**RFI 013**
**Pebble Project EIS**

## Request for Information

| | |
|---|---|
| **Title/Subject:** | **Iliamna Lake and Pipeline Landfall Hazards** |
| **Requestor:** | **AECOM** |
| **Date Transmitted:** | **4/26/18** |
| **Recipient:** | **Pebble Limited Partnership** |
| **Response Requested by:** | **5/10/2018** |
| **Rationale:** | **Limited information is available in the literature or EBD/SEBD (Chapter 7, Appendix B) on Iliamna Lake physical conditions and hazards such as wave heights, bathymetry, water level, shoreline erosion, ice conditions, or seiches (from major earthquakes or slumping). In addition, limited information is provided in the Project Description regarding potential ferry effects on shore erosion, or pipeline landfalls at the port and ferry terminals. Evaluation of pipeline safety and shore erosion is required under PHMSA and USACE regulations. The requested information is needed to evaluate potential impacts to ferry operations, lake port facilities, and the pipeline, and related impacts from project components on shore erosion. Ice rideup on the north shore of Iliamna Lake was a concern identified in scoping comments.** |
| **Describe the Information Requested and Level of Detail:** | **1) Provide additional available in-house data or anecdotal information from villages regarding: Iliamna Lake maximum wave height, bathymetry, seasonal and historical water level changes, shoreline erosion, ice coverage/seasons, ice thickness, ice movement/ridges, potential for shore ice rideup, and historical seiches or unusual flooding events.**<br>**2) The Project Description indicates that the pipeline would be buried beneath 36" depth of cover on land, and that pipeline burial in Lake Iliamna would be similar to that of Cook Inlet crossing, which is described as "sufficiently deep to ensure that the top of the pipe is below the ground surface" from the point west of the HDD emergence on the seafloor at east Cook Inlet. This implies that the depth of cover would be minimal in shoreline areas of the port and ferry terminals. Clarify the depth of cover in the landfall transitions from offshore to onshore at the port and ferry terminals that would minimize potential shoreline erosion or navigation hazards.**<br>**3) Provide additional information on ferry draft, speed, propeller size, ferry-generated wave heights, and the potential for ferry-induced shoreline or lake bottom erosion.** |

## Recipient Response Form

| | |
|---|---|
| **Date Received from USACE:** | Click here to enter text. |
| **Response from Recipient (Describe Information Requested to the Level of Detail Requested; Provide Attachments as Needed):** | 1) Attached please find the updated version of the lake ice report.<br>2) Previously addressed.<br>3) Previously addressed. |
| **List Number and Type of Response Attachments:** | **Pebble_Lake_Ice_2000-2018_Summary.pdf** |
| **Date Returned to USACE:** | **8/7/2018** |

## AECOM Intake Form

| | |
|---|---|
| **Date Response was Received:** | **8/7/2018** |
| **Received by:** | **AECOM** |
| **Describe any Follow-up Related to this RFI:** | **None at this time.** |

**RFI 013**
**Pebble Project EIS**

## Request for Information

| | |
|---|---|
| **Title/Subject:** | **Iliamna Lake and Pipeline Landfall Hazards** |
| **Requestor:** | **Nancy Darigo/Jack Colonell/James Dietzmann, AECOM** |
| **Date Transmitted:** | **4/26/18** |
| **Recipient:** | **Pebble Limited Partnership** |
| **Response Requested by:** | **5/10/2018** |
| **Rationale:** | **Limited information is available in the literature or EBD/SEBD (Chapter 7, Appendix B) on Iliamna Lake physical conditions and hazards such as wave heights, bathymetry, water level, shoreline erosion, ice conditions, or seiches (from major earthquakes or slumping). In addition, limited information is provided in the Project Description regarding potential ferry effects on shore erosion, or pipeline landfalls at the port and ferry terminals. Evaluation of pipeline safety and shore erosion is required under PHMSA and USACE regulations. The requested information is needed to evaluate potential impacts to ferry operations, lake port facilities, and the pipeline, and related impacts from project components on shore erosion. Ice rideup on the north shore of Iliamna Lake was a concern identified in scoping comments.** |
| **Describe the Information Requested and Level of Detail:** | **1) Provide additional available in-house data or anecdotal information from villages regarding: Iliamna Lake maximum wave height, bathymetry, seasonal and historical water level changes, shoreline erosion, ice coverage/seasons, ice thickness, ice movement/ridges, potential for shore ice rideup, and historical seiches or unusual flooding events.**<br>**2) The Project Description indicates that the pipeline would be buried beneath 36" depth of cover on land, and that pipeline burial in Lake Iliamna would be similar to that of Cook Inlet crossing, which is described as "sufficiently deep to ensure that the top of the pipe is below the ground surface" from the point west of the HDD emergence on the seafloor at east Cook Inlet. This implies that the depth of cover would be minimal in shoreline areas of the port and ferry terminals. Clarify the depth of cover in the landfall transitions from offshore to onshore at the port and ferry terminals that would minimize potential shoreline erosion or navigation hazards.**<br>**3) Provide additional information on ferry draft, speed, propeller size, ferry-generated wave heights, and the potential for ferry-induced shoreline or lake bottom erosion.** |

## Recipient Response Form

| | |
|---|---|
| **Date Received from USACE:** | **4/27/2018** |
| **Response from Recipient (Describe Information Requested to the Level of Detail Requested; Provide Attachments as Needed):** | 1) The current version of an assessment of lake ice conditions is attached (Iliamna Lake Ice Technical Memo.pdf). The coverage does not include the full proposed ferry route. PLP has requested a timeline from the consultant to expand the coverage to include the proposed route this and will notify USACE as soon as the schedule is confirmed. PLP has no additional data.<br>2) PLP contractors are currently collecting marine offshore data and will collect lake bottom data next month that will provide additional high-resolution sea bottom bathymetry data that will allow for refinement of the pipeline design during project detailed engineering. PHMSA code (49CFR 192.327) requires burial of a natural gas transmission pipeline with 36" of cover to at least 12' water depth, with the top of the pipe below the natural bottom, or protected by alternate means in deeper waters. Final details will be determined during detailed design, but PLP will at a minimum comply with PHMSA code requirements for pipeline cover. The pipeline will either be HDD or trenched offshore to at least 12' water depths for both the lake |

