2016-2017 Ice Observation Survey
Mud Lake Crossing, Lower Churchill River
LC-EV-107

Prepared For:
Golder Associates Ltd.
Suite 204, 62 Pippy Place
St. John’s, NL
A1B 4H7

Prepared By:
Sikumiut Environmental Management Ltd.
2nd Floor, 79 Mews Place
St. John’s, NL
A1B 4N2

September 21, 2017
Figure 3.1  Mud Lake Web Camera Images During the Freeze-Up Process, November 15-30, 2016..............................................................................................................................16
Figure 3.2  Mud Lake Web Camera Images During the Freeze-Up Process, December 1 - 6, 2016.................................................................................................................................17
Figure 3.3  Mud Lake Web Camera Images During the Break-Up Process, May 13-18, 2017.................................................................................................................................18
Figure 3.4  Mud Lake Web Camera Images During the Break-Up Process, May 19 - 24, 2017.................................................................................................................................19
Figure 3.5  Maximum and Minimum Temperatures for Happy Valley – Goose Bay, Labrador During Freeze-up.................................................................25
Figure 3.6  Maximum and Minimum Temperatures for Happy Valley – Goose Bay, Labrador During Break-up.................................................................26

LIST OF APPENDICES

APPENDIX A  Mud Lake Freeze-Up Satellite Imagery
APPENDIX B  Mud Lake Break-Up Satellite Imagery
EXECUTIVE SUMMARY

The Ice Survey Program for the Lower Churchill Project (LCP) is focussed on surveying ice freeze-up and break-up in the Lower Churchill River pre- and post-impoundment. The program during the 2016-2017 ice season was the fourth in a continuation of previous monitoring during the construction period of the LCP to confirm 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 concentration;
- 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 Environment and Conservation, Water Resources Management Division (NLDEC/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 15 to December 6, 2016, and May 13 to 24, 2017, 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 (three for freeze-up and five 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 of coverage.

During freeze-up, percent of ice cover increased from November 30 (41.6 % ice cover) to December 4 (59.0 % ice cover) to December 5 (77.1 % ice cover). The proportion of ice cover on November 30 was greatest at the river mouth at Lake Melville and proportions were lower from the river mouth upstream to Site 5 and then increased at Site 6 (Muskrat Falls) and Site 7 (above Muskrat Falls). This same pattern was also evident on December 4 and 5, with the river being almost fully frozen over in the lower Sites 1 and 2 on those dates.
During break-up, the percent of ice cover decreased consistently from May 16 (59.4 % ice cover) to May 17 (36.9 % ice cover) to May 18 (25.9 % ice cover) to May 19 (13.6 % ice cover) to May 20 (11.0 % ice cover). There was no ice cover over this period above Muskrat Falls (Site 7) while below Muskrat Falls (Site 6) the proportion of ice was always greatest below the falls on each day of monitoring. The pattern of declining ice cover with each consecutive day was consistent for sites lowest in the river; Sites 1, 2, and 3.

The timing of the freeze-up and break-up processes during the 2016-2017 ice season were documented and compared with the long-term data record and the last 10 years of observations. The date of freeze-up, as indicated by the day of the first snowmobile crossing, was December 5, 2016. The date of break-up, as indicated by the date of the first boat crossing, was May 21, 2017. The date of freeze-up was seven days later than the long-term average (November 28), four days later than the freeze-up in 2016, and the same as the average for the last 10 years (December 5). The date of break-up was seven days later than the long term average (May 14), three days later than the break-up in 2016 (May 18), and six days later than the average for the last ten years (May 15). The later freeze-up date in 2016 (December 5) and break-up date in 2016 (May 21) resulted in total ice covered period of 167 days in the 2016-2017 ice season.

A total of 20 images, 10 images for each of the freeze-up and break-up periods, were acquired using the COSMO-SkyMed (CSK) constellation (consisting of four SAR satellites), the Sentinel 1 (S1) constellation (consisting of two SAR satellites) and Landsat 8 (L8), an optical satellite. 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 10 days. Image plans were created and modified to adjust to the freeze-up and break-up times.

The 20 images acquired consisted of a combination of high, medium, and low resolution SAR images and one, medium resolution optical image. When a primary image was not acquired, the secondary image was tasked, which was typically 12 hours later. The S1 satellite cannot be tasked but image plans on the European Space Agency website were monitored to acquire the required Churchill River images. One L8 image was used to fill a gap when no SAR images were acquired.
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.

