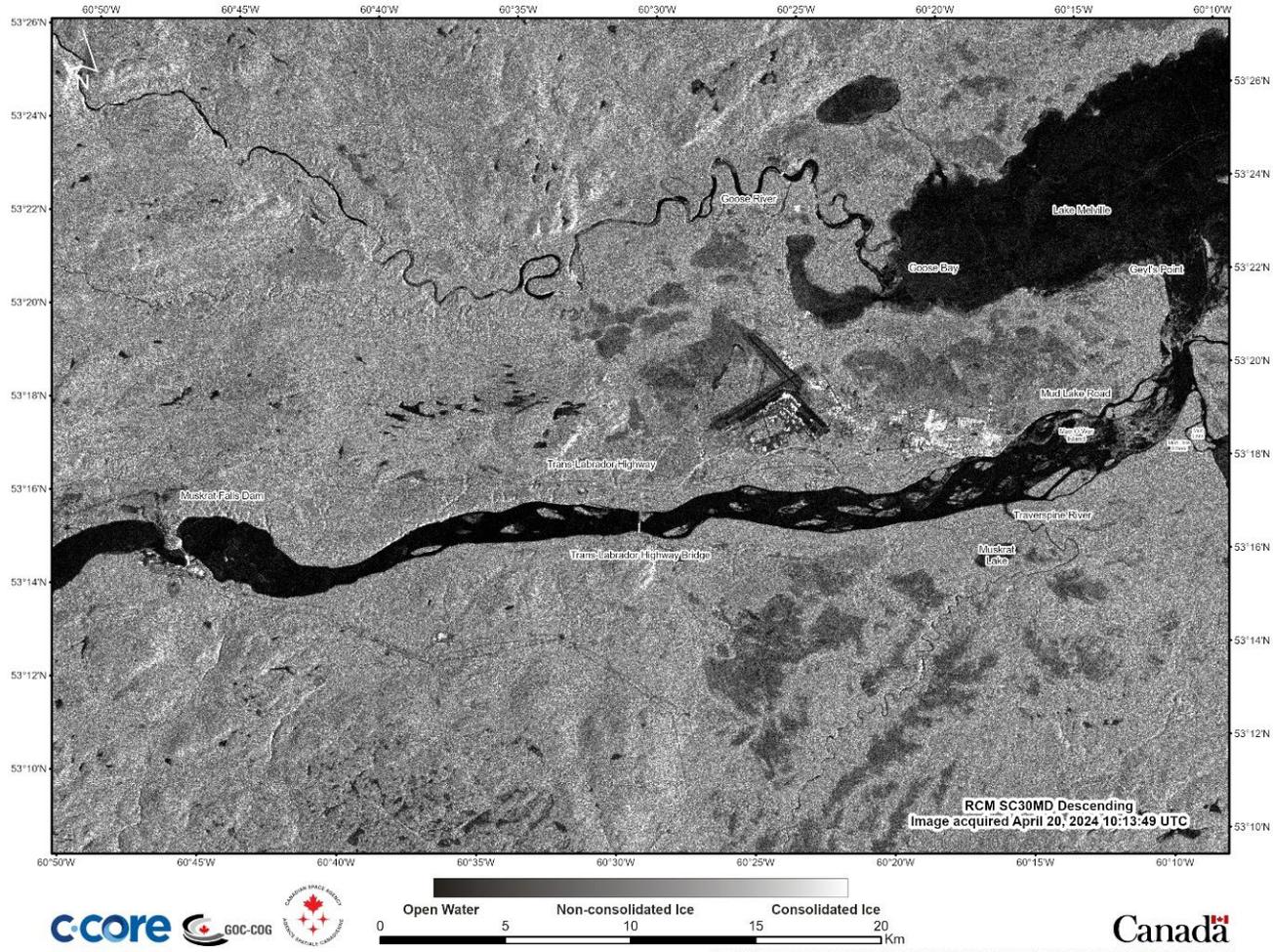
Figure B-15: Ice Cover – April 20, 2024.
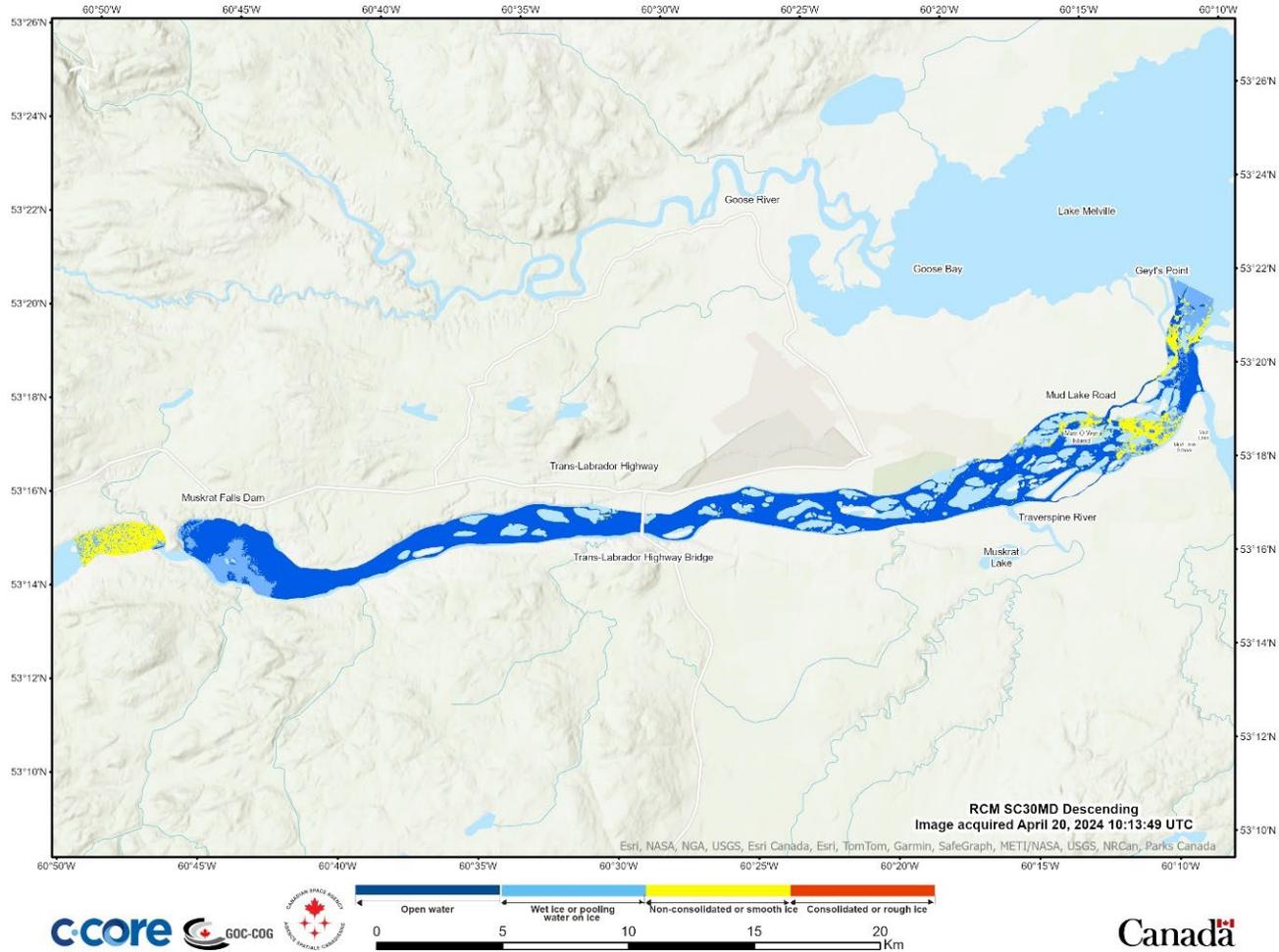
Figure B-16: Ice Classification – April 20, 2024.