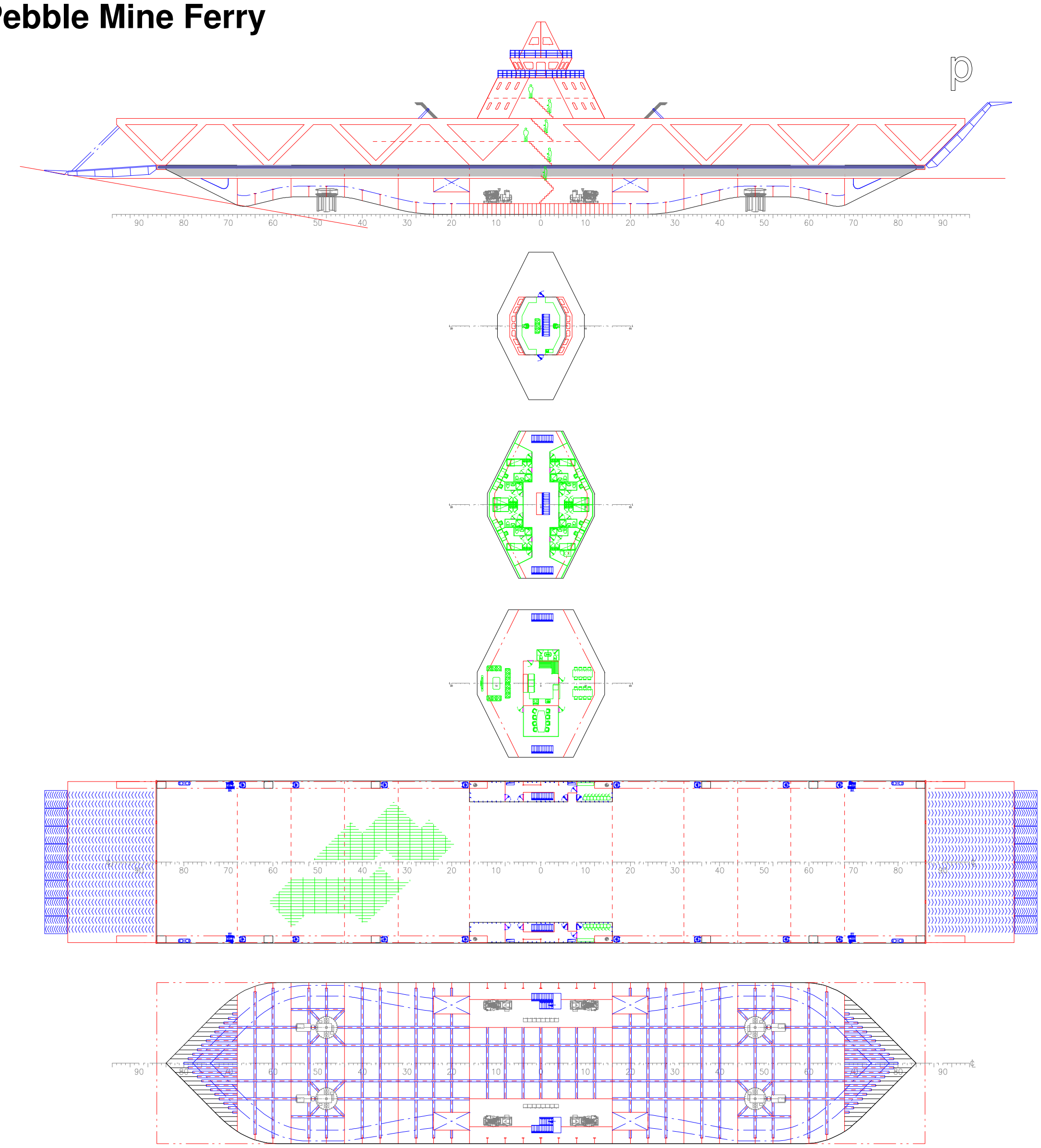
| | |
|---|---|
| | and the Amakdedori shore transitions.<br>3) Please see attached Ferry Wave Modeling report for additional detail.<br>a. Ferry draft – 16'-0"<br>b. Speed – 6 knots on shore approach, 11 knots in open water<br>c. Propeller size – 6'-0" – Note that there are 4 motors driving 4 propellers. Two are only used when breaking ice.<br>d. Please see attached wave size model run's from PLP's consultant using Computational Fluid Dynamics (CFD) Numeca software. At the 6 kn berth approach speed, the hull generates a wave height of 4" at the hull, which dissipates within 30 ft from the hull. The ferry route is from north to south across the lake and the ferry will approach the shore perpendicularly. As such, there is limited potential for wake induced shoreline erosion associated with ferry operations.<br>e. The hull is designed with two symmetrical ice breaking bows and the propellers are located away from the bows up in hull recesses. The ferry draft is 16'-0", the propeller diameter is 6'-0" and the propeller center is located at 12'-0" depth. The propellers will therefore not protrude below the keel of the vessel. The vessel will maintain a minimum under keel clearance of 6' when running and will be operating at low power as it approaches the shore. The ferry route is from north to south across the lake and the ferry will approach the shore perpendicularly. As such, there is limited potential for propeller induced lake bottom erosion associated with ferry operations. |
| **List Number and Type of Response Attachments:** | Ferry Wave Modeling.pdf<br>Iliamna Lake Ice Technical Memo.pdf |
| **Date Returned to USACE:** | **05/11/2018** |

## AECOM Intake Form

| | |
|---|---|
| **Date Response was Received:** | **5/14/2018** |
| **Received by (Name):** | **POA Special Projects** |
| **Describe any Follow-up Related to this RFI (Communications, Clarifications):** | **None at this time** |

| | |
|---|---|
| Project Title: Pebble Mine Ice Ferry | |
| | |
| | |
| Date: 07 May 2018 | |

## Pebble Mine Ferry



# CFD RESISTANCE CURVE

LAKE LLIAMNA FERRY

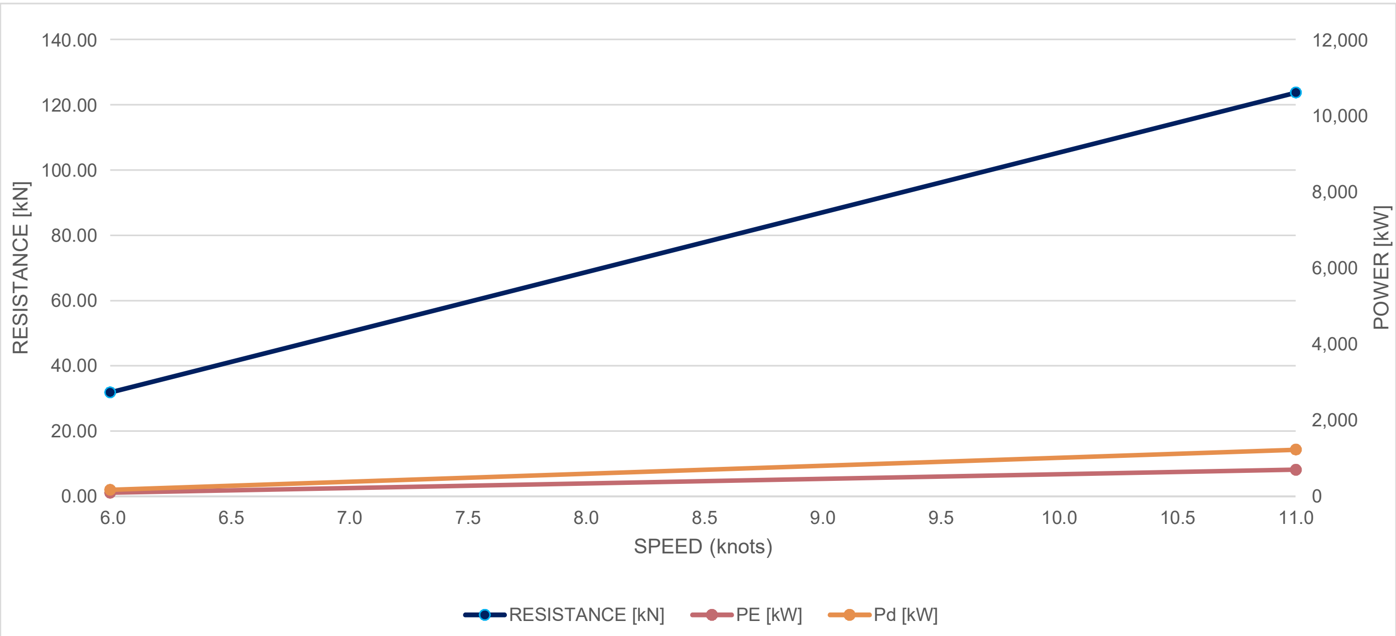
**DRAFT** 4.8768 m (16ft)

