# Document Front Sheet

nalcor energy LOWER CHURCHILL PROJECT

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| Jackie Wells | 15-Oct-2019 | | |
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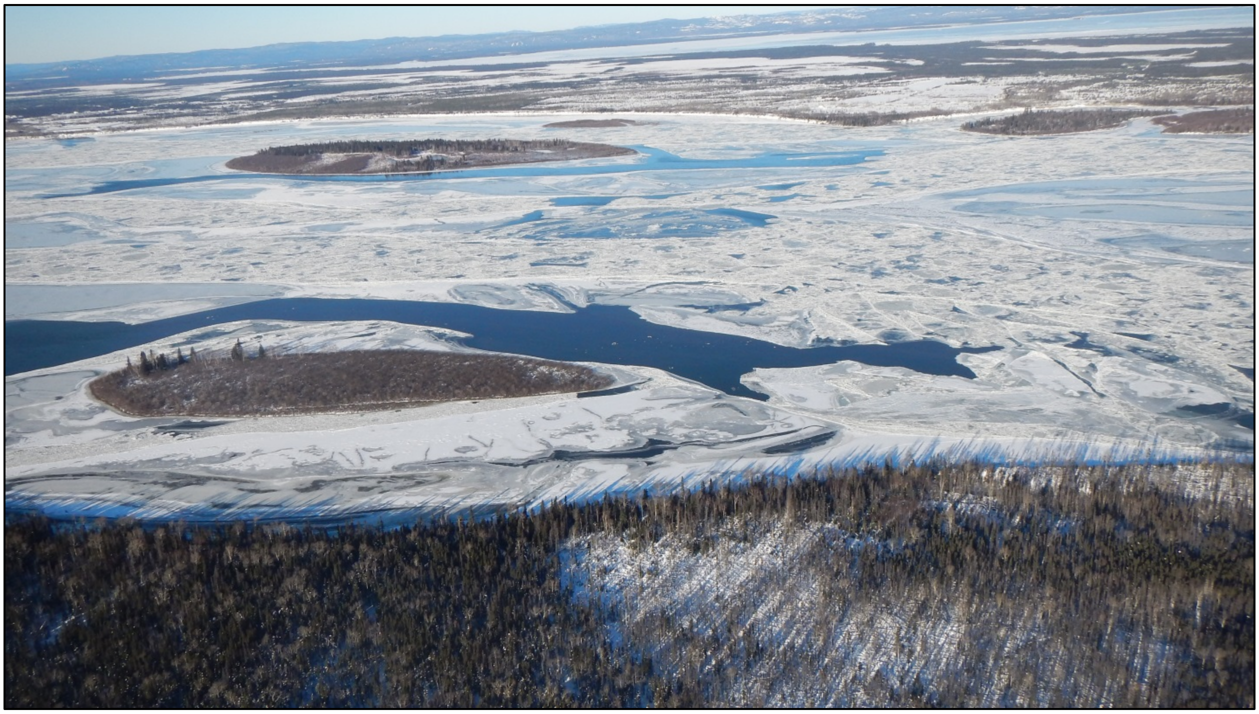
Rev changed to B2

# 2018-2019 Ice Observation Survey
# Mud Lake Crossing, Lower Churchill River
# LC-EV-107



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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 pre- and post-impoundment. The program during the 2018-2019 ice season was the sixth in a continuation of previous monitoring during the baseline and construction period of the LCP to document baseline conditions and collect additional data to better understand the ice conditions in areas potentially influenced by the LCP. The survey program included the following objectives and activities:

- Review of web camera images at Mud Lake for planning purposes;
- Communications with Mud Lake residents to document freeze-up and break-up processes;
- Estimation of ice floe concentrations; and
- Acquisition and interpretation of satellite imagery to monitor the freeze-up and break-up processes.

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 Municipal Affairs and Environment, Water Resources Management Division (NLDMAE/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 12 to December 5, 2018, and May 4 to 25, 2019, were used to further document and describe the freeze-up and break-up conditions.

An ice floe concentration analysis was performed on selected satellite images (eight images for freeze-up and 12 images for break-up) for the purpose of studying ice concentrations in the reach between Muskrat Falls and Mud Lake. The results included a processed image with ice cover and open water classes, with their respective area as percent of coverage.

The percent of ice cover increased quickly from November 14 (mean ± Std. Dev.; 2.0 ± 1.8% ice cover) to November 17 (mean ± Std. Dev.; 37.6 ± 36.2% ice cover). Ice formed first at the river mouth (Site 1) and above Muskrat falls (Site 7) with ice percentage increasing in an upstream direction from November 18 through November 25. The river reach from Lake Melville to Muskrat Falls was mostly fully iced covered by November 25 excepting the reach below Blackrock Bridge (Site 4) which had a small amount of open water. In previous years, Section 4 was always the last site to consolidate ice owing to the faster water associated with the Blackrock Bridge and causeway.

The percent of ice cover decreased slowly but consistently during the break-up period from May 1 (mean ± Std. Dev.; 97.0 ± 4.1% ice cover) to May 15 (mean ± Std. Dev.; 77.5 ± 35.1% ice cover). Ice cover then declined rapidly from May 16 to May 20 with the river completely ice free by May 21. The break-up showed that the mid-reach sites were the first to lose ice cover with Site 5 having lost most of the ice cover by May 15, and Sites 2, 3, and 4 being effectively ice free after May 17. Sites 6 and 7, in and just below the Muskrat Falls reservoir retained a considerable proportion of ice in the later stages of the break up. In previous years, Site 6 was always the last to lose ice cover.

The timing of the freeze-up and break-up processes during the 2018-2019 ice season were documented and compared with the long-term data record and the last ten years of observations. The date of freeze-up, as indicated by the day of the first snowmobile crossing, was November 21, 2018. The date of break-up, as indicated by the date of the first boat crossing, was May 19, 2019. The date of freeze-up was eight days earlier than the long-term average (November 29), 16 days earlier than the freeze-up in 2017, and 14 days earlier than the average for the last ten years (December 5). The date of break-up was three days later than the long term average (May 16), two days earlier than the break-up in 2018 (May 17), and seven days later than the average for the last ten years, 2007 to 2016 (May 12). The freeze-up date in 2018 (November 21), and break-up date in 2019 (May 19), resulted in total ice covered period of 179 days in the 2018-2019 ice season.

A total of 14 Cosmo-SkyMed (CSK) images and six Sentinel-1 (S1) SAR images were acquired during the freeze-up and break-up periods. 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 Goose River, north of the Churchill River, is also a break-up indicator as the Goose River break-up typically precedes the Lower Churchill River by approximately ten days. Image plans were created and modified to adjust to the freeze-up and break-up times.

The spatial resolution of images analyzed ranged from 20 to 30 meters. A secondary image was tasked when a primary image could not be acquired, which was typically 12 hours later. 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 when the CSK images were not available.

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.

# 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 proposed LCP on the ice dynamics in the reach below Muskrat Falls (Nalcor 2009). Hydraulic conditions downstream of Muskrat Falls were predicted not to 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 affected by the LCP, other than the change in timing.

Ice bridging under pre-LCP conditions occurs at an approximate distance of 0.2 km above Lake Melville and the ice cover progresses 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 was completed to assess 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 what could occur during construction and operation of the LCP. The LCP has committed to surveying ice formation in the Lower Churchill River during pre- (baseline and LCP construction period) and post-impoundment (operations) conditions. These predictions would allow Nalcor to take appropriate precautions and develop mitigation measures to manage potential problems due to ice. Nalcor contracted Golder Associates Ltd. (Golder), who sub-contracted Sikumiut Environmental Management Ltd. (SEM), to develop and implement an ice surveying program to be completed 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.

This report presents the results of studies completed in the 2018-2019 ice season (Year 6) during the construction phase of the LCP (SEM 2014, 2015, 2016, 2017, and 2018). Satellite Synthetic Aperture Radar (SAR) and Optical satellite images were used to monitor ice conditions on the Lower Churchill River. A total of 20 SAR images were acquired by Cosmo-SkyMed (CSK, n=14) and Sentinel-1 (S1, n=6) satellites. Images provide 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.

## 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 2018-2019 ice season was the sixth survey in a continuation of previous monitoring during the construction period of the LCP (SEM 2014, 2015, 2016, 2017, and 2018). Objectives 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.

The survey program included the following objectives and activities:

- Daily review of images from the Government of Newfoundland and Labrador, Department of Municipal Affairs and Environment, Water Resources Management Division (NLDMAE/WRMD) web camera at Mud Lake for the purpose of planning satellite image acquisition;
- Communications 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 concentration via analysis of satellite images; and
- Acquisition and interpretation of satellite imagery to determine ice formation (freeze-up) at Mud Lake and to monitor the break-up process.

## 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, in communication with Golder. SEM staff monitored the Mud Lake webcam and communicated with Mud Lake residents to coordinate, along with the Center for Cold Ocean Resource Engineering (C-CORE) project manager, acquisition of satellite images. SEM coordinated completion the project report with support and input from other team members.

C-CORE acquired and analyzed Synthetic Aperture Radar (SAR) images from the Cosmo-Skymed (CSK, n=14) and Sentinel 1 (S-1, n=6) satellites to monitor ice conditions on the Lower Churchill River for the 2018-2019 ice season. Images were analyzed to identify ice types and delineate areas of open water during freeze-up and break-up of the ice cover in the Mud Lake area. C-CORE also completed an ice floe concentration analysis on eight satellite images taken during the ice surveys.

**Table 2.1 Team Members for the 2018-2019 Ice Observations Surveys.**

| Team Member | Roles and Responsibility |
|---|---|
| **SEM** | |
| Dave Scruton, MES, Senior Scientist | Project Manager, coordination, client liaison, project report |
| Leroy Metcalfe, B. Sc., President | Financial control, project report QA/QC |
| 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 | Project Manager, project control, internal project coordination of resources and technical advisor. Coordination with client and reporting. |
| Pamela Burke, MSc. Coastal Zone Mgmt., Advanced Diploma Integrated Coastal and Ocean Mgmt., Image Analyst | Plan, order and archive 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 NLDMAE/WRMD, in cooperation with LCP and Environment 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 NLDMAE/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 12 to December 5, 2018, and May 4 to 25, 2019, 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 six 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, have been used to plan the acquisition of satellite imagery for detailed analyses. Mr. Hope provided SEM with the dates for the first snowmobile crossing on November 21, 2018, and the first boat crossing in May 19, 2019, to continue the time series for these important dates for the residents of Mud Lake.

## 2.5 Existing Conditions

River conditions during the 2018-2019 ice season were similar to the previous ice season (2017-2018) with water impounded in the Muskrat Falls reservoir. Water levels in the reservoir were maintained at close to 23.5 meters above sea level (masl) for most of the ice season with a small increase in February to 24.0 masl for a few days and again in April to 25.0 masl (Jackie Wells, Environment and Sustainability Department, Nalcor Energy, pers. comm.). 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 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 of the powerful rapids that push ice under the existing ice cover in this area.

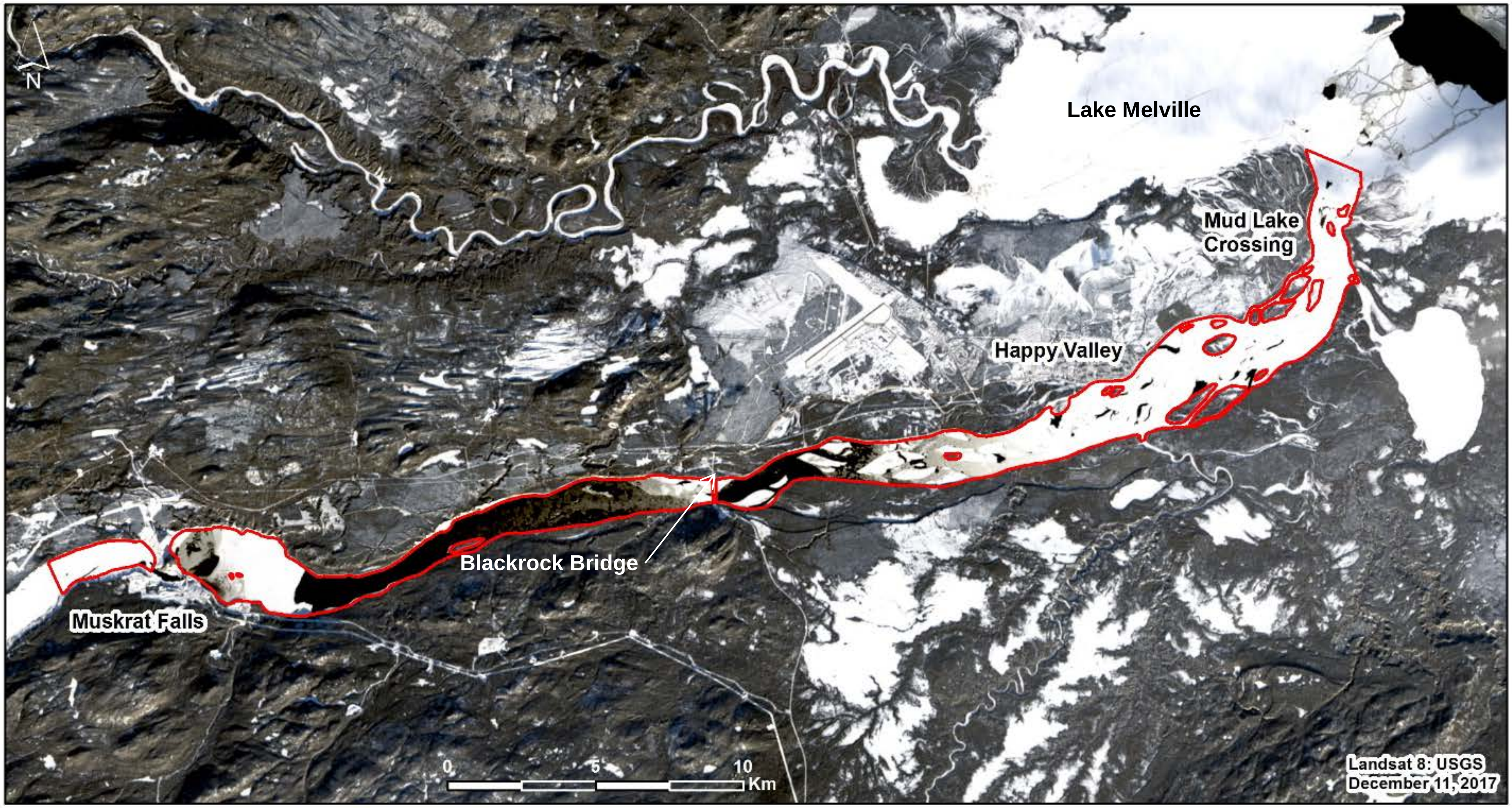


**Figure 2.1 The Section of the Lower Churchill River Monitored Between Muskrat Falls and Lake Melville.**

### 2.6.2 Satellite Image Planning and Acquisition

A total of 20 images were acquired using the COSMO-SkyMed (CSK) constellation, consisting of four SAR satellites, and the S1 constellation, consisting of two SAR satellites. Image orders for CSK required a primary and a secondary (i.e., back-up) plan. When a primary image was not acquired, the secondary image was tasked, which was typically 12 hours later. The S1 acquisitions could not be tasked but image plans were published on a regular basis on the European Space Agency (ESA) website[1], which was monitored regularly to ensure the required Churchill River images were acquired to address gaps in the CSK satellite imagery. S1 images were available at no cost and were used to lower project costs.

Preparation of image acquisition plans considered several factors including optimizing spatial resolution, incidence angle, look direction, and the area of interest. 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 images at 20 and 30 m spatial resolutions. 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 2018-2019 Ice Season.**

| Satellite | Beam Mode | Spatial Resolution (m) | Image Width (km) | Number of Images |
|---|---|---|---|---|
| CSK | ScanSAR Wide | 30 | 100 | 14 |
| S1 | Interferometric Wide | 20 | 250 | 6 |

[1] ESA Sentinel-1 Acquisition Segments, available at https://sentinel.esa.int/web/sentinel/missions/sentinel-1/observation-scenario/acquisition-segments

**Table 2.3 Satellite Image Acquisition Schedule.**

| Date | Time ([1]UTC) | Spatial Resolution (m) | Satellite | Event |
|---|---|---|---|---|
| November 14, 2018 | 10:12 | 20 | S1 | Freeze-up |
| November 17, 2018 | 21:57 | 30 | CSK | Freeze-up |
| November 18, 2018 | 21:57 | 30 | CSK | Freeze-up |
| November 19, 2018 | 21:45 | 30 | CSK | Freeze-up |
| November 20, 2018 | 9:34 | 30 | CSK | Freeze-up |
| November 21, 2018 | 9:52 | 30 | CSK | Freeze-up |
| November 22, 2018 | 21:51 | 30 | CSK | Freeze-up |
| November 23, 2018 | 9:40 | 30 | CSK | Freeze-up |
| November 23, 2018 | 22:09 | 30 | CSK | Freeze-up |
| November 25, 2018 | 9:28 | 30 | CSK | Freeze-up |
| December 2, 2018 | 10:12 | 20 | S1 | Freeze-up |
| May 1, 2019 | 10:12 | 20 | S1 | Break-up |
| May 5, 2019 | 21:51 | 30 | CSK | Break-up |
| May 6, 2019 | 21:45 | 30 | CSK | Break-up |
| May 7, 2019 | 10:12 | 20 | S1 | Break-up |
| May 9, 2019 | 9:22 | 30 | CSK | Break-up |
| May 13, 2019 | 10:12 | 20 | S1 | Break-up |
| May 15, 2019 | 9:34 | 30 | CSK | Break-up |
| May 16, 2019 | 9:52 | 30 | CSK | Break-up |
| May 17, 2019 | 9:22 | 30 | CSK | Break-up |
| May 18, 2019 | 10:20 | 20 | S1 | Break-up |
| May 20, 2019 | 9:28 | 30 | CSK | Break-up |
| May 22, 2019 | 21:45 | 30 | CSK | Break-up |
| Notes: [1]UTC = Coordinated Universal Time | | | | |

### 2.6.3 Satellite Image Processing

Radar satellites are active sensors in that they transmit a signal to the Earth's surface and record the energy reflected back to the sensor, as backscatter. Pixel intensity within the satellite image is proportional to the backscatter. The sensor is side looking, so most of the signal will be deflected away from the sensor on smooth surfaces such as smooth ice. Rough surfaces, such as found with an ice jam, will deflect the signal in all directions including back to the sensor, producing bright areas as seen in the images. Generally, surfaces with roughness, complex geometry or corner reflectors have higher backscatter.

The radar response of river ice covers 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. Rougher surfaces therefore tend to generate a greater amount of surface scatter. 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. Non-homogeneous 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.

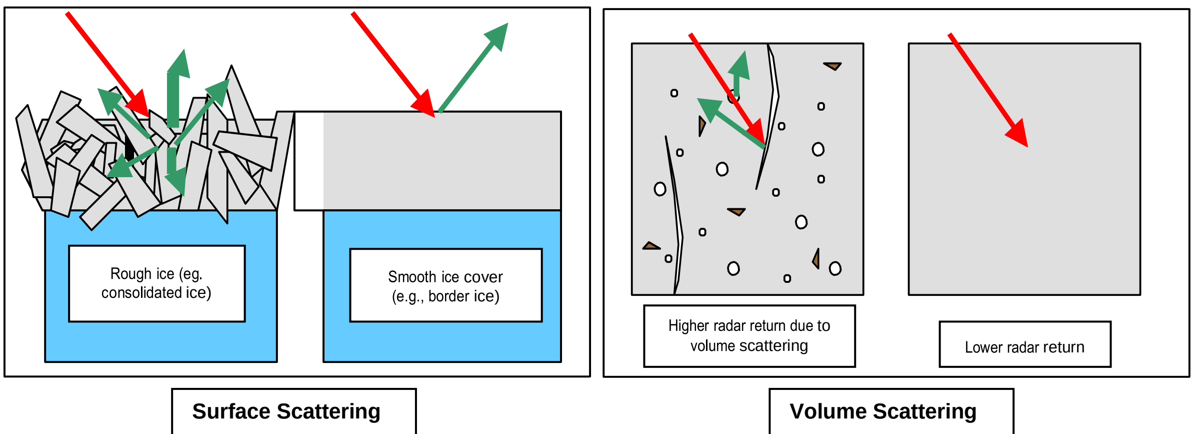


**Figure 2.2 River Ice Scattering Mechanisms (after Pelletier, Hicks and van der Sanden 2003).**

Image analysis included calibration, orthorectification, filtering and visual enhancement. Mask generation was required to isolate the river from the rest of the image for the purpose of classifying the water/ice surface only. Filter and enhancement techniques were unique to each image, due to different spatial resolutions, incidence angle and ice cover. Filters were used to remove noise and speckle, which are characteristic of SAR images. The choice of enhancement technique depended on weather conditions, ice textures and the amount of open water, all of which affected backscatter and the calibration results.

Late in the ice season, rough ice textures became smoother due to warmer temperatures resulting in less backscatter to the point that ice began to resemble open water. Prior knowledge of weather conditions, recent satellite images and field data were important factors to aid in separating open water from water on ice. Water pooling on the surface of ice resulting from melting or rainfall appeared similar to open water.

Information products generated from the satellite image analyses included ice cover, ice classification and ice cover change.

The ***Ice Cover*** product is one of three products included with this report and is depicted as a map containing the calibrated, visually enhanced, orthorectified SAR image. The darker sections of the river are areas of smooth ice or open water. There may also be pools of water on ice, depending on the time of year and weather conditions. Smooth surfaces appear the same within a SAR image prior to image processing, such as those described above. Figure 2.3 shows an example ice cover product from the May 15, 2019 CSK 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 May 15, 2019, CSK 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 May 13 and May 15, 2019, images.

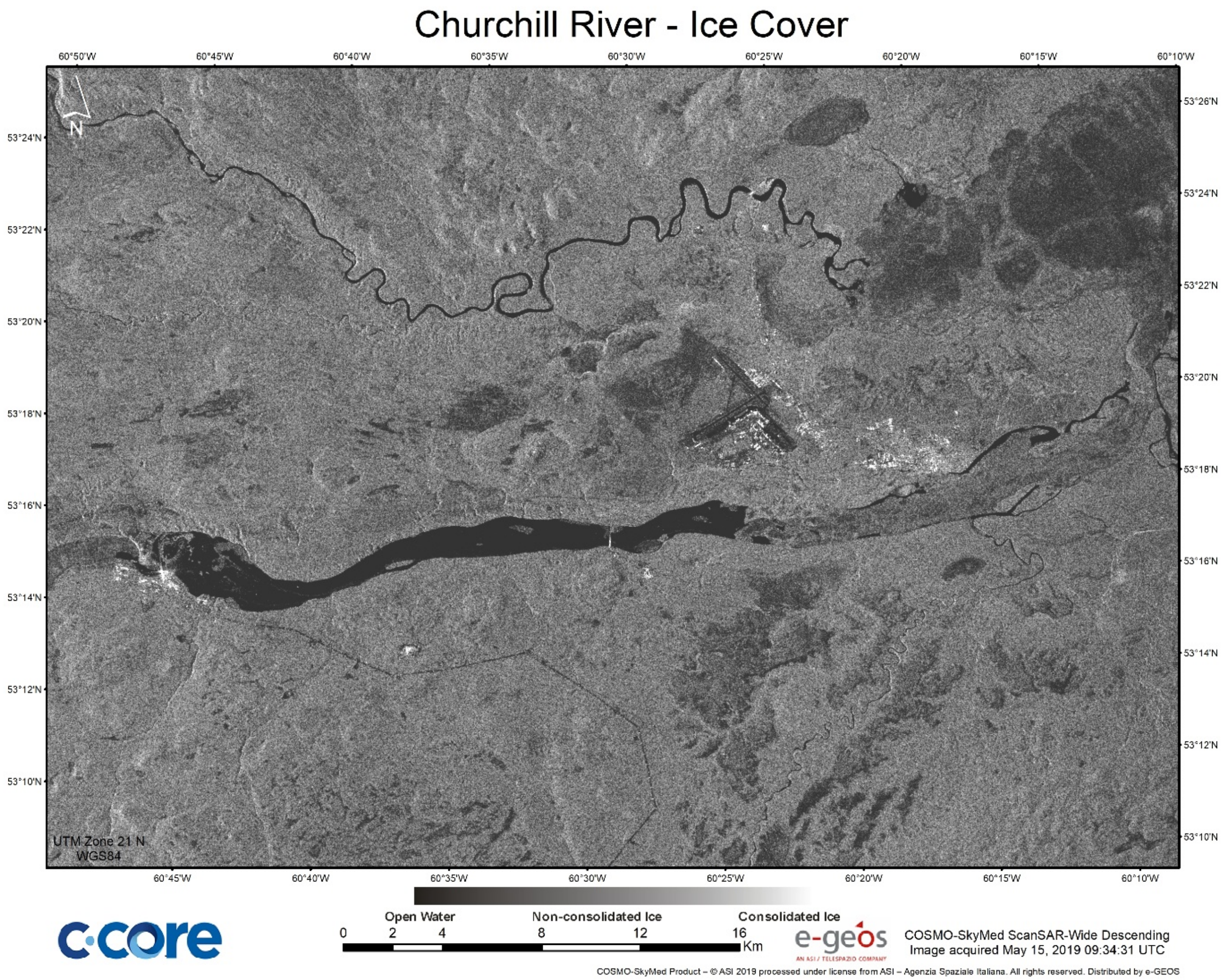


**Figure 2.3 Ice Cover Product Created From the May 15, 2019, CSK Image.**

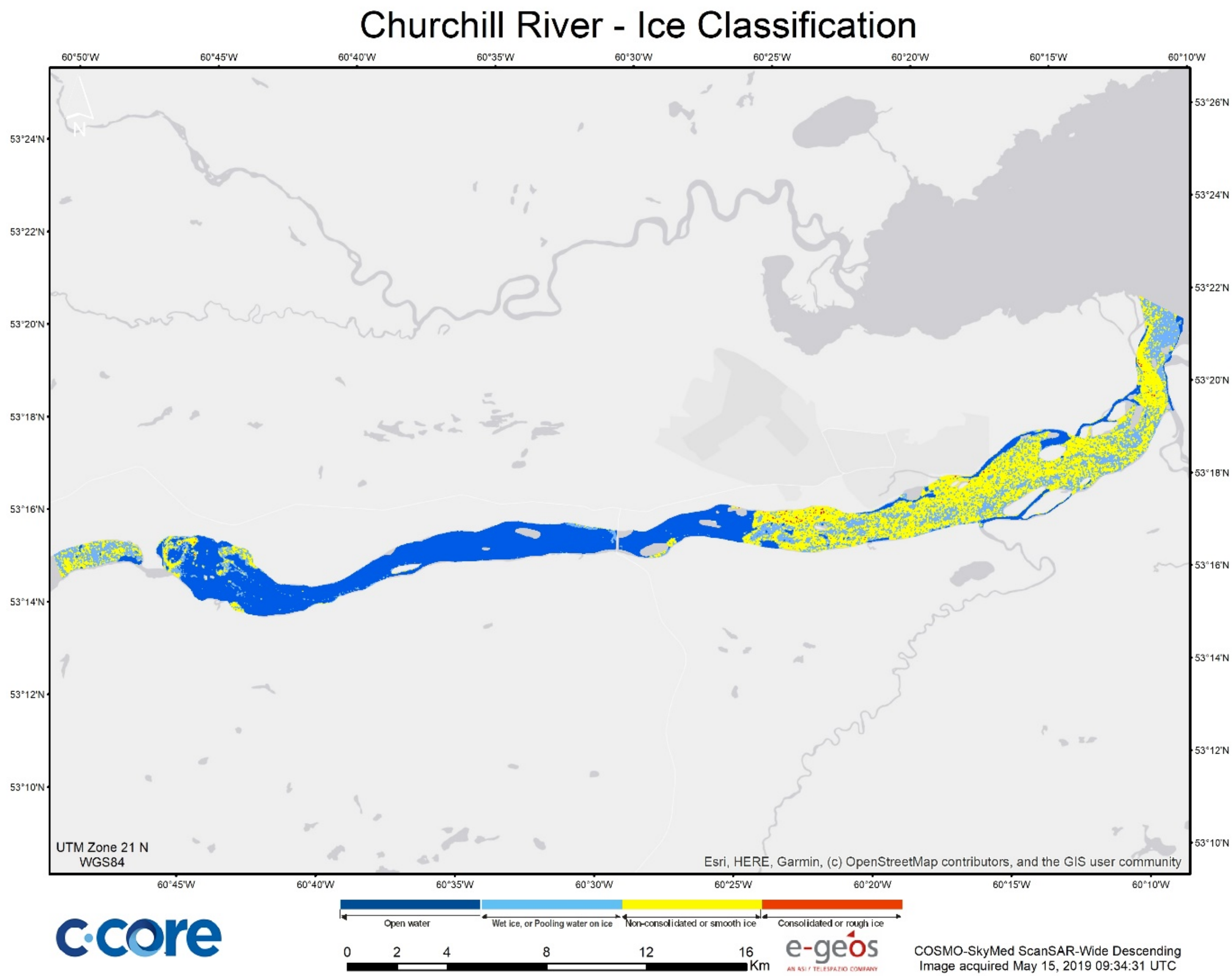


**Figure 2.4 Ice Classification Product Created From the May 15, 2019, CSK Image.**

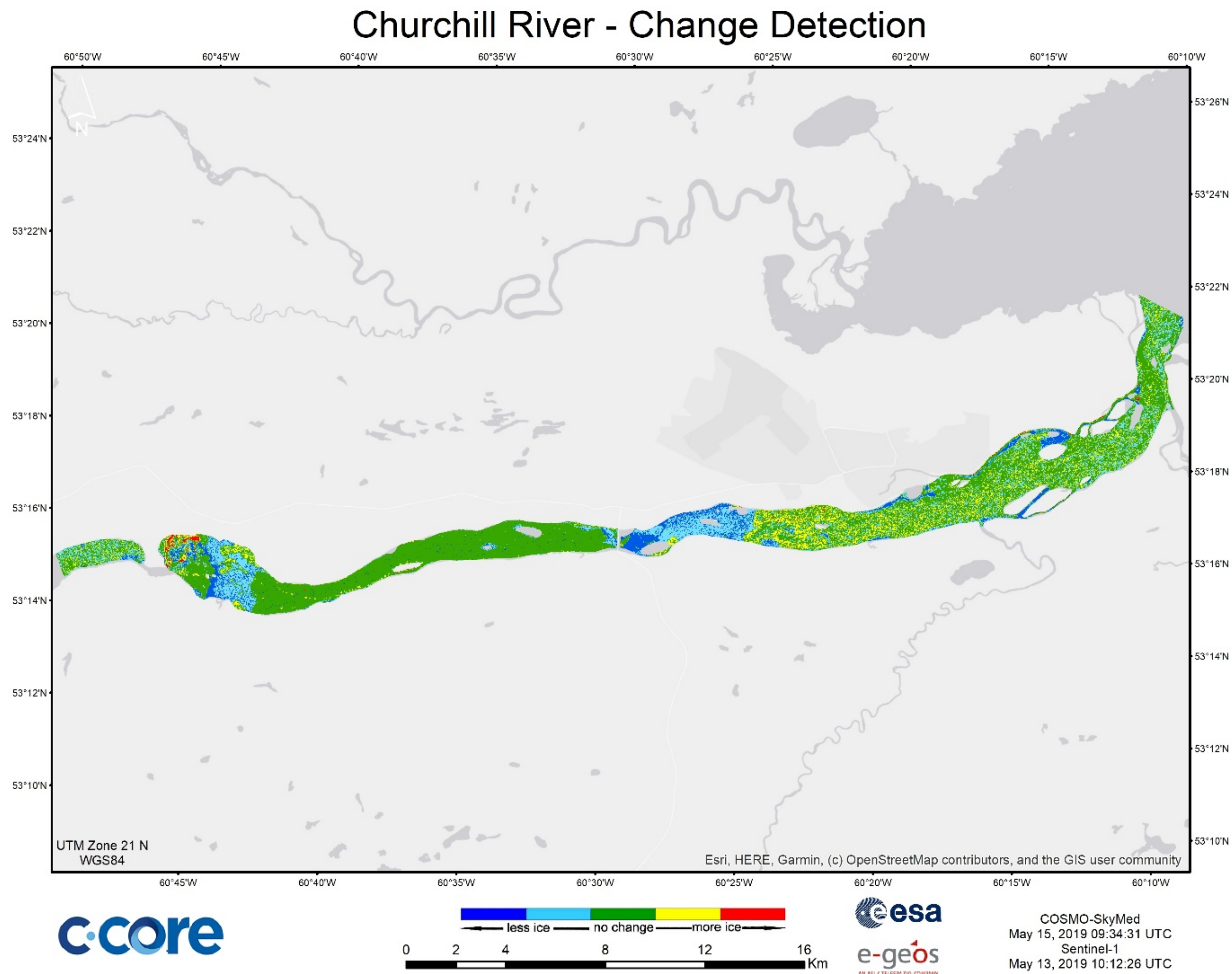


**Figure 2.5 Change Detection Product Comparing the May 13 and May 15, 2019, Images.**

## 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 locations of analyses completed in the 2017-2018 ice season to provide a comparable analysis to previous years (Figure 2.6). Ice floe analysis was conducted for the purpose of studying the changing ice cover during the freeze-up and break-up over the reach between Muskrat Falls and Lake Melville. The results of the ice floe analysis were based on the river ice classification. The categories of non-consolidated and consolidated ice classes were combined to represent total ice cover. Open water percentages were calculated from the open water class. The ice floe analysis evaluated progression in the respective proportions of ice and open water during the freeze-up and break-up process, and the river from Muskrat Falls to Lake Melville.

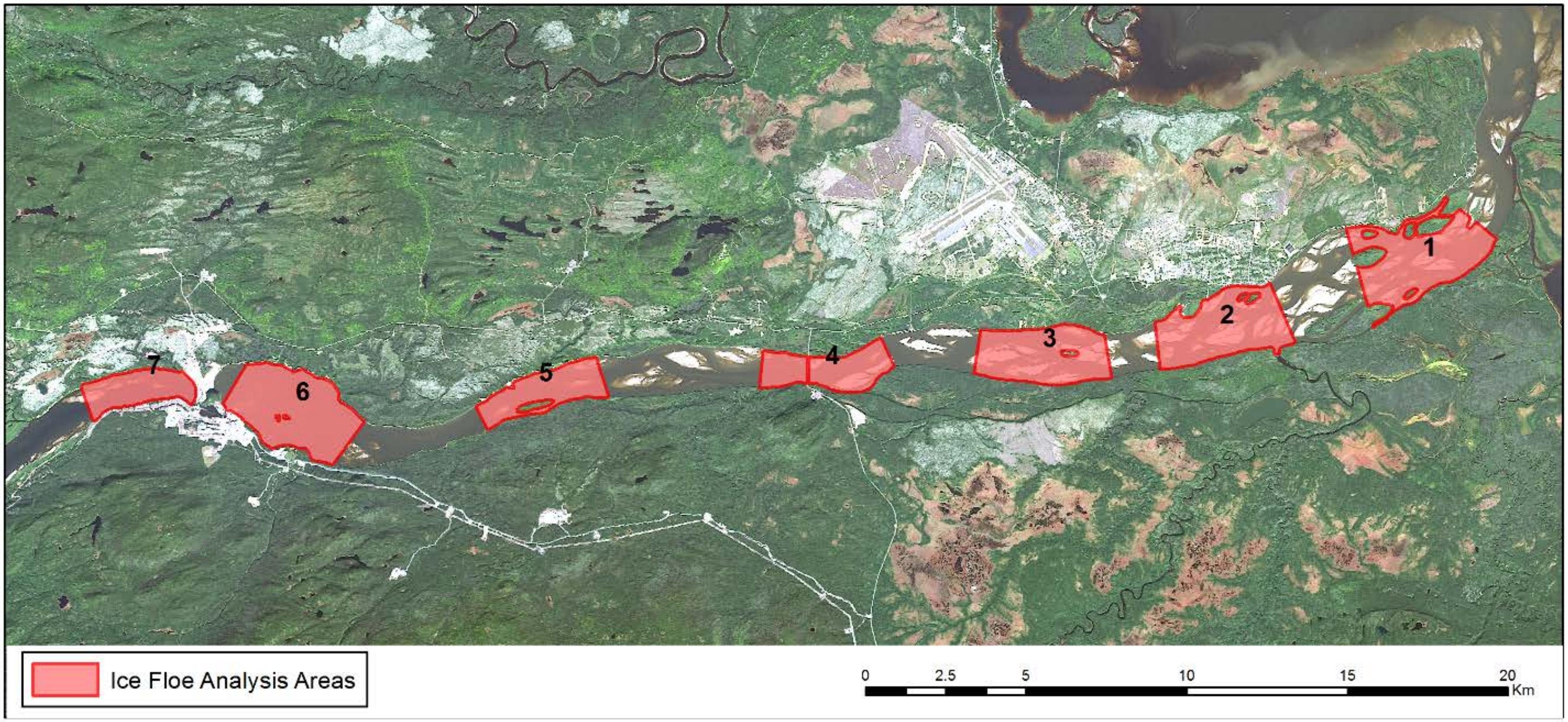


**Figure 2.6 Locations Used for Ice Floe Analysis for the 2018-2019 Ice Season.**

# 3.0 RESULTS

## 3.1 Mud Lake Web Camera

Images from the NLDMAE/WRMD web camera at the Mud Lake crossing site were downloaded daily from the Government of Newfoundland and Labrador website during 2018-2019 to monitor and document the freeze-up and break-up processes. Archived images were subsequently provided directly as digital files (Randy Parsons, Government of Newfoundland and Labrador, Department of Municipal Affairs and Environment, Water Resources Management Division, pers. comm.) so that the highest quality images could be included in this report. Images used in this report were for 10:00 each day except for November 12, 14, 24 and 26, 2018, where images collected at 12:00 were used owing to excessive glare in the images on those dates at 10:00.