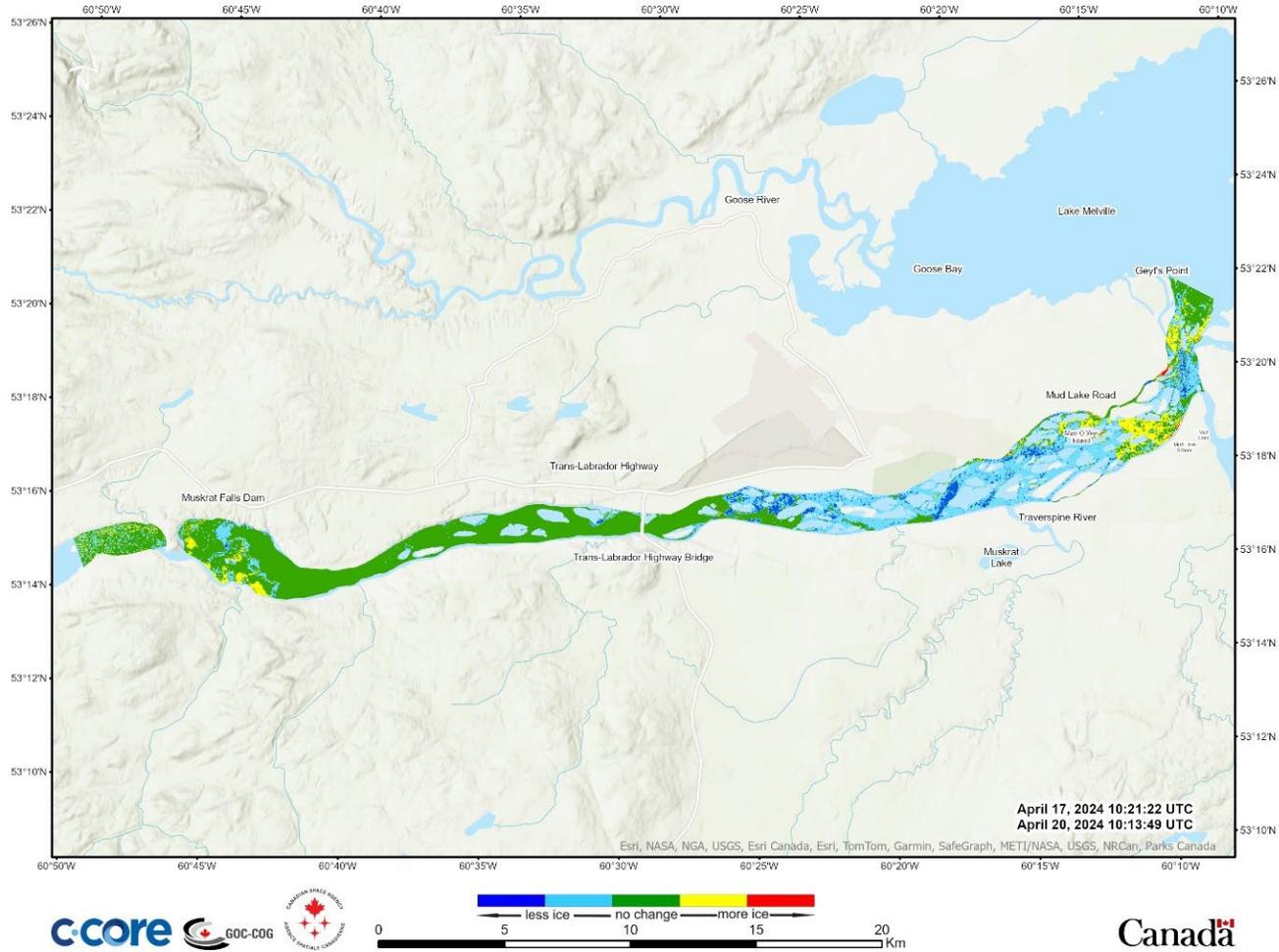
Figure B-17: Change Detection – April 17 and 20, 2024.