The focus area for freeze-up was the river section surrounding Mud Lake and high resolution CSK images captured detailed ice features. S1 and L8 images were also used to provide coverage that extended up river to Muskrat Falls permitting ice floe analysis. Images were acquired from November 28 to December 5. Imagery from November 28 showed small amounts of unconsolidated ice mainly as border ice along the edges of islands and sand bars in the river. Areas with unconsolidated ice increased and expanded upstream with a large concentration of ice below Muskrat Falls on November 30. By December 2 large concentrations of unconsolidated ice were forming from Lake Melville backing up to Happy Valley-Goose Bay while large areas of open water were still apparent upstream of Happy Valley-Goose Bay. Ice accumulation continued from December 3 through December 5 until the ice cover became stable and consolidated at the Mud Lake crossing on December 5.

The focus area for the break-up was expanded to include up to and above Muskrat Falls. Images were acquired from May 15 to May 25, 2017. All images, except for the May 15 image, contained the entire focus area. Open water first appeared originating from Mud Lake and along the northern bank of the Churchill River, east of Happy Valley-Goose Bay. Areas of open water increased on May 16, 17 and 18 except below Muskrat Falls and at the river mouth at Lake Melville. Open water increased considerably on May 19 and there was an open lead into Lake Melville. Open water was continuous from below Muskrat Falls through to Lake Melville on May 20. Ice cover conditions then largely remained the same through to May 25, the date of the last image acquisition. The first boat crossing in 2017 was on May 21. The ice below Muskrat Falls was thick and this is typically the last area in the lower reach of the Churchill River to become ice free.
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 would 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 is 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 will be reduced by the Muskrat Falls Dam 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 an 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 is an important aspect of construction and operation of the Muskrat Falls
hydroelectric plant and these studies have been 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 2016-2017 ice season (year 4) during the initial construction phase of the LCP (SEM 2014, 2015, and 2016). Satellite Synthetic Aperture Radar (SAR) and Optical satellite images were used to monitor ice conditions on the Lower Churchill River. A total of 19 SAR images were acquired by Cosmo-SkyMed (CSK) and Sentinel-1 (S1) satellites. One optical image was provided by Landsat 8 (L8) during freeze-up. 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 Hydroelectric Project. 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 Lower Churchill Project (LCP) is focused on surveying ice freeze-up and break-up in the Lower Churchill River pre- and post-impoundment. The program during the 2016-2017 ice season was the fourth survey in a continuation of previous monitoring during the construction period of the LCP (SEM 2014, 2015, and 2016). Objectives were to document baseline conditions prior to operations and collect additional data to better understand the ice conditions in areas potentially influenced by the LCP. In the 2016-2017 ice season, conditions were similar to previous surveys excepting that water had been impounded in the Muskrat Falls reservoir. 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. 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;
- 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 completed 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) and Sentinel 1 (S-1) satellites as well as an optical image from the Landsat 8 (L8) satellite to
monitor ice conditions on the lower Churchill River for the 2016-2017 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 2016-2017 Ice Observations Surveys.

<table>
<thead>
<tr>
<th>Team Member</th>
<th>Roles and Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEM</td>
<td>Project Manager, coordination, client liaison, project report</td>
</tr>
<tr>
<td>Dave Scruton, MES, Senior Scientist</td>
<td>Financial control, project report QA/QC</td>
</tr>
<tr>
<td>Leroy Metcalfe, B. Sc., President</td>
<td>Coordination and planning of surveys</td>
</tr>
<tr>
<td>Claire Moore-Gibbons, MES, Biologist</td>
<td>Communication on ice conditions</td>
</tr>
<tr>
<td>Jordan Hope, Mud Lake Resident</td>
<td>C-CORE Project Manager. Coordination with SEM, project control and reporting</td>
</tr>
<tr>
<td>C-CORE</td>
<td>Plan, order and archive imagery. Satellite image analysis, generation of river ice products, ice floe analysis</td>
</tr>
</tbody>
</table>

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 15 to December 6, 2016, and May 13 to 24, 2017, were used to document and describe the freeze-up and break-up conditions at the Mud Lake crossing, respectively.
2.4 Local Consultation

SEM also consulted with Mud Lake resident Mr. Jordan Hope for assistance and experience with respect to the timing of freeze-up and break-up processes. Mr. Hope also provided SEM with the dates for the first snowmobile crossing on December 5, 2016, and the first boat crossing in May 21, 2017, to continue the time series for these important dates for the residents of Mud Lake.