The freeze-up sequence for the period from November 12 to December 5, 2018, is shown in Figures 3.1 and 3.2. The river was ice free on images November 12 and 13 and surface ice first appeared by November 14. Ice formed quickly starting on November 14 and 15 with open water apparent on the north side of the river. The ice consolidated over the period from November 15 through 21 with rough ice apparent in the river center suggesting accumulation of ice that had formed upstream. The ice on the river margin further solidified over this period. The ice bridge was considered formed on November 21, 2018, the date of the first snowmobile crossing for the 2018-2019 ice season (Jordan Hope, pers. comm.).

The break-up sequence for the period from May 4 to 25, 2019, is shown in Figures 3.3 and 3.4. The images from May 4 through 10 document the period pre-break-up where the river was still frozen over completely. Some melting along the margin of the river was starting to appear over this period, however the amount of melting along the shoreline only increased marginally over nine days. On May 18 there were still considerable amounts of unconsolidated ice in the river and this cleared rapidly over the next two days. The date of first crossing by boat was May 19, 2019 (Jordan Hope, pers. comm.). The duration of the break-up was about 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) and 2018 (five days, SEM 2018).

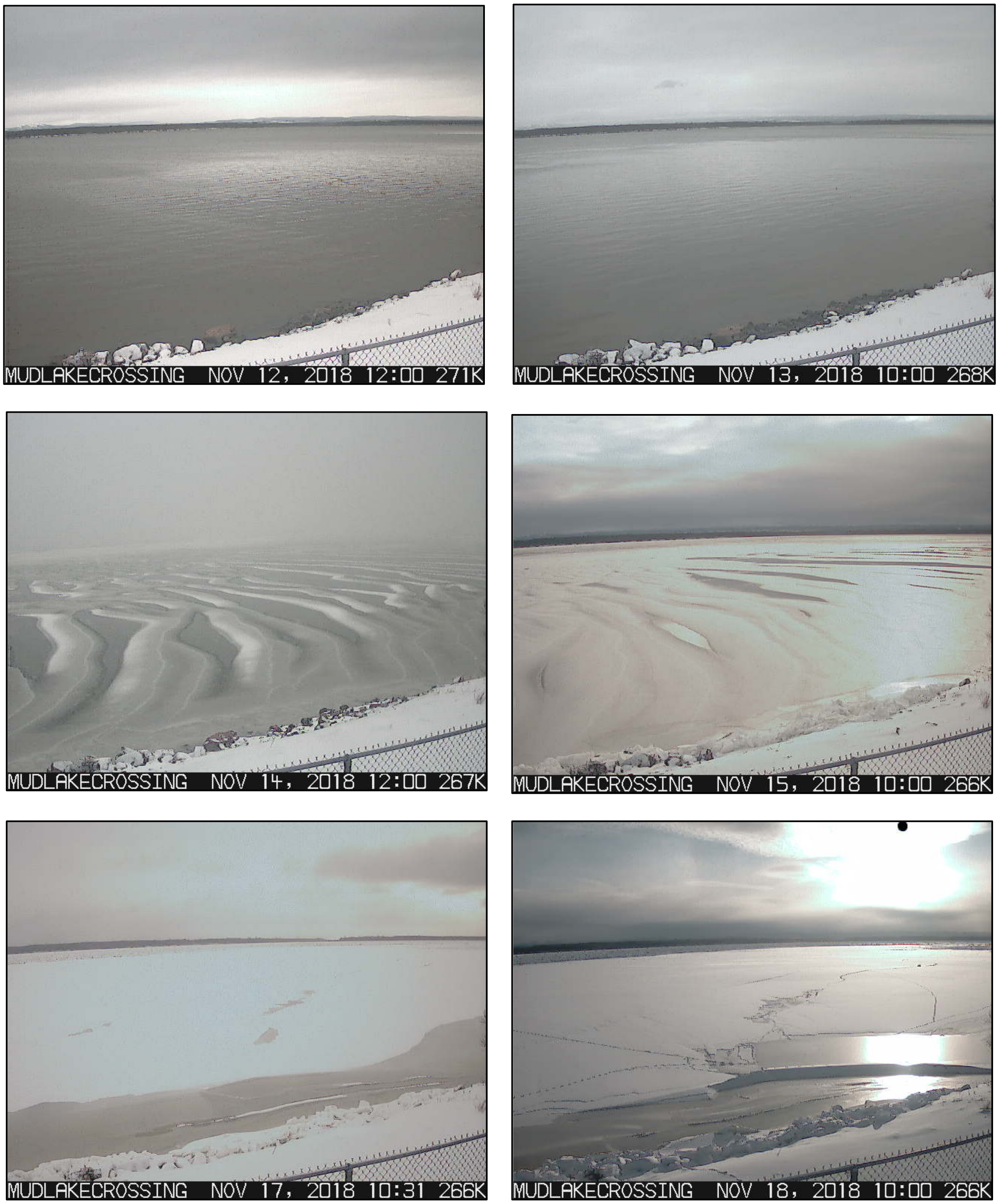


**Figure 3.1 Mud Lake Web Camera Images During the Freeze-Up Process, November 12 - 18, 2018.**

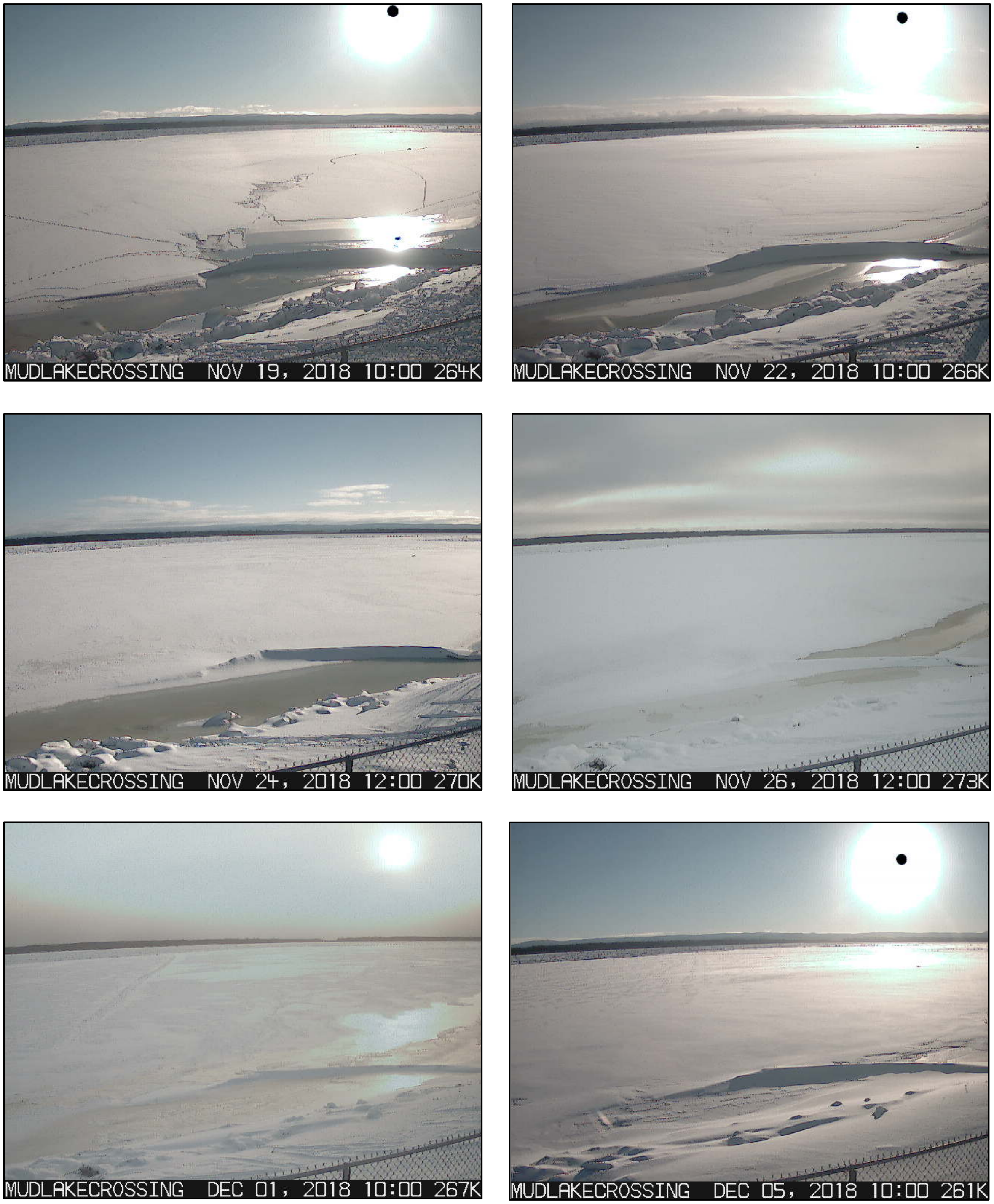


**Figure 3.2 Mud Lake Web Camera Images During the Freeze-Up Process, November 9 to December 5, 2018.**


**Figure 3.3 Mud Lake Web Camera Images During the Break-Up Process, May 4 to 14, 2019.**


**Figure 3.4 Mud Lake Web Camera Images During the Break-Up Process, May 16-25, 2019.**

## 3.2 Timing of Freeze-Up and Break-Up

The timing of the freeze-up and break-up processes during the 2018-2019 ice season, in comparison to the long-term data record, and in comparison to 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 November 21, 2018. The date of freeze-up was eight days earlier than the long-term average (November 29), 16 days earlier than the freeze-up in 2017, and 14 days earlier than the average for the last ten years (December 5). Over the period of record from 1972, there has only been 6 years where the freeze up date was earlier than November 21: 1976 (November 17); 1978 (November 19); 1985 (November 18); 1986 (November 13); 1992 (November 19); and 1993 (November 13).

The date of break-up, as indicated by the date of the first boat crossing, was May 19, 2019. The date of break-up was three days later than the long term average (May 16), two days later than the break-up in 2018 (May 17), and seven days later than the average for the last ten years, 2010 to 2019 (May 12).

It is apparent over the last ten years that the date of freeze-up has been later, with the latest date on record in 2011 (January 7), with 2018 being the earliest freeze-up date over the last ten years (November 21). The average date of break-up has been getting slightly earlier over the last ten years (May 12) in comparison to the long-term average (May 16), with the earliest date of break-up on record in 2010 (April 20).

**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 |

**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) |
|---|---|---|
| 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 |
| 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 |

**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) |
|---|---|---|
| 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 | TBD | 19-May-19 |
| Long Term Average | 29-Nov | 16-May |
| Average 2010 – 2019 (last 10 Years) | 5-Dec | 12-May |

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 2018 (November 21) and break-up date in 2019 (May 19) resulted in total ice covered period of 179 days for the 2018-2019 ice season. Historically the ice season has ranged between 125 and 190 days, averaging 166.25 days since 1975-76 and 159.2 days over the last 10 year period. The ice season in 2018-19 (179 days) was the sixth longest on record only being exceeded in 1976-77 (181 days), 1984-85 (187 days), 1989-90 (179 days), 1992-93 (days), and 1993-94 (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 |

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

| Ice Season | Duration (Days) |
|---|---|
| 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 |
| 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 |
| Long Term Average | 166.25 |
| Last 10 Year Average | 159.2 |
| 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. Eight images were selected for analysis during the freeze up period; November 14, 17, 18, 19, 21, 23, 25 and December 2. The site numbers correspond to the numbered sections in Figure 2.6.

The percent of ice cover increased quickly from November 14 (mean ± Std. Dev.; 2.0 ± 1.8% ice cover) to November 17 (mean ± Std. Dev.; 37.6 ± 36.2% ice cover). Ice formed first at the river mouth (Site 1) and above Muskrat falls (Site 7) with ice percentage increasing in an upstream direction from November 18 through November 25. The river was mostly full iced covered by November 25 (mean ± Std. Dev.; 96.7 ± 4.8% ice cover) excepting the reach below Blackrock Bridge (Site 4) which had a small amount of open water (12.6 % water). In previous years, Section 4 was always the last site to consolidate ice owing to the faster water associated with the Blackrock Bridge and causeway and this was evident over the period from November 21 to 25 in 2018.

**Table 3.3 Ice Cover and Open Water Percent Coverage for the Freeze-Up Period in 2018.**

| Site | 14-Nov-18 | | 17-Nov-18 | | 18-Nov-18 | | 19-Nov-18 | |
|---|---|---|---|---|---|---|---|---|
| | Water (%) | Ice (%) | Water (%) | Ice (%) | Water (%) | Ice (%) | Water (%) | Ice (%) |
| 1 | 95.1 | 4.9 | 20.5 | 79.5 | 1.7 | 98.3 | 1.9 | 98.1 |
| 2 | 96.8 | 3.2 | 67.4 | 32.6 | 41.8 | 58.2 | 0.3 | 99.7 |
| 3 | 96.9 | 3.2 | 80.0 | 20.0 | 53.1 | 46.9 | 61.4 | 38.6 |
| 4 | 98.9 | 1.1 | 85.2 | 14.8 | 71.5 | 28.5 | 73.0 | 27.0 |
| 5 | 99.2 | 0.8 | 95.3 | 4.7 | 88.6 | 11.4 | 93.6 | 6.4 |
| 6 | 99.8 | 0.2 | 86.4 | 13.6 | 57.5 | 42.5 | 58.0 | 42.0 |
| 7 | 99.6 | 0.5 | 2.3 | 97.7 | 2.4 | 97.6 | 1.3 | 98.8 |
| **Mean** | 98.0 | 2.0 | 62.4 | 37.6 | 45.2 | 54.8 | 41.3 | 58.7 |
| **Std. Dev.** | 1.8 | 1.8 | 36.2 | 36.2 | 33.0 | 33.0 | 39.3 | 39.3 |
| **Site** | **21-Nov-18** | | **23-Nov-18** | | **25-Nov-18** | | **02-Dec-18** | |
| | **Water (%)** | **Ice (%)** | **Water (%)** | **Ice (%)** | **Water (%)** | **Ice (%)** | **Water (%)** | **Ice (%)** |
| 1 | 1.6 | 98.4 | 2.0 | 98.0 | 1.4 | 98.6 | 1.3 | 98.8 |
| 2 | 0.1 | 99.9 | 0.3 | 99.8 | 0.1 | 99.9 | 0.1 | 99.9 |
| 3 | 0.9 | 99.1 | 1.0 | 99.1 | 0.8 | 99.2 | 0.7 | 99.4 |
| 4 | 13.0 | 87.0 | 13.0 | 87.0 | 12.6 | 87.4 | 12.4 | 87.6 |
| 5 | 84.3 | 15.7 | 47.4 | 52.6 | 0.4 | 99.7 | 0.0 | 100.0 |
| 6 | 22.7 | 77.3 | 7.8 | 92.3 | 7.2 | 92.8 | 13.5 | 86.5 |
| 7 | 1.0 | 99.1 | 0.5 | 99.5 | 0.3 | 99.7 | 0.0 | 100.0 |
| **Mean** | 17.6 | 82.4 | 10.3 | 89.7 | 3.3 | 96.7 | 4.0 | 96.0 |
| **Std. Dev.** | 30.6 | 30.6 | 17.0 | 17.0 | 4.8 | 4.8 | 6.1 | 6.1 |

### 3.3.2 Break-Up Period

Table 3.4 shows the results of the break-up ice floe analysis. Eleven images were selected for analysis for the break-up period: May 1, 5, 6, 7, 13, 15, 16, 17, 18, 20 and 22. The site numbers correspond to the numbered sections in Figure 2.6. All images provided complete coverage of the eleven sites for ice floe analysis.

The percent of ice cover decreased slowly but consistently from May 1 (mean ± Std. Dev.; 97.0 ± 4.1% ice cover) to May 15 (mean ± Std. Dev.; 77.5 ± 35.1% ice cover). Ice cover then declined rapidly from May 16 (mean ± Std. Dev.; 33.7± 38.7 % ice cover) to May 20 (mean ± Std. Dev.; 11.0 ± 20.0 % ice cover) with the river completely ice free by May 22. The break-up showed that the mid-reach sites were the first to lose ice cover with Site 5 having lost most of the ice cover by May 15, and Sites 2, 3, and 4 being effectively ice free after May 17. Sites 6 and 7, in and just below the Muskrat Falls reservoir retained a considerable proportion of ice in the later stages of the break up. Site 6 had 61.7% and 50.7% ice cover on May 18 and 20, respectively while Site 7 had 31.7 % and 26.1 %, on those dates. In previous years, Site 6 was always the last to lose ice cover.

**Table 3.4 Ice Cover and Open Water Percent Coverage for the Break-Up Period in 2019.**

| Site | 01-May-19 | | 05-May-19 | | 06-May-19 | | 07-May-19 | | 13-May-19 | | 15-May-19 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Water (%) | Ice (%) | Water (%) | Ice (%) | Water (%) | Ice (%) | Water (%) | Ice (%) | Water (%) | Ice (%) | Water (%) | Ice (%) |
| 1 | 0 | 100 | 0 | 100 | 0 | 100 | 0 | 100 | 1.43 | 98.57 | 3.39 | 96.61 |
| 2 | 0 | 100 | 0 | 100 | 0 | 100 | 0 | 100 | 0.38 | 99.62 | 0.46 | 99.54 |
| 3 | 0 | 100 | 0 | 100 | 0 | 100 | 0 | 100 | 0 | 100 | 0 | 100 |
| 4 | 4.72 | 95.28 | 4.75 | 95.25 | 4.39 | 95.61 | 4.67 | 95.33 | 5.35 | 94.65 | 24.21 | 75.79 |
| 5 | 6.32 | 93.68 | 21.06 | 78.94 | 34.89 | 65.11 | 39.43 | 60.57 | 68.09 | 31.91 | 96.64 | 3.36 |
| 6 | 10.05 | 89.95 | 8.99 | 91.01 | 15.56 | 84.44 | 15.53 | 84.47 | 16.56 | 83.44 | 31.21 | 68.79 |
| 7 | 0 | 100 | 0 | 100 | 0 | 100 | 0 | 100 | 0.56 | 99.44 | 1.3 | 98.7 |
| **Mean** | 3.0 | 97.0 | 5.0 | 95.0 | 7.8 | 92.2 | 8.5 | 91.5 | 13.2 | 86.8 | 22.5 | 77.5 |
| **Std. Dev.** | 4.1 | 4.1 | 7.9 | 7.9 | 13.2 | 13.2 | 14.8 | 14.8 | 24.9 | 24.9 | 35.1 | 35.1 |
| **Site** | **16-May-19** | | **17-May-19** | | **18-May-19** | | **20-May-19** | | **22-May-19** | | | |
| | **Water (%)** | **Ice (%)** | **Water (%)** | **Ice (%)** | **Water (%)** | **Ice (%)** | **Water (%)** | **Ice (%)** | **Water (%)** | **Ice (%)** | | |
| 1 | 7.48 | 92.52 | 25.33 | 74.67 | 67.4 | 32.6 | 99.89 | 0.11 | 100 | 0 | | |
| 2 | 42.38 | 57.62 | 100 | 0 | 99.01 | 0.99 | 100 | 0 | 100 | 0 | | |
| 3 | 95.6 | 4.4 | 100 | 0 | 99.49 | 0.51 | 100 | 0 | 100 | 0 | | |
| 4 | 98.35 | 1.65 | 100 | 0 | 98.15 | 1.85 | 100 | 0 | 100 | 0 | | |
| 5 | 98.91 | 1.09 | 100 | 0 | 84.27 | 15.73 | 99.73 | 0.27 | 100 | 0 | | |
| 6 | 91.9 | 8.1 | 80.31 | 19.69 | 38.3 | 61.7 | 49.29 | 50.71 | 100 | 0 | | |
| 7 | 29.46 | 70.54 | 19.48 | 80.52 | 68.32 | 31.68 | 73.89 | 26.11 | 100 | 0 | | |
| **Mean** | 66.3 | 33.7 | 75.0 | 25.0 | 79.3 | 20.7 | 89.0 | 11.0 | 100.0 | 0.0 | | |
| **Std. Dev.** | 38.7 | 38.7 | 36.7 | 36.7 | 22.8 | 22.8 | 20.0 | 20.0 | 0.0 | 0.0 | | |

## 3.4 Satellite Image Analyses

The following sections document the results of the Lower Churchill River freeze-up and break-up monitoring for the 2018-2019 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. Breakup on the Goose River, which is just north of the Lower Churchill River, is a 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, sand bars were masked out and not included in the classifications for the freeze-up and break-up events. The mask used for freeze-up included more sand bars as they were apparent in the images. For break-up, fewer sand bars were visible because they were covered by ice or water and therefore included in the classifications.

Ice cover and ice classification products were generated for all images. Change detection products were generated for all pairs of current and preceding images. Appendix A and B contain the results of the ice analysis for freeze-up and break-up, respectively.

### 3.4.1 Freeze-Up Period

Appendix A contains the results of the ice analysis for the freeze-up period. Eight SAR images were used for freeze-up analysis between November 14, 2018 and December 2, 2018. Ice cover, ice classification, and change detection products were produced for all images except for November 14 where no change detection was produced because it was the first image in the series. Figure 3.5 shows the maximum and minimum temperatures, as recorded by Environment Canada[1] for Goose Bay, Labrador between November 10 and December 19, 2018. During the early stages of freeze-up, ice accumulates at the mouth of the Churchill River due to ice buildup in Lake Melville. Figure 3.6 shows the ice classification for November 14, 2018. Ice accumulated upstream towards Muskrat Falls over the next two weeks until the entire section is ice covered. Areas next to the bridge and the dam at Muskrat Falls remain open on the downstream side throughout the freeze-up event. Figure 3.7 shows the ice classification for December 2, 2018.

1 http://climate.weather.gc.ca/climate_data/daily_data_e.html?hlyRange=1953-01-01%7C2019-01-30&dlyRange=1941-12-01%7C2019-01-30&mlyRange=1941-01-01%7C2017-12-01&StationID=6777&Prov=NL&urlExtension=_e.html&searchType=stnProv&optLimit=yearRange&StartYear=1840&EndYear=2019&selRowPerPage=25&Line=122&lstProvince=NL&timeframe=2&Day=27&Year=2018&Month=11#

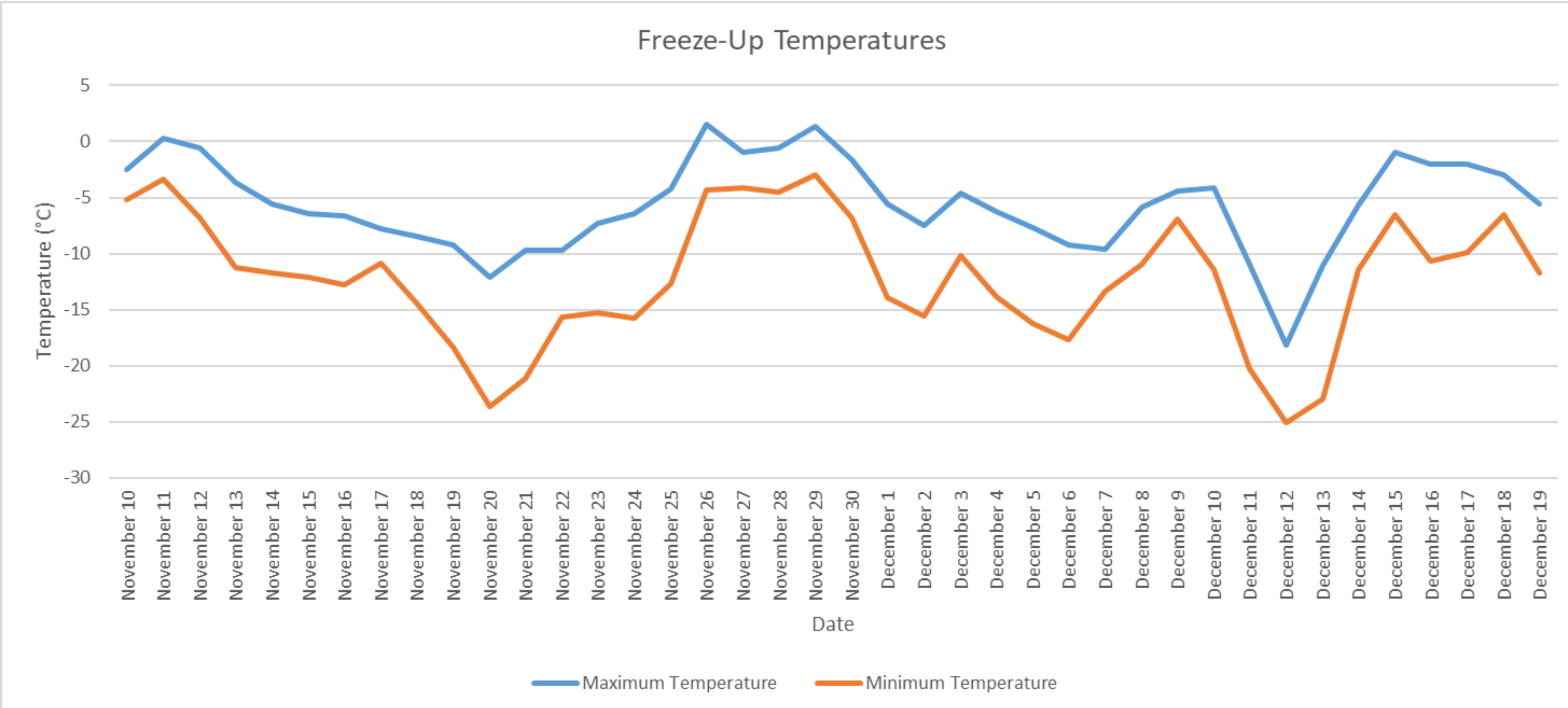


**Figure 3.5 Maximum and Minimum Daily Temperatures for Happy Valley – Goose Bay, Labrador During Freeze-up in 2018.**

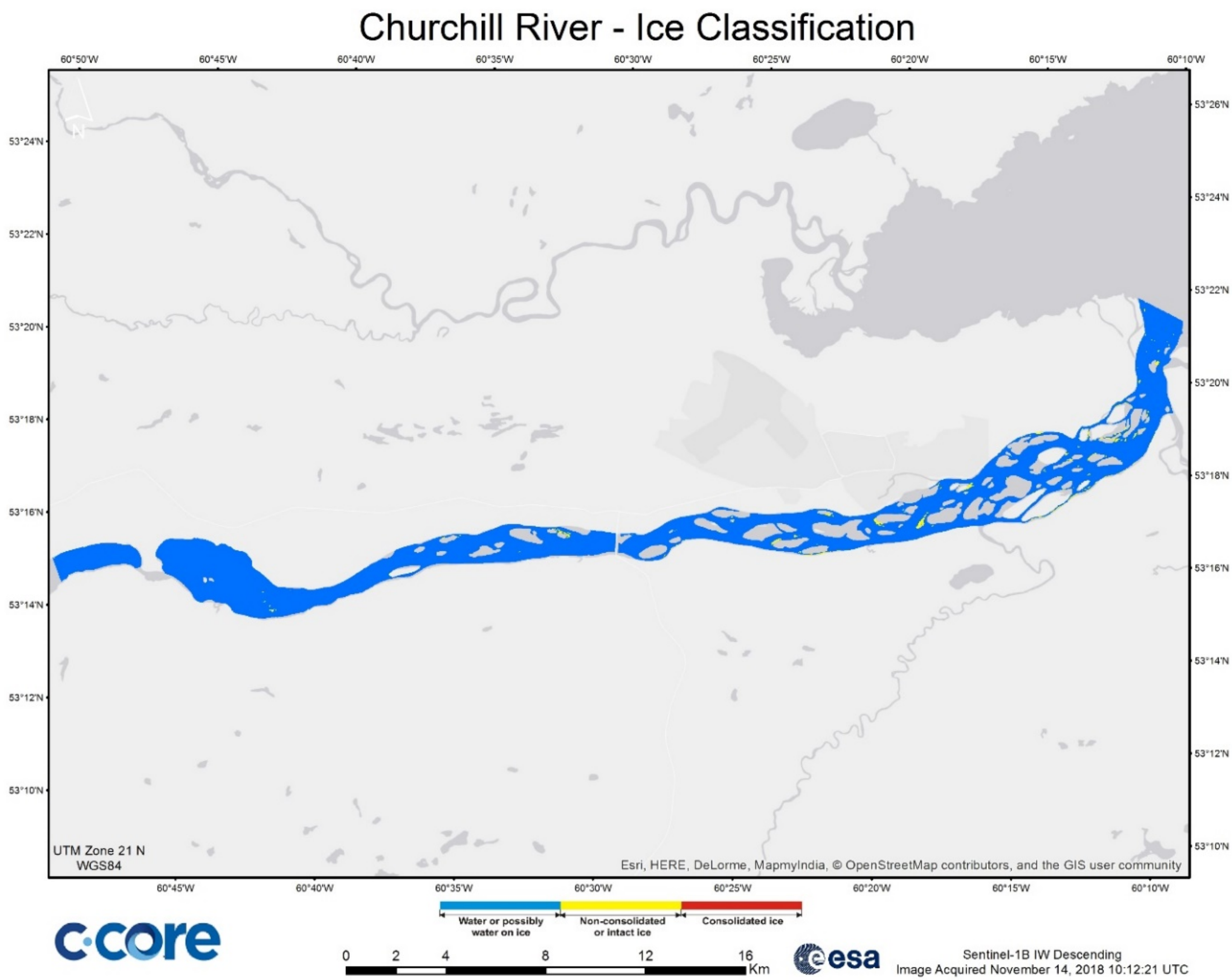


**Figure 3.6 Ice Classification Product for November 14, 2018.**

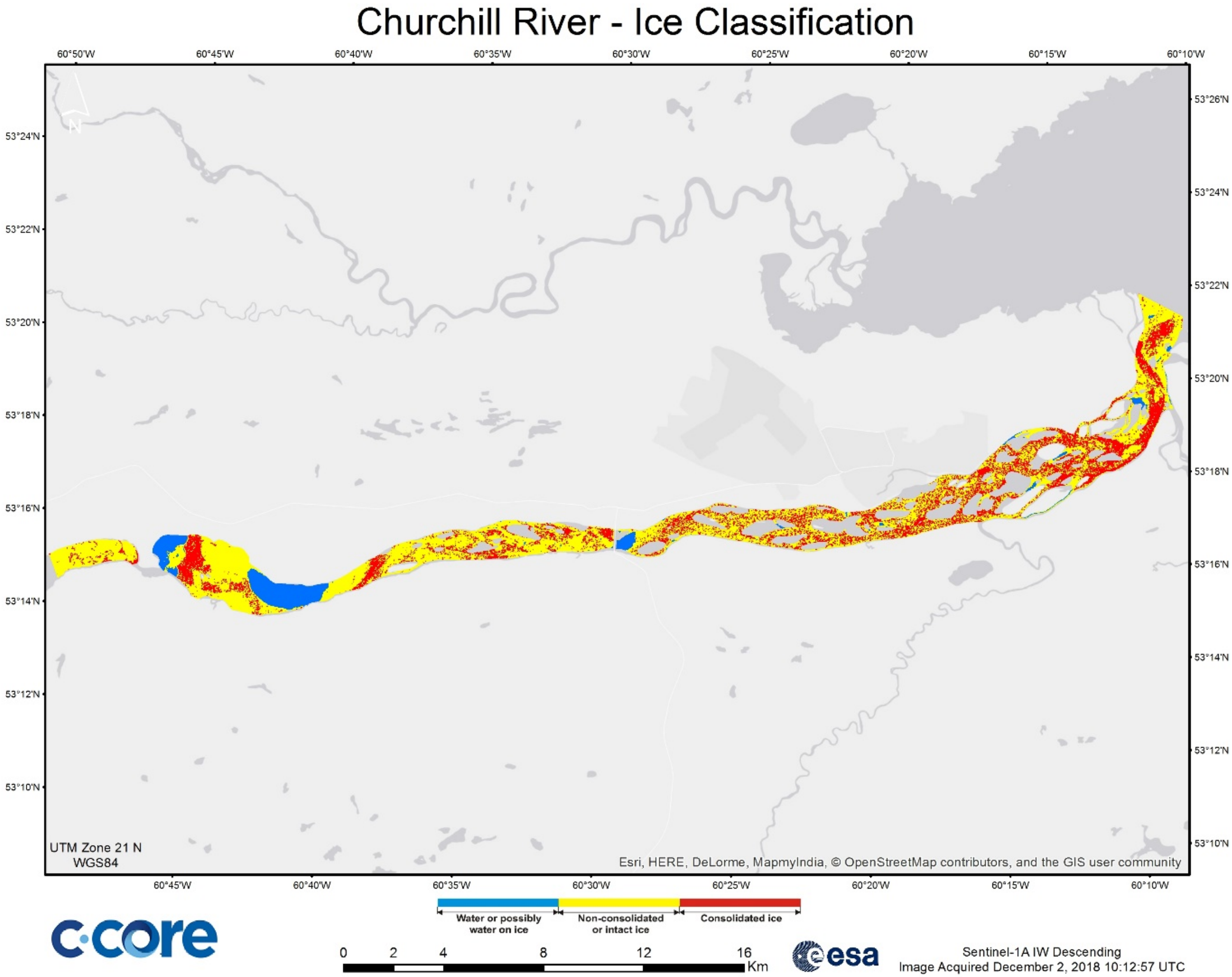


**Figure 3.7 Ice Classification Product for December 2, 2018.**

### 3.4.2 Break-Up Period

Appendix B contains the results of the ice analysis for the break-up period. Image analysis began on May 1, 2019, due to a warming temperature trend that began one week earlier. Figure 3.8 shows the maximum and minimum temperatures, as recorded by Environment Canada in Goose Bay, Labrador between April 10, 2019 and May 31, 2019. Temperatures were recorded above freezing beginning on April 10, 2019 with a daytime high of 1.2°C. Warm temperatures continued to rise well into May, triggering the beginning of the break-up. A fourth class was added to the classification for the break-up event to show areas of the ice where water was accumulating on the surface. Figure 3.9 shows the four classification scheme for the May 1, 2019 image and also shows the first area of the river to open up just below Muskrat Falls. The first boat crossing in 2019, historically used as the date of break-up, was on May 19. Break-up occurred two days later this year than last (SEM 2018) and was three days later than the average for the last ten year period.