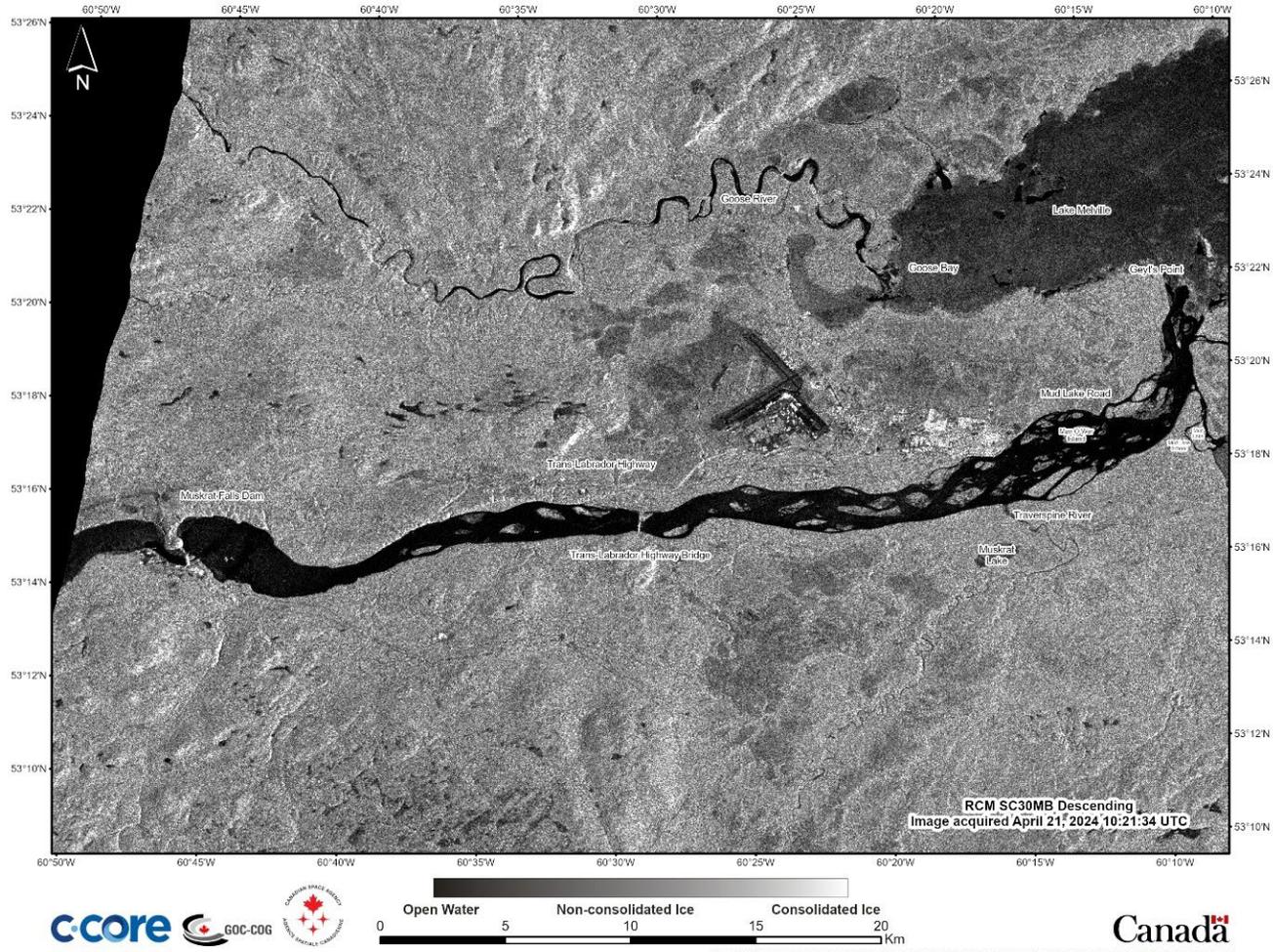
Figure B-18: Ice Cover – April 21, 2024.
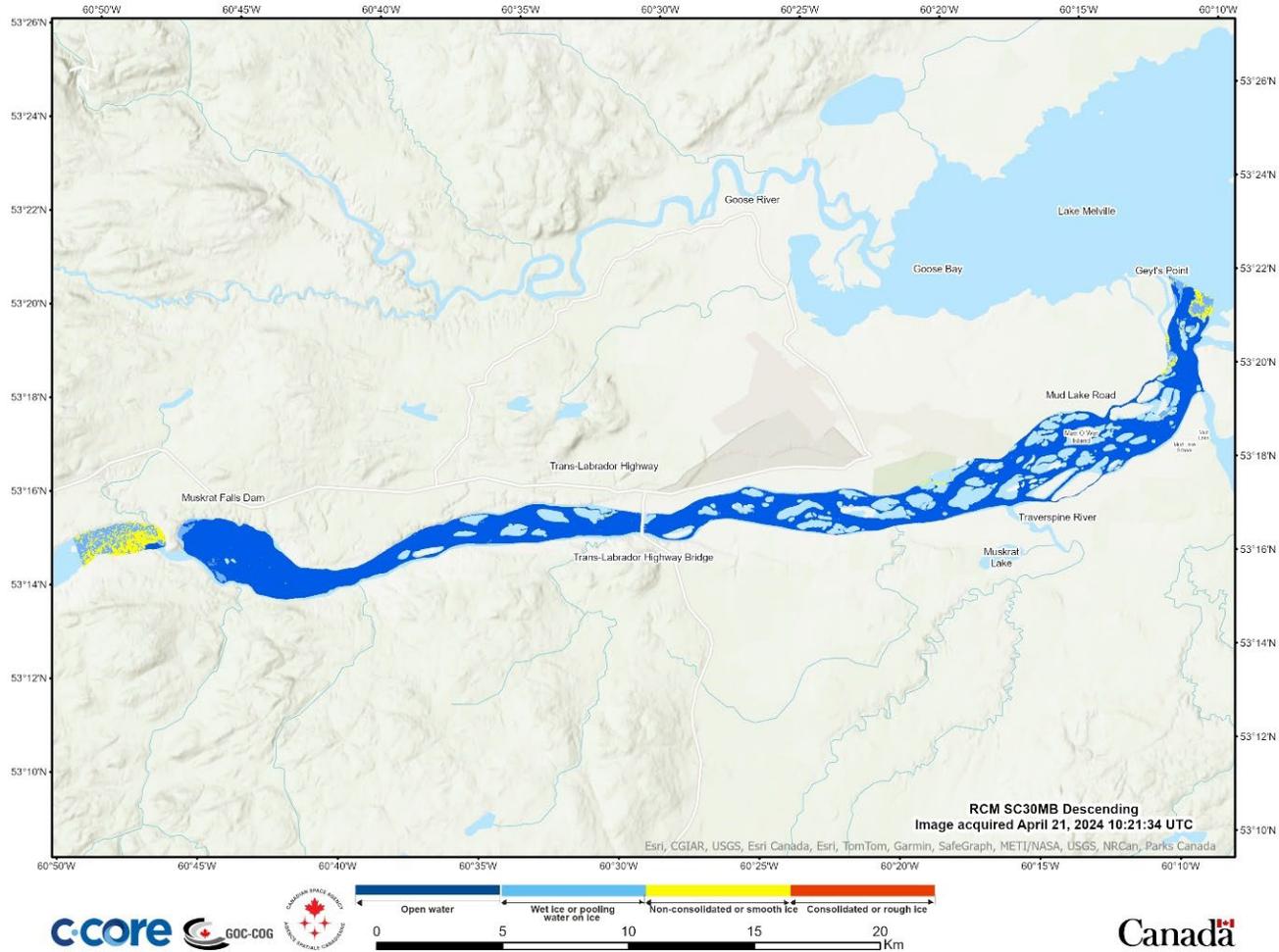
Figure B-19: Ice Classification – April 21, 2024.