2.5 Satellite Observations

2.5.1 Monitoring Area

The section of the Lower Churchill River monitored is shown in Figure 2.1, which spans 40 km and covers an area of approximately 60 km2. The width of the river varies between 100 m to 3200 m, with the elevation ranging from 15 m at Muskrat Falls to 0 m at the mouth of the river. The largest accumulation of ice occurs just below Muskrat Falls where the river suddenly widens and quickly narrows again, trapping enormous amounts of ice. Ice build-up here is a result of the powerful rapids that push ice under the existing ice cover in this area.

2.5.2 Satellite Image Planning and Acquisition

A total of 20 images were acquired using the COSMO-SkyMed (CSK) constellation (consisting of four SAR satellites), the S1 constellation (consisting of two SAR satellites) and L8, which is an optical satellite. 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 satellite could not be tasked but image plans were published on a regular basis on the European Space Agency (ESA) website, which was monitored regularly to ensure the required Churchill River images were acquired. One L8 image was used with the ice monitoring service to fill a gap in the image plan when no SAR images were acquired. S1 and L8 were available at no cost and were used to lower project costs.

The preparation of image acquisition plans considered several factors including 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 high, medium, and low resolution SAR images and one, medium resolution optical image. 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.
Figure 2.1. The Section of the Lower Churchill River Monitored Between Muskrat Falls and Lake Melville.
Table 2.2  Satellite Image Specifications for the 2016-2017 Ice Season.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Beam Mode</th>
<th>Spatial Resolution (m)</th>
<th>Image Width (km)</th>
<th>Number of Images</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSK</td>
<td>StripMap</td>
<td>5</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>CSK</td>
<td>ScanSAR Wide</td>
<td>30</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>S1</td>
<td>Interferometric Wide</td>
<td>20</td>
<td>250</td>
<td>8</td>
</tr>
<tr>
<td>S1</td>
<td>Extra Wide Swath</td>
<td>40</td>
<td>400</td>
<td>1</td>
</tr>
<tr>
<td>Landsat 8</td>
<td>Operational Land Imager</td>
<td>15</td>
<td>200</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2.3  Satellite Image Acquisition Schedule.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UTC)</th>
<th>Spatial Resolution (m)</th>
<th>Satellite</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 28, 2016</td>
<td>21:40</td>
<td>20</td>
<td>Sentinel-1A</td>
<td>Freeze-Up</td>
</tr>
<tr>
<td>November 30, 2016</td>
<td>10:12</td>
<td>20</td>
<td>Sentinel-1A</td>
<td>Freeze-Up</td>
</tr>
<tr>
<td>December 1, 2016</td>
<td>14:53</td>
<td>15</td>
<td>Landsat 8</td>
<td>Freeze-UP</td>
</tr>
<tr>
<td>December 2, 2016</td>
<td>21:51</td>
<td>5</td>
<td>CSK-2</td>
<td>Freeze-Up</td>
</tr>
<tr>
<td>December 3, 2016</td>
<td>9:40</td>
<td>5</td>
<td>CSK-1</td>
<td>Freeze-Up</td>
</tr>
<tr>
<td>December 4, 2016</td>
<td>9:34</td>
<td>5</td>
<td>CSK-4</td>
<td>Freeze-Up</td>
</tr>
<tr>
<td>December 5, 2016</td>
<td>10:21</td>
<td>20</td>
<td>Sentinel-1A</td>
<td>Freeze-Up</td>
</tr>
<tr>
<td>May 15, 2017</td>
<td>21:40</td>
<td>20</td>
<td>Sentinel-1A</td>
<td>Break-Up</td>
</tr>
<tr>
<td>May 16, 2017</td>
<td>10:19</td>
<td>50</td>
<td>Sentinel-1B</td>
<td>Break-Up</td>
</tr>
<tr>
<td>May 17, 2017</td>
<td>10:12</td>
<td>20</td>
<td>Sentinel-1A</td>
<td>Break-Up</td>
</tr>
<tr>
<td>May 18, 2017</td>
<td>9:52</td>
<td>30</td>
<td>CSK-1</td>
<td>Break-Up</td>
</tr>
<tr>
<td>May 19, 2017</td>
<td>21:50</td>
<td>30</td>
<td>CSK-1</td>
<td>Break-Up</td>
</tr>
<tr>
<td>May 20, 2017</td>
<td>21:48</td>
<td>20</td>
<td>Sentinel-1A</td>
<td>Break-Up</td>
</tr>
<tr>
<td>May 21, 2017</td>
<td>9:39</td>
<td>30</td>
<td>CSK-3</td>
<td>Break-Up</td>
</tr>
<tr>
<td>May 22, 2017</td>
<td>10:21</td>
<td>20</td>
<td>Sentinel-1A</td>
<td>Break-Up</td>
</tr>
<tr>
<td>May 23, 2017</td>
<td>10:12</td>
<td>20</td>
<td>Sentinel-1B</td>
<td>Break-Up</td>
</tr>
<tr>
<td>May 24, 2017</td>
<td>9:39</td>
<td>30</td>
<td>CSK-4</td>
<td>Break-Up</td>
</tr>
</tbody>
</table>