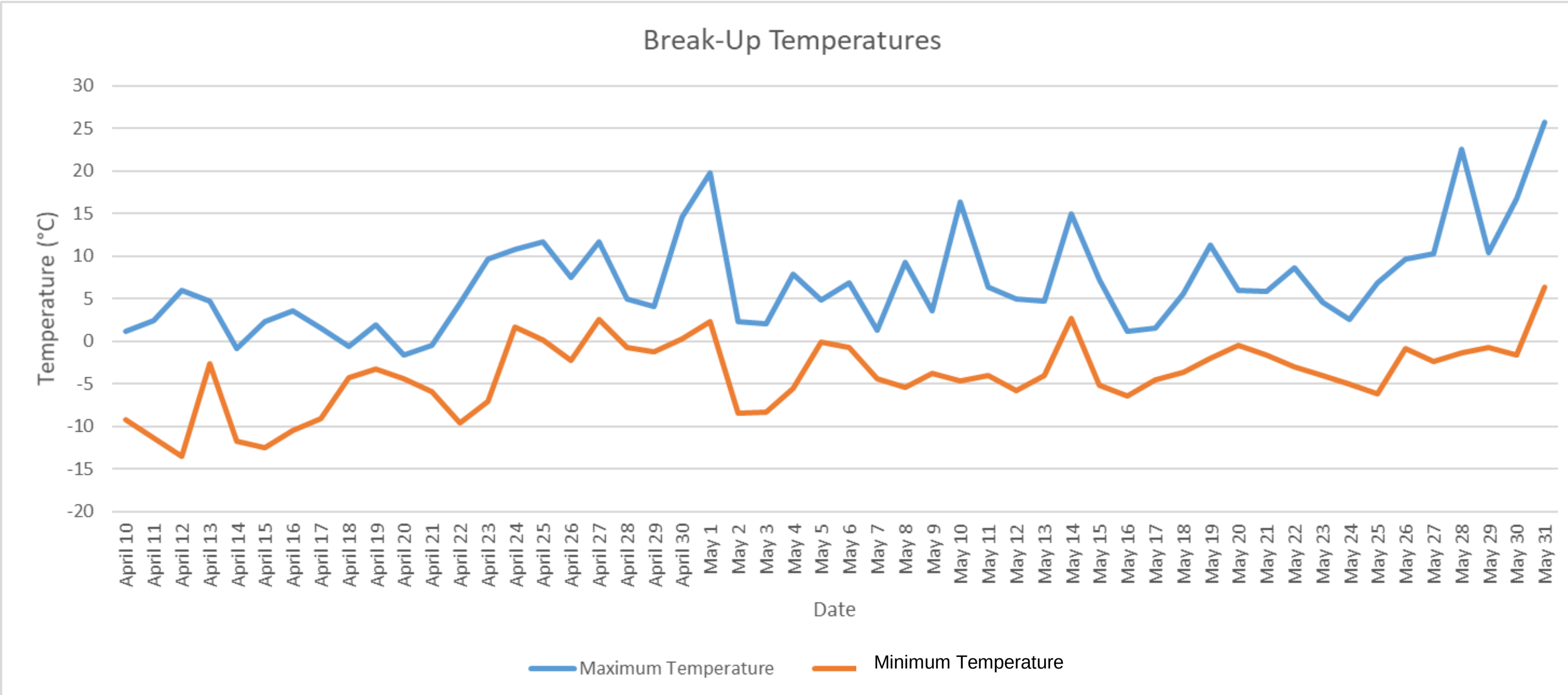


**Figure 3.8 Maximum and Minimum Daily Temperatures for Happy Valley – Goose Bay, Labrador During Break-up in 2019.**

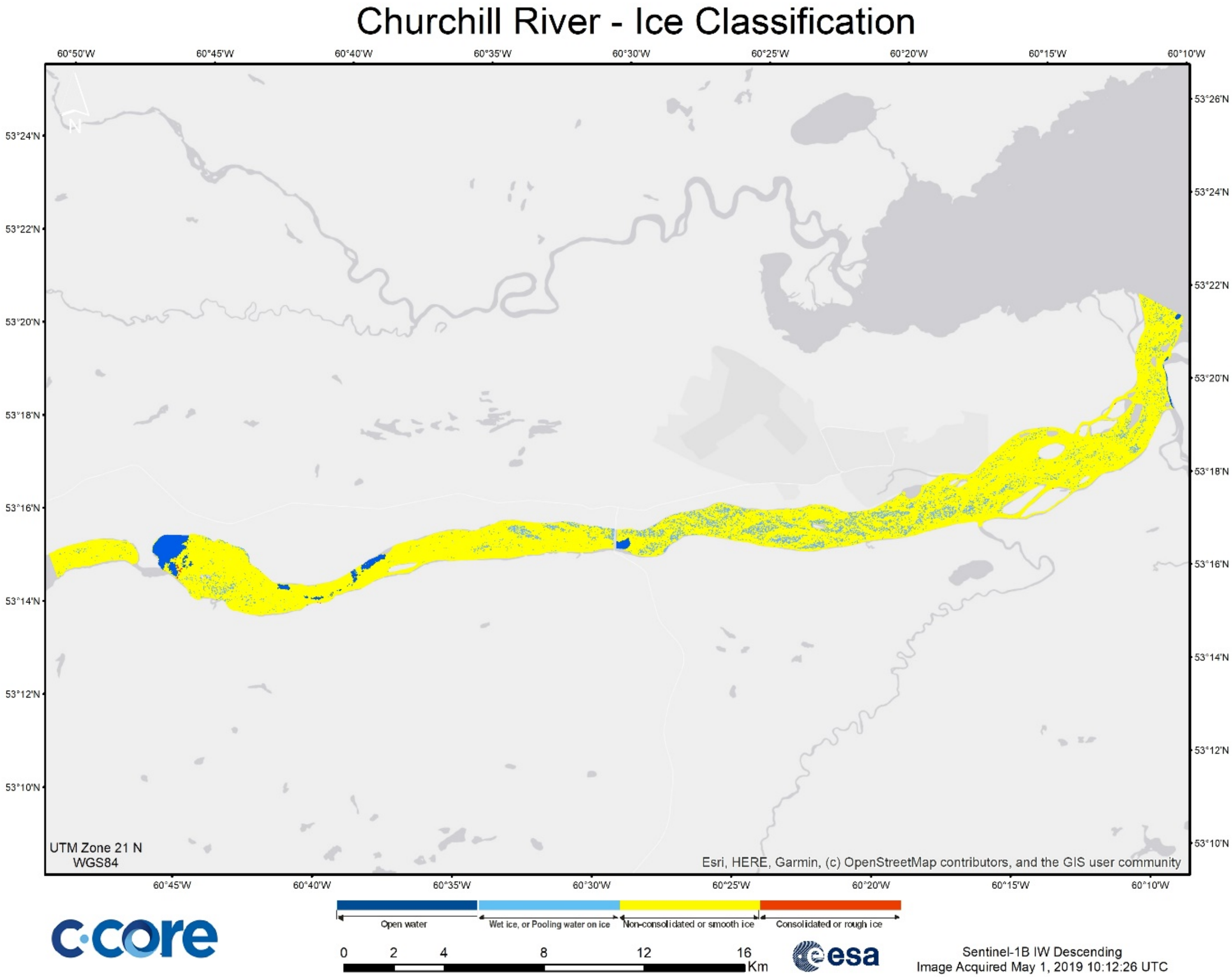


**Figure 3.9 Ice Classification Product for May 1, 2019.**

# 4.0 SUMMARY AND RECOMMENDATIONS

This report presents a summary of the activities for monitoring of river ice for the 2018-2019 ice season in relation to the Lower Churchill River Hydroelectric Project in Labrador. Satellite images were used to monitor ice conditions between Muskrat Falls and Lake Melville. Images analyzed during the freeze-up period were acquired between November 14 and December 2, 2018. Images covering the break-up period were collected from May 1 to May 22, 2019. 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 ordering for the 2018-2019 ice season was very successful with acquisition of all 20 images during ice freeze-up and break-up at the requested temporal frequencies. The image ordering process for CSK required a secondary plan, which was the key to the successful capture of the required image quota as well as the flexibility with the provider to quickly re-plan lost images. Freely available S1 SAR images were included among the 20 images analyzed this season to maximize cost efficiency. The continued surveillance over consecutive years is valuable for understanding trends in the ice conditions, development and break-up as well as their variability from year to year.

It is recommended to use 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. Approximately 13 images were acquired per month between December 2018 and May 2019, with a maximum gap in image coverage of five days. This acquisition frequency is sufficient for the ice monitoring service to be effective. Other sources of freely available imagery include the optical satellite missions Sentinel-2 (S2) and L8, which serve to enhance significantly the day-time spatial and temporal coverage during cloud-free conditions. All systematically acquired, freely available satellite scenes have been 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.

It is recommended to continue to use CSK images for the monitoring freeze-up and break-up events in the Mud Lake section of the Churchill River. At least five medium-resolution images should be captured during each event to provide a good record of ice conditions and help understand the underlying processes. In instances where ice-related flood risk is considered, daily image coverage is recommended to capture rapidly changing conditions. In addition, freely available optical images acquired by L8, and S2 should be used to complement all SAR image analysis. The impact of cloud cover can be minimized by using optical imagery in concert with S1 data.

## 5.0 REFERENCES

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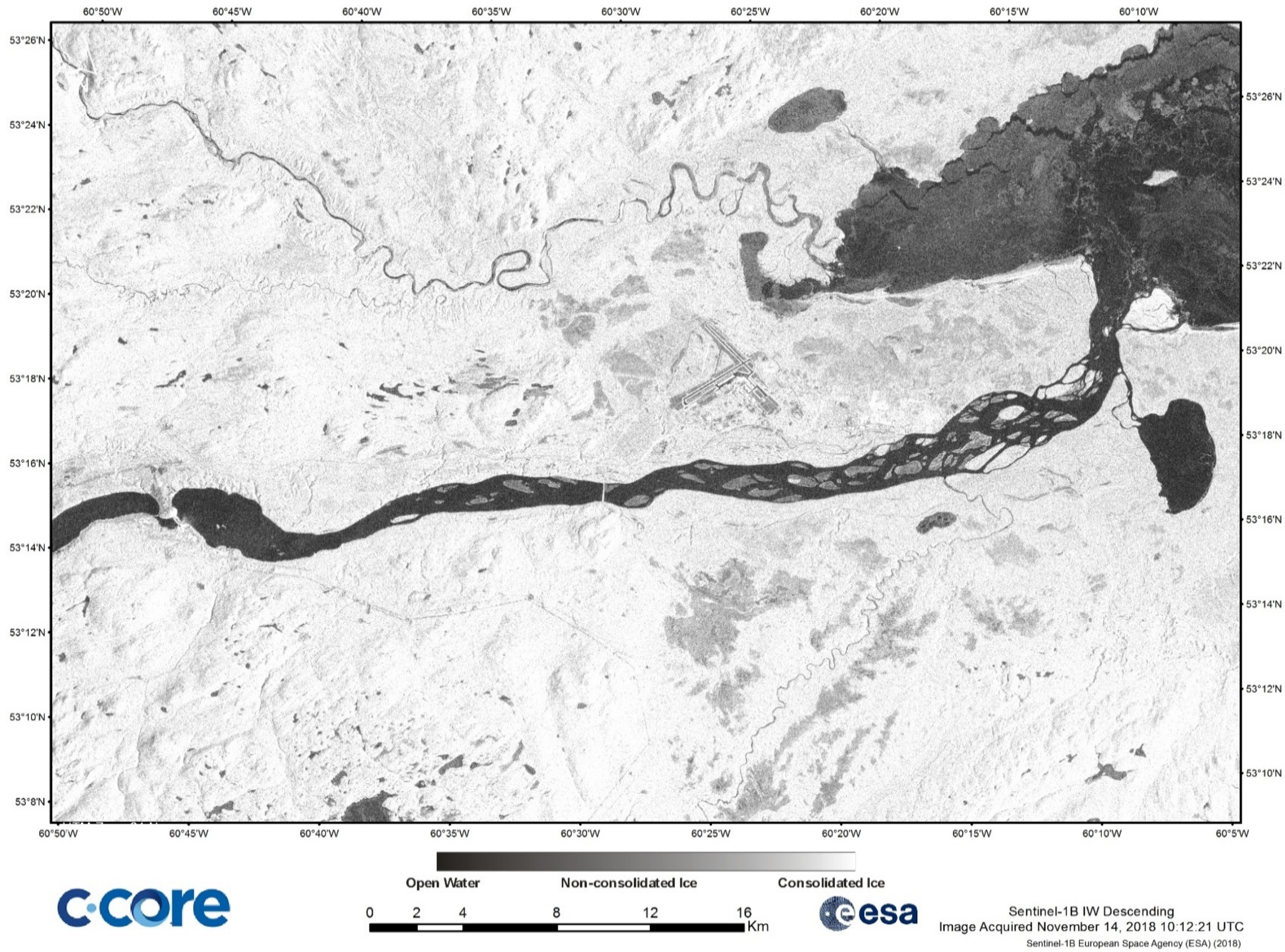
SNC-Lavalin. 2012b. Review of Ice Study Work. Prepared for Nalcor Energy - Lower Churchill Project. v + 55 pp., + 1 appendix.

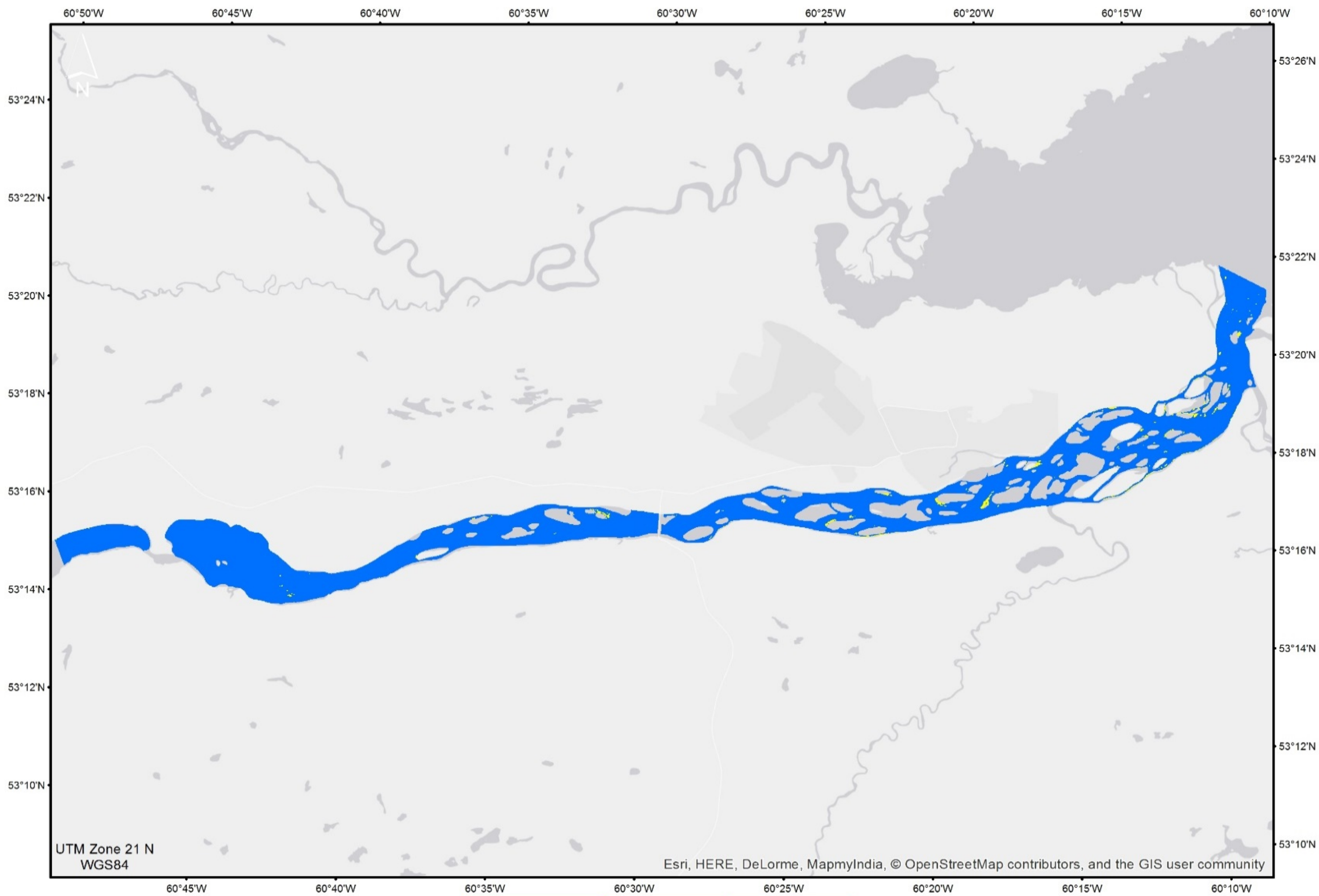
# APPENDIX A

## Lower Churchill River Freeze-Up Satellite Imagery

# Churchill River - Ice Cover



# Churchill River - Ice Classification




Water or possibly water on ice | Non-consolidated or intact ice | Consolidated ice

0 2 4 8 12 16 Km

Sentinel-1B IW Descending
Image Acquired November 14, 2018 10:12:21 UTC

# Churchill River - Ice Cover

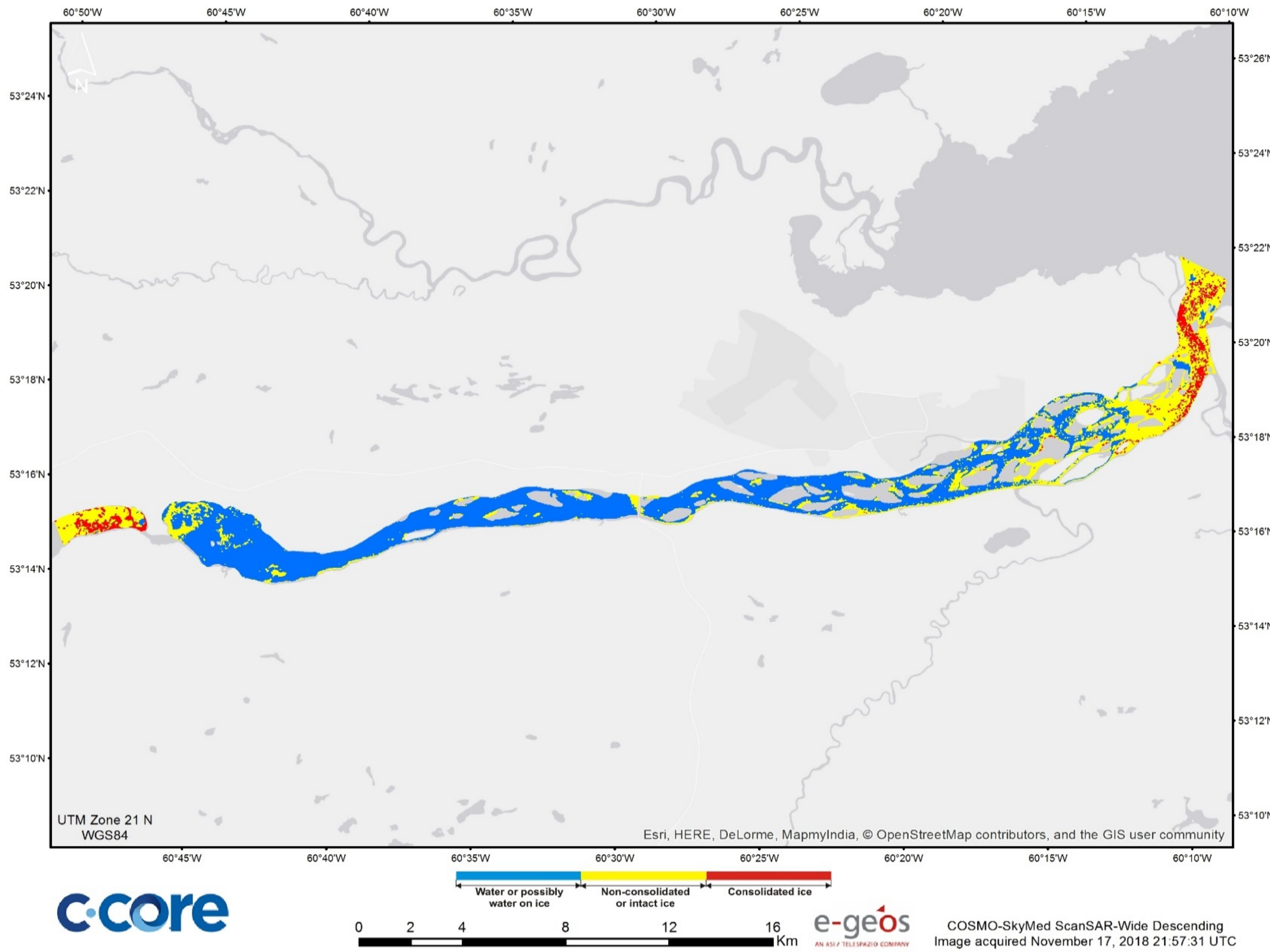

Open Water — Non-consolidated Ice — Consolidated Ice

0 2 4 8 12 16 Km

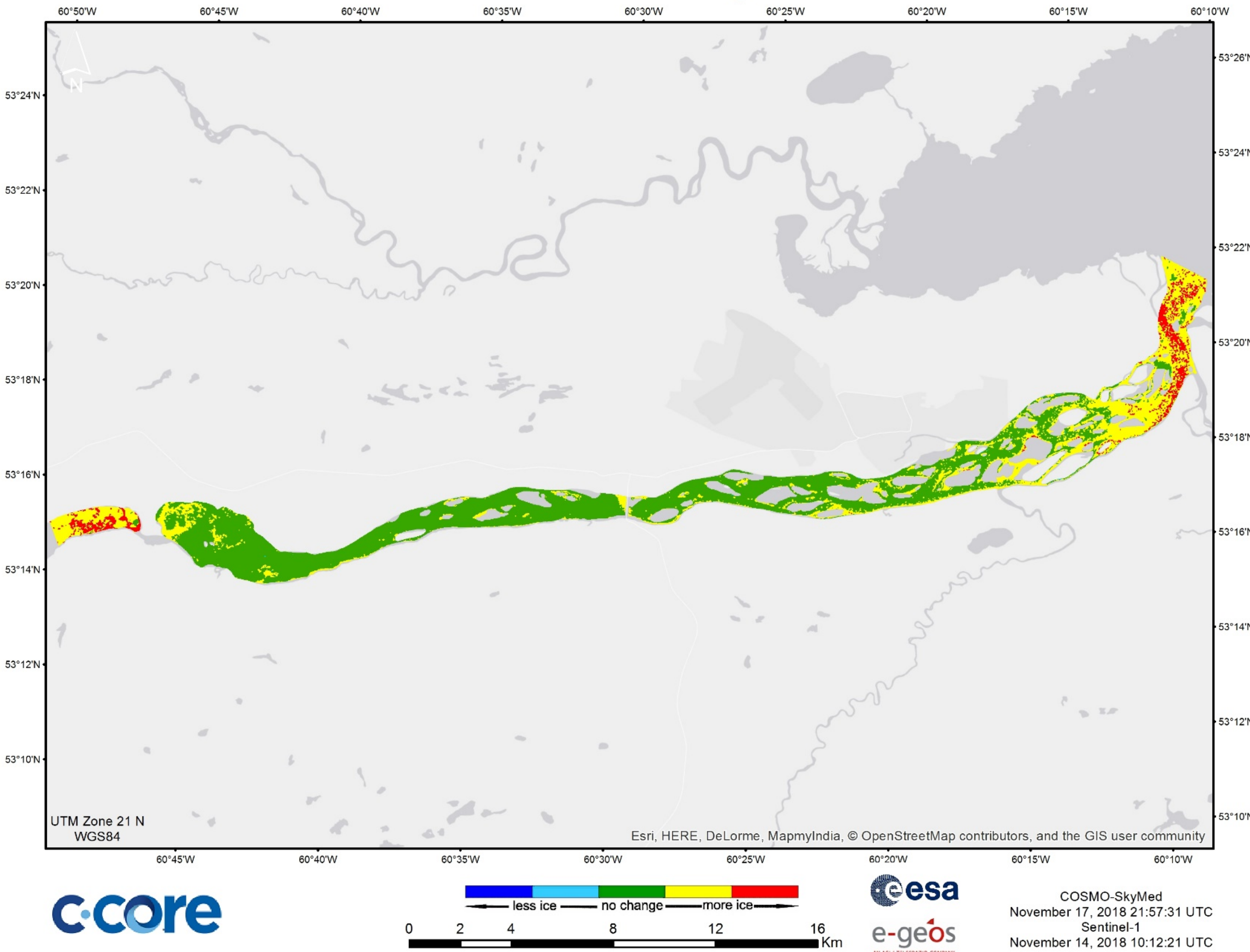
e-geos AN ASI / TELESPAZIO COMPANY

COSMO-SkyMed ScanSAR-Wide Descending
Image acquired November 17, 2018 21:57:31 UTC

# Churchill River - Ice Classification

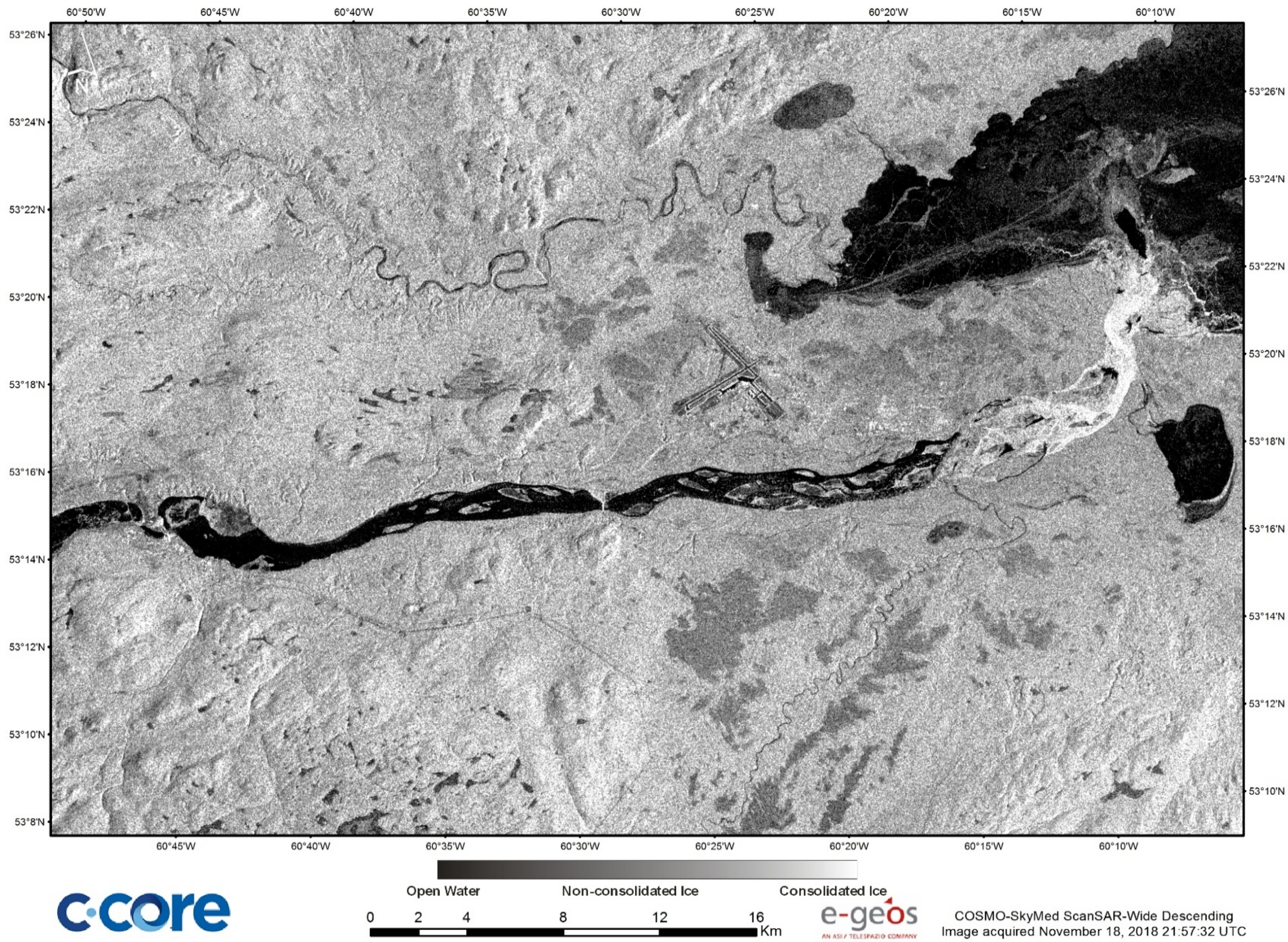


# Churchill River - Change Detection

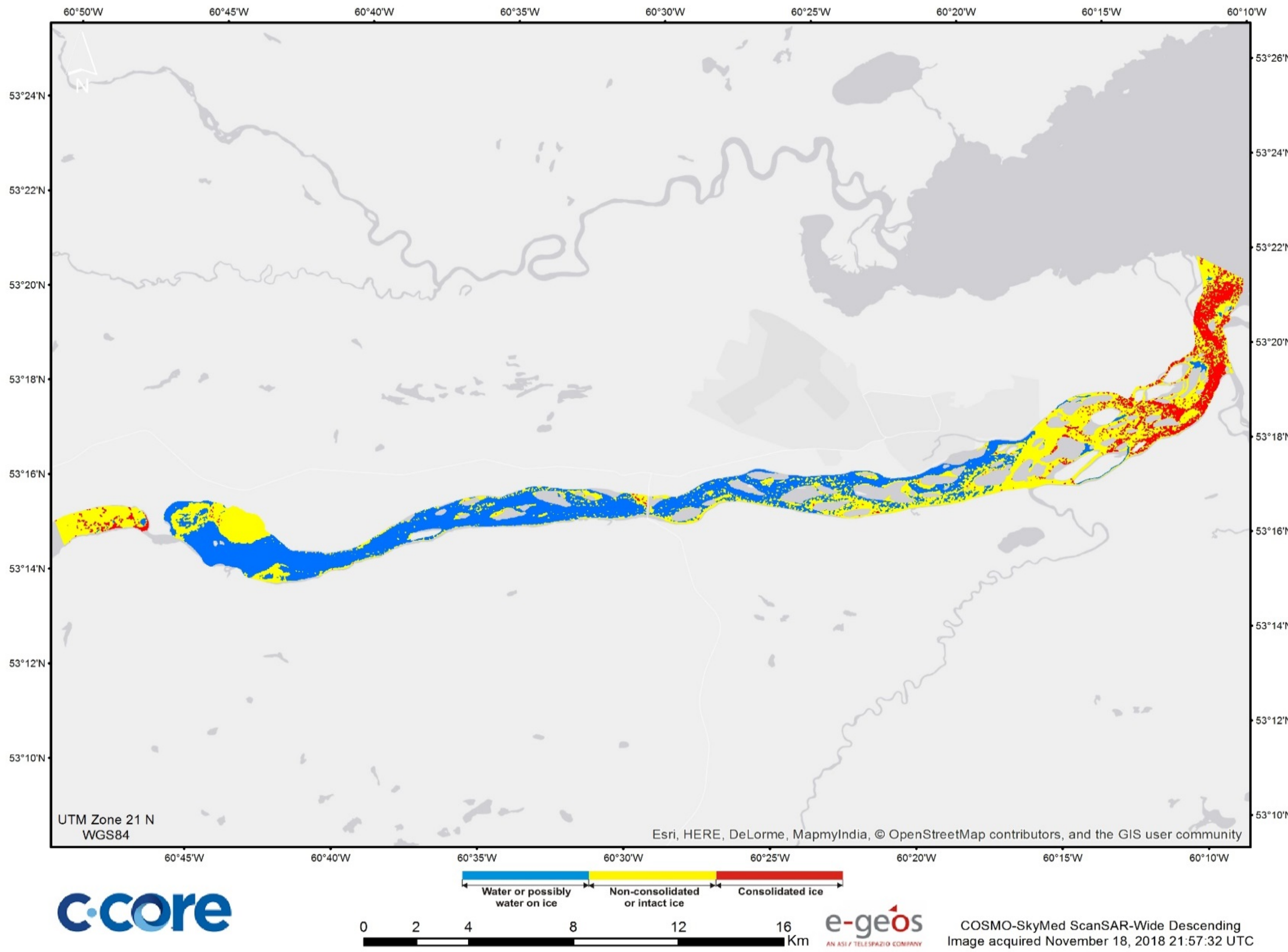



COSMO-SkyMed
November 17, 2018 21:57:31 UTC
Sentinel-1
November 14, 2018 10:12:21 UTC

# Churchill River - Ice Cover



# Churchill River - Ice Classification

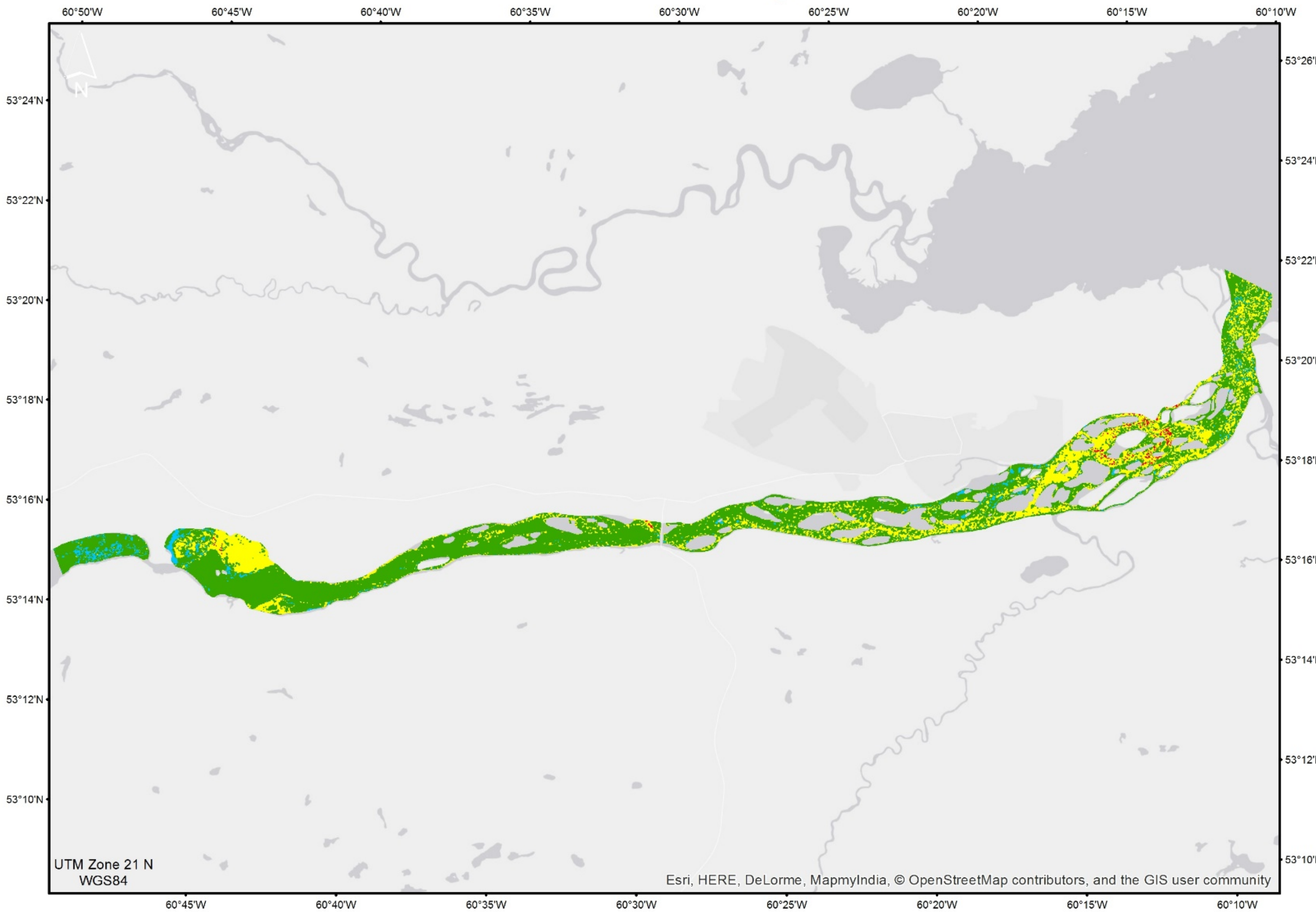



c·core

e-geos AN ASI / TELESPAZIO COMPANY

COSMO-SkyMed ScanSAR-Wide Descending
Image acquired November 18, 2018 21:57:32 UTC