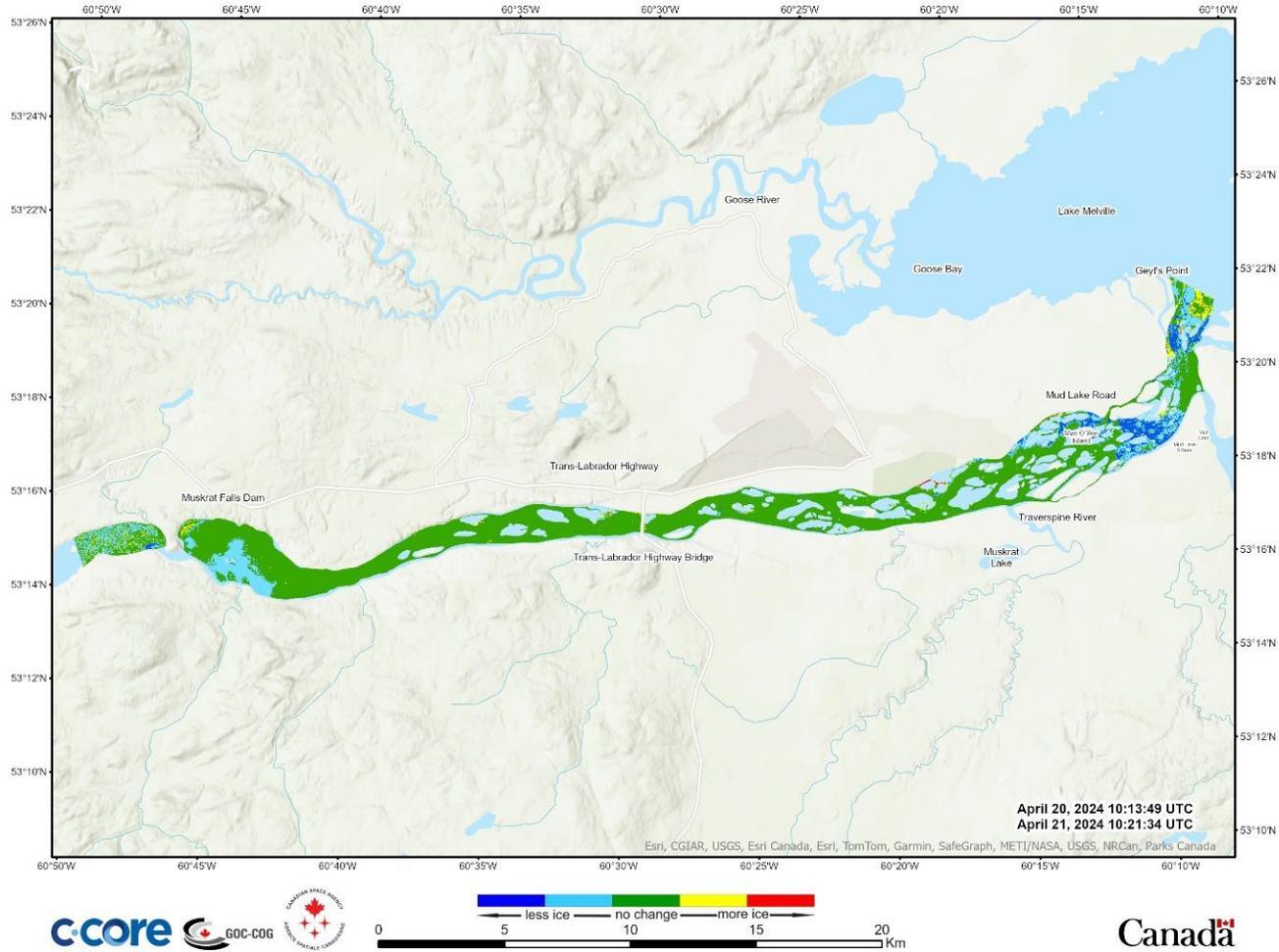
Figure B-20   Change Detection – April 20 and 21, 2024.
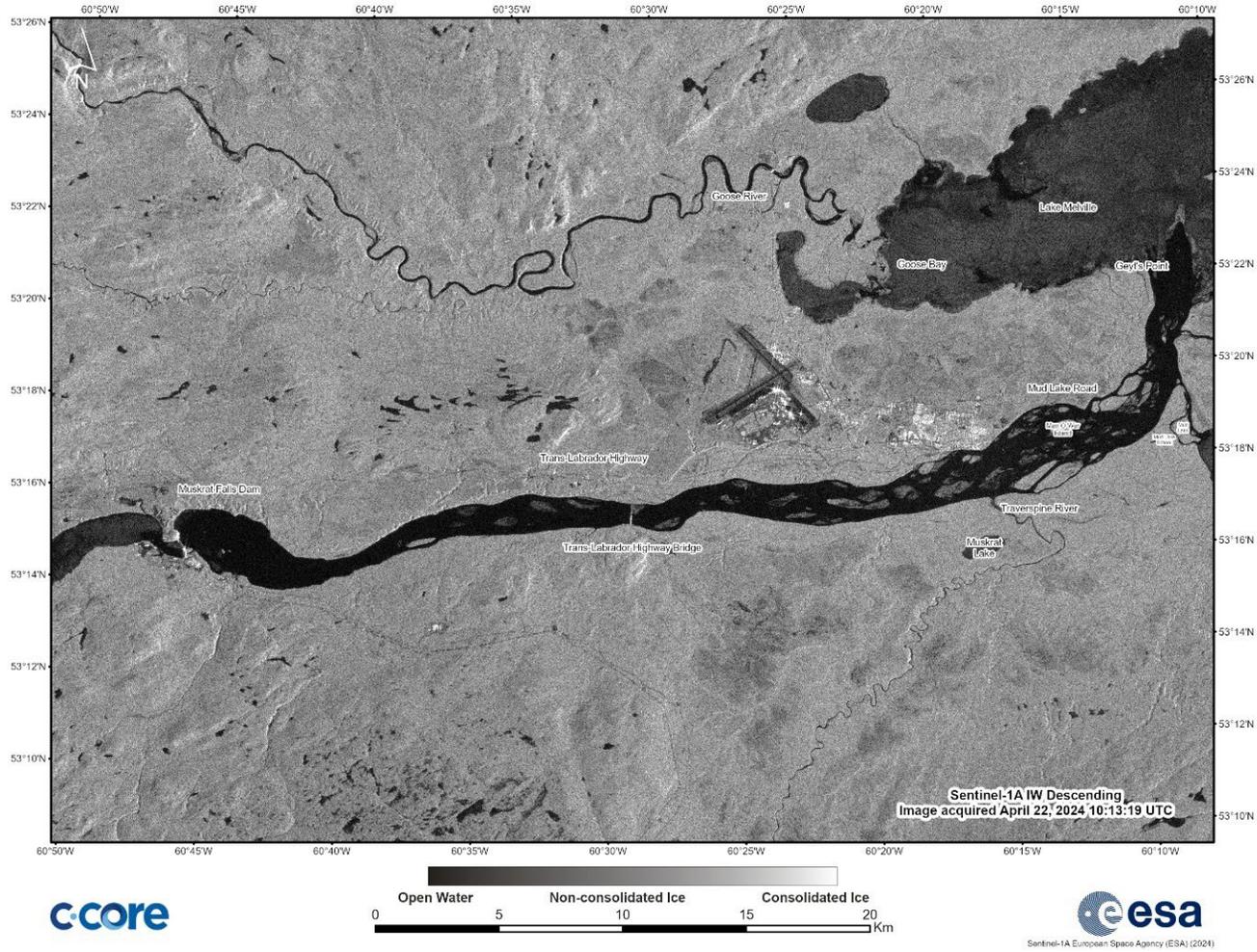
Figure B-21: Ice Cover – April 22, 2024.