2.5.3  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. 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 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.

![Surface and Volume Scattering Diagram](image)

**Figure 2.2** River Ice Scattering Mechanisms (Pelletier and Hicks 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 river 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, 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.

The 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 17, 2017 S1 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 17, 2017 S1 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. Figure 2.5 shows an example of a Change Detection product for the comparison of classifications from May 16 and May 17 CSK images.

The L8 image products were processed slightly differently than the SAR images. Top of atmospheric correction and visual enhancement techniques were used for pre-processing. Top of atmospheric correction is a method of removing the effects of the atmosphere on the quality of the image and is only necessary for optical satellite images. It provides a more accurate and consistent measure of ground reflectance for processes such as image classification. The classification method used was the same as that used with the SAR images. The change detection product is created from the subtraction of two classified images whether they are SAR classified or optical classified images.
Figure 2.3 Ice Cover Product Created From the May 17, 2017 S1 Image.
Figure 2.4  Ice Classification Product Created From the May 17, 2017 S1 Image.
2.6 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. In previous years, photos acquired during aerial ice surveys were used for ice floe analysis, however, in the 2016-2017 ice season no aerial surveys were completed. Seven areas were selected for analysis based on the locations of analyses completed in the 2015-2016 ice season and then buffered to include a distance of two kilometers to provide a comparable analysis to previous years (Figure 2.6). Ice floe analysis was conducted on these sections 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 are based on the river ice classification. Non-consolidated and consolidated ice classes were combined representing ice cover and a percentage was calculated. Open water percentages were calculated from the open water class.
Figure 2.6  Locations Used for Ice Floe Analysis for the 2016-2017 Ice Season.
3.0 RESULTS

3.1 Mud Lake Web Camera

Archived images from the NLDEC/WRMD web camera at the Mud Lake crossing site were either downloaded from the Government of Newfoundland and Labrador website or provided directly as digital files (Leona Hyde, NLDMAE/WRMD, pers. comm.). These images were used to monitor conditions and to document and describe the freeze-up and break-up processes at this location. Images were made available courtesy of the Government of Newfoundland and Labrador, Department of Municipal Affairs and Environment, Water Resources Management Division.

The freeze-up sequence for the period from November 15 to December 6, 2016, is shown in Figures 3.1 and 3.2. Open water conditions were recorded at the web camera site on November 15 and 21. Increasing concentrations of ice accumulating in an upstream direction were observed on November 26 and 28, with large increases in concentration on November 28, particularly along the shoreline. Concentrations then increased gradually from November 28 to December 1. The ice further solidified over the period from December 2 to 4 and the ice bridge was considered formed on December 5. The first date for snowmobile crossing for the 2016-2017 ice season was December 5.