**DISPLACEMENT** 5,472.0 MT

**SETUP NOTES**

K-Omega (SST-Menter) Turbulence model. Fresh water at 15°C
900 thousand cell count mesh

## ESTIMATED RESISTANCE AND POWER CURVE




## DATA

| SPEED [kn] | RESISTANCE [kN] | PE [kW] | Pd [kW] | NOTES |
|---|---|---|---|---|
| 6.0 | 31.84 | 98 | 172 | |
| 11.0 | 123.70 | 701 | 1,227 | |

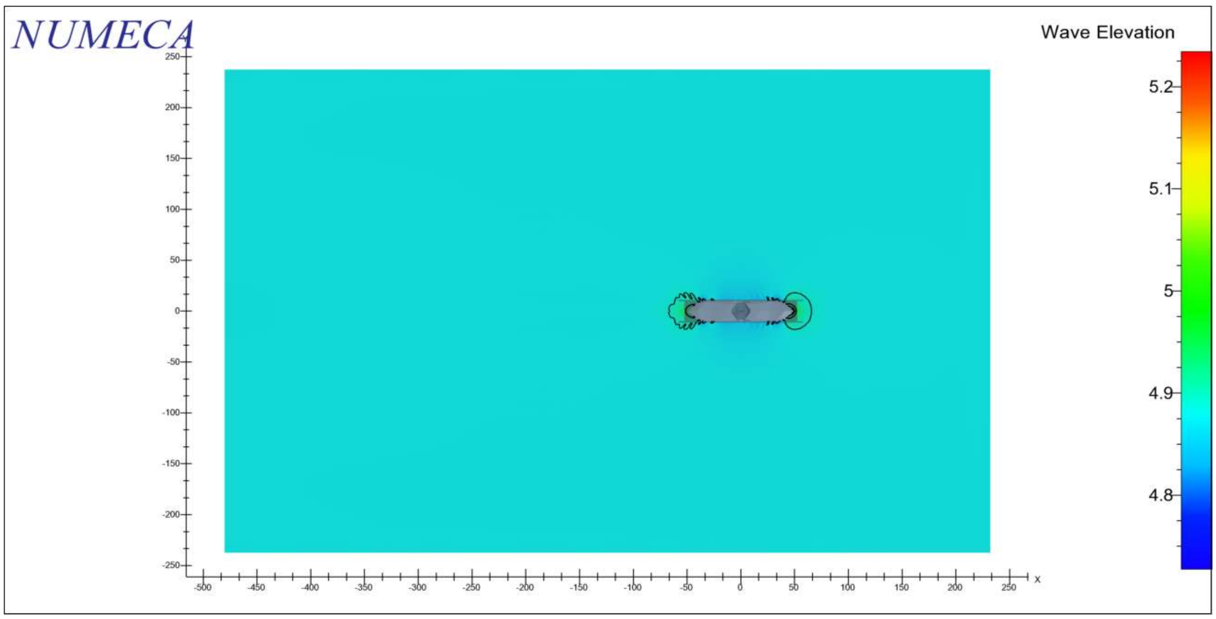
# CFD WAKE ANALYSIS

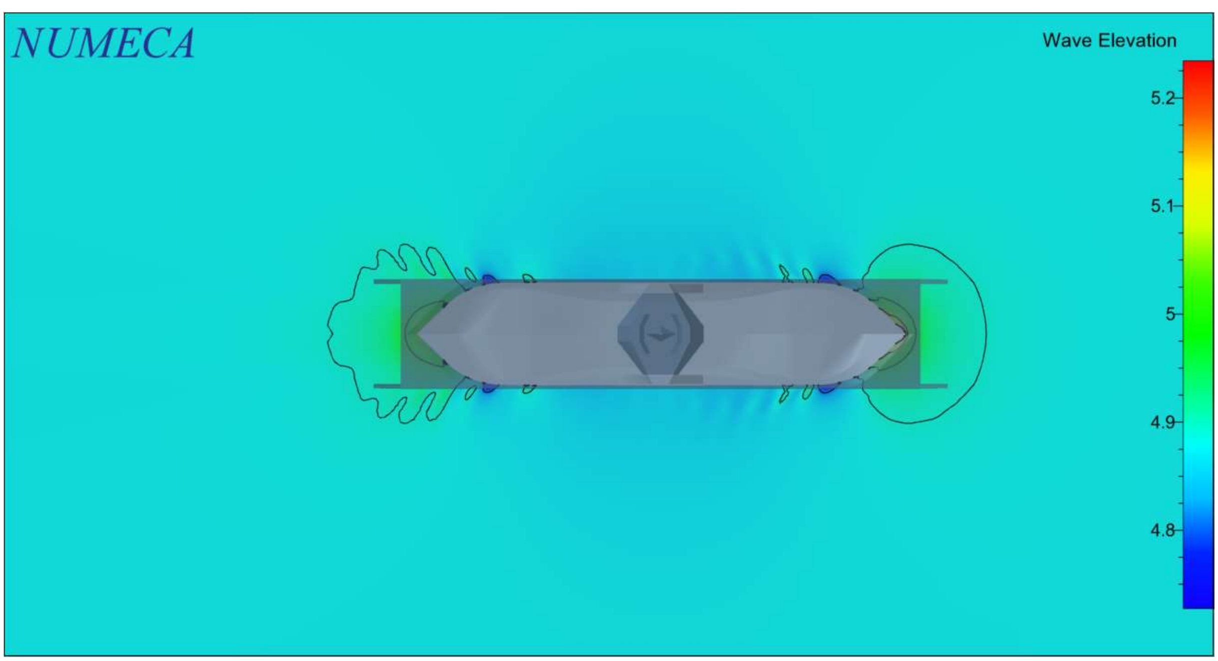
LAKE LLIAMNA FERRY

| | |
|---|---|
| **SPEED** | 6.0 kn |
| **DRAFT** | 4.8768 m |
| **RESISTANCE** | 31.8 kN |

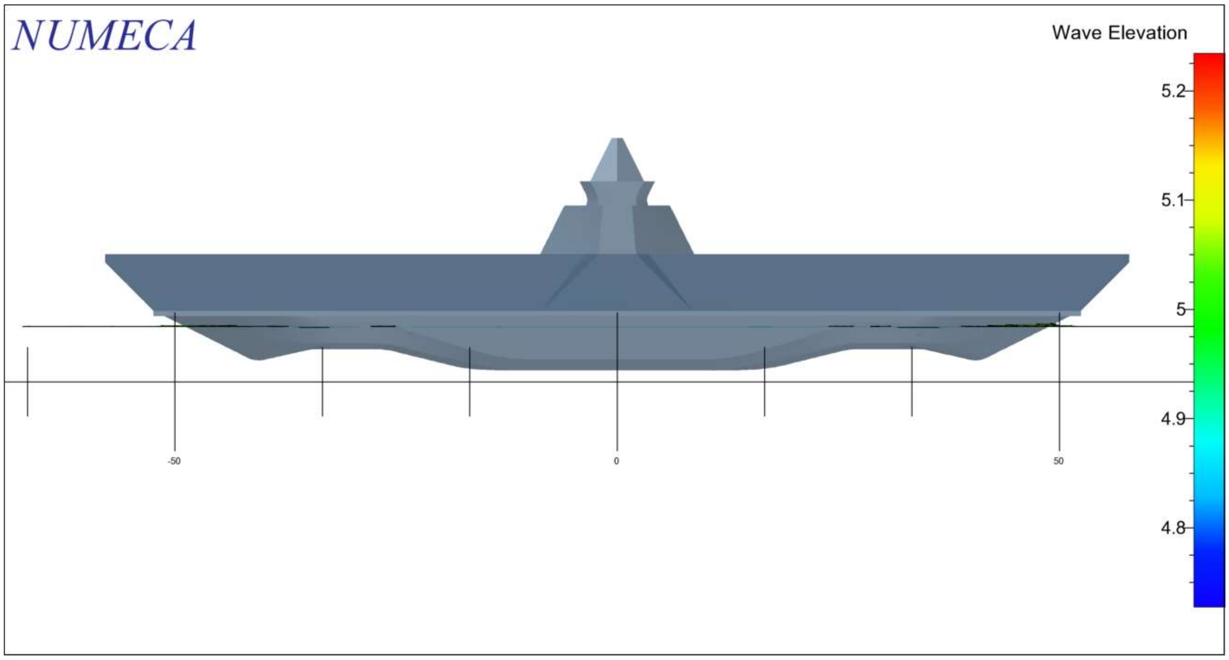
**NOTES**

## WAVETRAIN PLAN

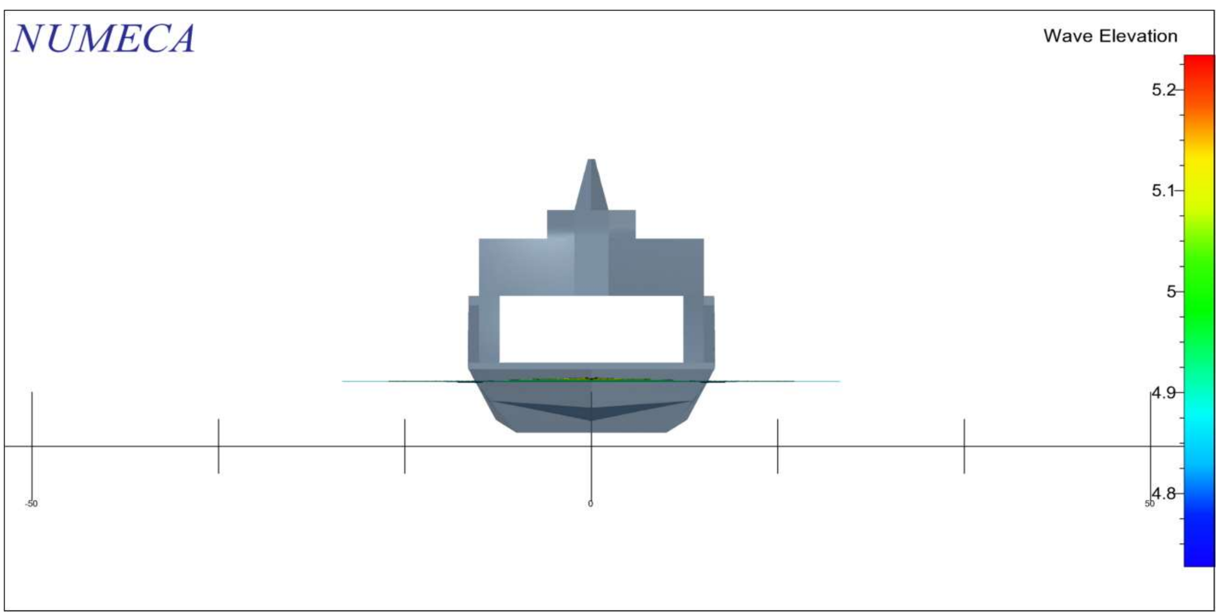


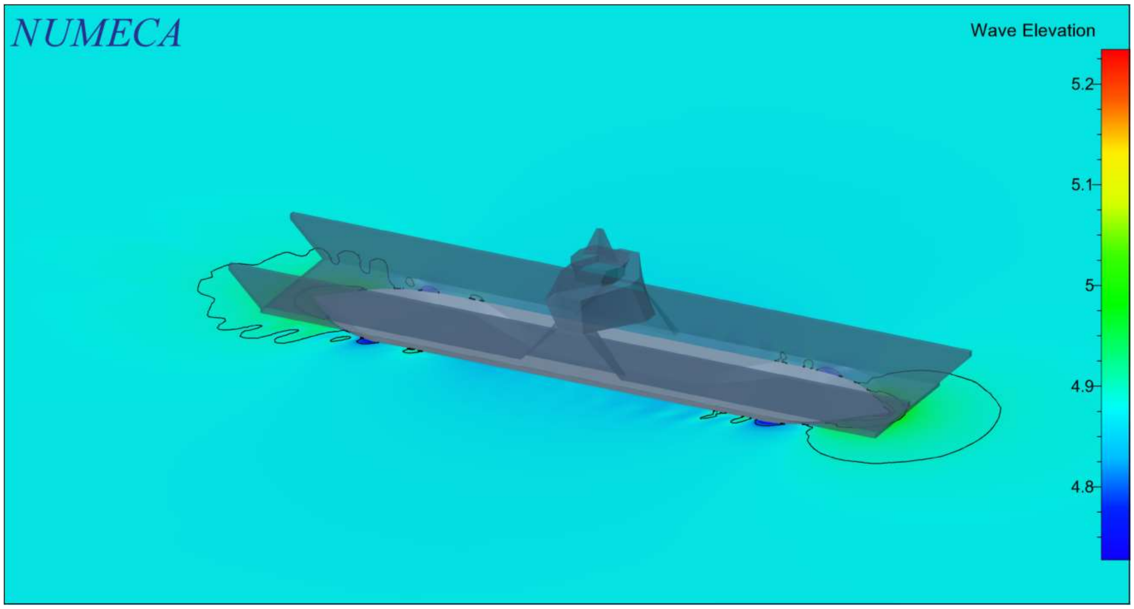



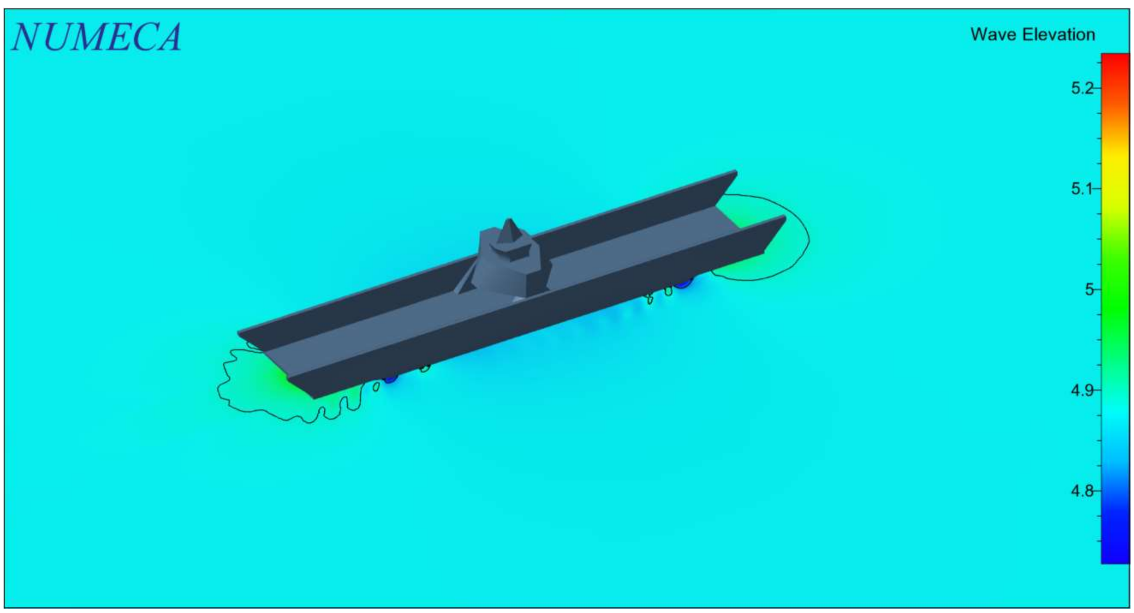
## WAVETRAIN PROFILE 6 KNOTS




## WAVETRAIN BODY 6 KNOTS




NUMECA
Wave Elevation
5.2
5.1
5
4.9
4.8


NUMECA
Wave Elevation
5.2
5.1
5
4.9
4.8

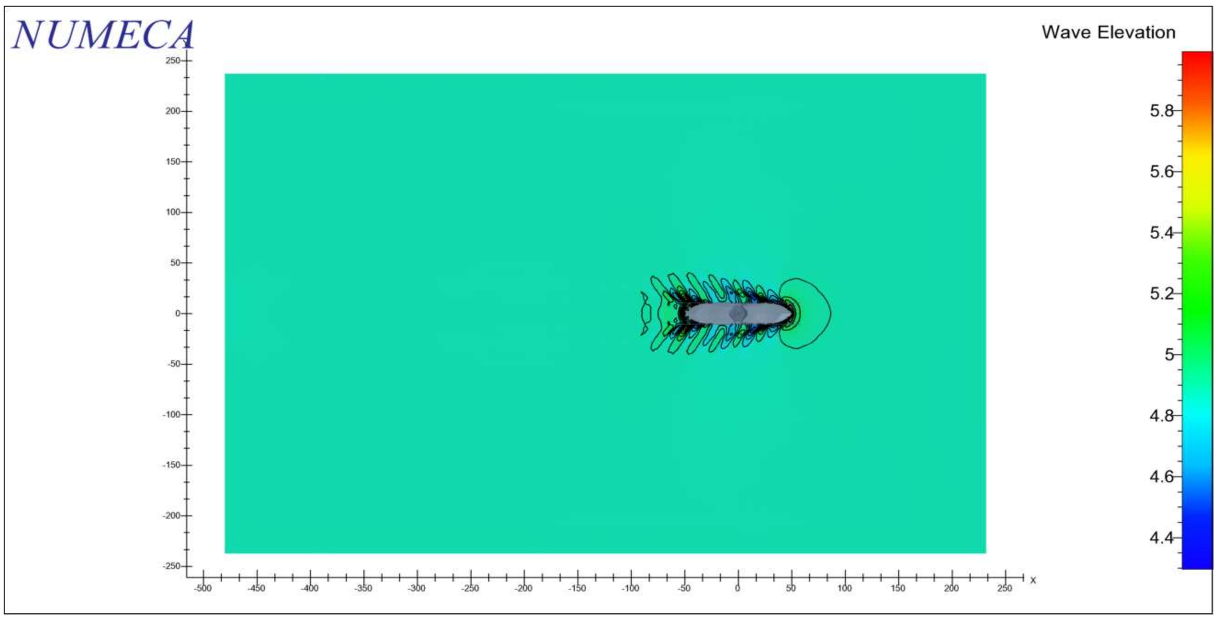
# CFD WAKE ANALYSIS

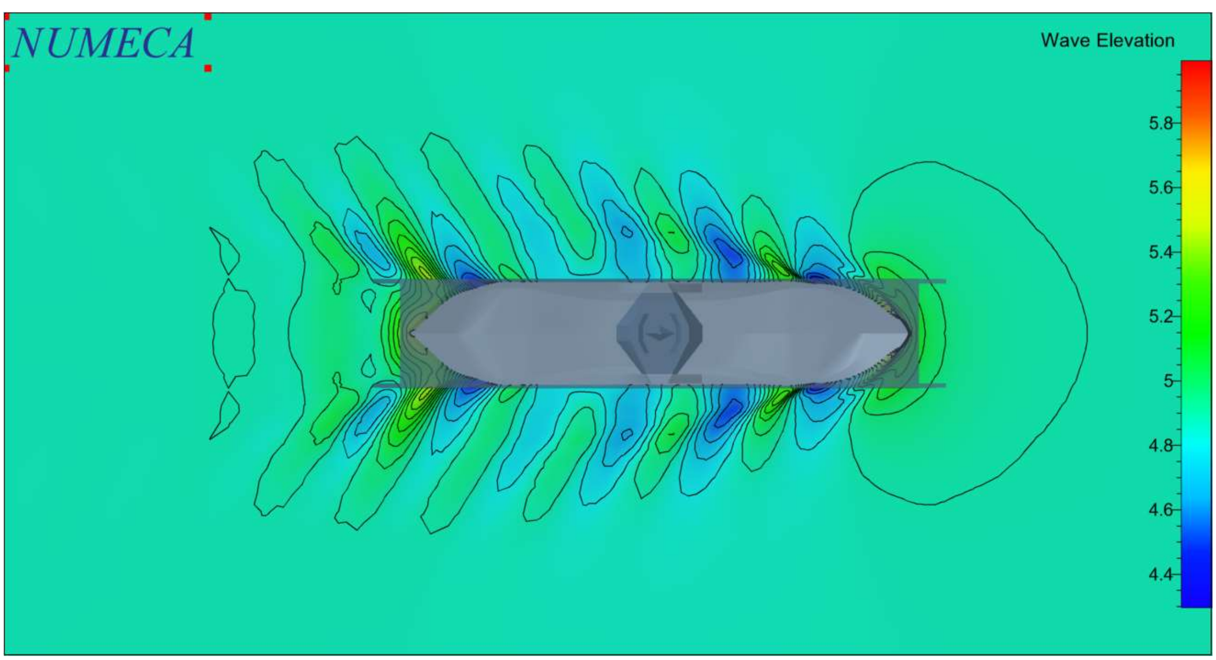
LAKE LLIAMNA  FERRY

| | |
|---|---|
| **SPEED** | 11.0 kn |
| **DRAFT** | 4.8768 m |
| **RESISTANCE** | 123.7 kN |