Figure B-22: Ice Classification – April 22, 2024.

Figure B-23: Change Detection – April 21 and 22, 2024.

Churchill River - Ice Cover
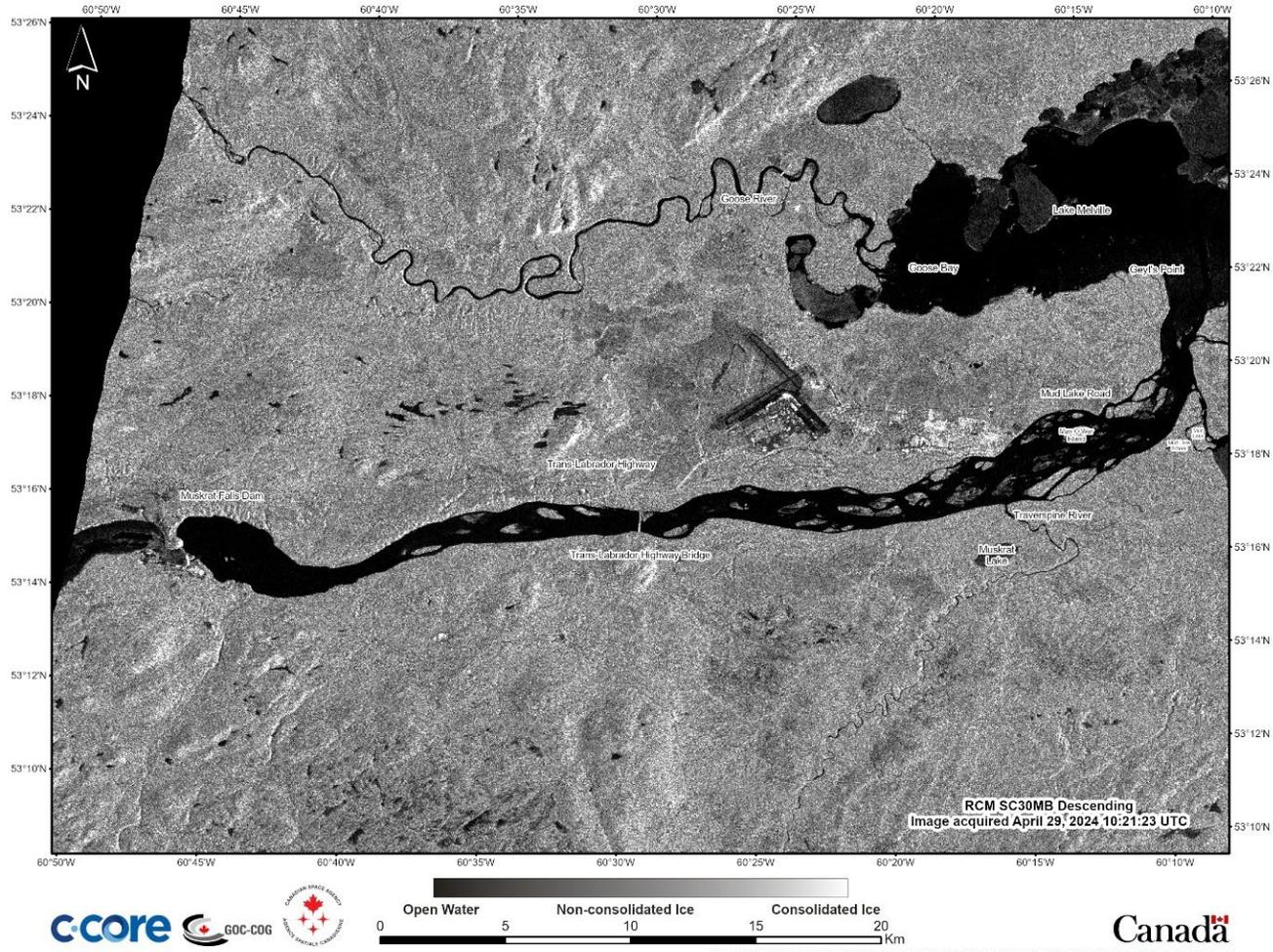
Figure B-24: Ice Cover – April 29, 2024.