The break-up sequence for the period from May 13 to 24, 2017, is shown in Figures 3.3 and 3.4. The images from May 13 through 16 demonstrated that the river was still frozen over completely with some melting along the margin of the river starting to appear. Open water sections were also evident over this period. Ice began breaking up over the period of May 16 to 18 with a large area of open ice apparent on May 18. Evidence of ice rafting was first apparent on May 17 and ice continued to build up over the period from May 18 to 20, particularly along the shoreline. Open water in the center of the river was apparent on May 20, with most ice gone on May 21, and the river completely open on May 22. The date of first crossing by boat was May 21. The duration of the break-up was about seven to nine days, which is comparable with observations from previous years and as reported by SNC-Lavalin (2012a) for 2012 (six days) and for 2014 (seven days, SEM 2014), 2015 (five to seven days, SEM 2015), and 2016 (seven days, SEM 2016).
Figure 3.1 Mud Lake Web Camera Images During the Freeze-Up Process, November 15-30, 2016.
Figure 3.2 Mud Lake Web Camera Images During the Freeze-Up Process, December 1 - 6, 2016.
Figure 3.3 Mud Lake Web Camera Images During the Break-Up Process, May 13-18, 2017.
Figure 3.4  Mud Lake Web Camera Images During the Break-Up Process, May 19 - 24, 2017.
3.2 Timing of Freeze-Up and Break-Up

The timing of the freeze-up and break-up processes during the 2016-2017 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 December 5, 2016. The date of break-up, as indicated by the date of the first boat crossing, was May 21, 2017. The date of freeze-up was seven days later than the long-term average (November 28), four days later than the freeze-up in 2016, and the same as the average for the last ten years (December 5). The date of break-up was seven days later than the long term average (May 14), three days later than the break-up in 2016 (May 18), and six days later than the average for the last ten years (May 15). 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 2014 being the earliest freeze-up date over the last ten years (November 24). 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 15), with the earliest date of break-up on record in 2010 (April 20). The later freeze-up date in 2016 (December 5) and break-up date in 2016 (May 21) resulted in total ice covered period of 167 days in the 2016-2017 ice season.

It is noteworthy that during the break-up of 2017, the river was relatively ice free on May 18, but the first boat crossing was not until May 21. Mud Lake was extensively flooded during the break-up in 2017 and residents were evacuated to Happy Valley-Goose Bay during this period.

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

<table>
<thead>
<tr>
<th>Date</th>
<th>Freeze-Up (first snowmobile crossing)</th>
<th>Break-Up (first boat crossing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972</td>
<td>22-Nov-72</td>
<td>5-Jun-72</td>
</tr>
<tr>
<td>1973</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1974</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1975</td>
<td>25-Nov-75</td>
<td>30-May-75</td>
</tr>
<tr>
<td>1976</td>
<td>17-Nov-76</td>
<td>17-May-76</td>
</tr>
<tr>
<td>1977</td>
<td>30-Nov-77</td>
<td>15-May-77</td>
</tr>
<tr>
<td>1978</td>
<td>19-Nov-78</td>
<td>27-May-78</td>
</tr>
<tr>
<td>1979</td>
<td>24-Nov-79</td>
<td>14-May-79</td>
</tr>
<tr>
<td>1980</td>
<td>29-Nov-80</td>
<td>17-May-80</td>
</tr>
<tr>
<td>1981</td>
<td>23-Dec-81</td>
<td>15-May-81</td>
</tr>
<tr>
<td>1982</td>
<td>28-Nov-82</td>
<td>1-May-82</td>
</tr>
<tr>
<td>1983</td>
<td>29-Nov-83</td>
<td>14-May-83</td>
</tr>
<tr>
<td>1984</td>
<td>23-Nov-84</td>
<td>15-May-84</td>
</tr>
</tbody>
</table>
Table 3.1 Long Term Record of Freeze-Up and Break-Up at the Mud Lake Crossing.