# Churchill River - Change Detection

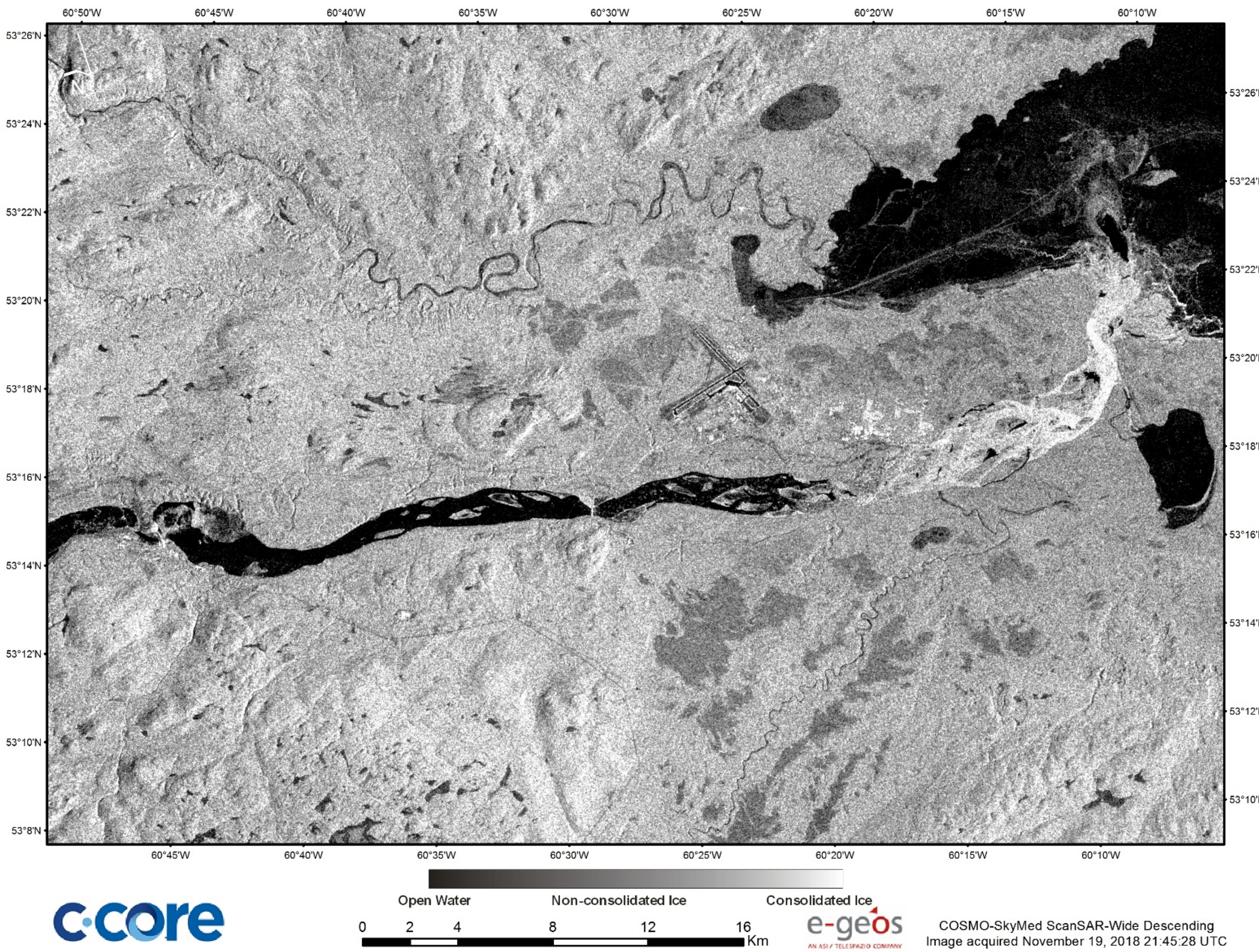



less ice — no change — more ice

0 2 4 8 12 16 Km

COSMO-SkyMed
November 18, 2018 21:57:32 UTC
November 17, 2018 21:57:31 UTC

# Churchill River - Ice Cover

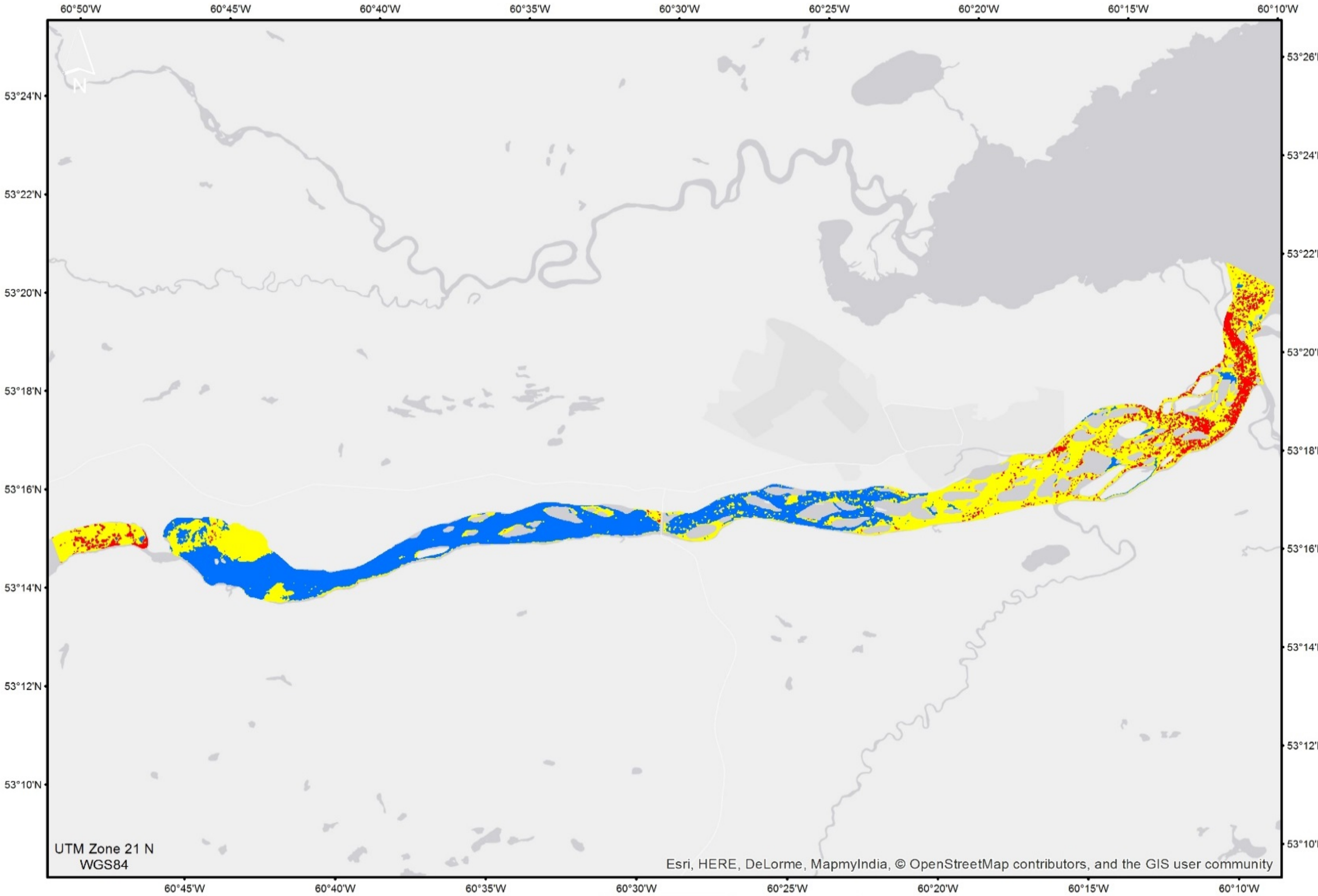



c·core

e-geos
AN ASI / TELESPAZIO COMPANY

COSMO-SkyMed ScanSAR-Wide Descending
Image acquired November 19, 2018 21:45:28 UTC

# Churchill River - Ice Classification

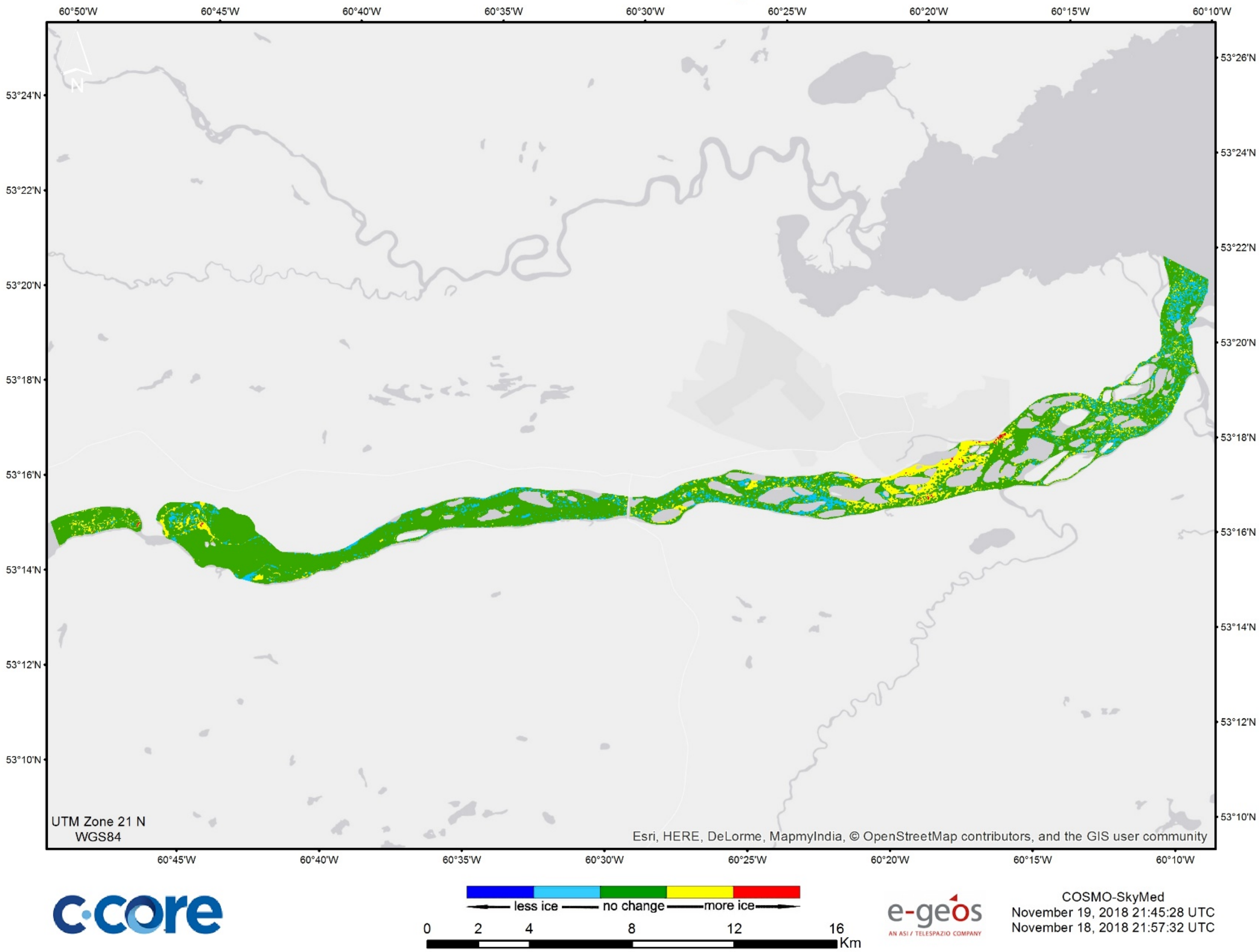



Water or possibly water on ice | Non-consolidated or intact ice | Consolidated ice

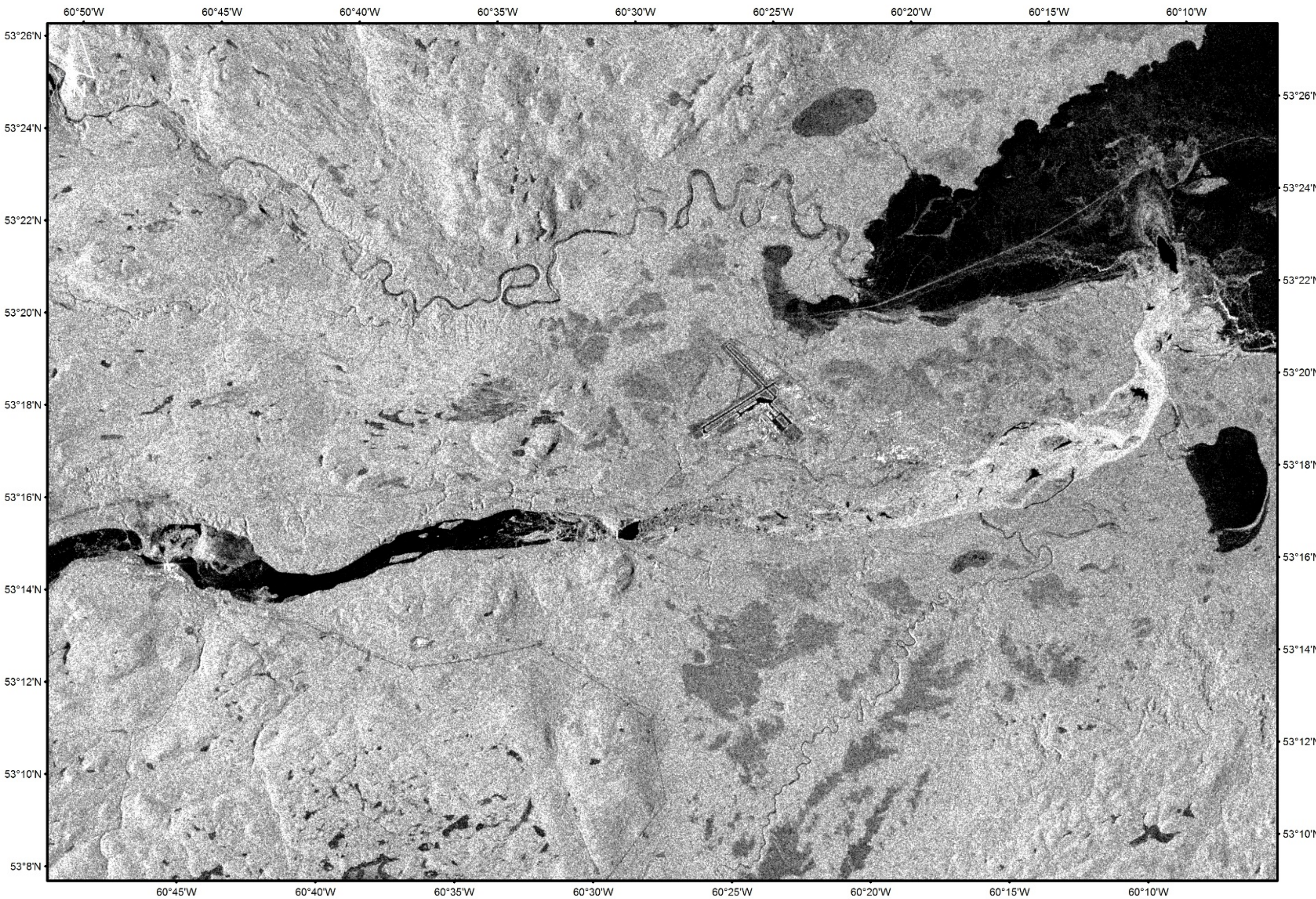
0 2 4 8 12 16 Km

COSMO-SkyMed ScanSAR-Wide Descending
Image acquired November 19, 2018 21:45:28 UTC

# Churchill River - Change Detection



# Churchill River - Ice Cover

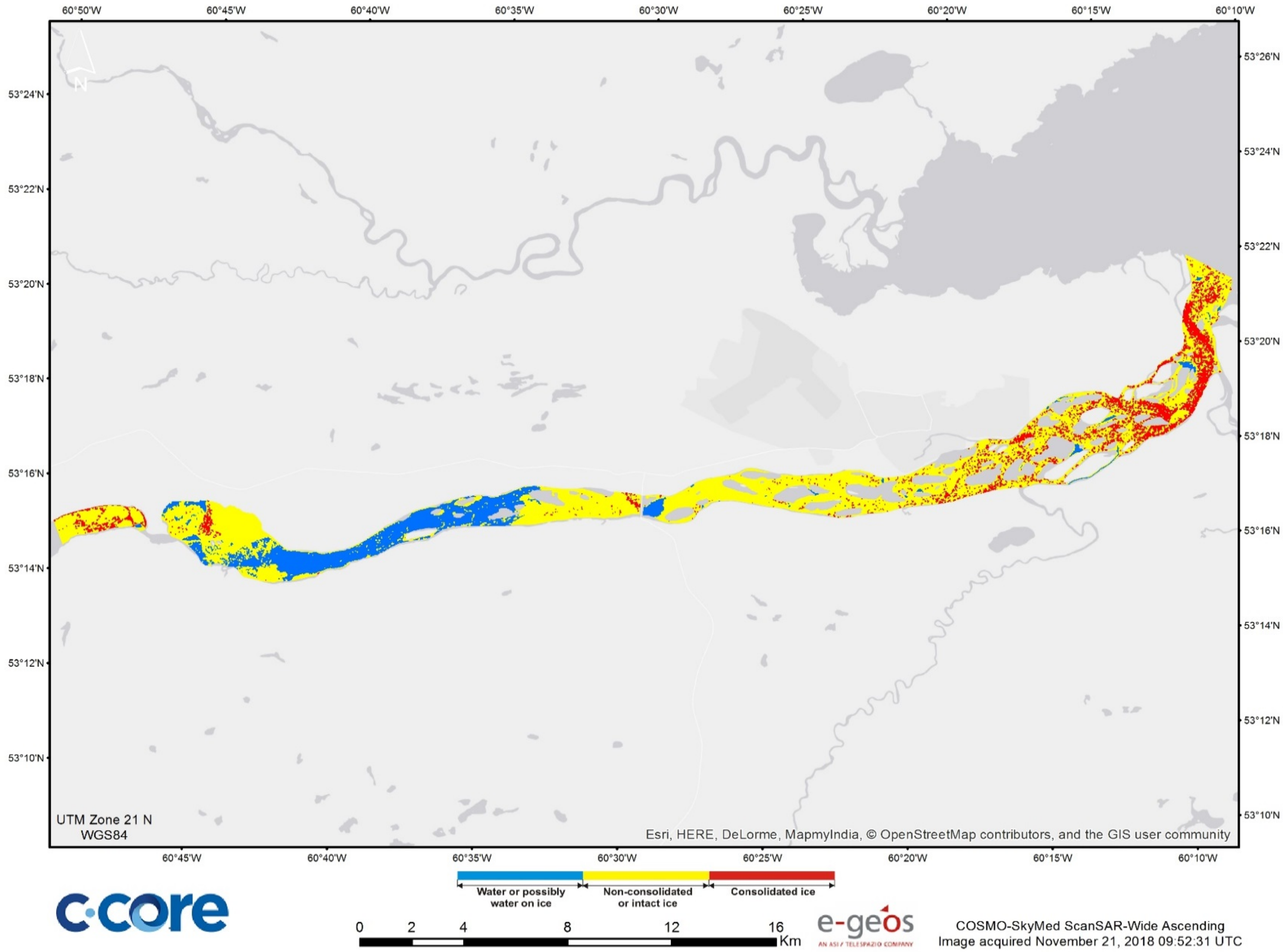



Open Water | Non-consolidated Ice | Consolidated Ice

0 2 4 8 12 16 Km

COSMO-SkyMed ScanSAR-Wide Ascending
Image acquired November 21, 2018 09:52:31 UTC

# Churchill River - Ice Classification

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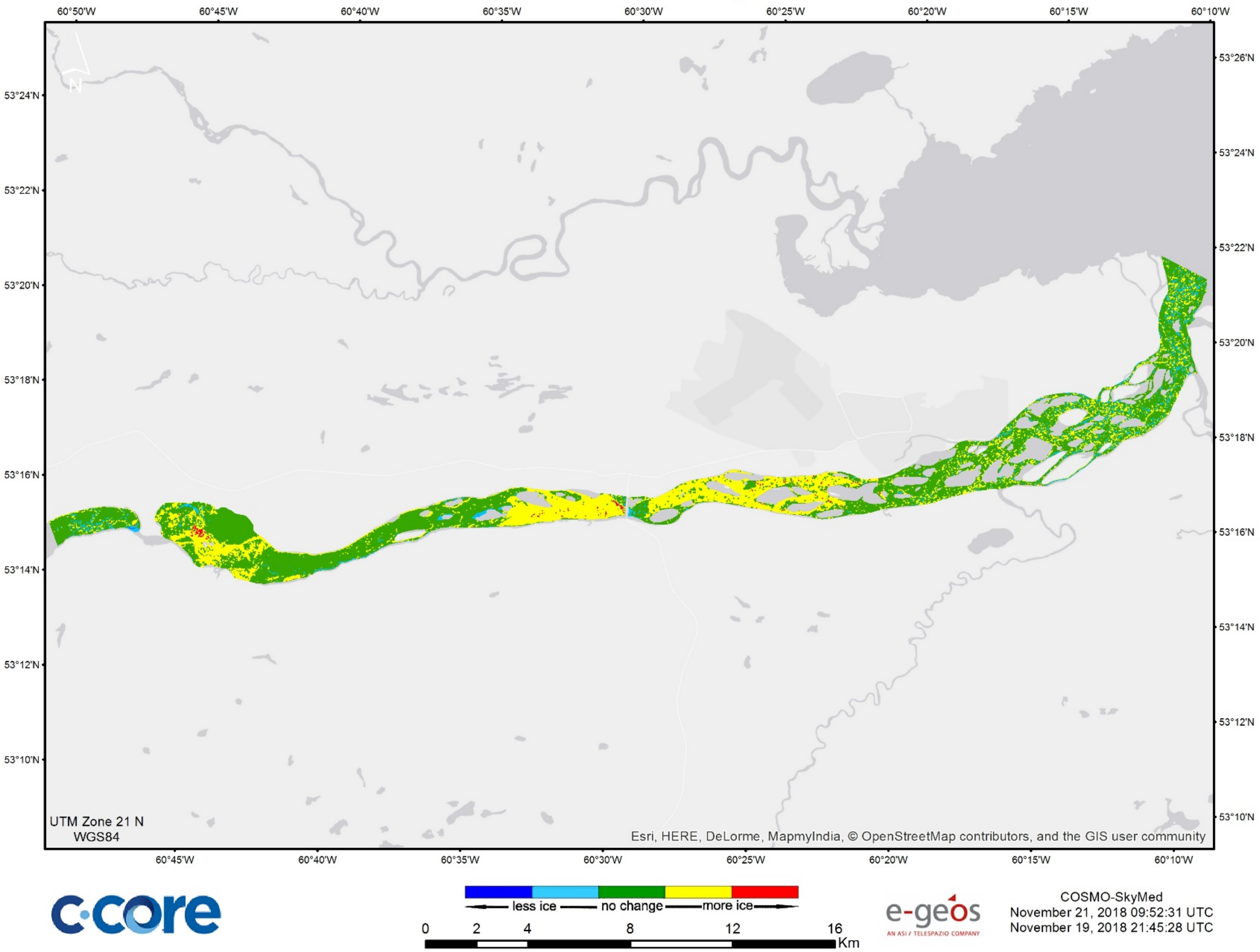
COSMO-SkyMed ScanSAR-Wide Ascending
Image acquired November 21, 2018 09:52:31 UTC

# Churchill River - Change Detection

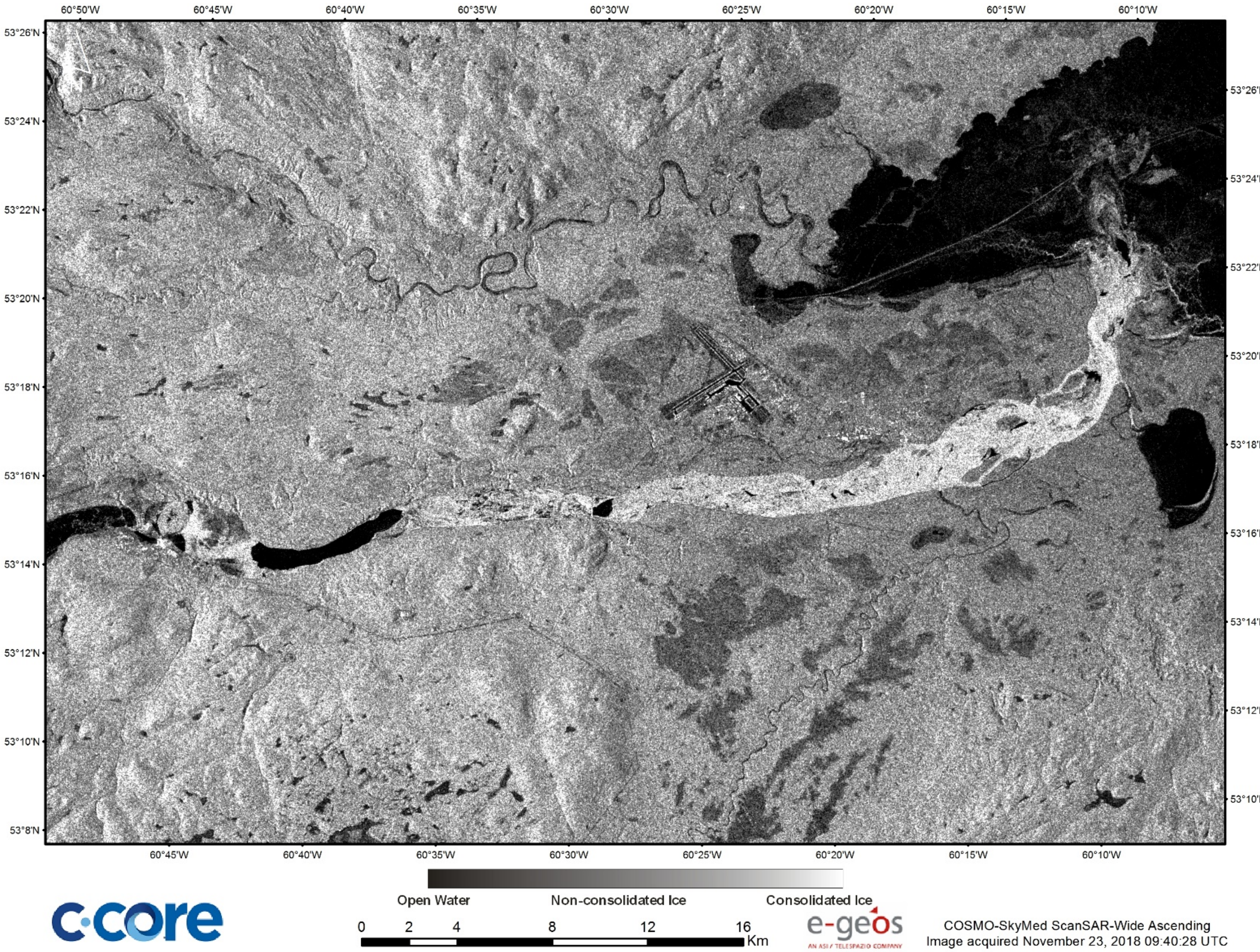



c-core

e-geos

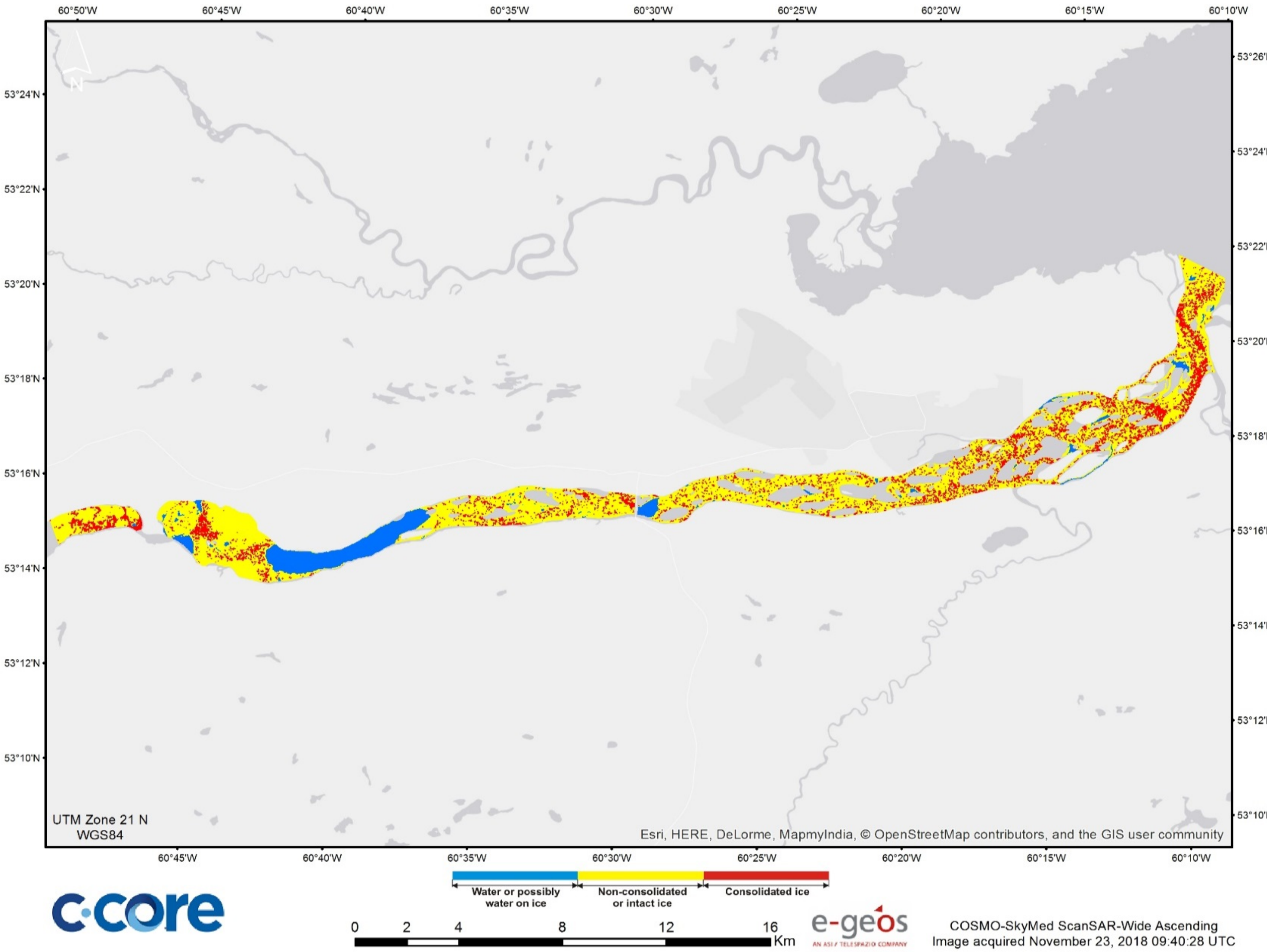
COSMO-SkyMed
November 21, 2018 09:52:31 UTC
November 19, 2018 21:45:28 UTC

# Churchill River - Ice Cover



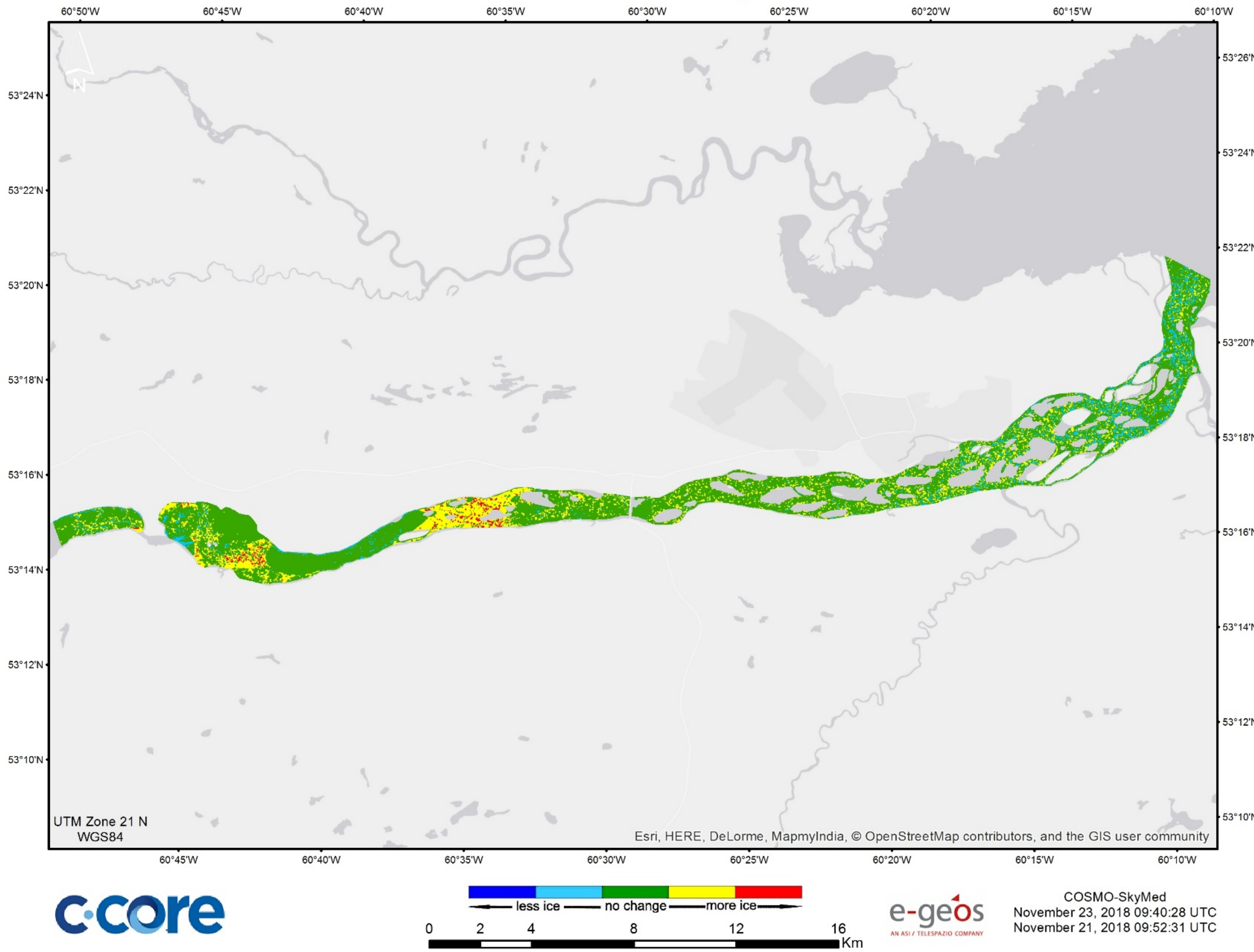

COSMO-SkyMed ScanSAR-Wide Ascending
Image acquired November 23, 2018 09:40:28 UTC

# Churchill River - Ice Classification

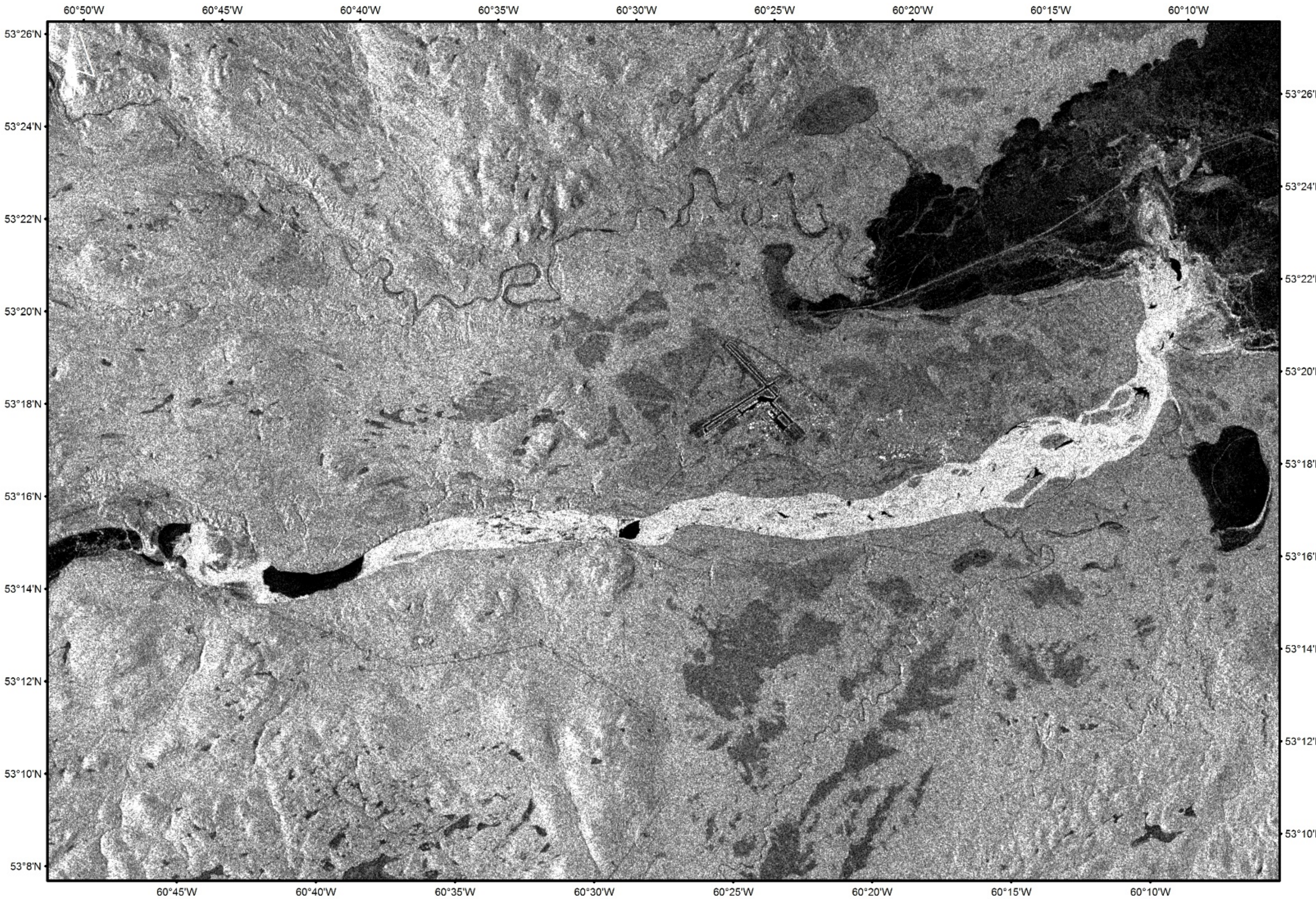



COSMO-SkyMed ScanSAR-Wide Ascending
Image acquired November 23, 2018 09:40:28 UTC

# Churchill River - Change Detection



# Churchill River - Ice Cover

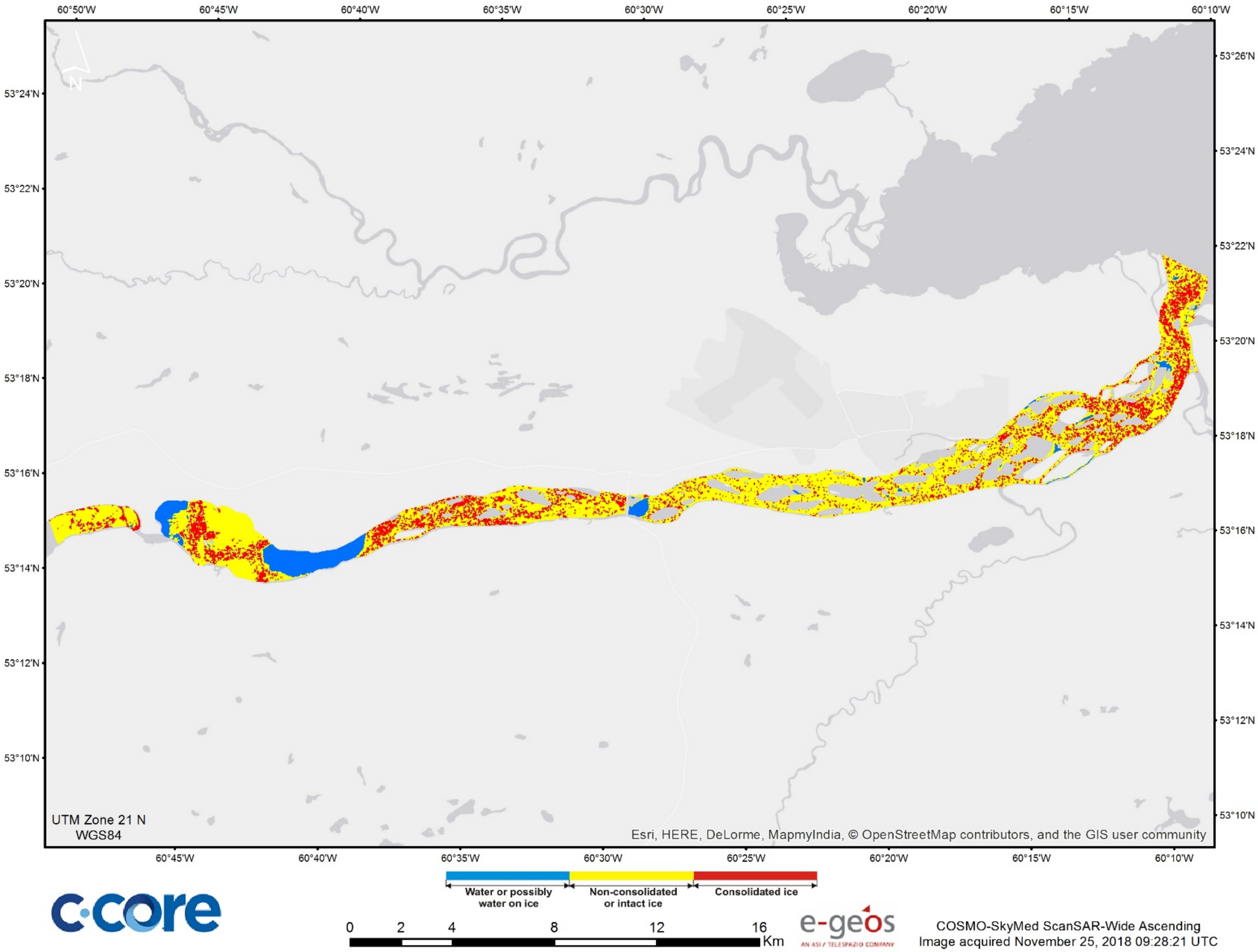



Open Water | Non-consolidated Ice | Consolidated Ice

0 2 4 8 12 16 Km

COSMO-SkyMed ScanSAR-Wide Ascending
Image acquired November 25, 2018 09:28:21 UTC