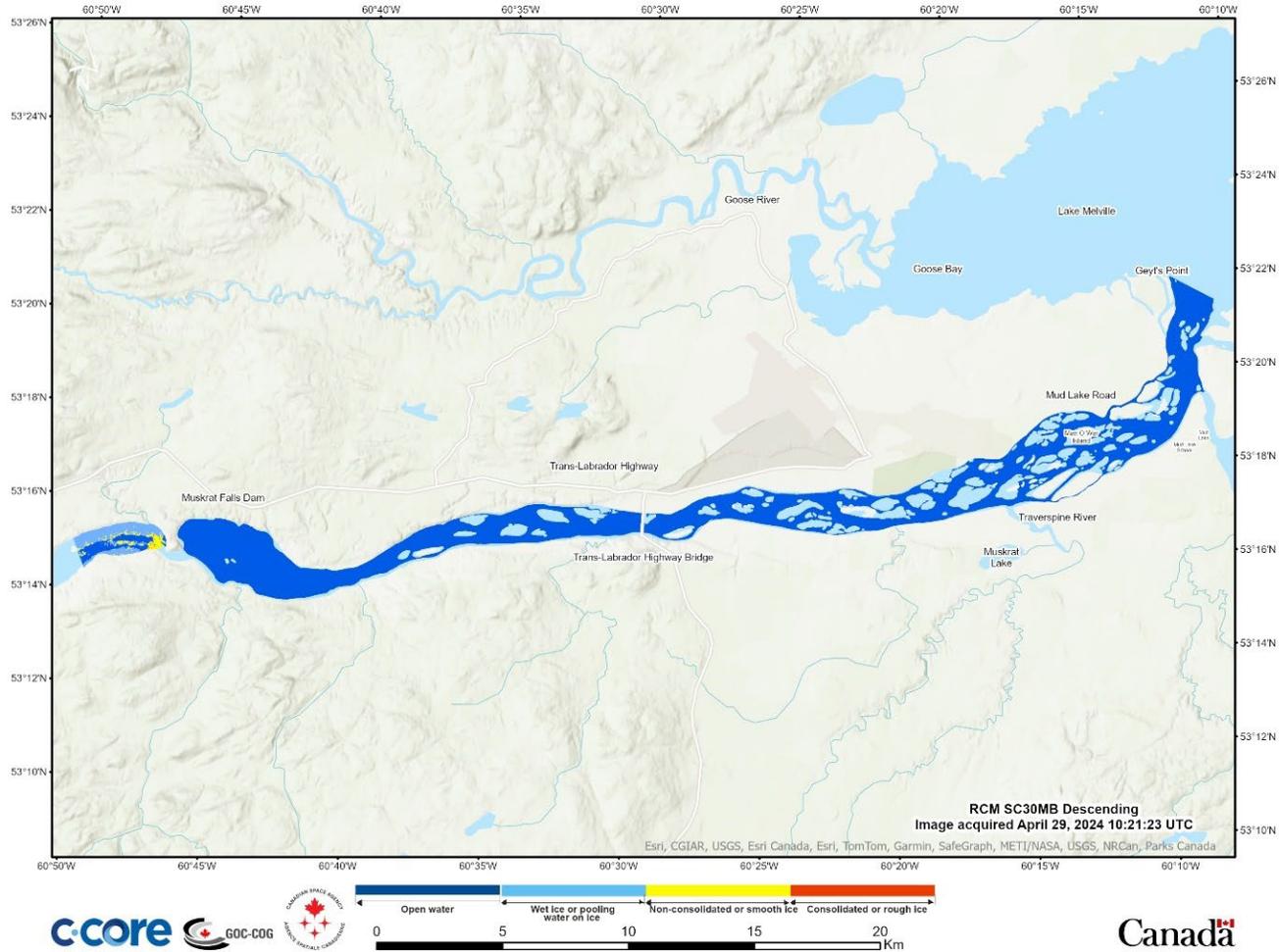
Figure B-25: Ice Classification – April 29, 2024.
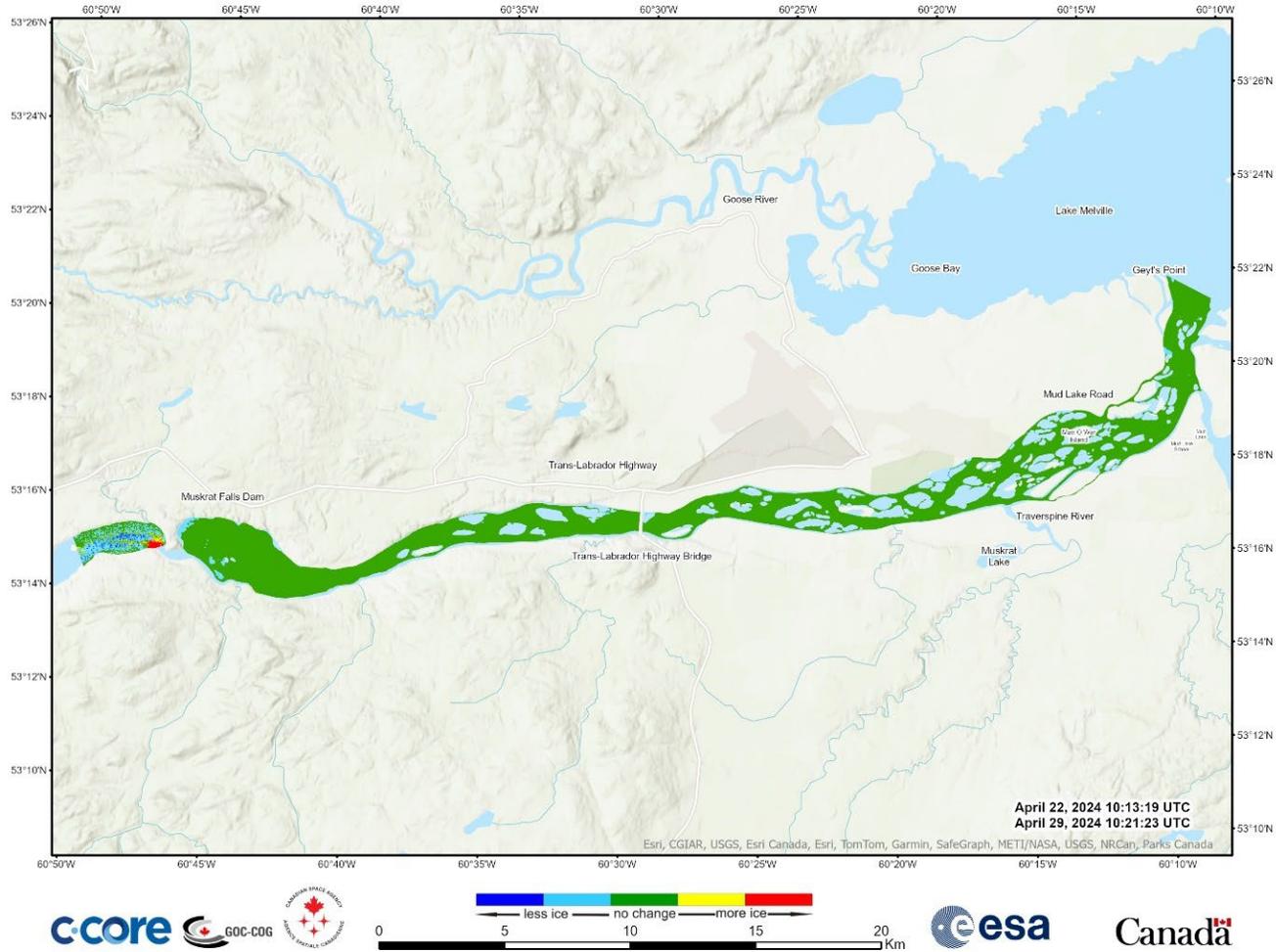
Figure B-26: Change Detection – April 22 and 29, 2024.