<table>
<thead>
<tr>
<th>Date</th>
<th>Freeze-Up (first snowmobile crossing)</th>
<th>Break-Up (first boat crossing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>18-Nov-85</td>
<td>28-May-85</td>
</tr>
<tr>
<td>1986</td>
<td>13-Nov-86</td>
<td>7-May-86</td>
</tr>
<tr>
<td>1987</td>
<td>28-Nov-87</td>
<td>23-Apr-87</td>
</tr>
<tr>
<td>1988</td>
<td>1-Dec-88</td>
<td>12-May-88</td>
</tr>
<tr>
<td>1989</td>
<td>24-Nov-89</td>
<td>15-May-89</td>
</tr>
<tr>
<td>1990</td>
<td>1-Dec-90</td>
<td>22-May-90</td>
</tr>
<tr>
<td>1991</td>
<td>2-Dec-91</td>
<td>26-May-91</td>
</tr>
<tr>
<td>1993</td>
<td>13-Nov-93</td>
<td>17-May-93</td>
</tr>
<tr>
<td>1994</td>
<td>27-Nov-94</td>
<td>22-May-94</td>
</tr>
<tr>
<td>1995</td>
<td>29-Nov-95</td>
<td>11-May-95</td>
</tr>
<tr>
<td>1996</td>
<td>1-Dec-96</td>
<td>4-May-96</td>
</tr>
<tr>
<td>1997</td>
<td>23-Nov-97</td>
<td>24-May-97</td>
</tr>
<tr>
<td>1998</td>
<td>30-Nov-98</td>
<td>12-May-98</td>
</tr>
<tr>
<td>2000</td>
<td>25-Nov-00</td>
<td>11-May-00</td>
</tr>
<tr>
<td>2001</td>
<td>4-Dec-01</td>
<td>14-May-01</td>
</tr>
<tr>
<td>2002</td>
<td>22-Nov-02</td>
<td>22-May-02</td>
</tr>
<tr>
<td>2003</td>
<td>7-Dec-03</td>
<td>17-May-03</td>
</tr>
<tr>
<td>2004</td>
<td>7-Dec-04</td>
<td>18-May-04</td>
</tr>
<tr>
<td>2005</td>
<td>11-Dec-05</td>
<td>8-May-05</td>
</tr>
<tr>
<td>2006</td>
<td>4-Dec-06</td>
<td>4-May-06</td>
</tr>
<tr>
<td>2007</td>
<td>30-Nov-07</td>
<td>17-May-07</td>
</tr>
<tr>
<td>2008</td>
<td>5-Dec-08</td>
<td>7-May-08</td>
</tr>
<tr>
<td>2009</td>
<td>9-Dec-09</td>
<td>18-May-09</td>
</tr>
<tr>
<td>2010</td>
<td>7-Jan-11</td>
<td>20-Apr-10</td>
</tr>
<tr>
<td>2011</td>
<td>2-Dec-11</td>
<td>12-May-11</td>
</tr>
<tr>
<td>2012</td>
<td>2-Dec-12</td>
<td>15-May-12</td>
</tr>
<tr>
<td>2013</td>
<td>2-Dec-13</td>
<td>1-May-13</td>
</tr>
<tr>
<td>2014</td>
<td>24-Nov-14</td>
<td>19-May-14</td>
</tr>
<tr>
<td>2015</td>
<td>1-Dec-15</td>
<td>18-May-15</td>
</tr>
<tr>
<td>2016</td>
<td>5-Dec-16</td>
<td>17-May-16</td>
</tr>
<tr>
<td>2017</td>
<td>TBD</td>
<td>21-May-17</td>
</tr>
</tbody>
</table>

Long Term Average 29-Nov 15-May

Average (last 10 Years) 5-Dec 12-May
3.3 Ice Floe Analyses

3.3.1 Freeze-Up Period

Three images were selected for analysis during the freeze up period; November 30, December 4 and December 5, 2016. Two of these images (November 30 and December 5) provided complete coverage of the monitoring area while the third (December 4) provided coverage for all but one site on the western end, above Muskrat Falls (Site 7). The ice and water coverage were determined from the ice classification of each image and presented as a percentage. Table 3.2 contains the results of the analysis. The site numbers correspond to the numbered sections in Figure 2.6.

The percent of ice cover increased from November 30 (mean ± Std. Dev.; 41.6 ± 19.6% ice cover) to December 4 (mean ± Std. Dev.; 59.0 ± 30.6% ice cover) to December 5 (mean ± Std. Dev.; 77.1 ± 33.2% ice cover). The proportion of ice cover on November 30 was greatest at the river mouth at Lake Melville and then was generally in lower proportions from the river mouth in an upstream direction to Site 5 and then increased at Site 6 (Muskrat Falls) and Site 7 (above Muskrat Falls). This same pattern was also evident on December 4 and 5, with the river being almost fully frozen over in the lower Sites 1 and 2 on those dates.

Table 3.2 Ice Cover and Open Water Percent Coverage for the Freeze-Up Period in 2016.