# Churchill River - Ice Classification

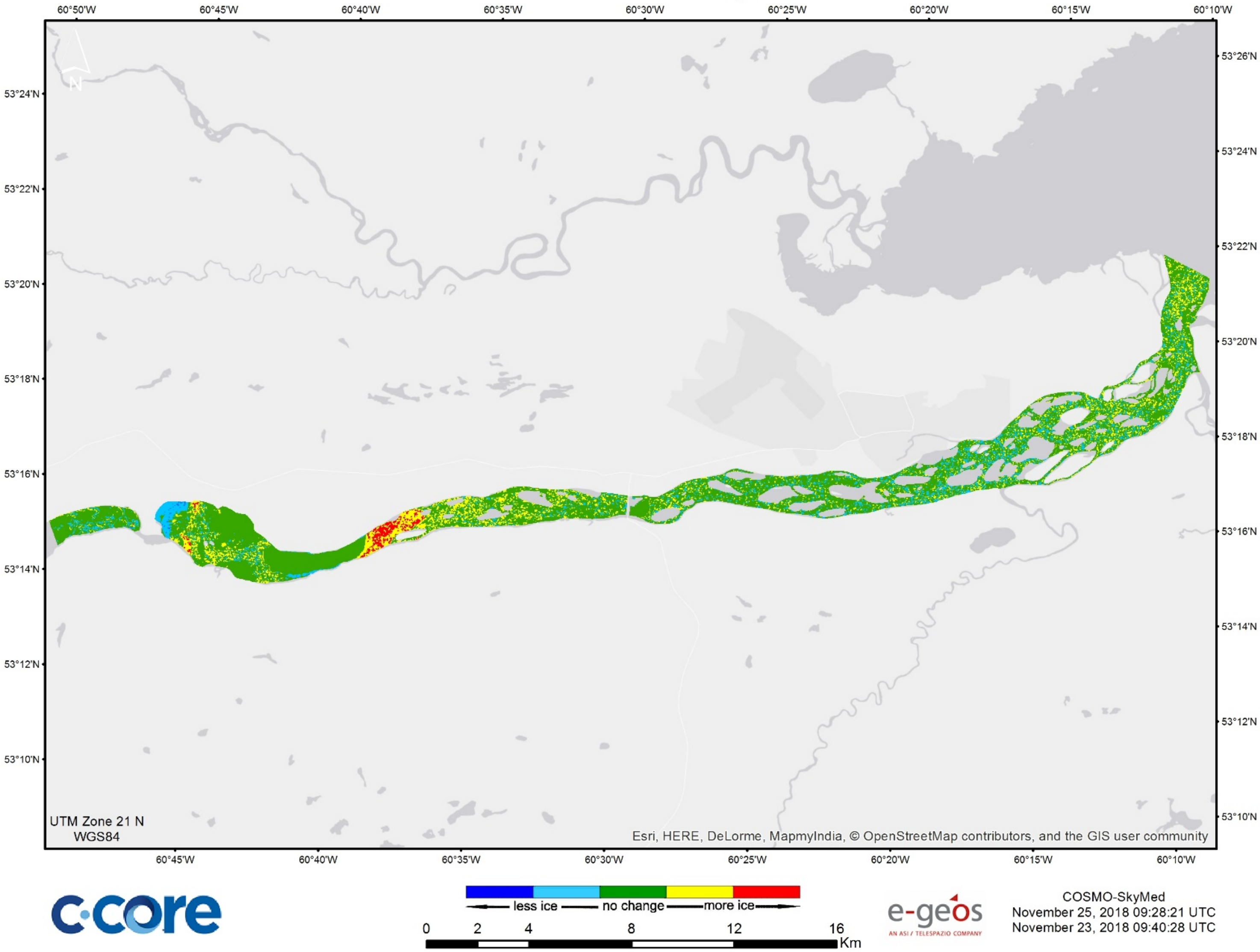



c·core

e-geos

COSMO-SkyMed ScanSAR-Wide Ascending
Image acquired November 25, 2018 09:28:21 UTC

# Churchill River - Change Detection




c-core

e-geos

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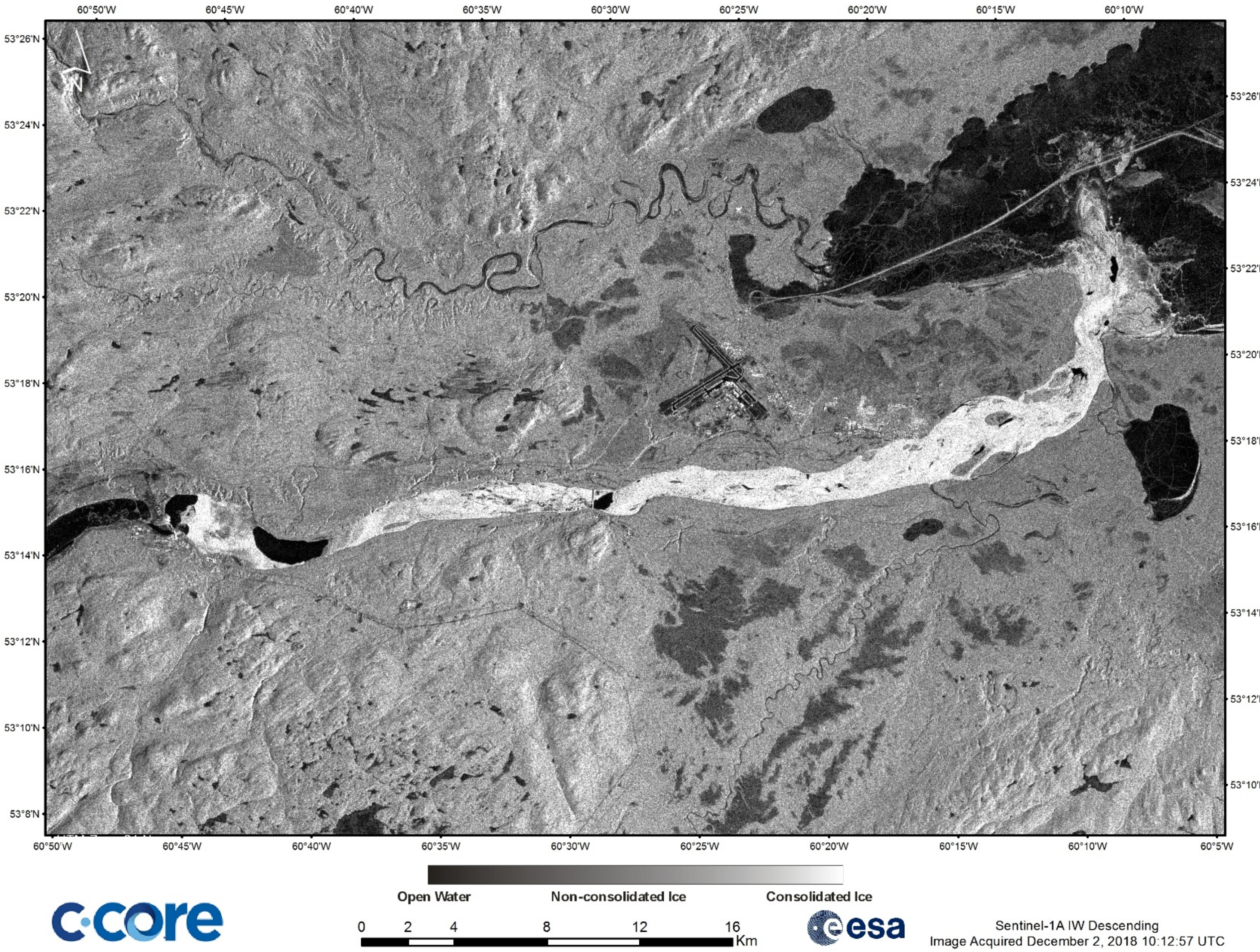
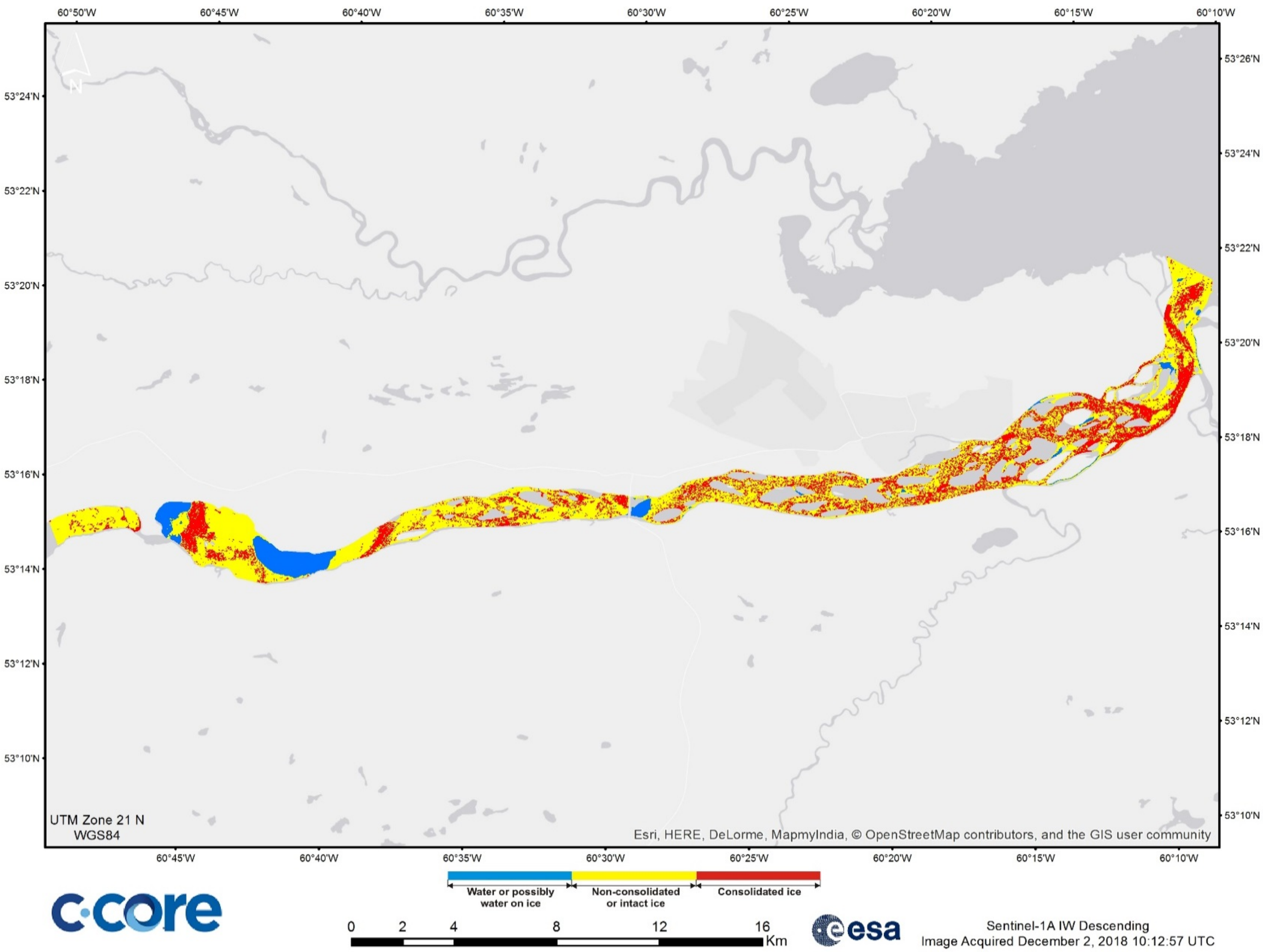
COSMO-SkyMed
November 25, 2018 09:28:21 UTC
November 23, 2018 09:40:28 UTC

# Churchill River - Ice Cover



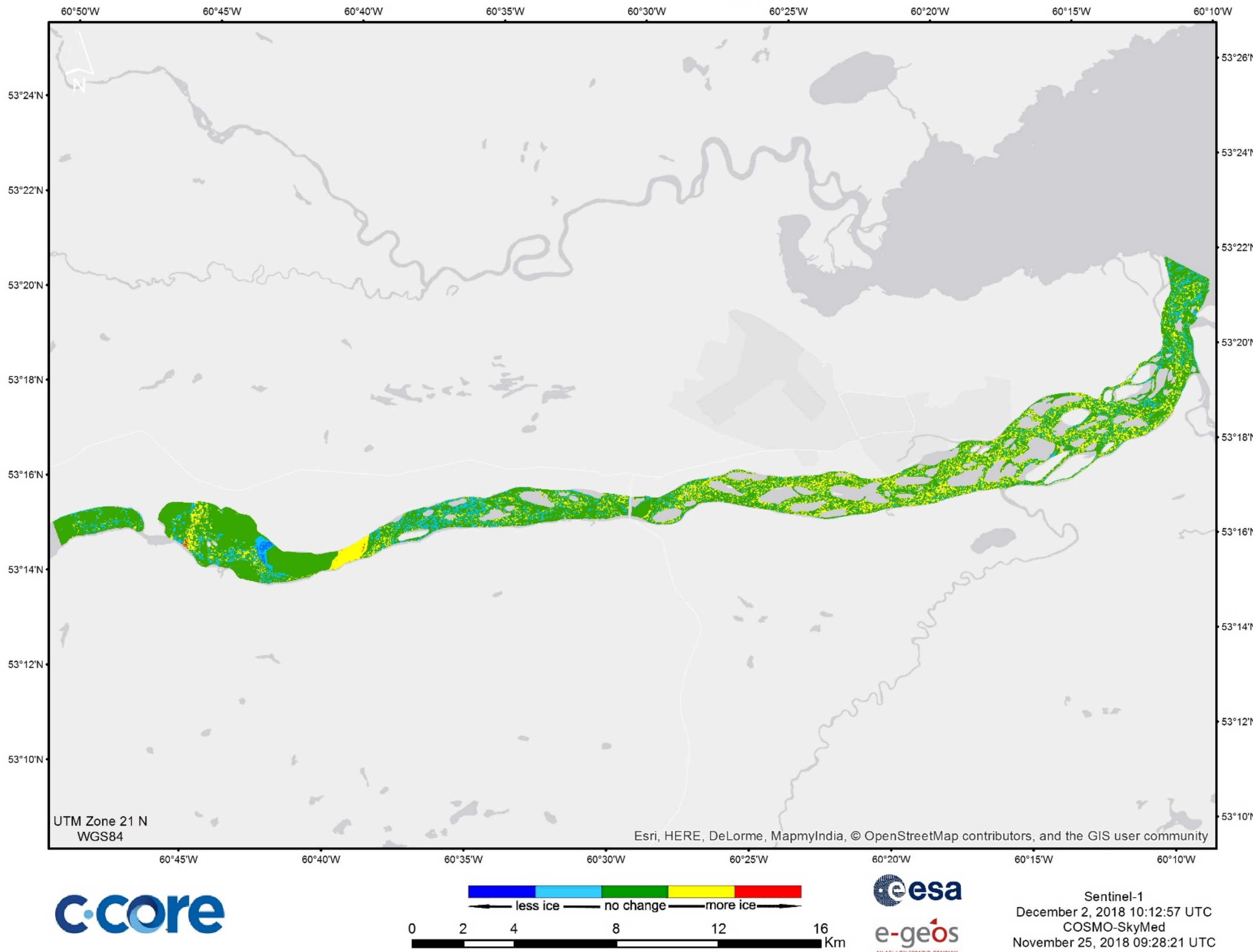

Sentinel-1A IW Descending
Image Acquired December 2, 2018 10:12:57 UTC

# Churchill River - Ice Classification




Sentinel-1A IW Descending
Image Acquired December 2, 2018 10:12:57 UTC

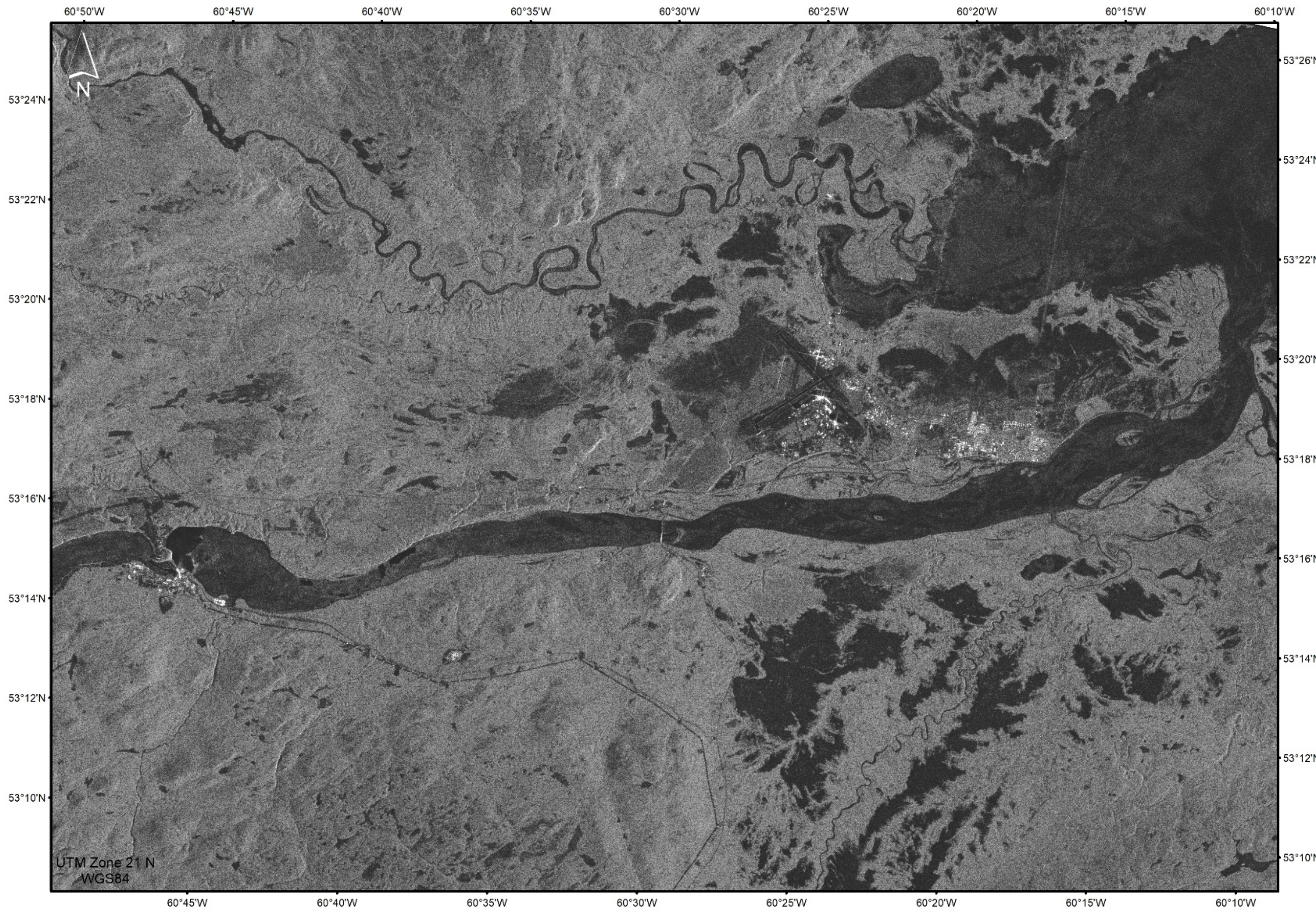
# Churchill River - Change Detection



# APPENDIX B

## Lower Churchill River Break-Up Satellite Imagery

# Churchill River - Ice Cover




Open Water | Non-consolidated Ice | Consolidated Ice

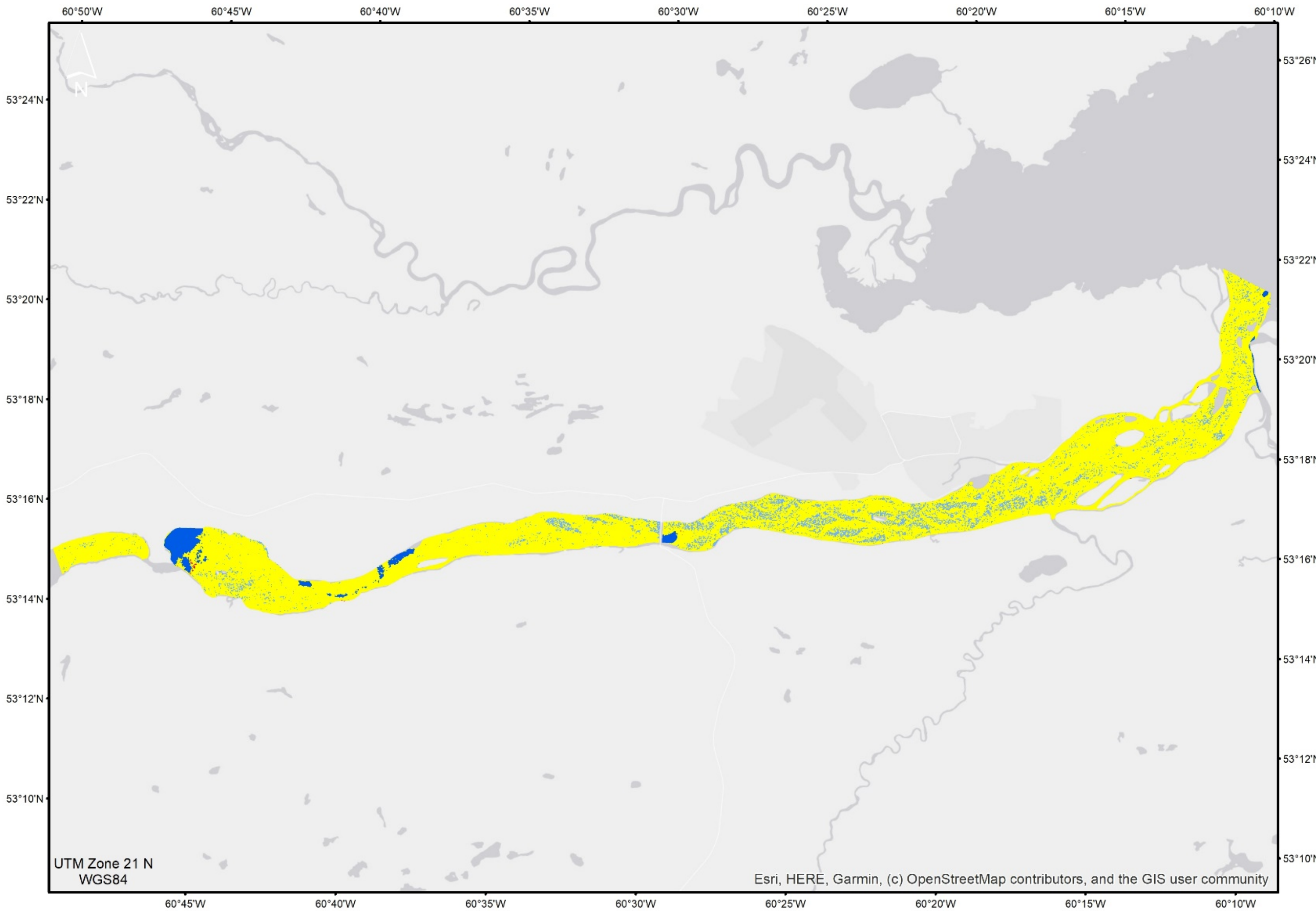
0 2 4 8 12 16 Km

C-CORE

esa

Sentinel-1B IW Descending
Image Acquired May 1, 2019 10:12:26 UTC

# Churchill River - Ice Classification

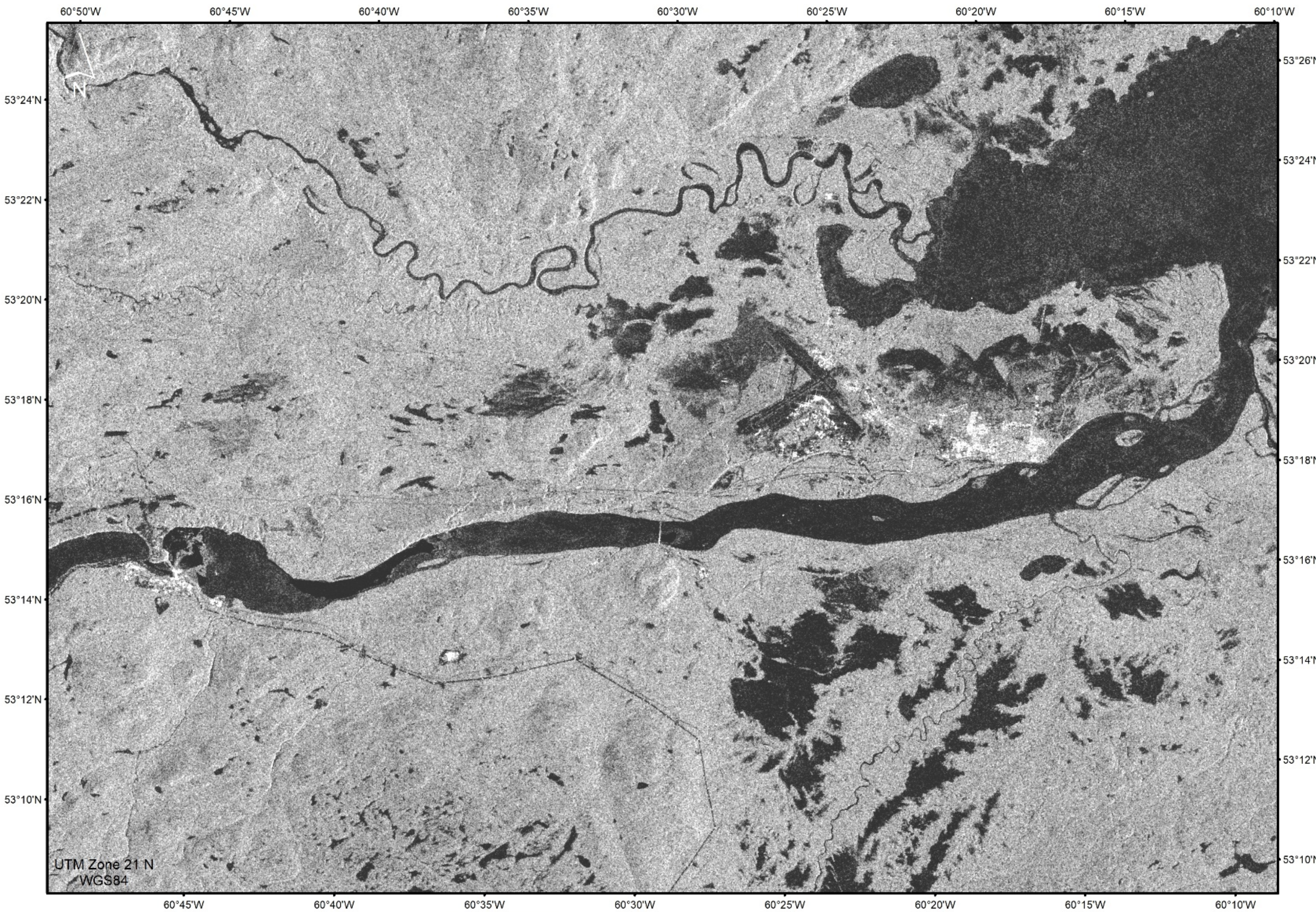



Open water | Wet ice, or Pooling water on ice | Non-consolidated or smooth ice | Consolidated or rough ice

0 2 4 8 12 16 Km

Sentinel-1B IW Descending
Image Acquired May 1, 2019 10:12:26 UTC

# Churchill River - Ice Cover

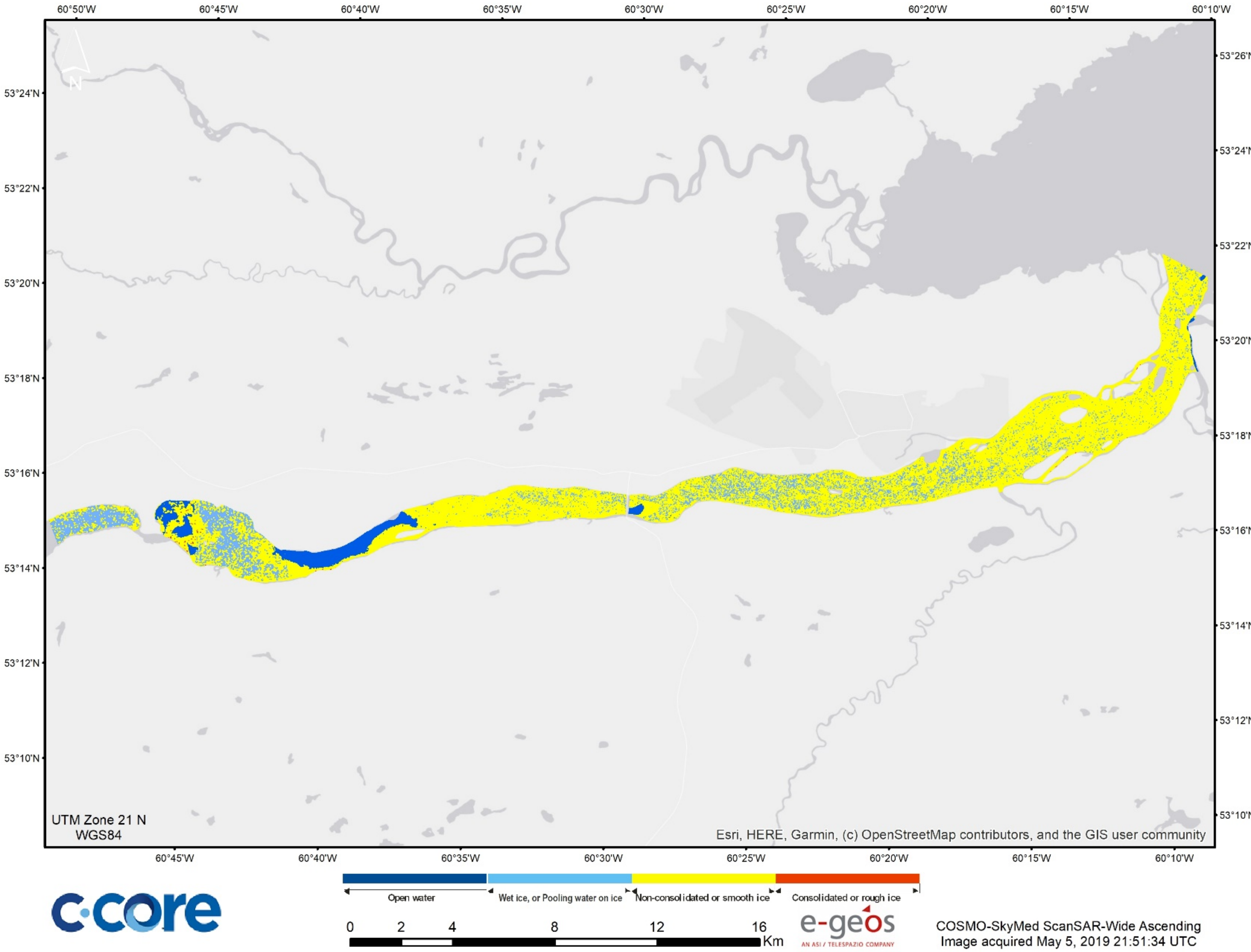



Open Water | Non-consolidated Ice | Consolidated Ice

0 2 4 8 12 16 Km

COSMO-SkyMed ScanSAR-Wide Ascending
Image acquired May 5, 2019 21:51:34 UTC

# Churchill River - Ice Classification

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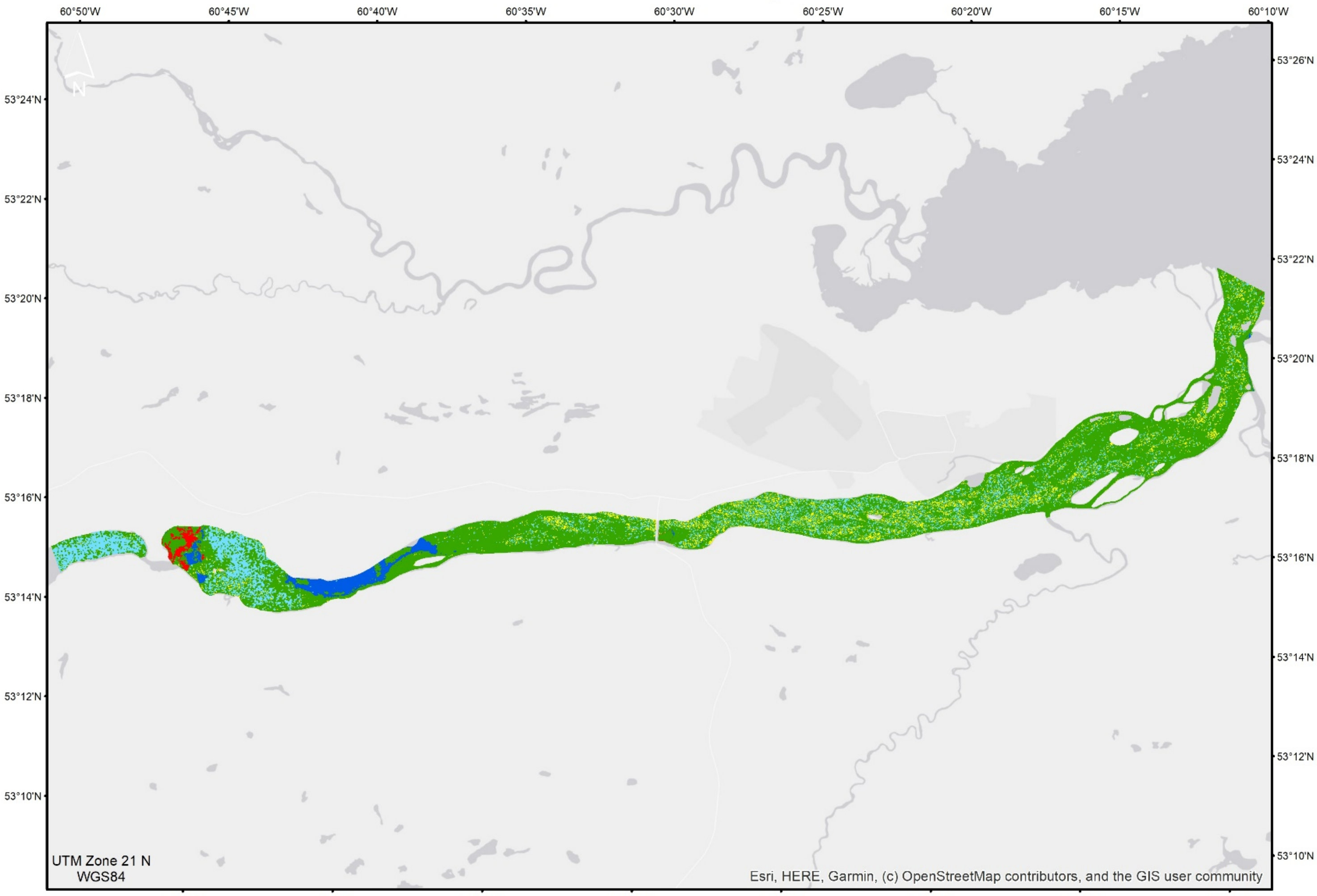
COSMO-SkyMed ScanSAR-Wide Ascending
Image acquired May 5, 2019 21:51:34 UTC