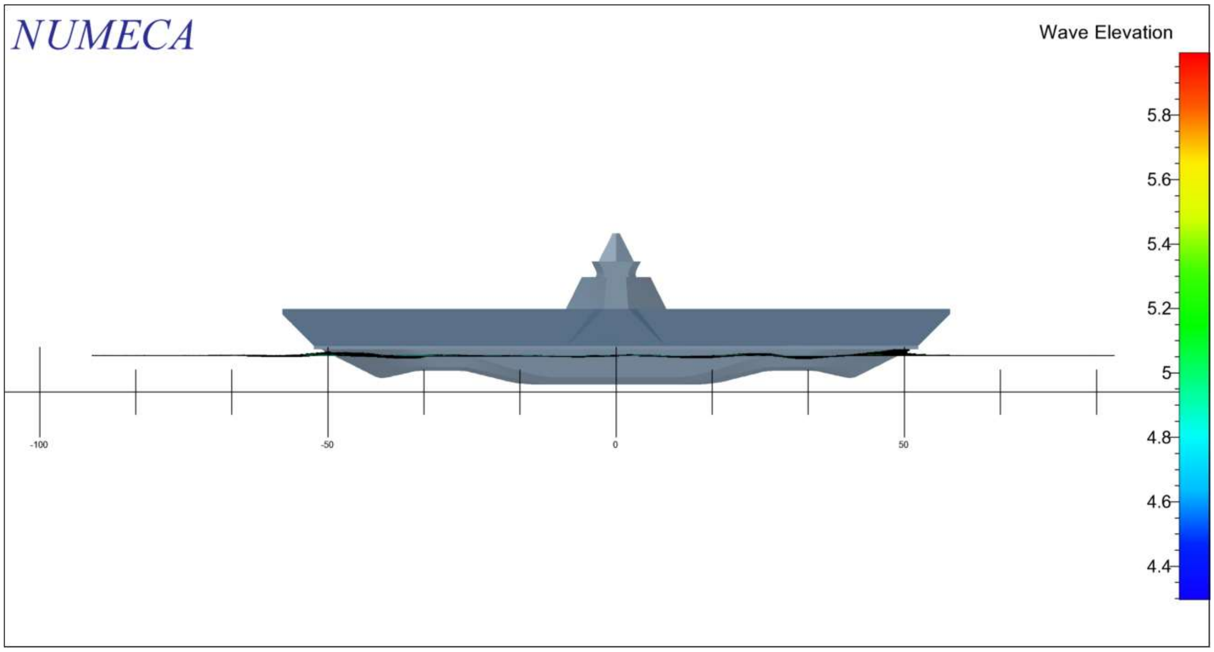
**NOTES**

## WAVETRAIN PLAN

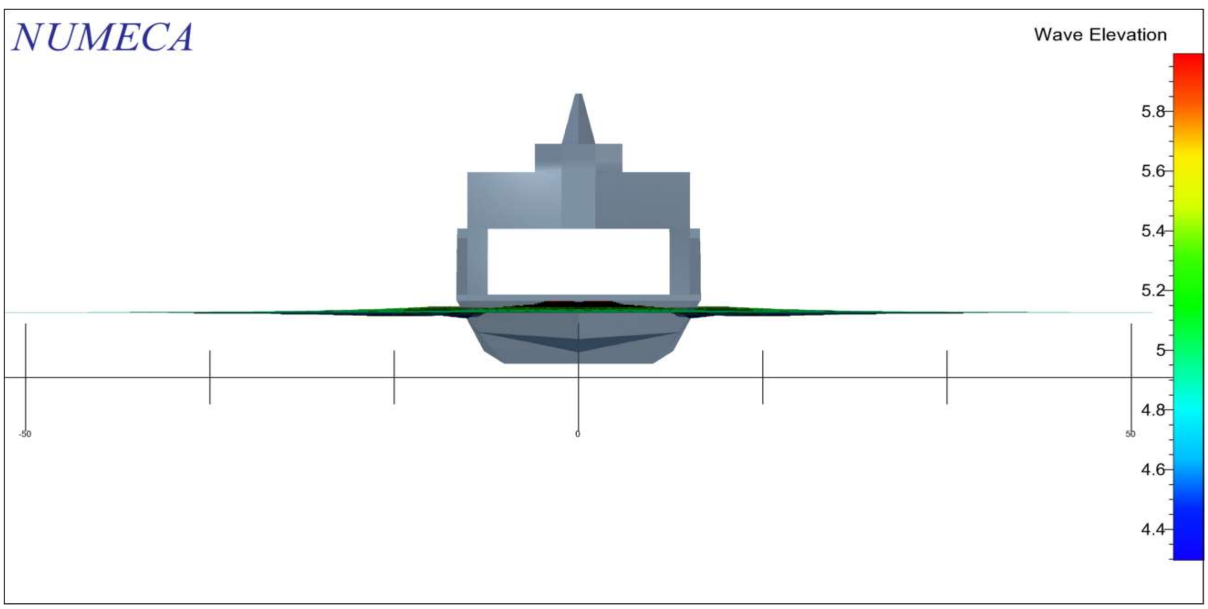


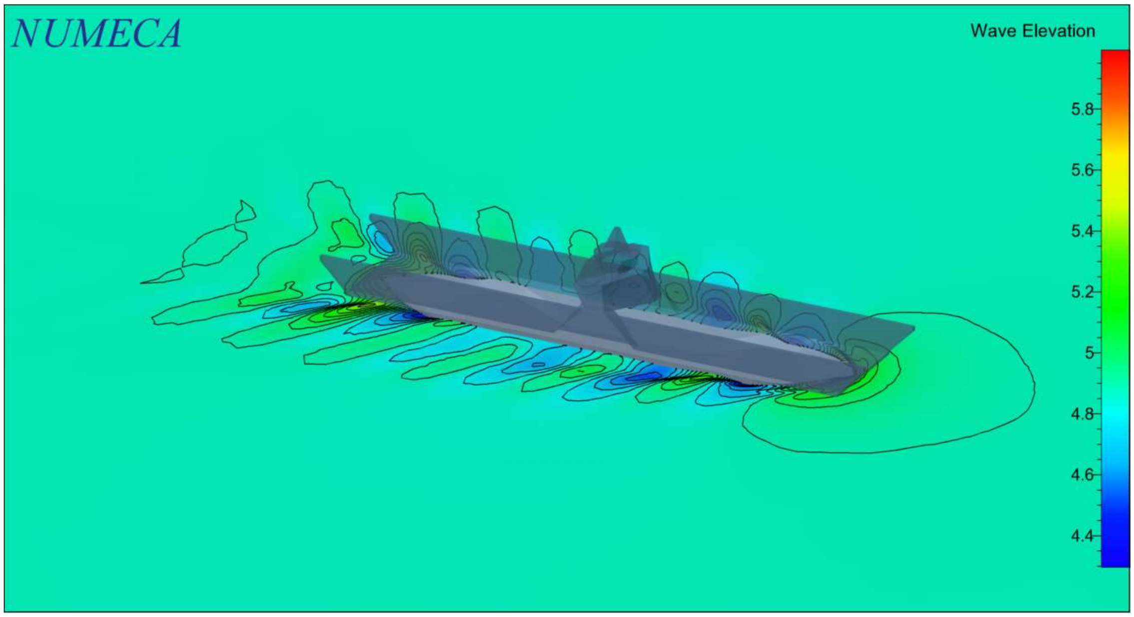



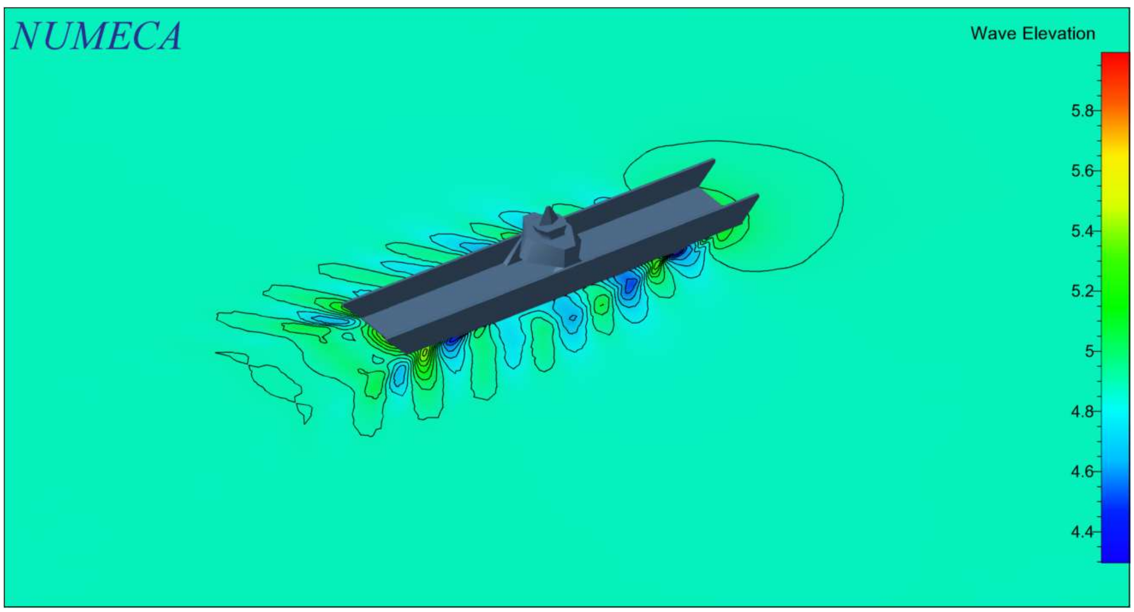
## WAVETRAIN PROFILE 11 KNOTS




## WAVETRAIN BODY 11 KNOTS




NUMECA
Wave Elevation
5.8
5.6
5.4
5.2
5
4.8
4.6
4.4


NUMECA
Wave Elevation
5.8
5.6
5.4
5.2
5
4.8
4.6
4.4

TECHNICAL MEMORANDUM

# Lake Ice, Eastern Iliamna Lake, Alaska: Dates of Ice Formation and Ice Melt Interpreted from MODIS Satellite Imagery, 2000–2011

Matt Macander

December 13, 2011

Prepared for:
Pebble Partnership

Prepared by:
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# LIST OF FIGURES (following tables)

# LAKE ICE, EASTERN ILIAMNA LAKE

## 1. EXECUTIVE SUMMARY

Satellite imagery was reviewed for eastern Iliamna Lake, from the mouth of the Newhalen River east to Pile Bay, for twelve winters (winter 1999/2000 through winter 2010/2011). Permanent winter lake ice has formed a near complete cover over eastern Ilaimna Lake during ten of the previous twelve winters (83% of winters), and generally persisted from late December or January through late April or