<table>
<thead>
<tr>
<th>Site</th>
<th>Nov 30 Water (%)</th>
<th>Nov 30 Ice (%)</th>
<th>Dec 4 Water (%)</th>
<th>Dec 4 Ice (%)</th>
<th>Dec 5 Water (%)</th>
<th>Dec 5 Ice (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51</td>
<td>49</td>
<td>5</td>
<td>95</td>
<td>4</td>
<td>96</td>
</tr>
<tr>
<td>2</td>
<td>67</td>
<td>33</td>
<td>3</td>
<td>97</td>
<td>2</td>
<td>98</td>
</tr>
<tr>
<td>3</td>
<td>65</td>
<td>35</td>
<td>54</td>
<td>46</td>
<td>1</td>
<td>99</td>
</tr>
<tr>
<td>4</td>
<td>73</td>
<td>27</td>
<td>66</td>
<td>34</td>
<td>38</td>
<td>62</td>
</tr>
<tr>
<td>5</td>
<td>80</td>
<td>20</td>
<td>76</td>
<td>24</td>
<td>56</td>
<td>44</td>
</tr>
<tr>
<td>6</td>
<td>21</td>
<td>79</td>
<td>42</td>
<td>58</td>
<td>13</td>
<td>87</td>
</tr>
<tr>
<td>7</td>
<td>52</td>
<td>48</td>
<td>-</td>
<td>-</td>
<td>46</td>
<td>54</td>
</tr>
<tr>
<td>Mean</td>
<td>58.4</td>
<td>41.6</td>
<td>41.0</td>
<td>59.0</td>
<td>22.9</td>
<td>77.1</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>19.5</td>
<td>19.5</td>
<td>30.9</td>
<td>30.9</td>
<td>23.2</td>
<td>23.2</td>
</tr>
</tbody>
</table>
### 3.3.2 Break-Up Period

Five images were selected for analysis for the break-up period from May 16 to May 20 inclusive. All images provided complete coverage of the seven sites for ice floe analysis. Table 3.3 contains the results of the analysis. The site numbers correspond to the numbered sections in Figure 2.6.

The percent of ice cover decreased consistently from May 16 (mean ± Std. Dev.; 59.4 ± 37.6% ice cover) to May 17 (mean ± Std. Dev.; 36.9 ± 31.7% ice cover) to May 18 (mean ± Std. Dev.; 25.9 ± 30.4% ice cover) to May 19 (mean ± Std. Dev.; 13.6 ± 23.7% ice cover) to May 20 (mean ± Std. Dev.; 11.0 ± 25.2% ice cover). There was no ice cover over this period above Muskrat Falls (Site 7) while below Muskrat Falls (Site 6) the proportion of ice was always greatest at this location on each day. The pattern of declining ice cover with each consecutive day was consistent for Sites 1, 2, and 3. The lowest proportion of ice in the lower river below Muskrat Falls was always at Site 5.

#### Table 3.3 Ice Cover and Open Water Percent Coverage for the Break-Up Period in 2017.

<table>
<thead>
<tr>
<th>Site</th>
<th>May 16 Water (%)</th>
<th>May 16 Ice (%)</th>
<th>May 17 Water (%)</th>
<th>May 17 Ice (%)</th>
<th>May 18 Water (%)</th>
<th>May 18 Ice (%)</th>
<th>May 19 Water (%)</th>
<th>May 19 Ice (%)</th>
<th>May 20 Water (%)</th>
<th>May 20 Ice (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13</td>
<td>87</td>
<td>37</td>
<td>63</td>
<td>39</td>
<td>61</td>
<td>91</td>
<td>9</td>
<td>97</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>34</td>
<td>66</td>
<td>61</td>
<td>39</td>
<td>86</td>
<td>14</td>
<td>95</td>
<td>5</td>
<td>99</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>87</td>
<td>50</td>
<td>50</td>
<td>78</td>
<td>22</td>
<td>96</td>
<td>4</td>
<td>98</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>70</td>
<td>78</td>
<td>22</td>
<td>96</td>
<td>4</td>
<td>95</td>
<td>5</td>
<td>99</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>87</td>
<td>13</td>
<td>100</td>
<td>0</td>
<td>96</td>
<td>4</td>
<td>95</td>
<td>5</td>
<td>98</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>93</td>
<td>16</td>
<td>84</td>
<td>24</td>
<td>76</td>
<td>33</td>
<td>67</td>
<td>32</td>
<td>68</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Mean</td>
<td>40.6</td>
<td>59.4</td>
<td>63.1</td>
<td>36.9</td>
<td>74.1</td>
<td>25.9</td>
<td>86.4</td>
<td>13.6</td>
<td>89.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>37.6</td>
<td>37.6</td>
<td>31.7</td>
<td>31.7</td>
<td>30.4</td>
<td>30.4</td>
<td>23.7</td>
<td>23.7</td>
<td>25.2</td>
<td>25.2</td>
</tr>
</tbody>
</table>