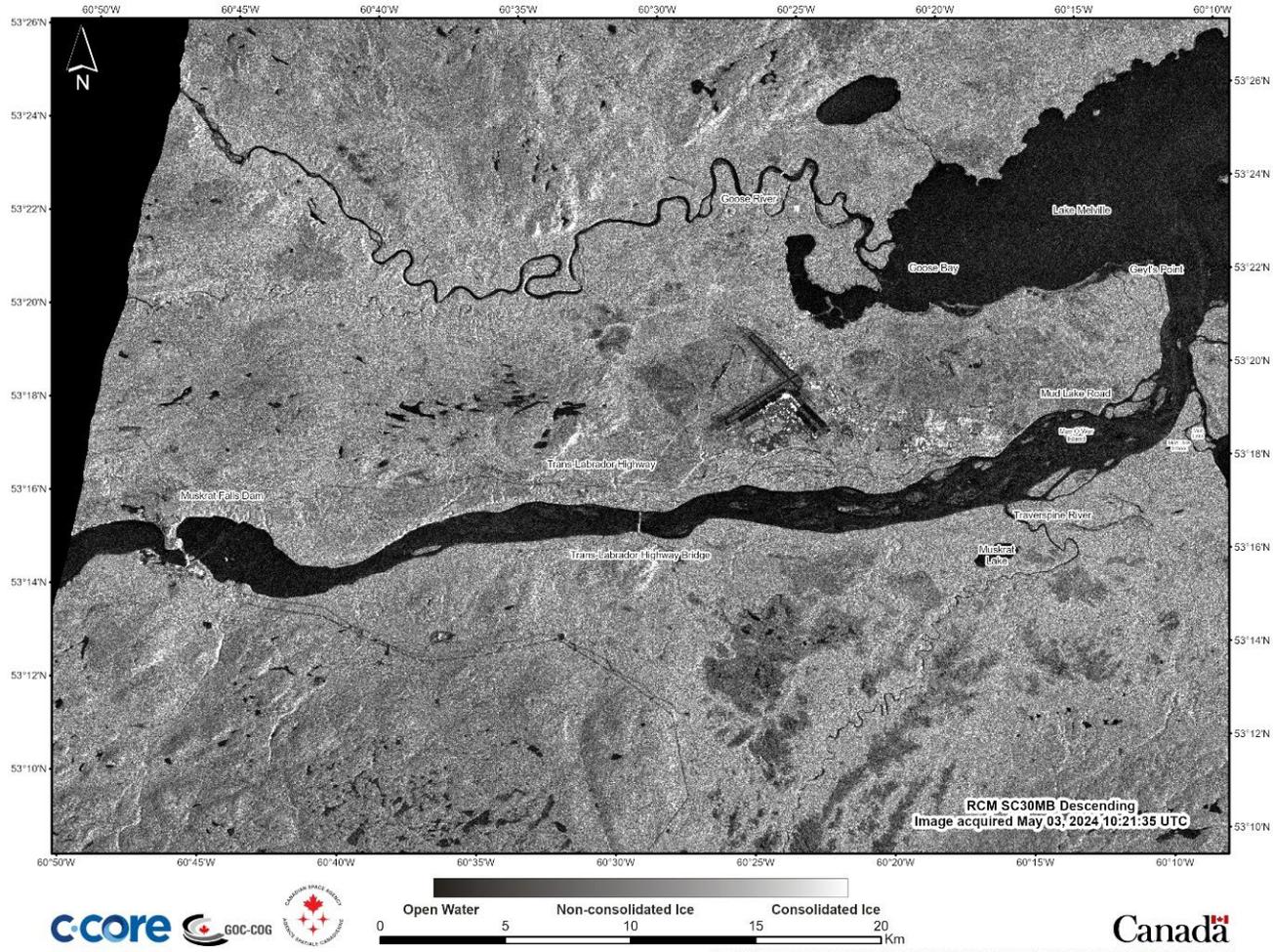
Figure B-27: Ice Cover – May 3, 2024.