May. Late winter and spring observations indicated that permanent lake ice did not form in the study area during two winters (winter 2000/2001 and winter 2002/2003). Cloud cover often prevented precise estimates of freeze-up and break-up dates. Uncertainty of date estimates was on average 8–10 days for freeze-up and 4–5 days for break-up.

Freeze-up timing was estimated for six winters (winter 2005/2006 through winter 2010/2011). During these winters, freeze-up started (≥ 10% ice cover) at dates ranging between December 18 and January 14 (average date December 29). Final freeze-up (> 90% ice cover) occurred on dates between December 23 and February 1 (average date January 9).

Ice break-up timing was estimated for twelve winters (winter 1999/2000 through winter 2010/2011). For the ten winters when permanent winter ice formed in the study area, start of break-up (≤ 90% ice cover) occurred at dates ranging between April 2 and May 20 (average date May 5). Final break-up (< 10% ice cover) occurred at dates between April 27 and May 22 (average date May 14).

Ice duration for the six winters (winter 2005/2006 through winter 2010/2011) ranged from 110 days to 149 days. The average ice duration was 129.5 days.

Analysis of spatial patterns of lake ice across years indicated that the average ice-on date varied by up to eleven days within the study area, with deeper water and the northern shore freezing later. Average break-up dates varied by thirteen days within the study area, with break-up occurring latest at the western edge of the study area, where wind-blown ice floes often accumulated.

## 2. INTRODUCTION

Iliamna Lake is the largest freshwater lake in Alaska, with a total surface area of 2,622 square kilometers, a volume of 115 cubic kilometers, a mean depth of 44 meters, and a maximum depth of 301 meters (Anderson, 1969).

Lake ice forms on Iliamna Lake during most winters. The timing of ice establishment and ice melt affects the regional climate, wildlife habitats (PLP, 2011b), subsistence activity (Gaul, 2007), and could constrain winter and spring barge traffic on the lake. Lake ice integrates weather (primarily temperatures) over a time period of several months, and trends in lake ice cover over decades or centuries have been used as one line of evidence for climate change (Magnuson et al., 2000).

Remote sensing provides an opportunity to retrospectively observe the ice cover on Iliamna Lake. The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor provides daily coverage since March 2000 with an appropriate spatial resolution (250–500-m pixels) and spectral bands suitable for distinguishing ice, snow, open water, clouds, and shadows.

The Southwest Alaska Network of National Parks (SWAN) has compiled records for several lakes in southwest Alaska, including Iliamna Lake (Reed, 2009 et al.; Lindsay, pers. comm., 2011). However, their dataset is for whole lakes and does not include specific information about eastern Iliamna Lake. The SWAN dataset records the first observed date when the lake reaches ≥90% ice cover, and the first observed date when ice cover reaches ≤10% ice cover, but these dates may be biased late due to extensive periods with cloud cover—particularly during ice formation in early winter when cloudy weather is more prevalent. Finally, the SWAN dataset does not yet include data for winters 1999/2000, 2000/2001, or 2010/2011.