### 3.4 Satellite Image Analyses

This section provides an overview of the Lower Churchill River ice conditions during freeze-up and break-up in the 2016-2017 ice season. Monitoring was not conducted during the period of continuous ice cover. Ice cover, classification and change detection products derived from SAR images from the ice monitoring program are provided in Appendices A (freeze-up period) and B (break-up period).
C-CORE worked closely with SEM to estimate when break-up and freeze-up would occur. Local knowledge, weather data, webcam images and freely available satellite image data were some of the tools used to assist with estimating the timing of these events. The Goose River, which is just north of the Churchill River, is another break-up indicator, since on the Goose River typically precedes break-up on the Lower Churchill River by approximately 10 days. Image 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.

3.4.1 Freeze-Up Period

Appendix A contains the ice products for the freeze-up period. The focus area was the section of river surrounding the Mud Lake crossing of the Churchill River. High resolution CSK images were ordered to capture detailed ice features and the image extents only provided coverage for the Mud Lake location. S1 and L8 images were also used for freeze-up analysis which provided extended coverage and allowed for ice floe analysis. The image dates ranged from November 28 to December 5. Ice cover, ice classification, and change detection products were produced for all images with the exception of a change detection product for the first scene, since this analysis required two images.

Figure 3.5 shows the maximum and minimum temperatures for Happy Valley-Goose Bay, Labrador during freeze-up period. Temperatures were consistently below freezing from November 23 onwards.
Figure 3.5 Maximum and Minimum Temperatures for Happy Valley – Goose Bay, Labrador During Freeze-up.

Freeze-up occurred four days later this year than last (SEM 2016) and was the same as the average for the last 10 year period.

The image acquired on November 28 showed small amounts of unconsolidated ice mainly as border ice along the edges of the islands and sand bars within the river. On November 30 these areas with unconsolidated ice had increased and expanded upstream with a large concentration of ice below Muskrat Falls. Small areas of consolidated ice were starting to form. The December 2 image shows large concentrations of unconsolidated ice from Lake Melville backing up to Happy Valley-Goose Bay. Large areas of open water were still apparent west of Happy Valley-Goose Bay. The remaining image products from December 3 through December 5 show the accumulation continuing until the ice cover becomes stable and consolidated at the Mud Lake crossing on December 5.
3.4.2 Break-Up Period

Appendix B contains the ice products for break-up period. The focus area was expanded from the freeze-up event to include Muskrat Falls. All images, except for the May 15 image, contained the entire focus area. Images acquired by S1 have set image extents and the May 15 image did not extend to Muskrat Falls. The image dates were from May 15 to May 25, 2017. Ice cover, ice classification, and change detection products were produced for all of the images with the exception of a change detection product for the first image.

Figure 3.6 shows the maximum and minimum temperatures for Happy Valley–Goose Bay, Labrador during the break-up period. Daily maximum temperatures were above freezing during May 2017 contributing to the break-up event.

![Break-Up Temperatures](image)

**Figure 3.6** Maximum and Minimum Temperatures for Happy Valley – Goose Bay, Labrador During Break-up.
Break-up occurred four days later this year than last (SEM 2016) and was nine days later than the average for the last 10 year period.

Open water first appeared in the river originating from Mud Lake and along the northern bank of the Churchill River, just east of Happy Valley-Goose Bay, with an additional small amount of open water along the southern bank, west of Lake Melville. Areas of open water increased on May 16. Areas of open water continued to increase on May 17 and 18 except below Muskrat Falls and west of Lake Melville. Open water increased considerably on May 19, except below Muskrat Falls, and there was an open lead into Lake Melville. These conditions continued through to May 23. On May 20 open water was continuous from below the ice accumulation below Muskrat Falls through to Lake Melville. Ice cover conditions remained the same through to May 25, the date of the last image acquisition. The first boat crossing in 2017 was on May 21. During the break-up period, the ice below Muskrat Falls was thick and this is typically the last area in the lower reach of the Churchill River to become ice free.
4.0 REFERENCES