# Churchill River - Change Detection

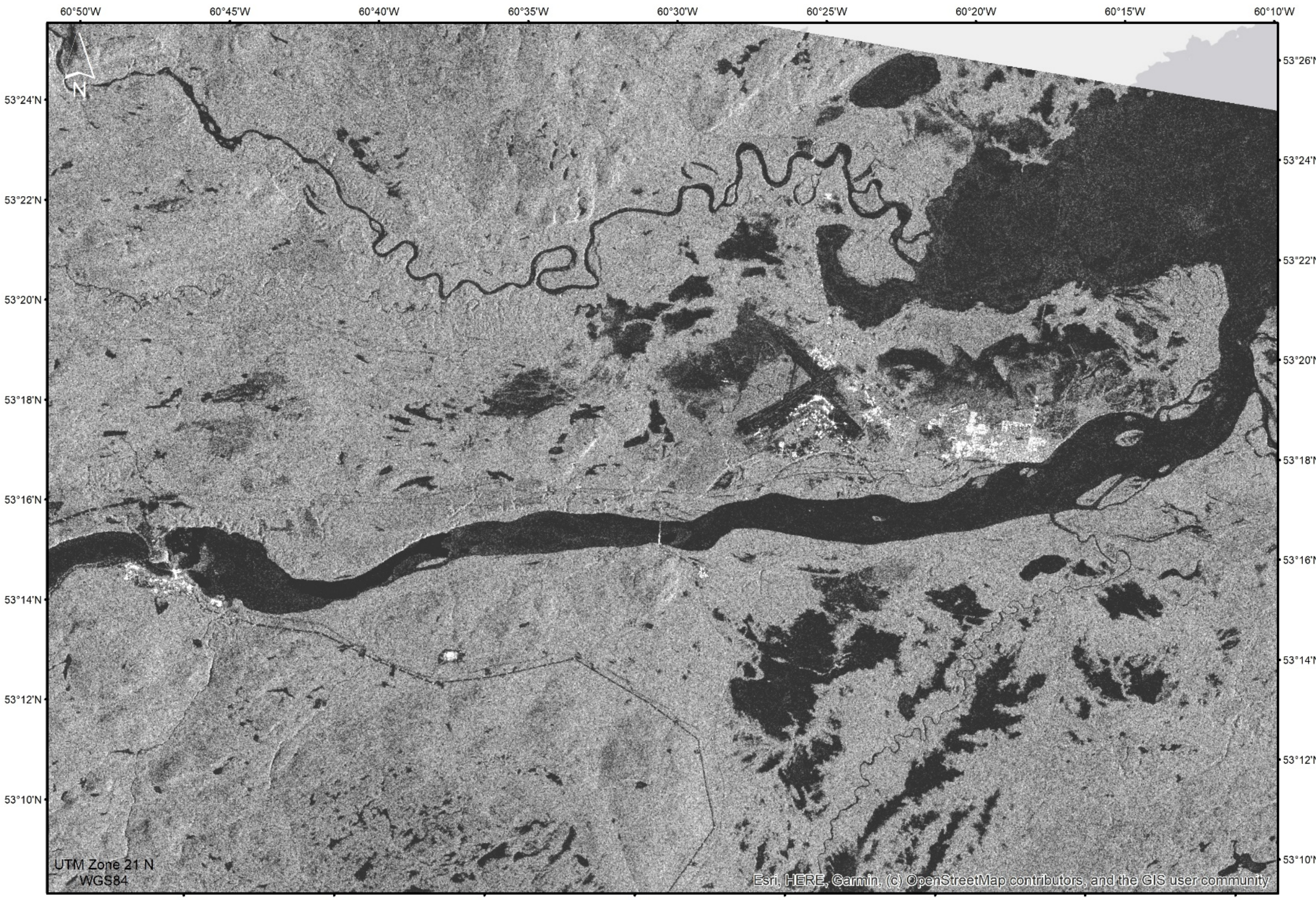



less ice — no change — more ice

0 2 4 8 12 16 Km

COSMO-SkyMed
May 5, 2019 21:51:34 UTC
Sentinel-1
May 1, 2019 10:12:26 UTC

# Churchill River - Ice Cover

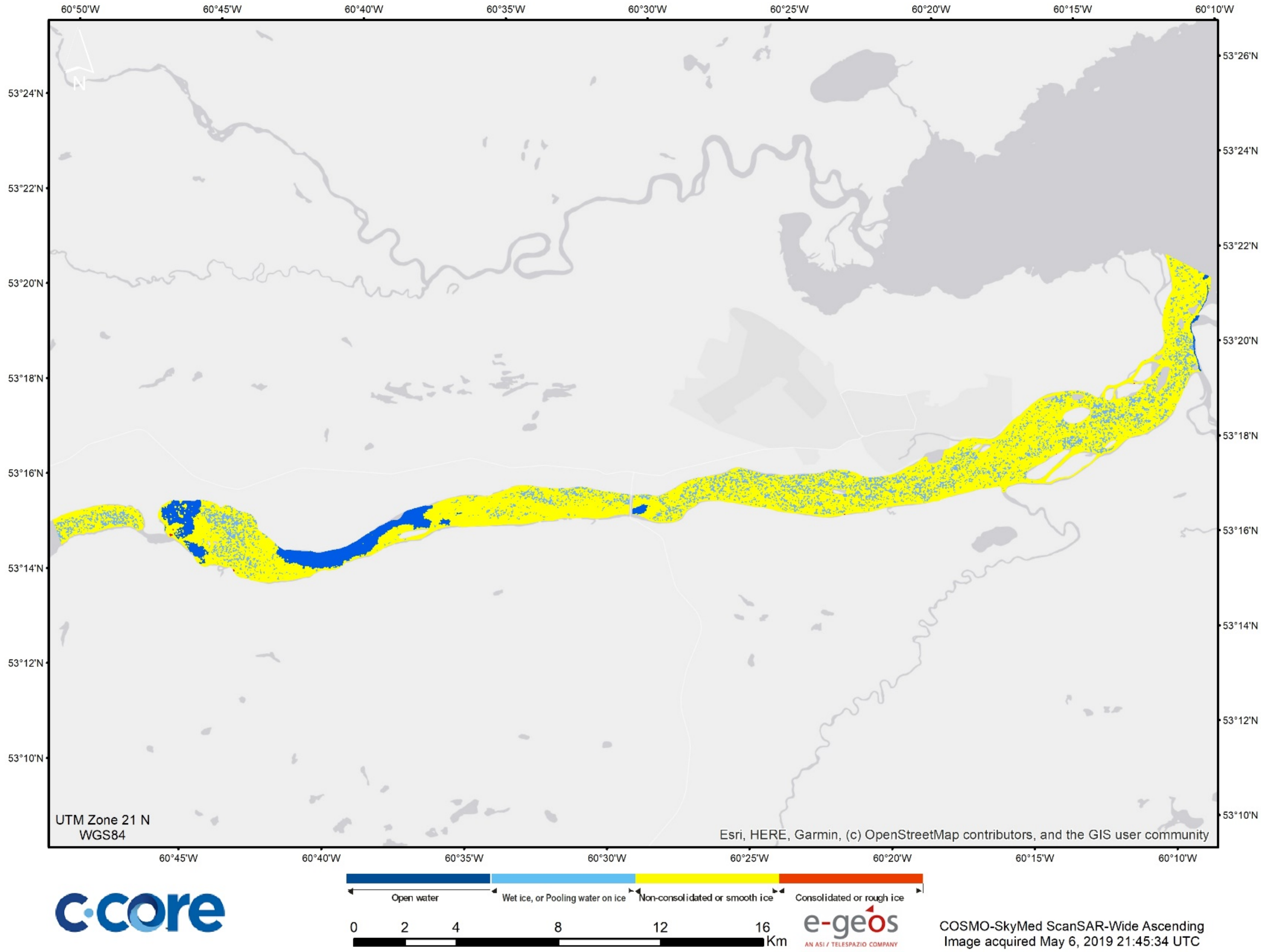



Open Water | Non-consolidated Ice | Consolidated Ice

0 2 4 8 12 16 Km

COSMO-SkyMed ScanSAR-Wide Ascending
Image acquired May 6, 2019 21:45:34 UTC

# Churchill River - Ice Classification

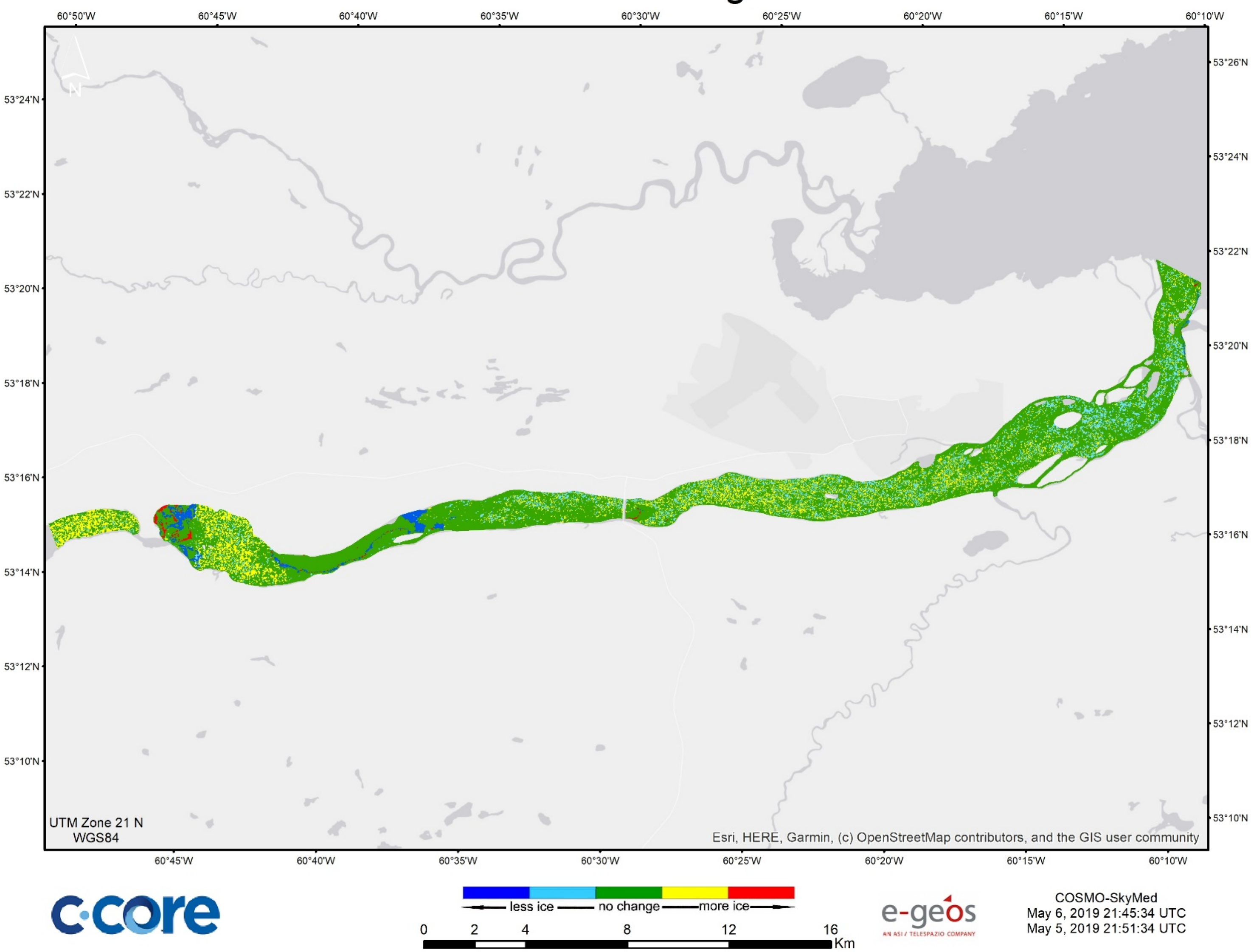



C-CORE

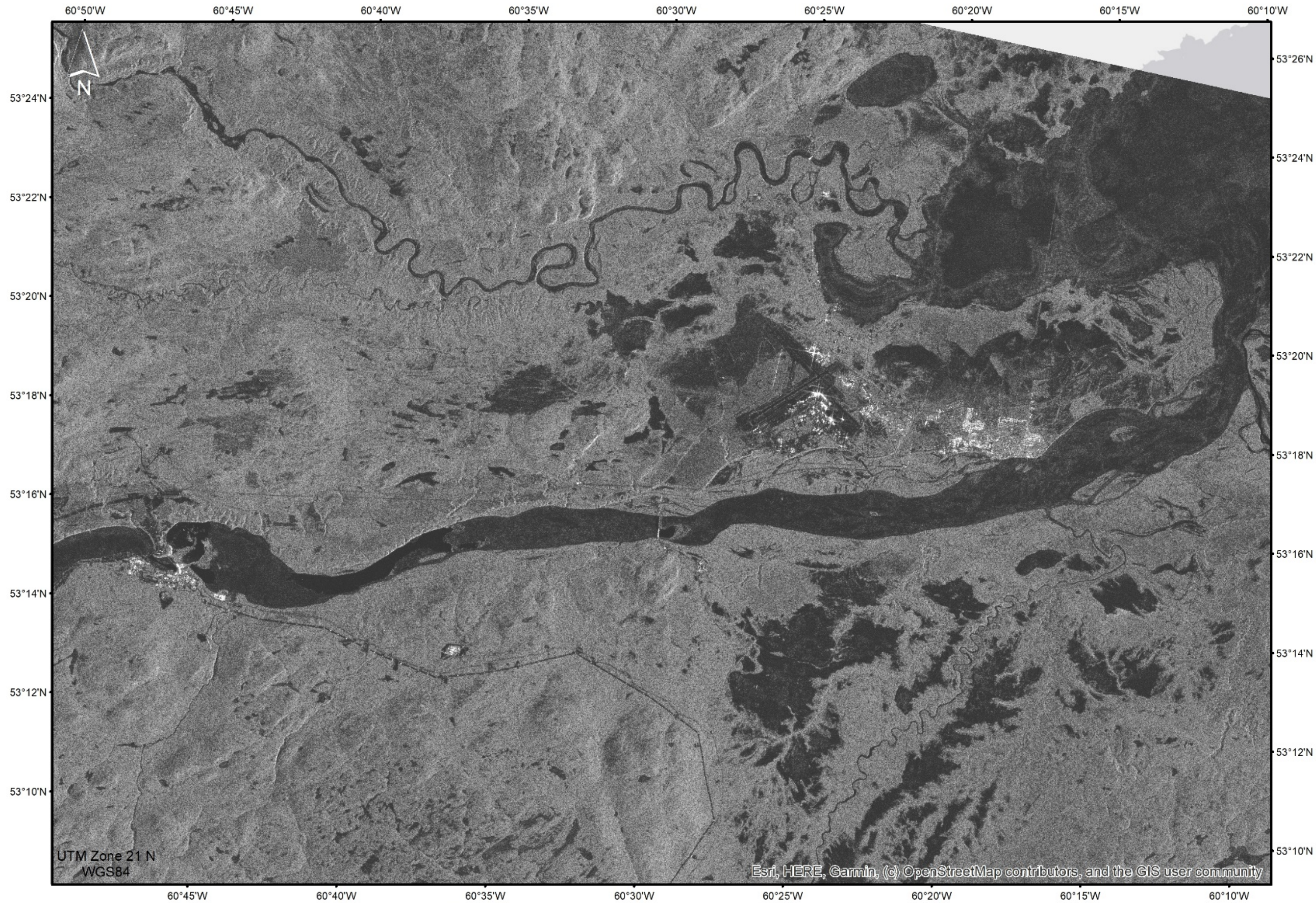
e-geos AN ASI / TELESPAZIO COMPANY

COSMO-SkyMed ScanSAR-Wide Ascending
Image acquired May 6, 2019 21:45:34 UTC

# Churchill River - Change Detection



# Churchill River - Ice Cover

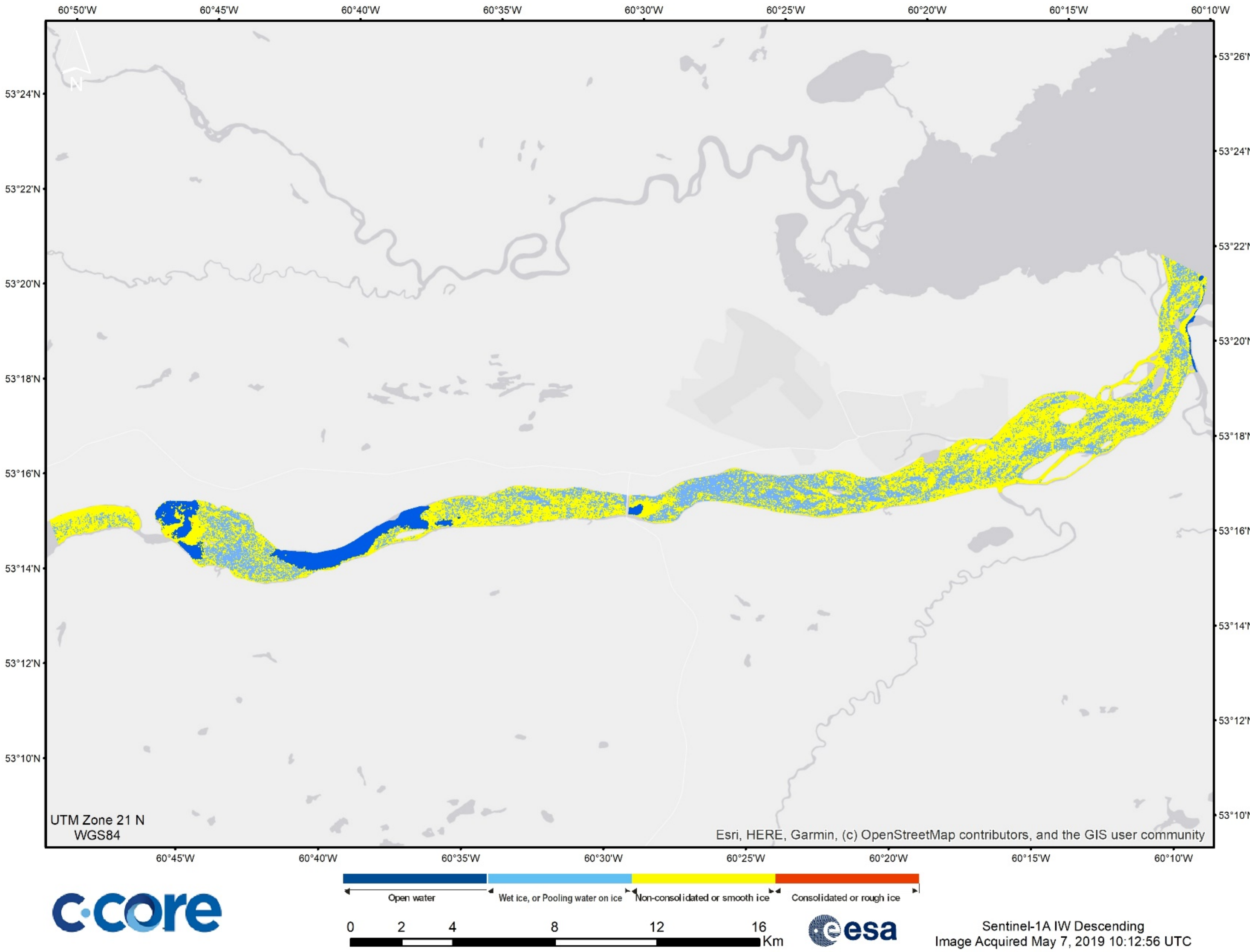



Open Water   Non-consolidated Ice   Consolidated Ice

0 2 4 8 12 16 Km

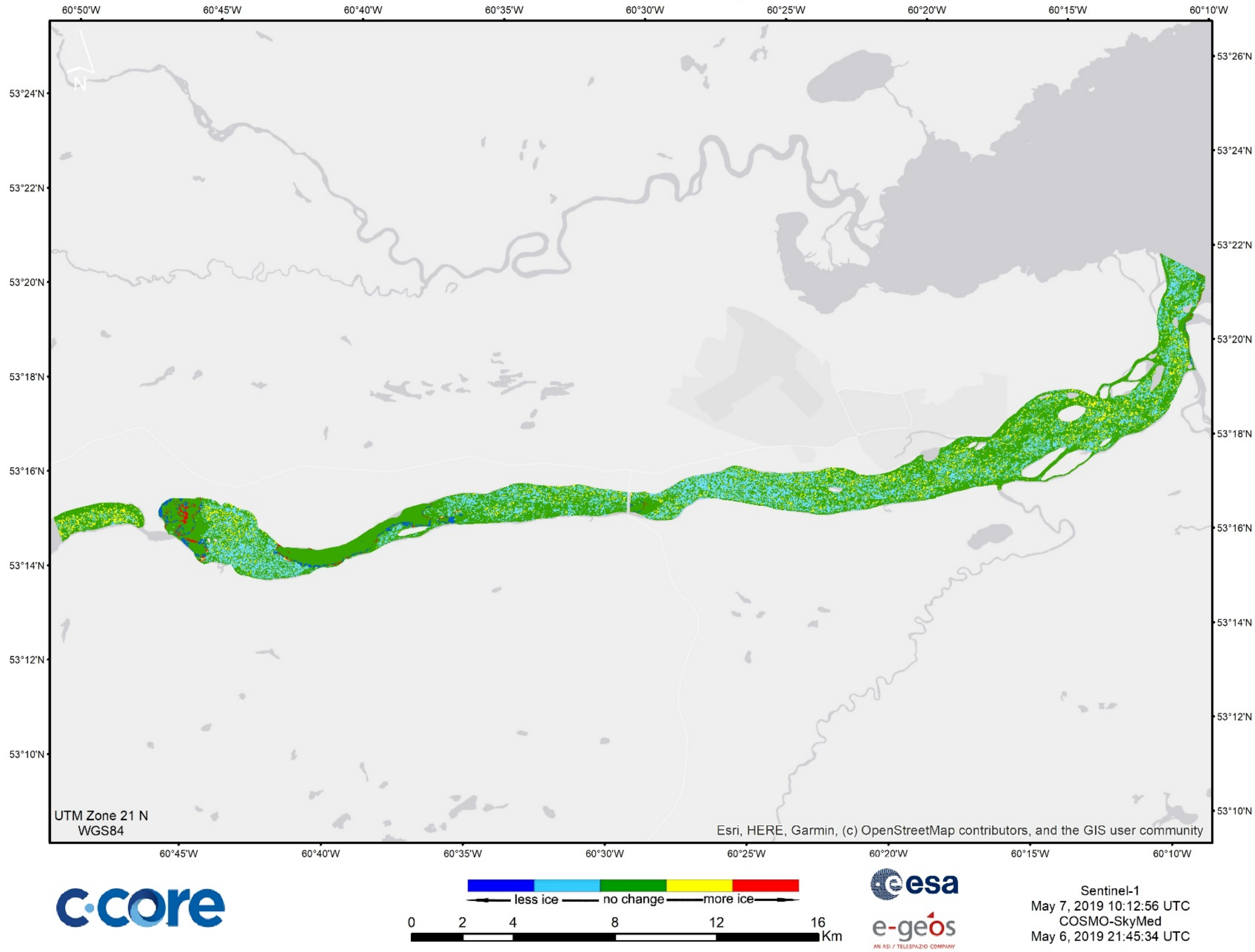
Sentinel-1A IW Descending
Image Acquired May 7, 2019 10:12:56 UTC
Sentinel-1A European Space Agency (ESA) (2019)