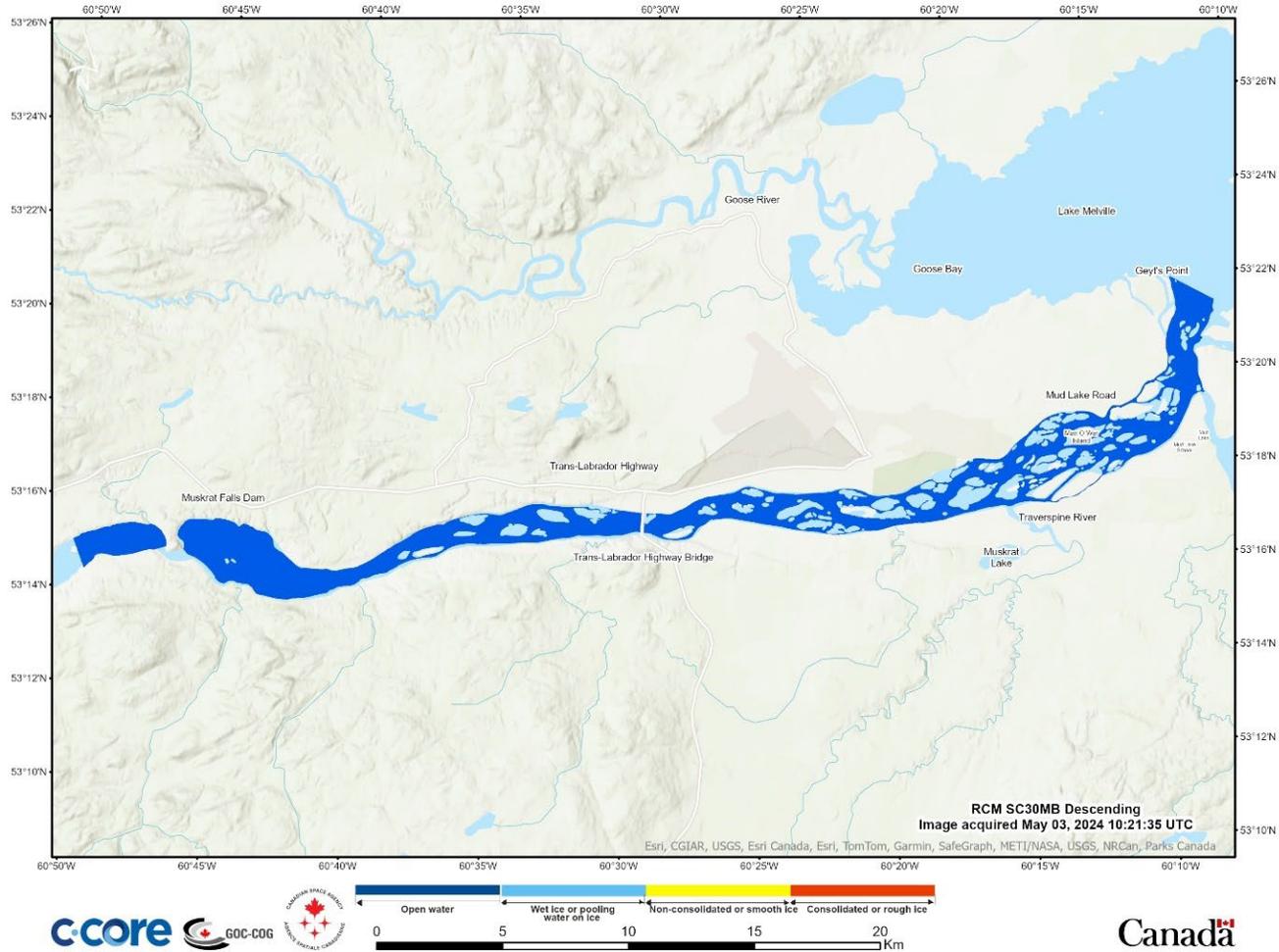
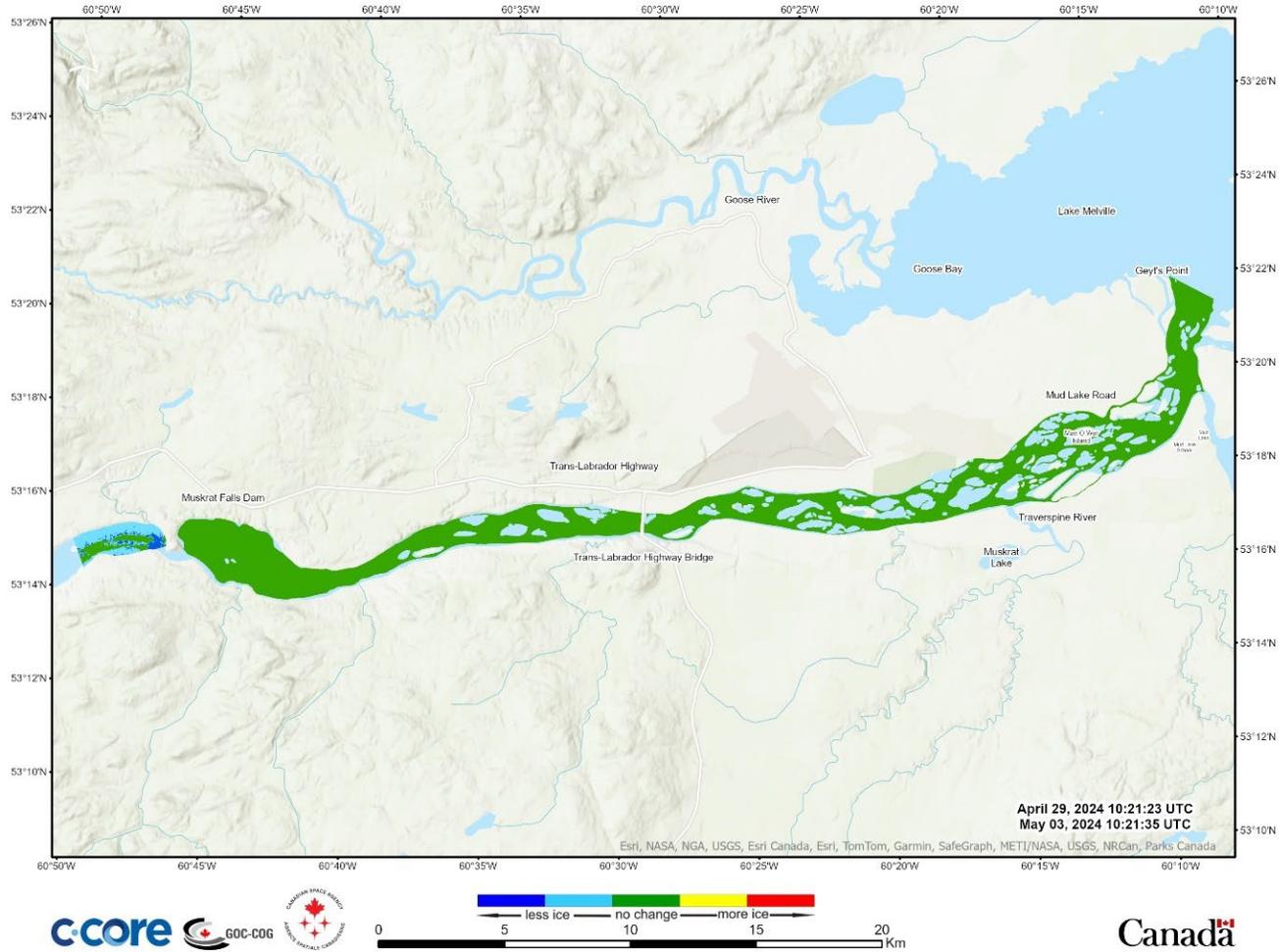**Figure B-28:** Ice Classification – May 3, 2024.

Figure B-29: Change Detection – April 29 and May 3, 2024.

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