# Churchill River - Ice Classification



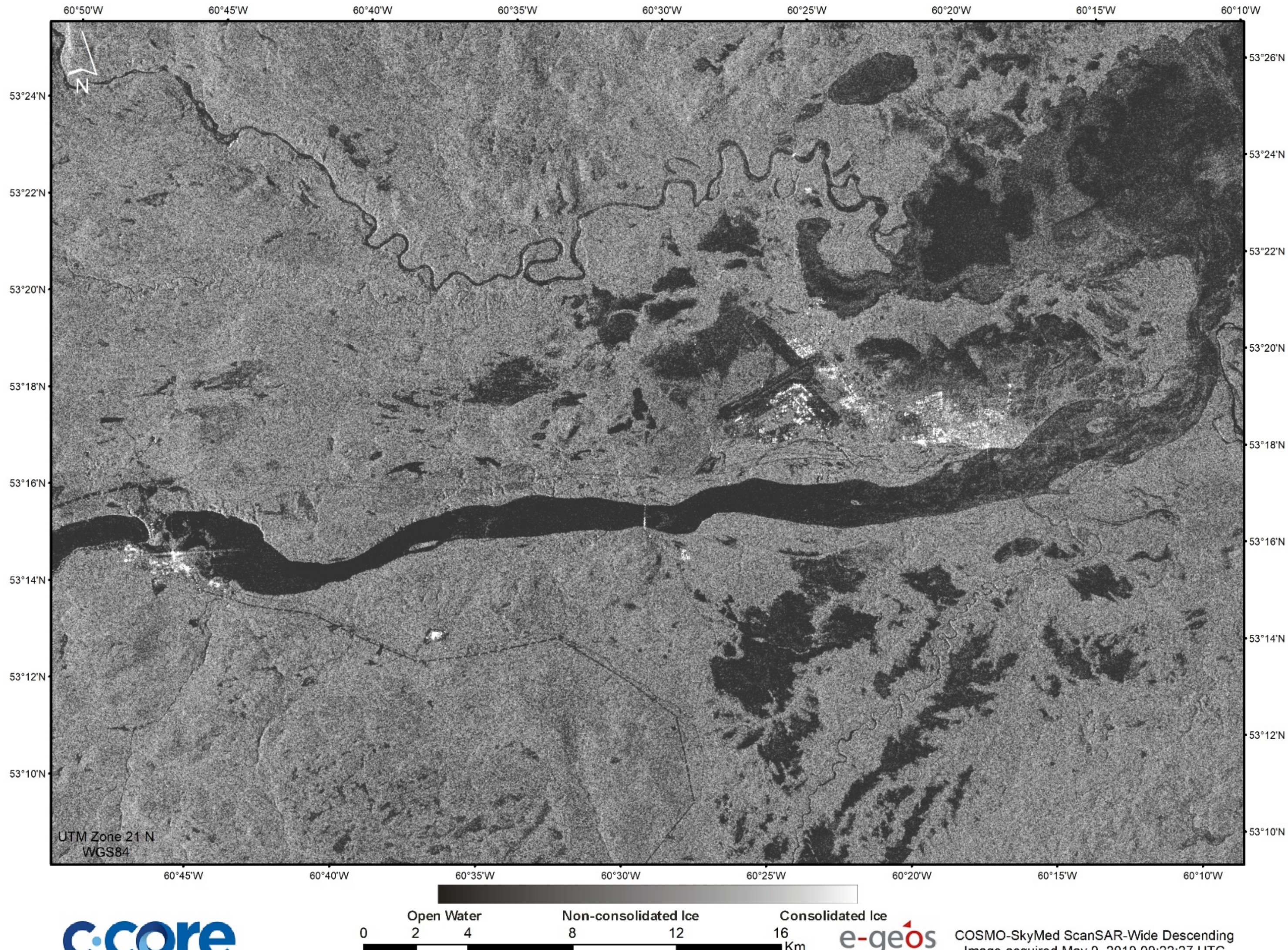

Sentinel-1A IW Descending
Image Acquired May 7, 2019 10:12:56 UTC

# Churchill River - Change Detection



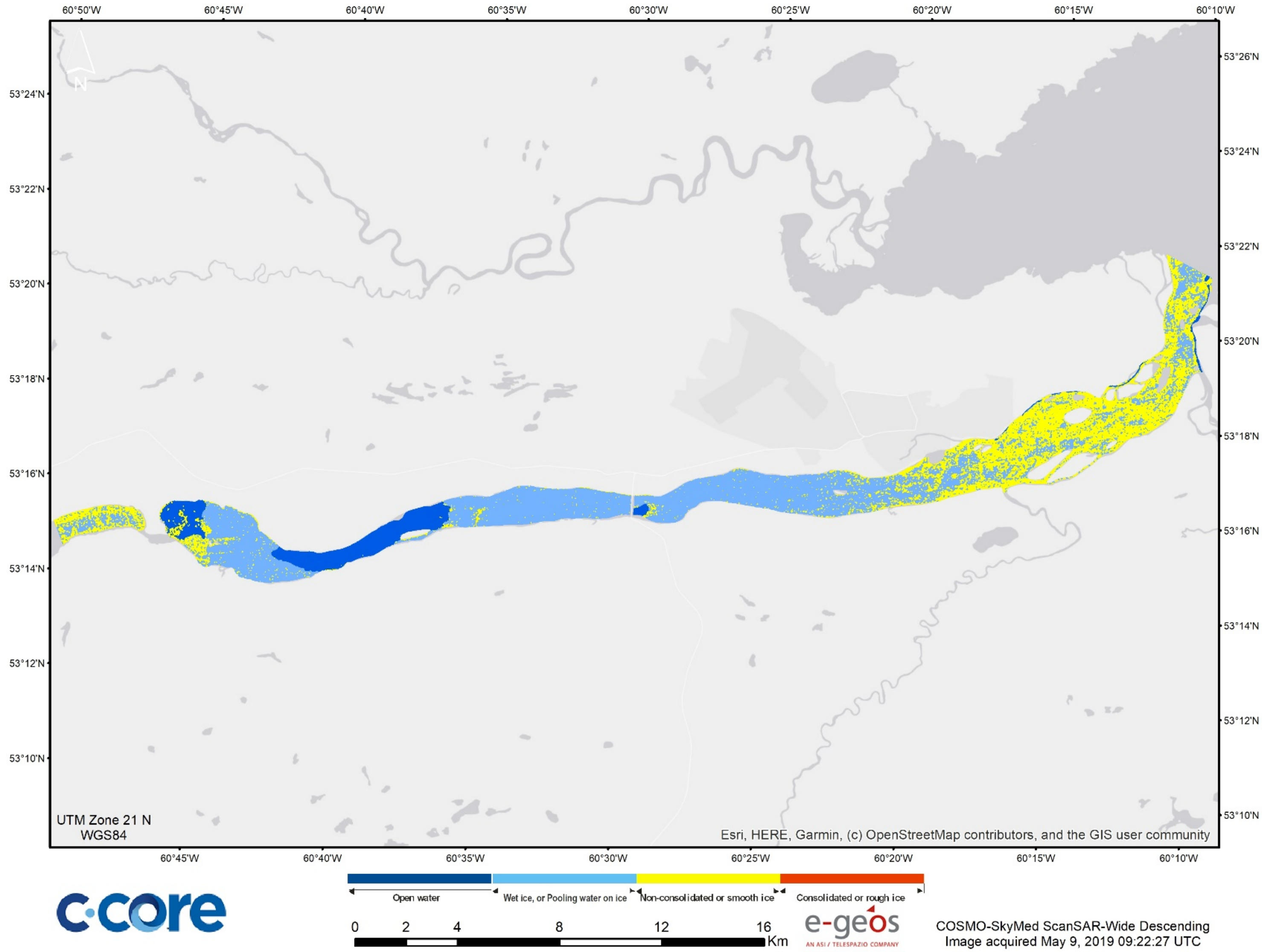

Sentinel-1
May 7, 2019 10:12:56 UTC
COSMO-SkyMed
May 6, 2019 21:45:34 UTC

# Churchill River - Ice Cover



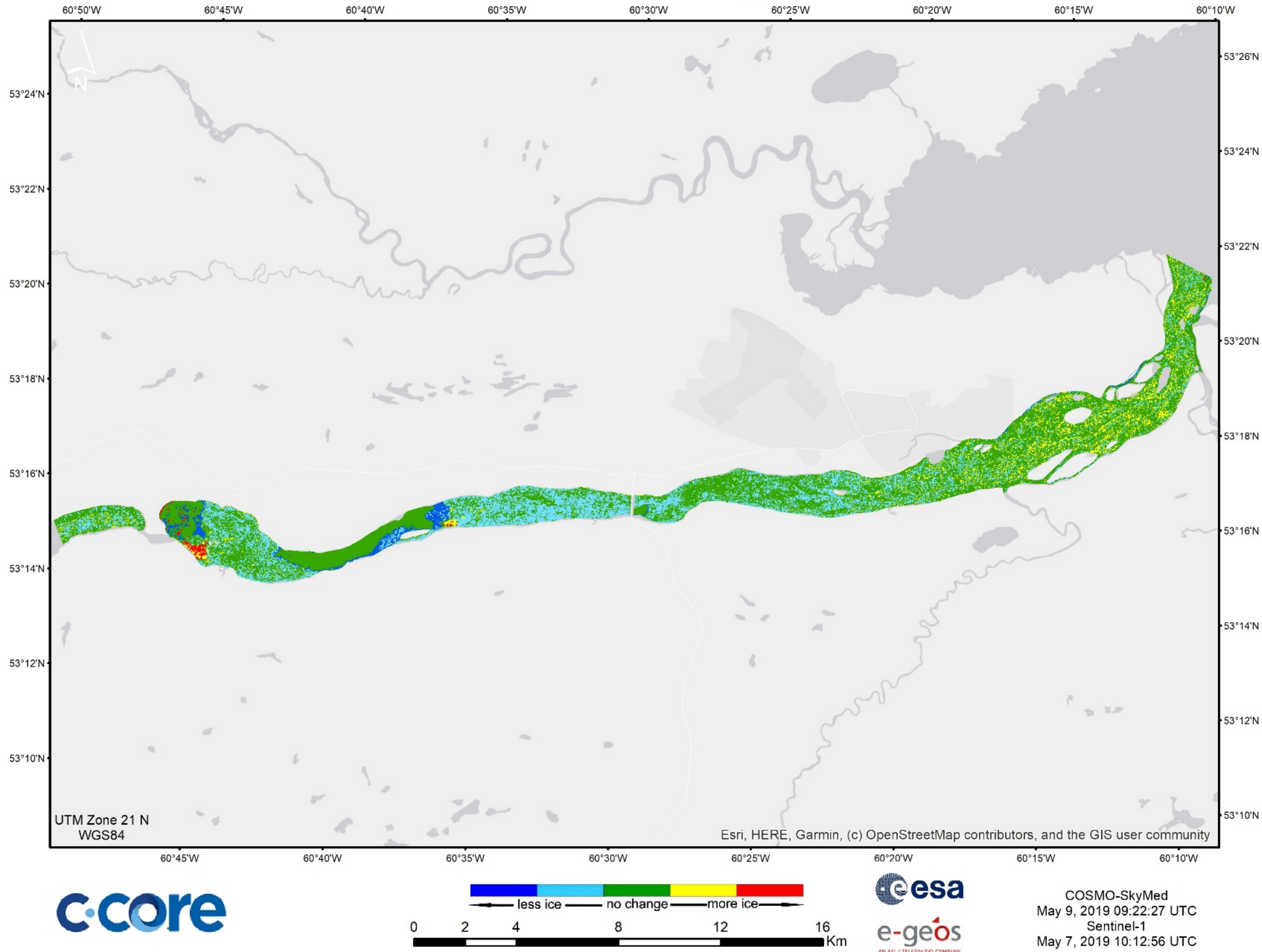

COSMO-SkyMed ScanSAR-Wide Descending
Image acquired May 9, 2019 09:22:27 UTC

# Churchill River - Ice Classification

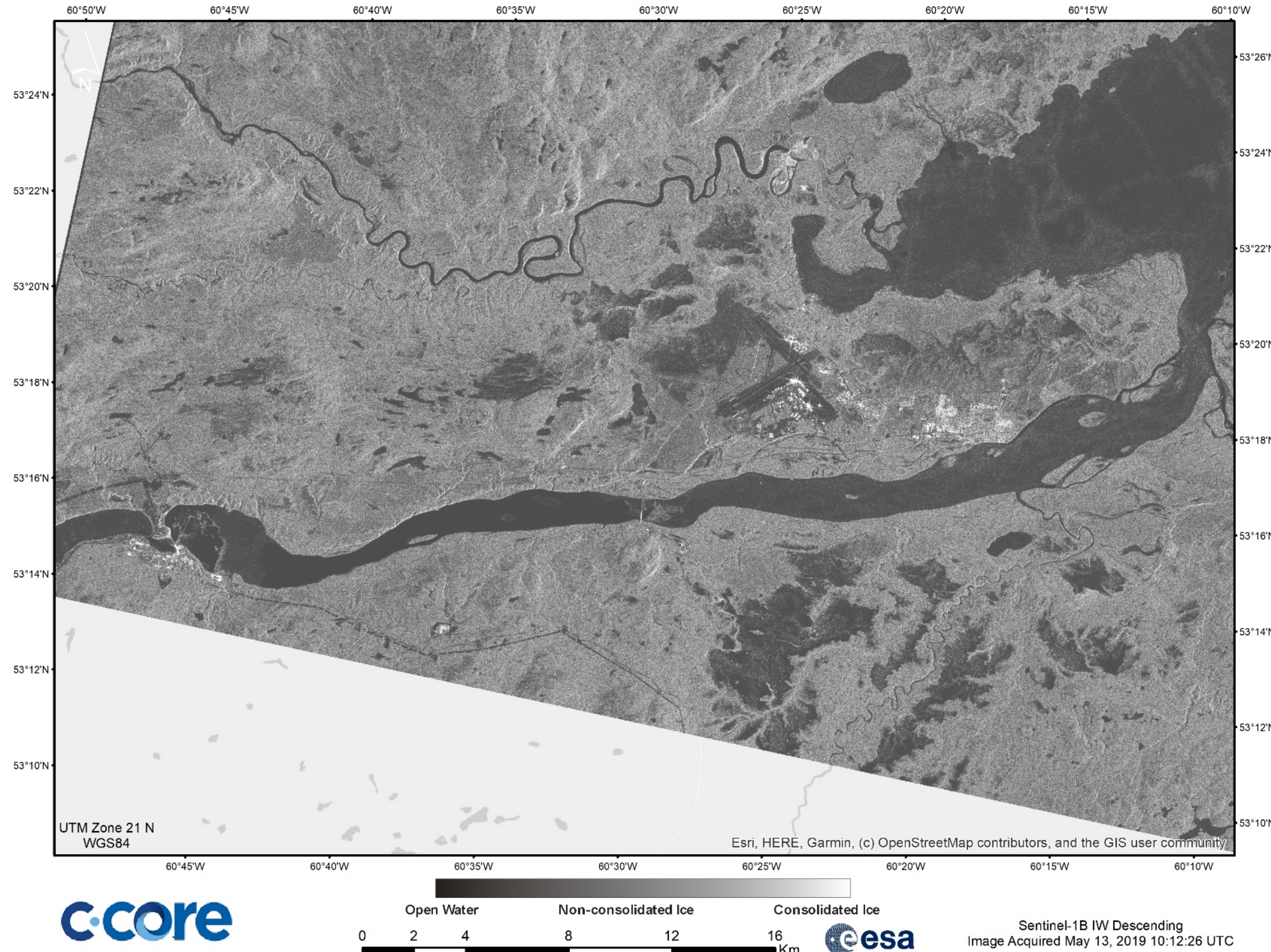



COSMO-SkyMed ScanSAR-Wide Descending
Image acquired May 9, 2019 09:22:27 UTC

# Churchill River - Change Detection

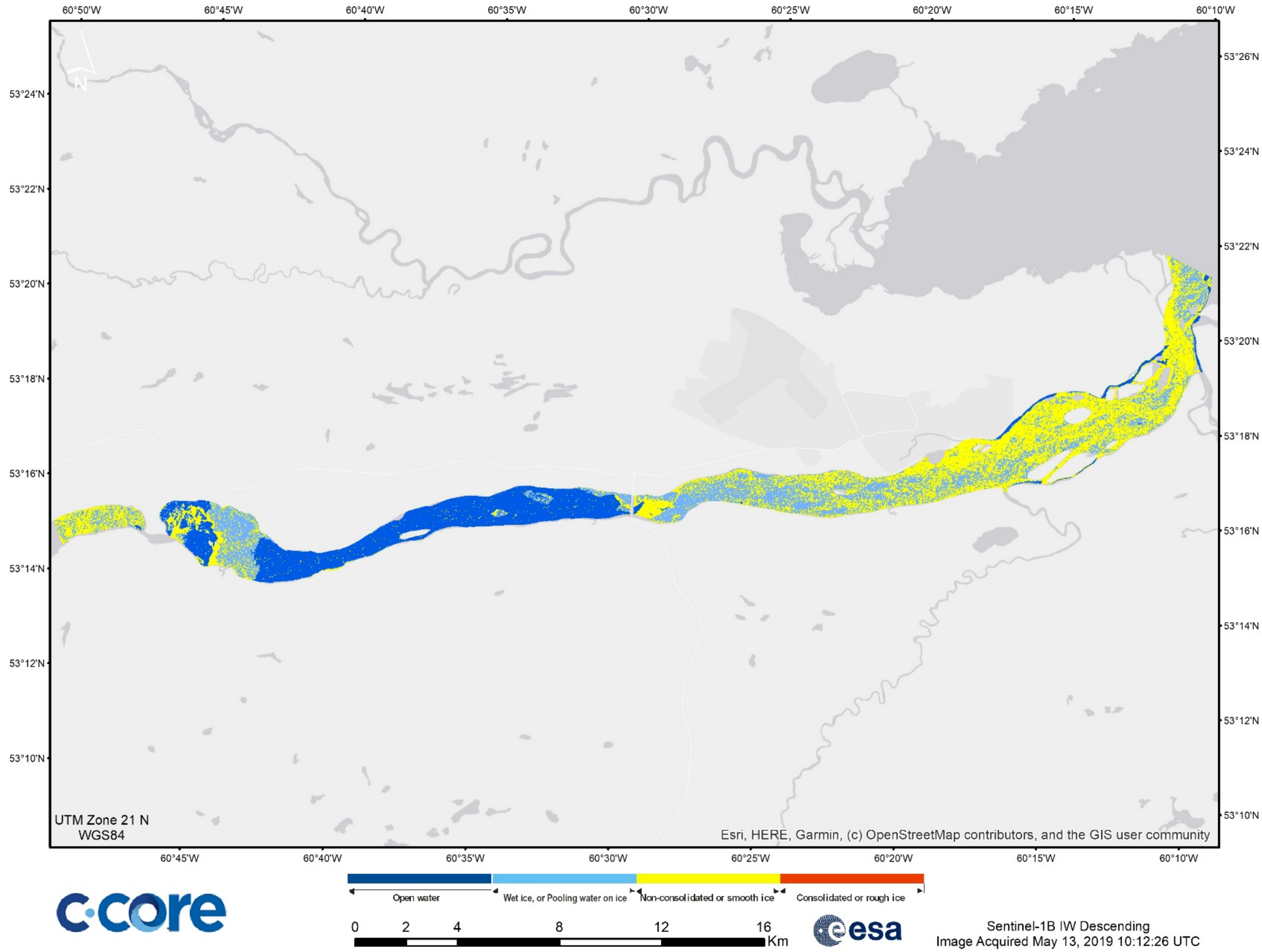


# Churchill River - Ice Cover

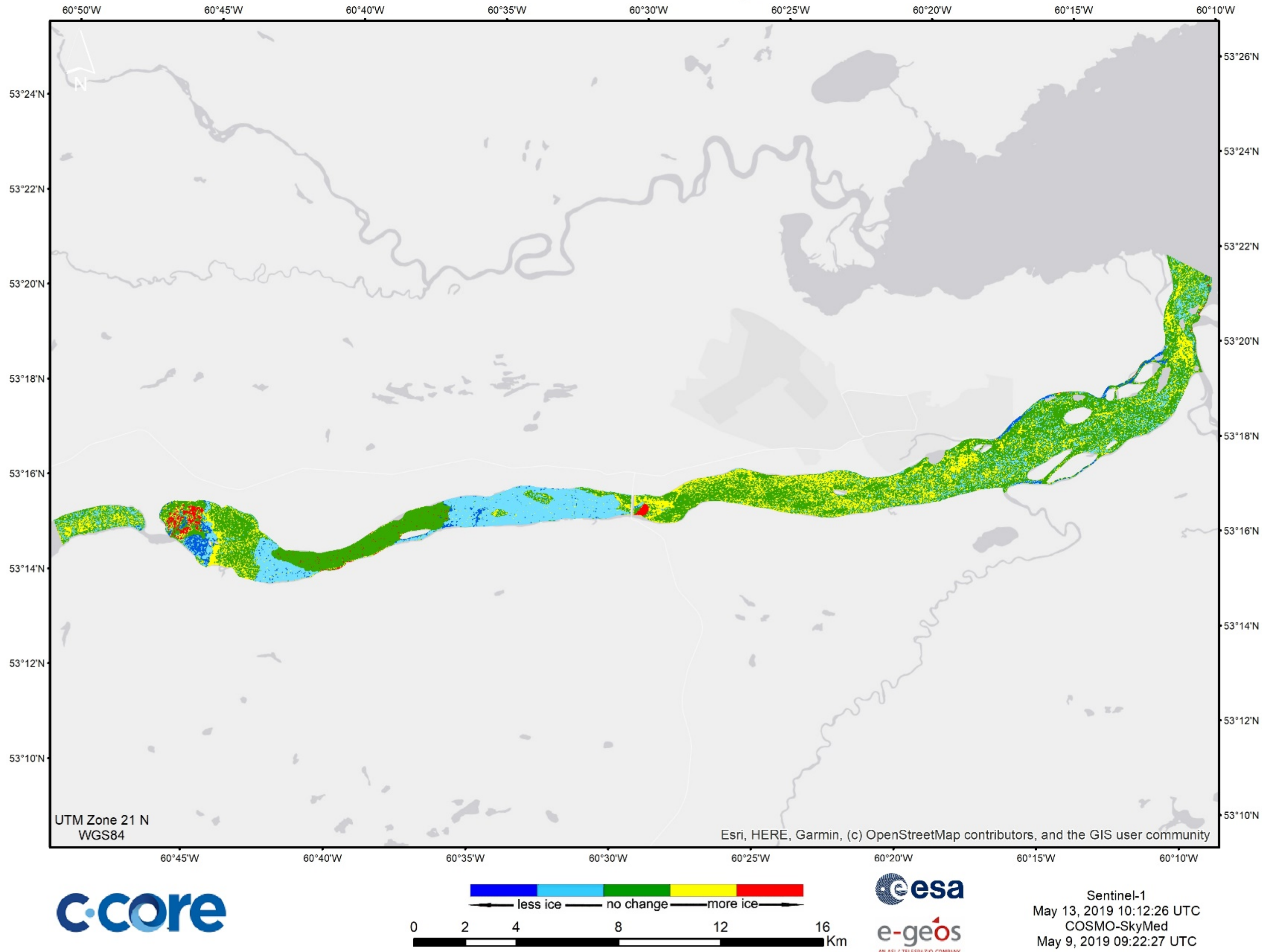



Sentinel-1B IW Descending
Image Acquired May 13, 2019 10:12:26 UTC

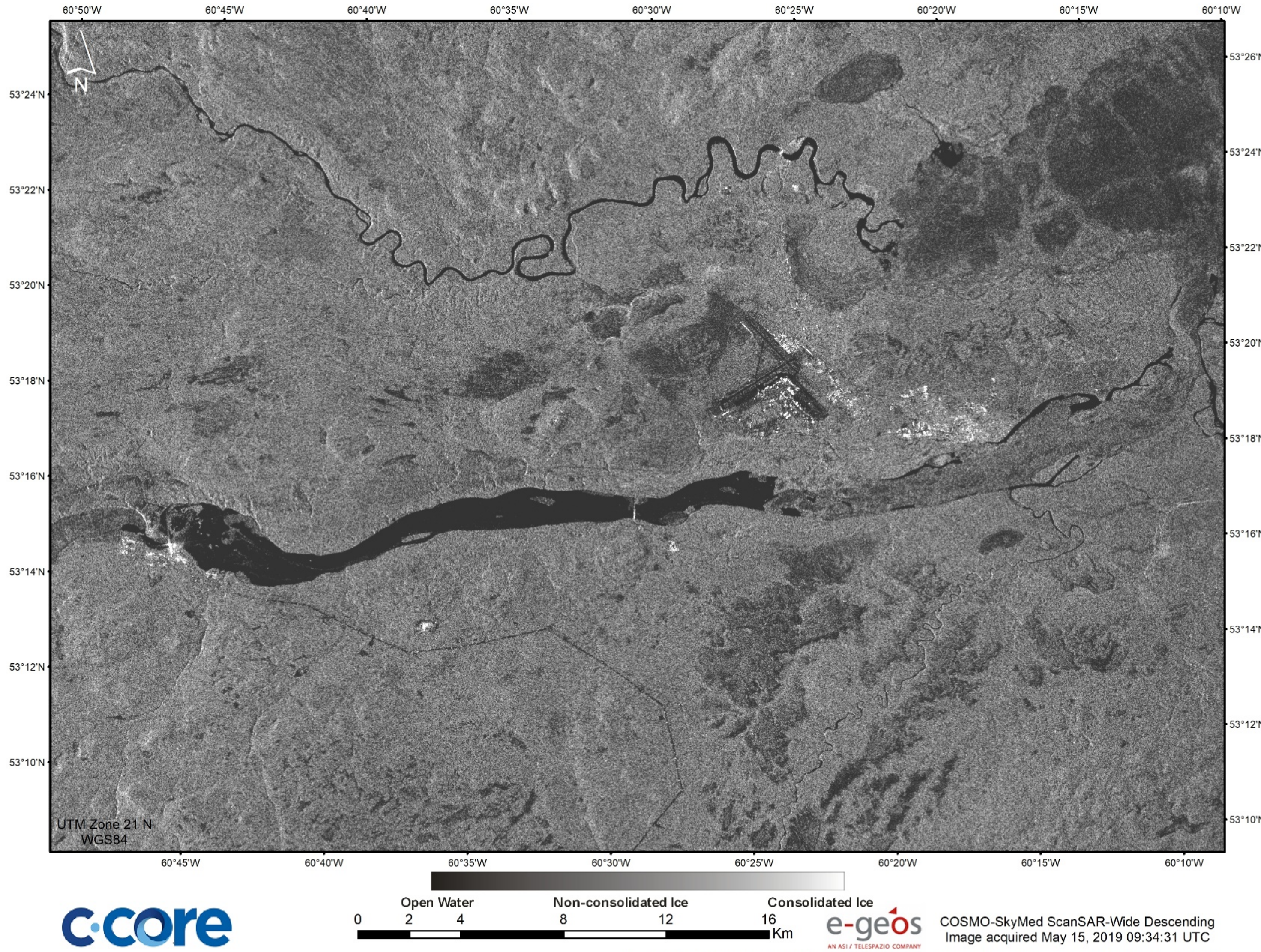
# Churchill River - Ice Classification



# Churchill River - Change Detection

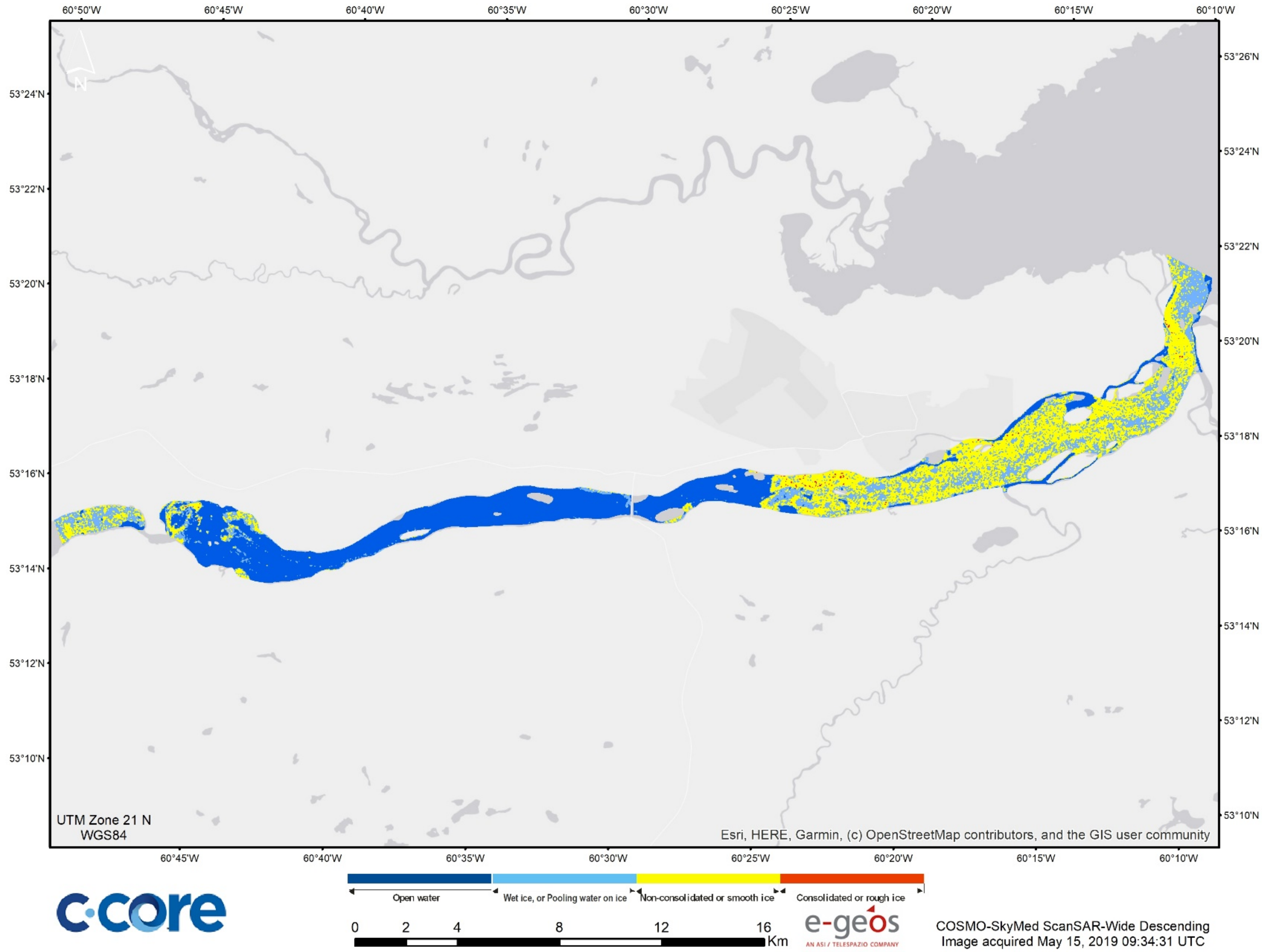


# Churchill River - Ice Cover



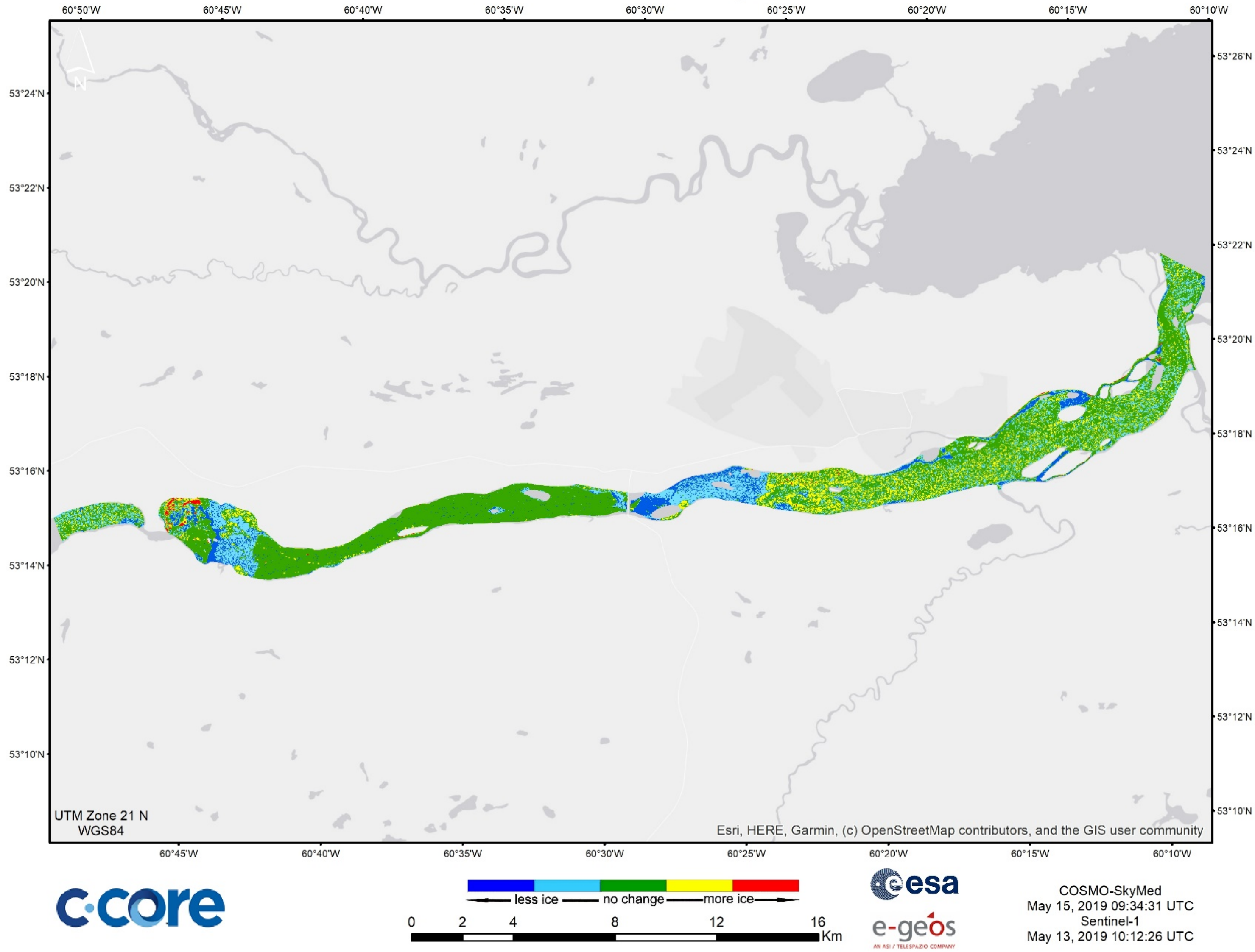

COSMO-SkyMed ScanSAR-Wide Descending
Image acquired May 15, 2019 09:34:31 UTC

# Churchill River - Ice Classification



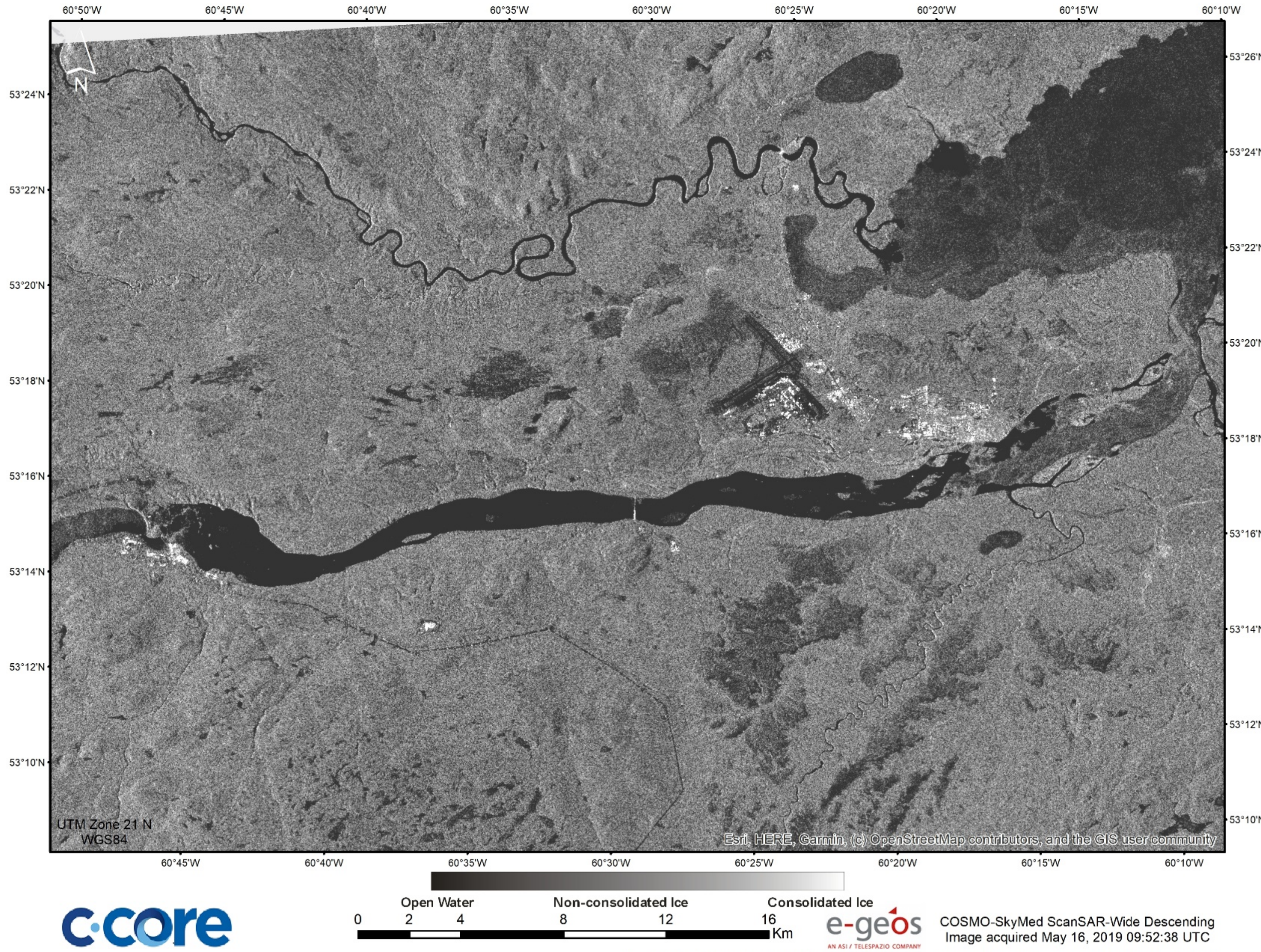

COSMO-SkyMed ScanSAR-Wide Descending
Image acquired May 15, 2019 09:34:31 UTC

# Churchill River - Change Detection



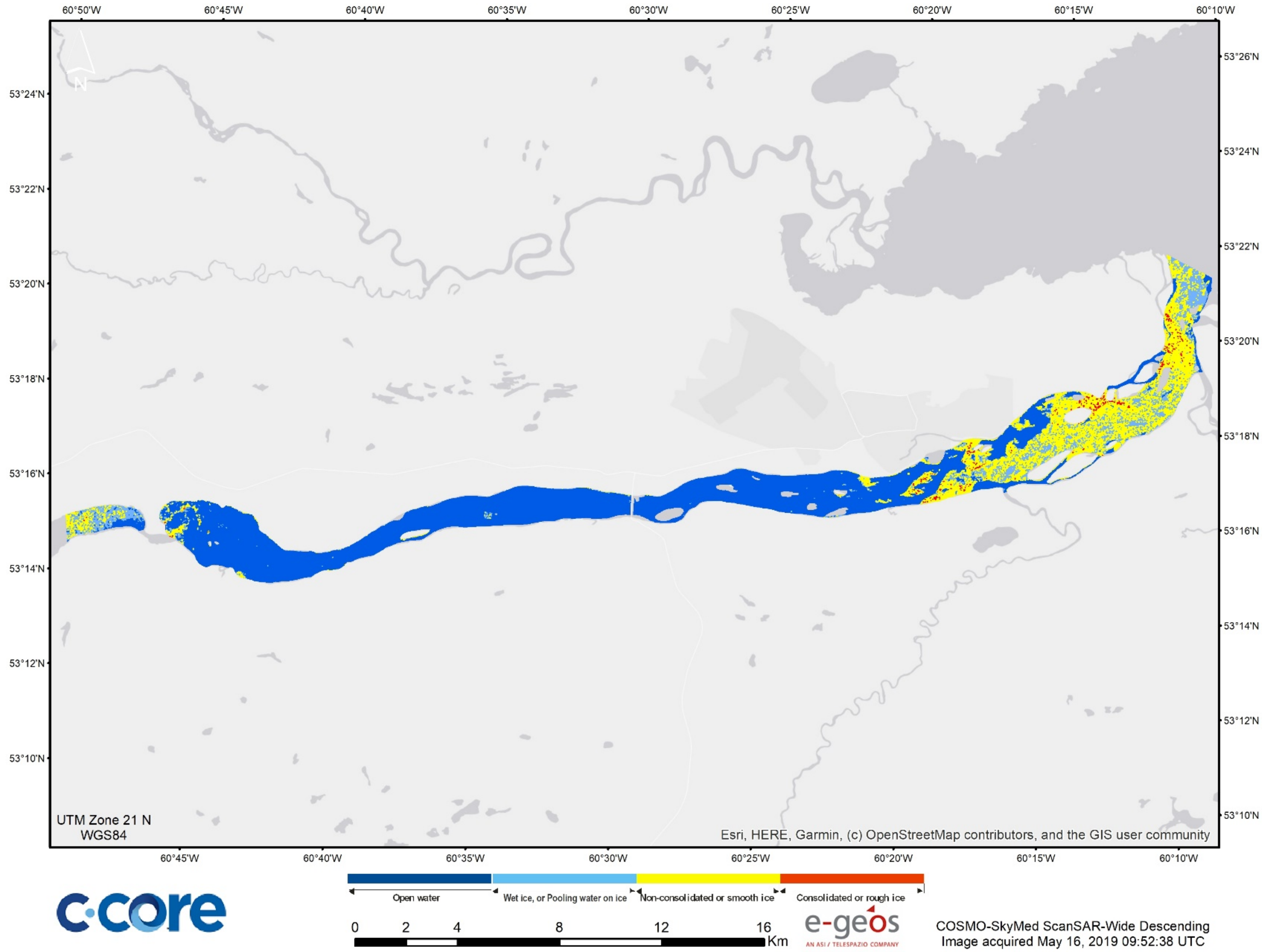

COSMO-SkyMed
May 15, 2019 09:34:31 UTC
Sentinel-1
May 13, 2019 10:12:26 UTC

# Churchill River - Ice Cover



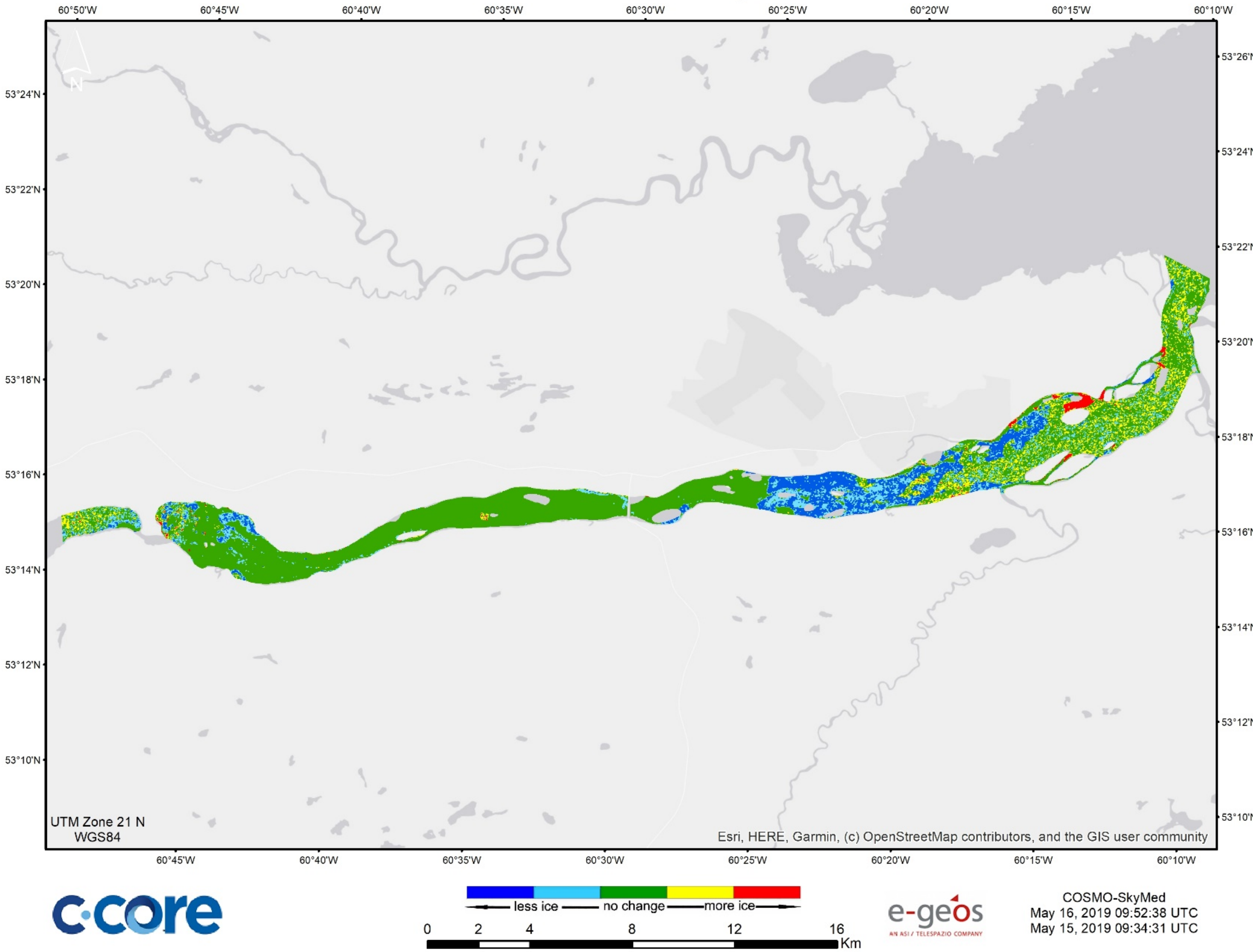

COSMO-SkyMed ScanSAR-Wide Descending
Image acquired May 16, 2019 09:52:38 UTC

# Churchill River - Ice Classification

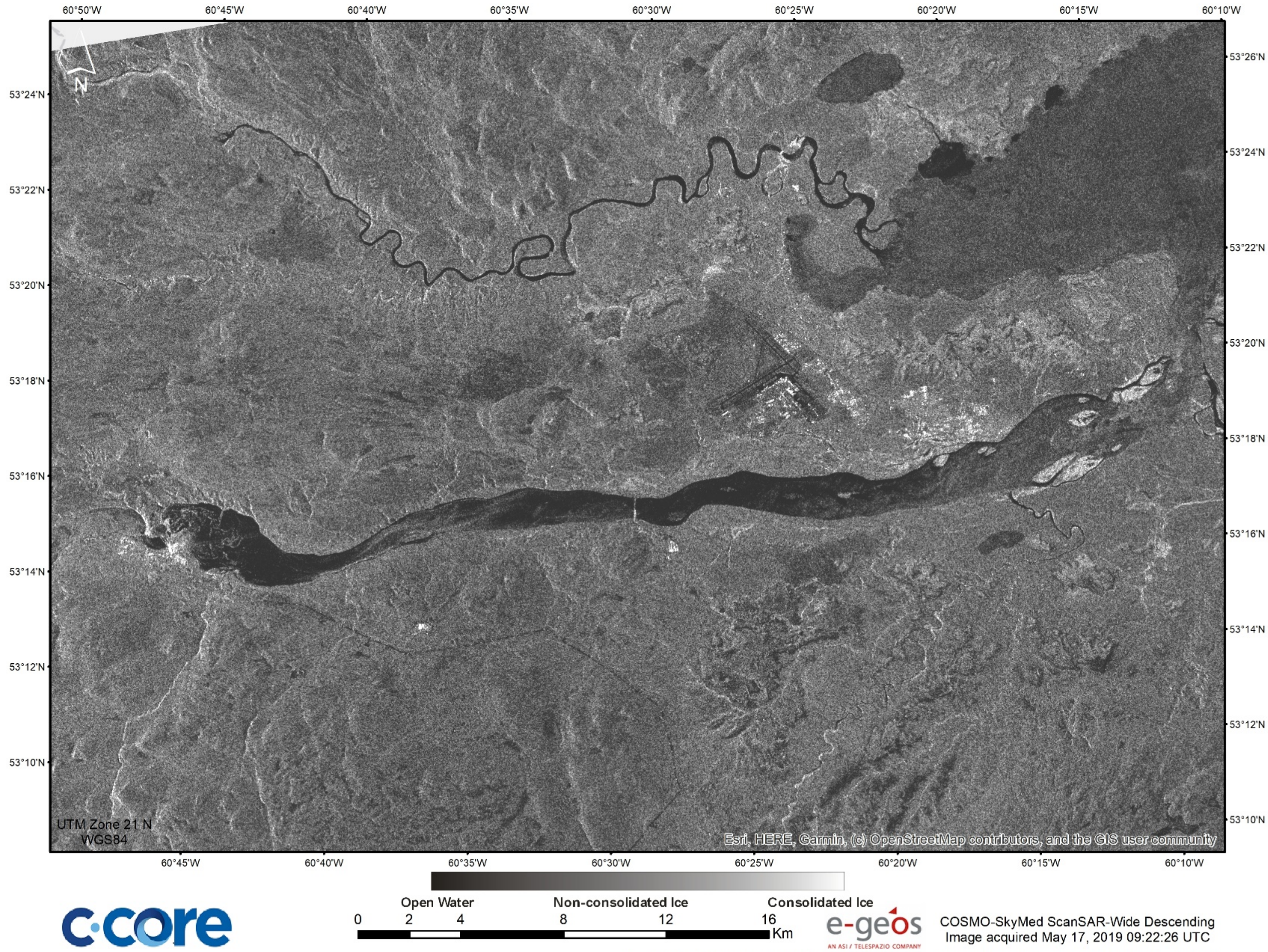



COSMO-SkyMed ScanSAR-Wide Descending
Image acquired May 16, 2019 09:52:38 UTC

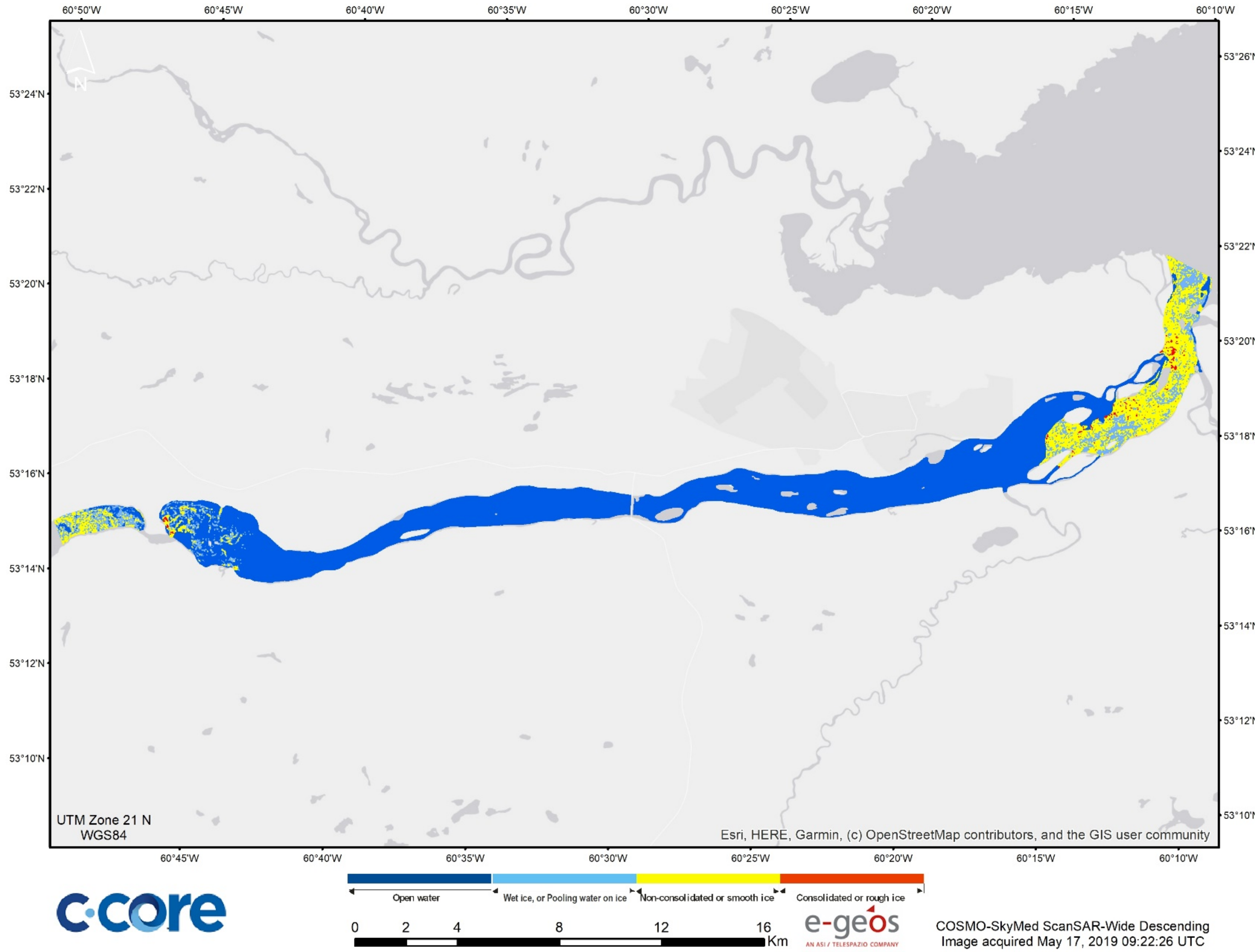
# Churchill River - Change Detection



# Churchill River - Ice Cover

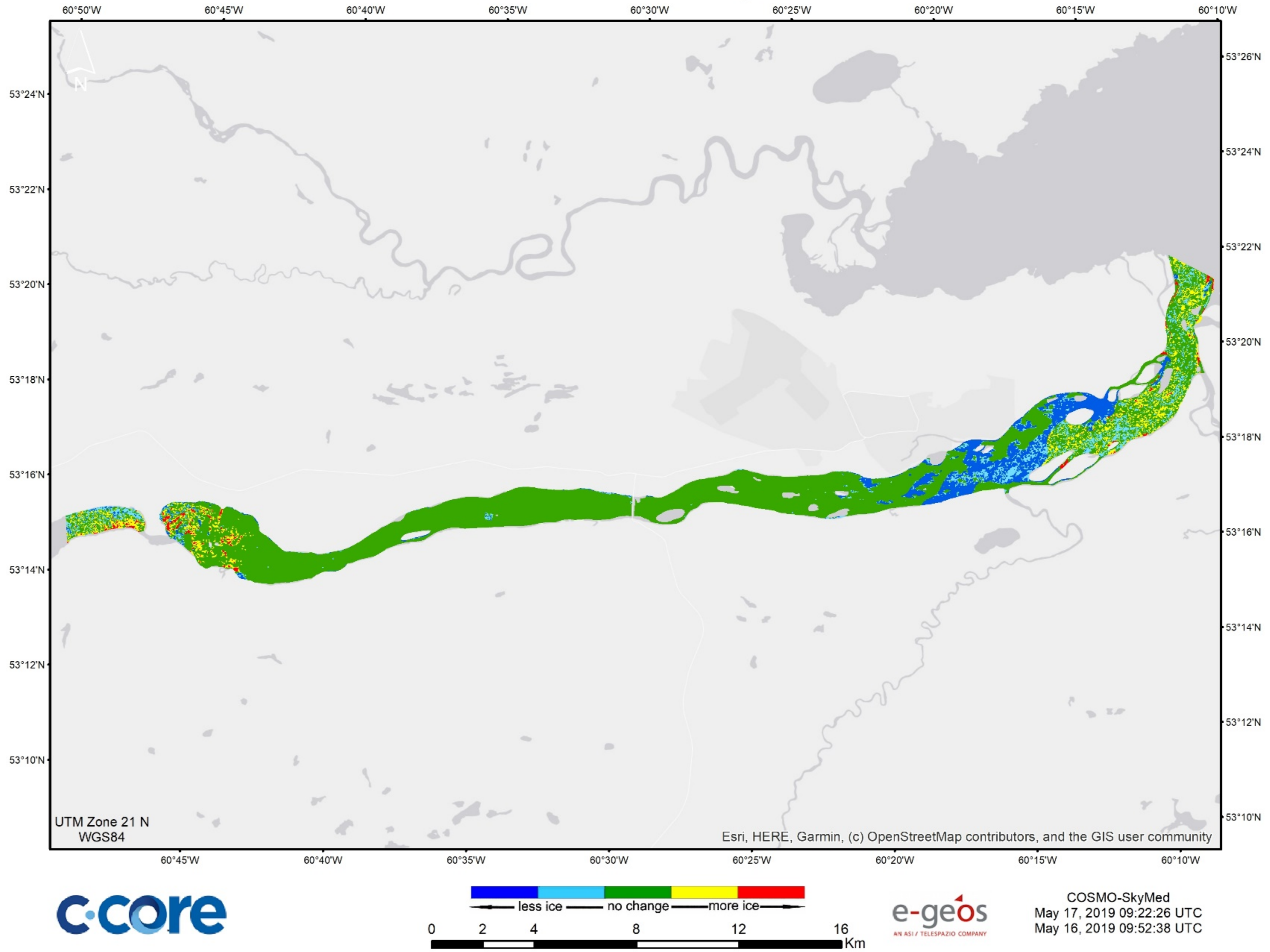


# Churchill River - Ice Classification

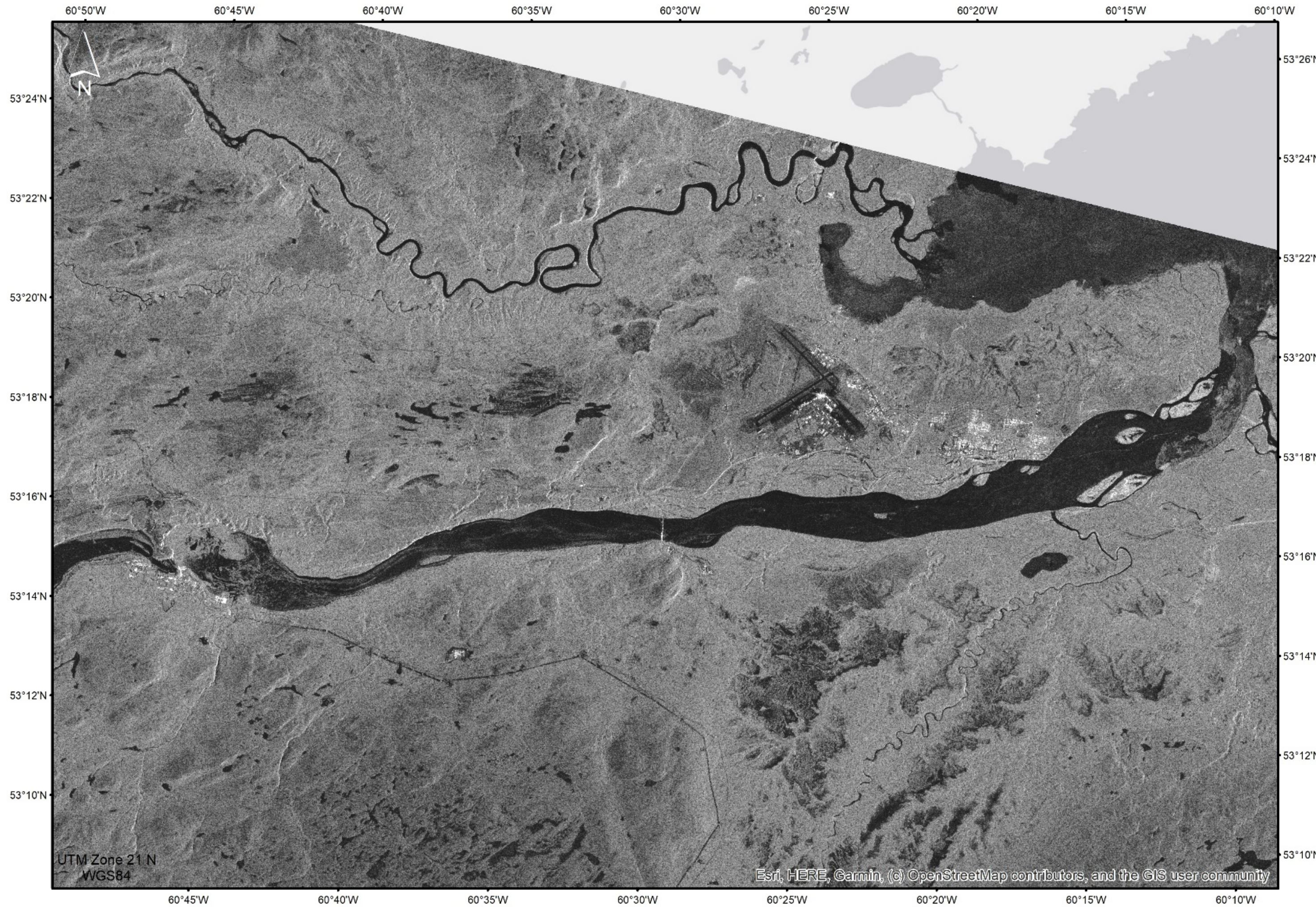



COSMO-SkyMed ScanSAR-Wide Descending
Image acquired May 17, 2019 09:22:26 UTC

# Churchill River - Change Detection



# Churchill River - Ice Cover

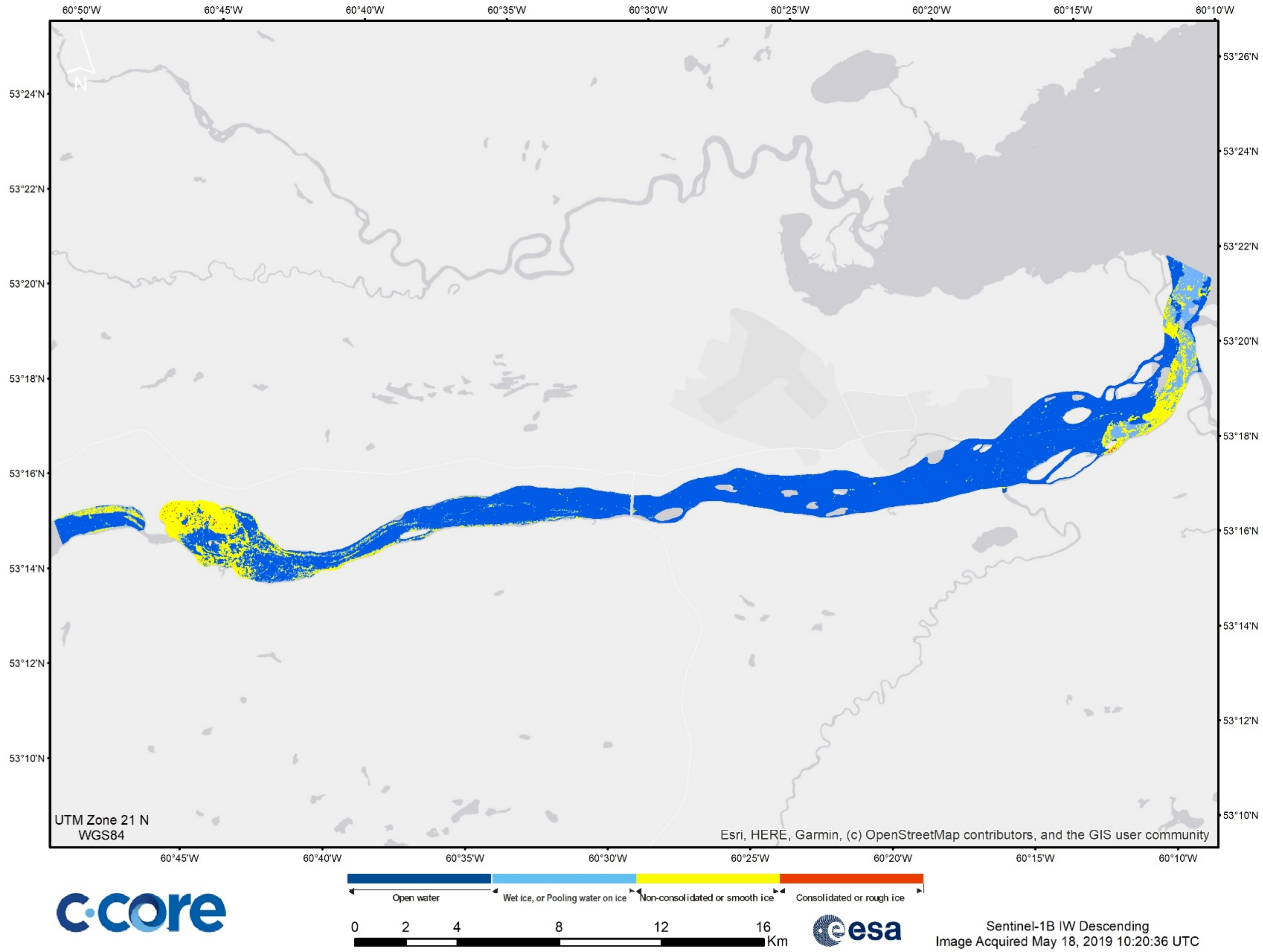



Open Water | Non-consolidated Ice | Consolidated Ice

0 2 4 8 12 16 Km

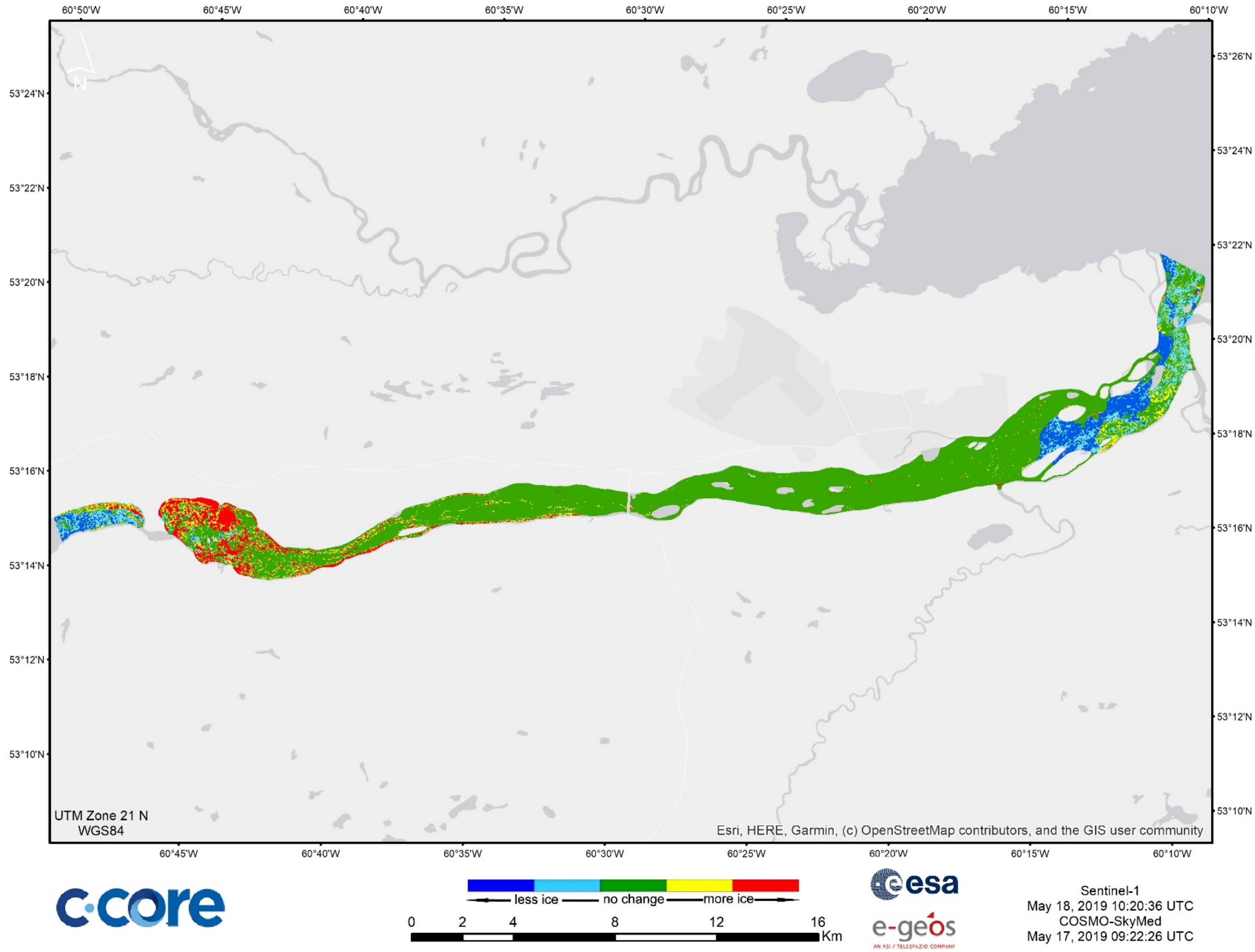
Sentinel-1B IW Descending
Image Acquired May 18, 2019 10:20:36 UTC
Sentinel-1B European Space Agency (ESA) (2019)

# Churchill River - Ice Classification




Sentinel-1B IW Descending
Image Acquired May 18, 2019 10:20:36 UTC

# Churchill River - Change Detection



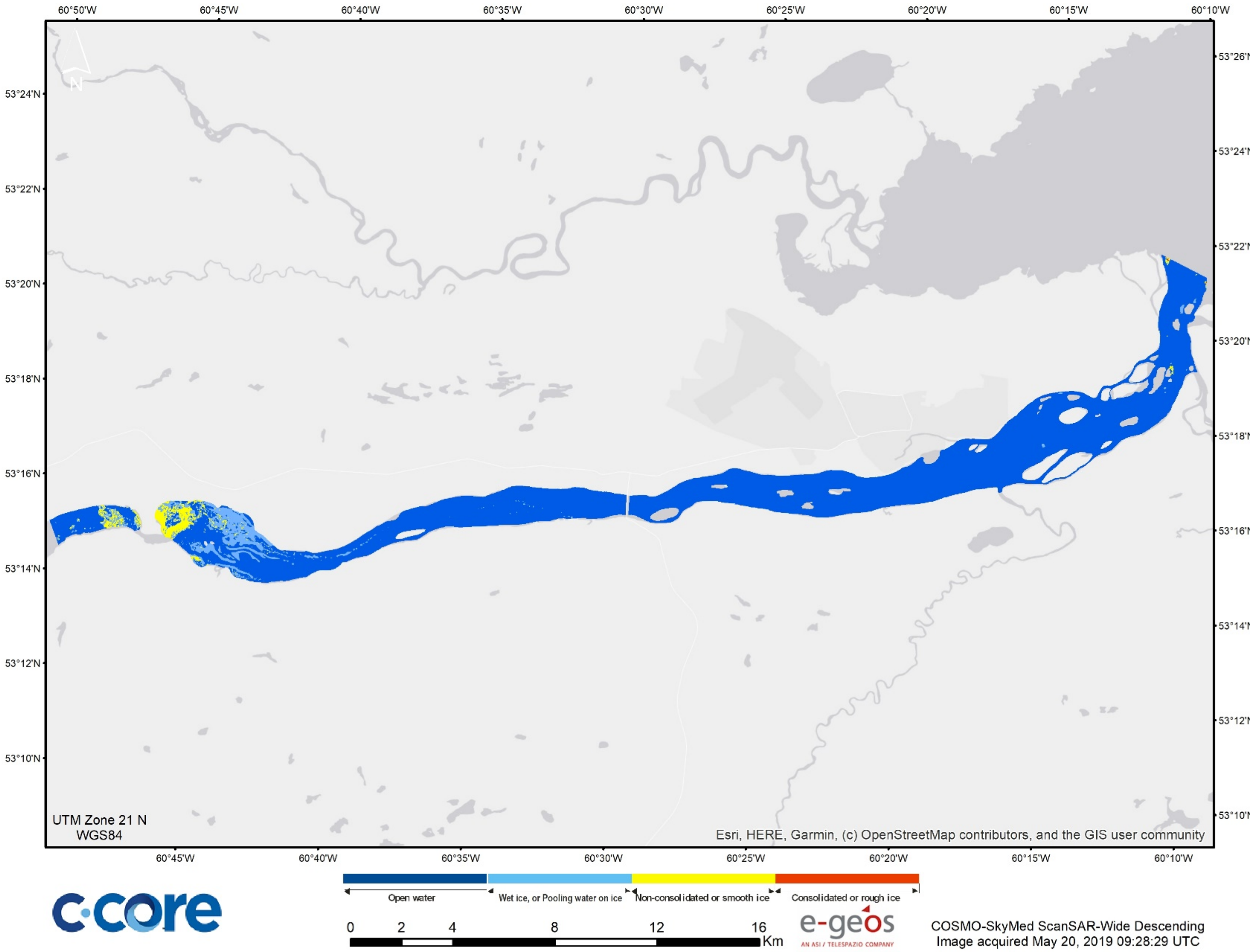
# Churchill River - Ice Cover


Open Water | Non-consolidated Ice | Consolidated Ice

0 2 4 8 12 16 Km

COSMO-SkyMed ScanSAR-Wide Descending
Image acquired May 20, 2019 09:28:29 UTC

# Churchill River - Ice Classification

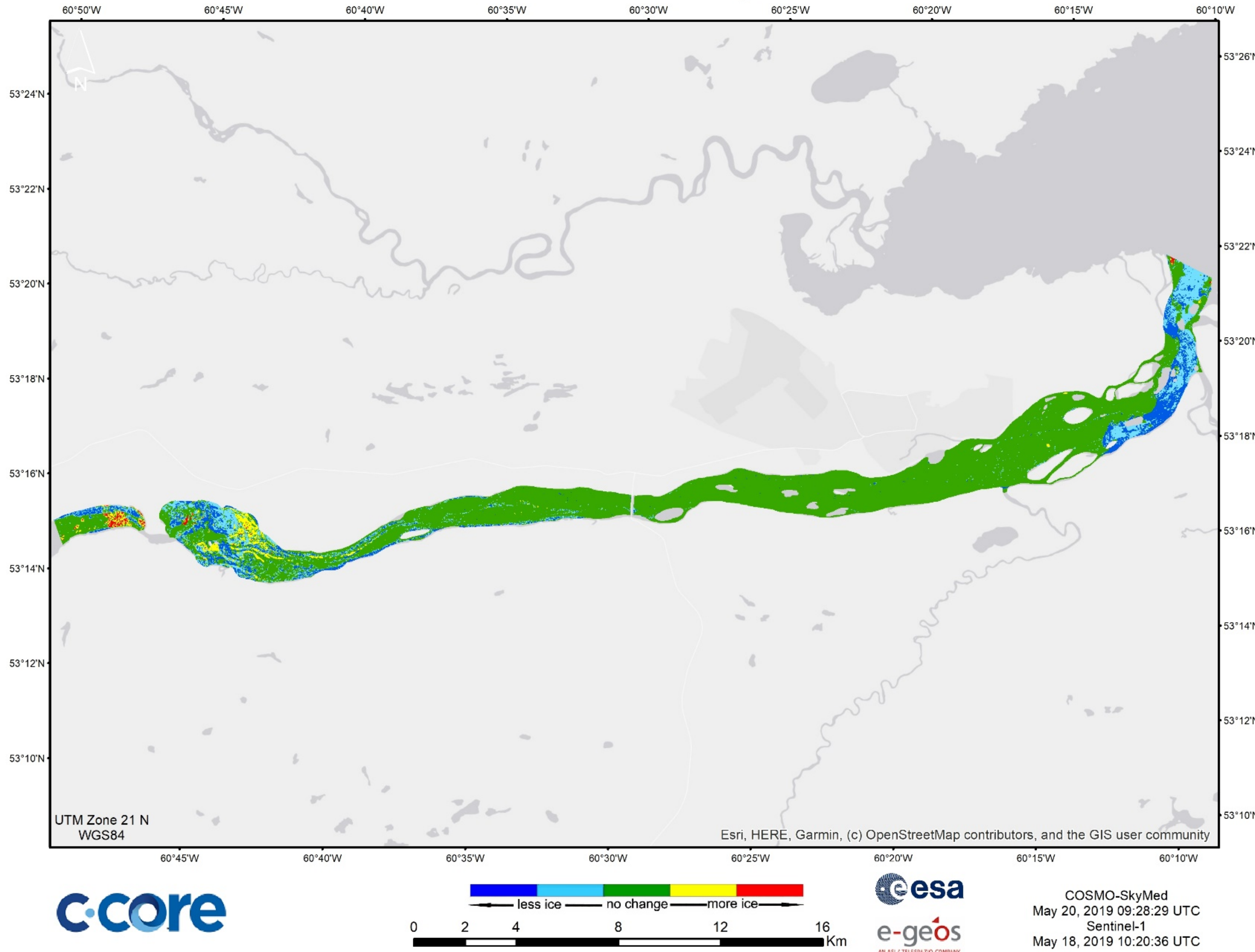



C-CORE

e-geos AN ASI / TELESPAZIO COMPANY

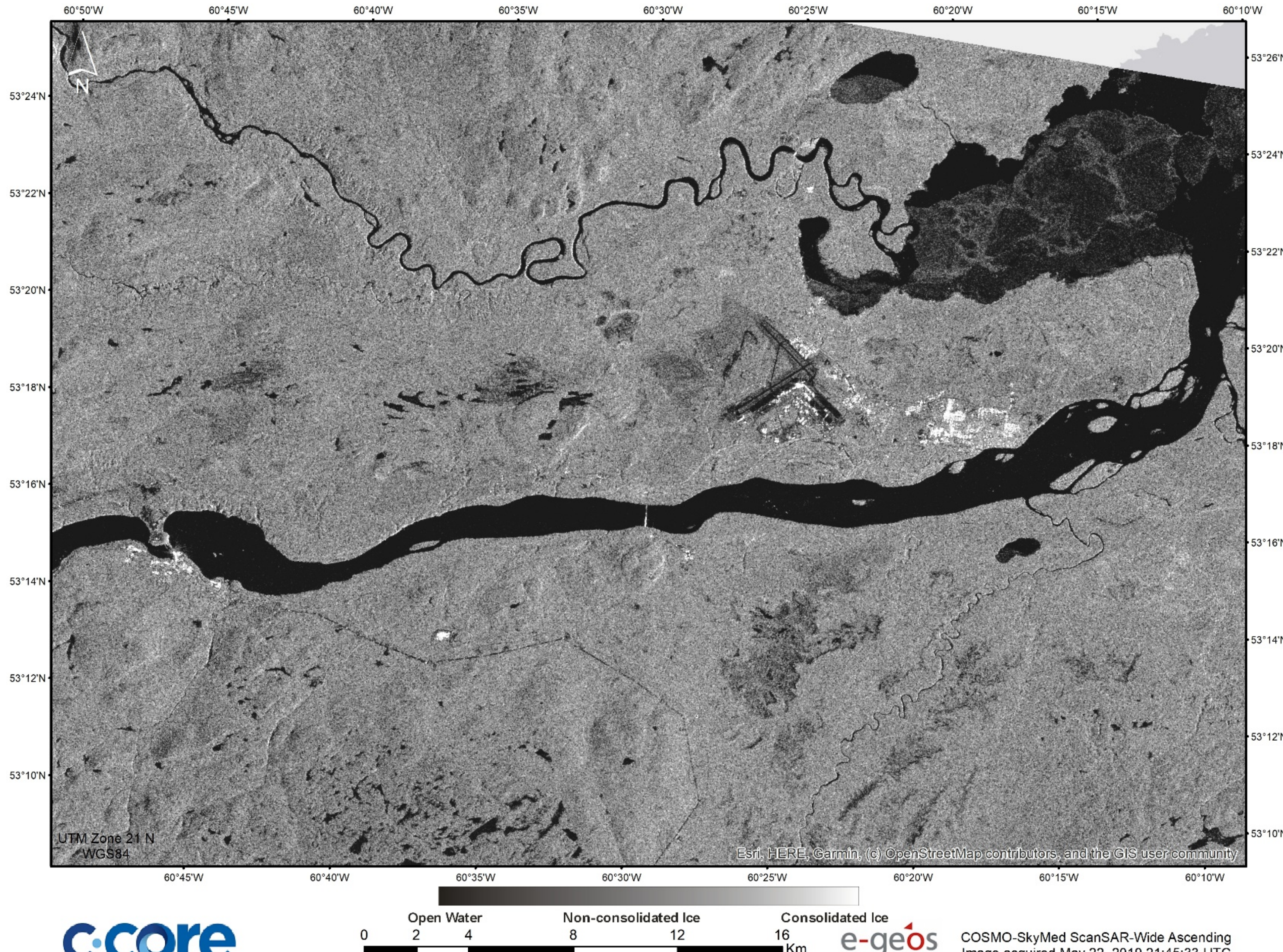
COSMO-SkyMed ScanSAR-Wide Descending
Image acquired May 20, 2019 09:28:29 UTC

# Churchill River - Change Detection




COSMO-SkyMed
May 20, 2019 09:28:29 UTC
Sentinel-1
May 18, 2019 10:20:36 UTC

# Churchill River - Ice Cover

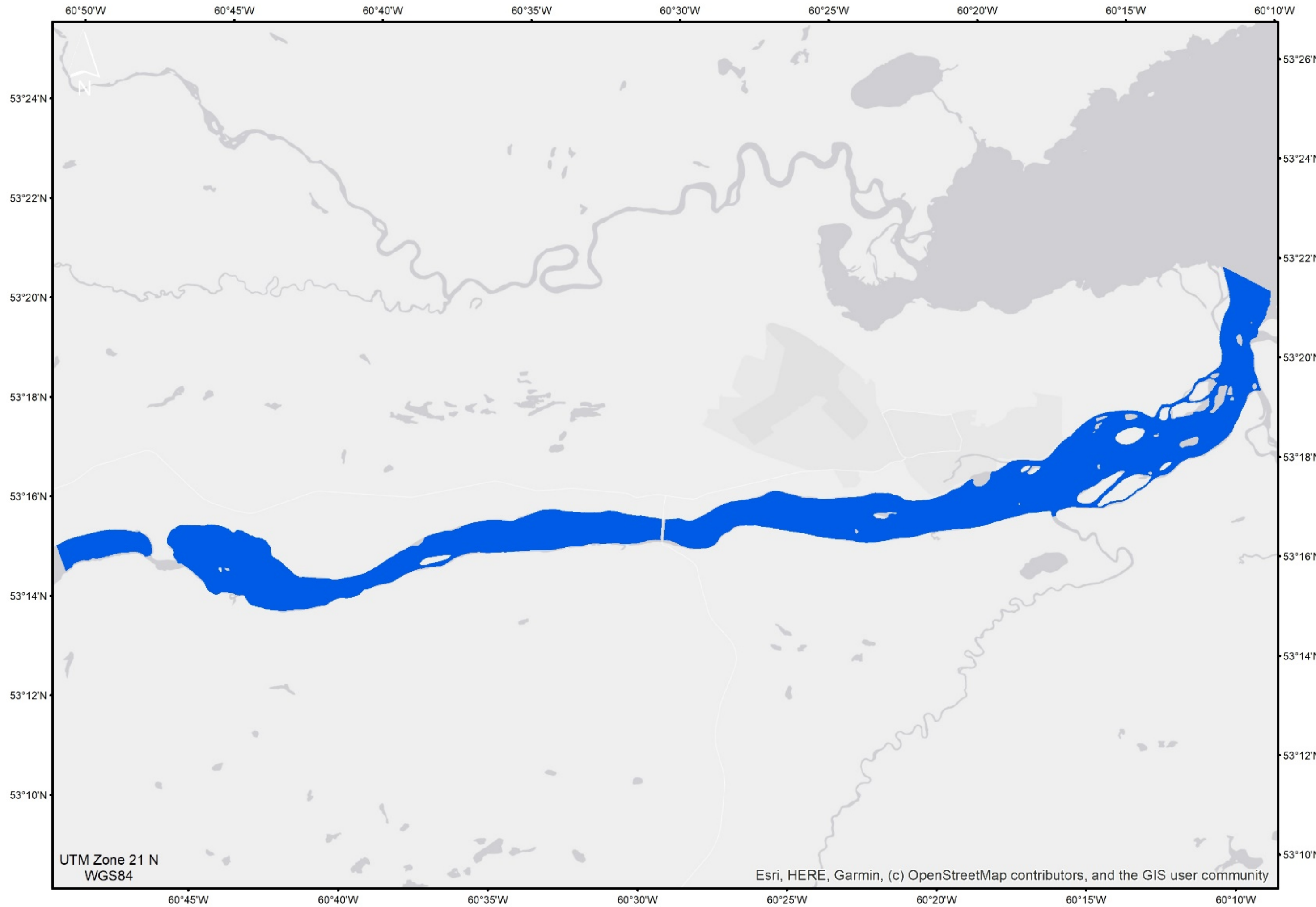



C-CORE

e-geos
AN ASI / TELESPAZIO COMPANY

COSMO-SkyMed ScanSAR-Wide Ascending
Image acquired May 22, 2019 21:45:33 UTC

# Churchill River - Ice Classification

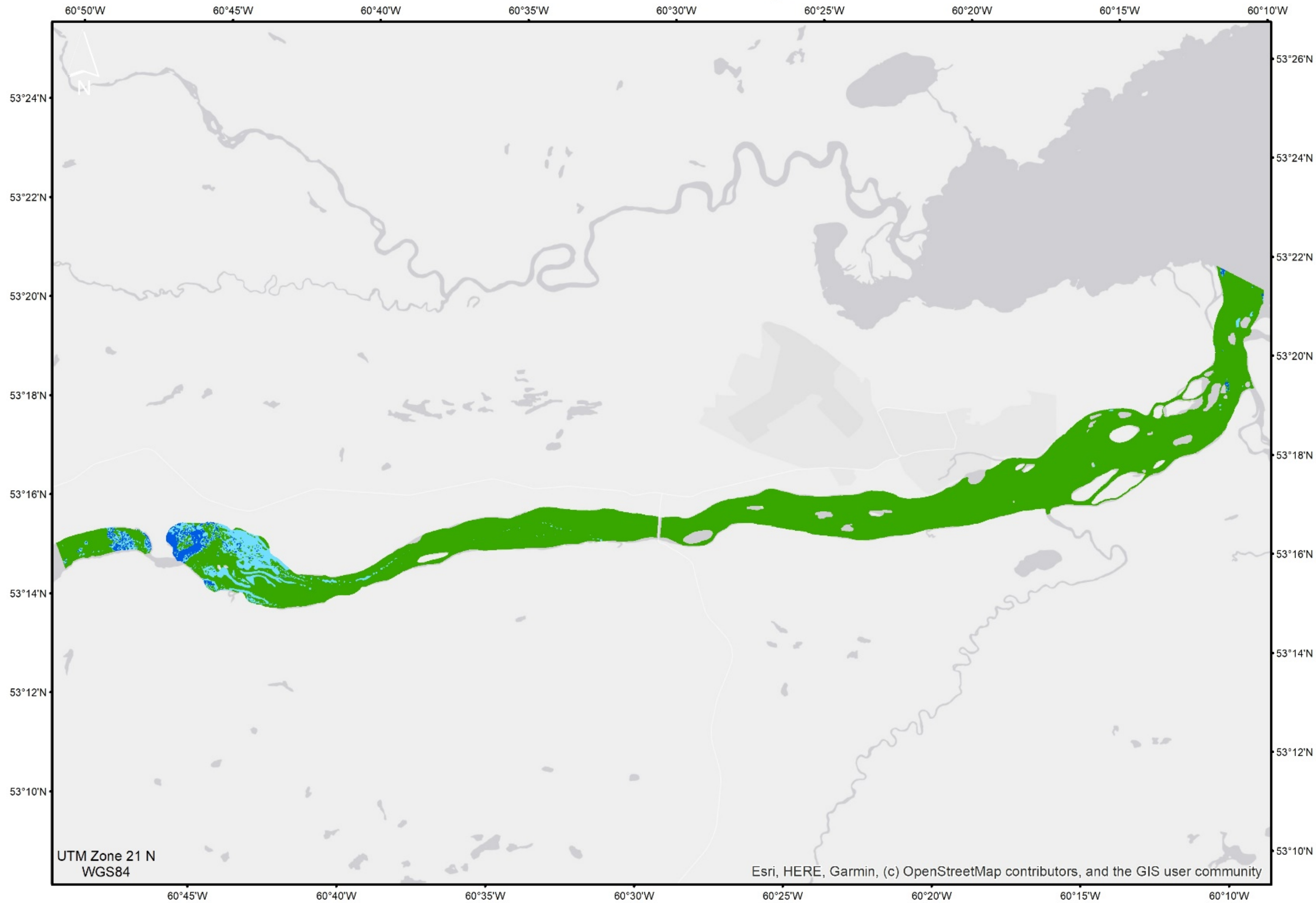



Open water | Wet ice, or Pooling water on ice | Non-consolidated or smooth ice | Consolidated or rough ice

0 2 4 8 12 16 Km

COSMO-SkyMed ScanSAR-Wide Ascending
Image acquired May 22, 2019 21:45:33 UTC

# Churchill River - Change Detection




less ice — no change — more ice

0 2 4 8 12 16 Km

COSMO-SkyMed
May 22, 2019 21:45:33 UTC
May 20, 2019 09:28:29 UTC