The objective of the Iliamna lake ice study is to characterize dates of ice formation and ice melt for the eastern portion of Iliamna Lake: all portions of the lake that are east of a line connecting the mouth of the Newhalen River and Tommy Point (Figure 1). The waters around the village of Iliamna are included, as well as Knutsen Bay, Pedro Bay, and Pile Bay. The specific objectives are:

- Compile a georeferenced time-series of MODIS imagery covering the dates of ice formation and ice melt during each winter.
- For grid cells in the study area, review the time-series to determine the last date with observed open water and the first date with observed, permanent winter lake ice during each winter.
- For grid cells in the study area, review the time-series to determine the last date with lake ice and the first date with open water during each spring.
- Summarize the dates when freeze-up started and was completed, and when break-up started and finished in the study area each winter using available imagery.
- Quantify the uncertainty in freeze-up and break-up dates resulting from cloud cover.
- Characterize spatial patterns observed in the dates of ice formation, ice melt, and ice duration.

# 3. METHODS

## 3.1 Compile MODIS Browse Imagery

The MODIS sensor onboard Terra has been collecting data since March 2000 and continues to operate to the present. MODIS Aqua was launched in May 2002 and also remains operational today. MODIS sensors capture data in 36 spectral bands at resolutions of 250 m (two bands), 500 m (five bands), and

1,000 m (29 bands) (Justice et al., 1997). The seven bands at 250–500 m resolution were used for this study.

Georeferenced browse imagery was required for this study. These are calibrated image datasets with some atmospheric correction and consistent radiometry that are gridded to a regular ground coordinate system. Browse imagery is intended for visual interpretation and may have reduced quality compared to the full scientific datasets used for automated algorithms–for example, browse imagery may be reduced to an 8-bit image format and be encoded using lossy compression. Available sources of browse imagery included:

a. MODIS time series compiled for the Pebble Partnership by ABR (PLP, 2011a) for assessing snow-covered area in the Pebble mine study area.

b. MODIS browse images produced by the Geographic Information Network of Alaska (GINA, http://www.gina.alaska.edu/data/gina-modis-images/).

c. MODIS Rapid Response southwest Alaska subsets (http://lance-modis.eosdis.nasa.gov/imagery/subsets/?project=other&subset=SouthwestAlaska.

Details of the available browse imagery are provided in Table 1. The MODIS Rapid Response southwest Alaska subset browse images were the most useful due to the high spatial resolution and multiple band combinations (which improve discrimination of snow, ice, and clouds). However, the browse record was shortest for these data. All three sources of browse imagery were used to construct the most complete time series possible. Two images that covered freeze-up in winter 2004/2005 were also available from an earlier effort assessing lake ice patterns that could affect seal habitat (PLP, 2011b); however this time-series was too sparse to analyze systematically.

## 3.2 Interpret MODIS Browse Imagery

Where available, two band combinations were used to interpret ice cover for Iliamna Lake. A false color infrared composite of MODIS bands 7/2/1 was used to identify suitable dates with sufficient cloud-free areas to infer lake ice conditions and to discriminate snow and ice from clouds. The natural color composite of MODIS bands 1/4/3 was reviewed to improve discrimination of snow-free ice, wet ice, and open water.

The study area was divided into 90 grid cells, with each cell 10,000 feet to a side (Figure 1). The key dates bracketing ice formation and ice melt were recorded for each grid cell, for each winter:

a. Last ice-free date: The last date when open water was observed in a grid cell. In some cases, early freeze-up events did not persist; they were likely broken up due to wind and/or warm temperatures. The last ice-free date recorded the last occurrence of open water before permanent freeze-up (i.e., a freeze-up that lasted for at least a month).

b. First ice date: The first date when permanent winter ice was observed. This could be as soon as the day after the last ice-free date. In cases when extensive cloud cover obscured events during the ice formation season, it could be up to several weeks after the last ice-free date.

c. Last ice date: The last date when ice was observed. In some cases, ice melt occurred in the spring but was followed by another freeze, or floating ice moved back into an area that previously had open water. The last ice date recorded the latest observation of ice for each grid cell.

d. First ice-free date: The first observed date with open water that occurred after the last ice day of year. This could be as soon as the day after the last ice date, or longer due to cloud cover.

These four metrics (a–d) bracketed the ice freeze-up and break-up dates. Additional derived metrics were calculated for each grid cell that summarized the estimated freeze-up and break-up dates, the precision of these estimates, and the ice duration for each cell in each winter:

e. Estimated ice freeze-up date: The average of the last ice-free date and the first ice date.

f. Estimated ice break-up date: The average of the last ice date and the first ice-free date.

g. Estimated ice duration: The number of days between the estimated ice freeze-up date and the estimated ice break-up date.

h. Freeze-up range: The difference between the first ice date and the last ice-free date. The freeze-up range represents the precision of the estimated ice freeze-up date. The actual freeze-up date occurred during the time period of the estimated ice freeze-up date ± half of the freeze-up range. The metric also provided a data check (values should be positive; and large values were checked to ensure that they were correct).

i. Break-up range: The difference between the first ice-free date and the last ice date. The break-up range represents the precision of the estimated ice break-up date. The actual break-up date occurred during the time period of the estimated ice break-up date ± half of the break-up range. The metric also provided a data check (values should be positive; and large values were checked to ensure that they were correct).

## 3.3 Summarize Lake Ice Data

The proportion of the study area covered by lake ice was estimated for each winter, for each date between December 1 and June 1 based on the estimated freeze-up date and break-up date for each cell. For winters when freeze-up data were not available, the time series was limited to March 1 to June 1. Because there was uncertainty as to the actual dates of freeze-up and break-up for each cell due to cloud cover, three different estimates of daily ice cover were produced: 1) maximum ice scenario, which assumed there was ice cover for all dates between the last ice-free date and the first ice-free date; 2) midpoint ice scenario, which assumed there was ice cover for all dates between the estimated freeze-up date and the estimated break-up date; and 3) minimum ice scenario, which assumed there was ice cover only for dates between the first ice date and the last ice date.

The results of the ice cover by date analysis were plotted for each winter to visually depict ice cover extent over the study area by date, providing detailed information about the rate of freeze-up and break-up in different years as well as depicting the uncertainty by date and winter. The results were also used to calculate several metrics for the full study area for each year with data. These metrics followed the protocols used by SWAN for characterizing the lake ice regime for southwest Alaska lakes (Lindsay et al., 2011):

j. Start freeze-up: Date when lake ice $\geq$ 10%.

k. Final freeze-up: Date when lake ice > 90%.

l. Start break-up: Date when lake ice $\leq$ 90%.

m. Final break-up: Date when lake ice < 10%.

n. Ice duration: Number of days from final freeze-up to final break-up.

For each metric, value was calculated for all three scenarios (maximum ice, midpoint ice, minimum ice). The range of dates for the three scenarios was calculated so that the uncertainty introduced by cloud cover could be quantified.

Across all the winters with available data, the values for estimated ice freeze-up date, estimated ice break-up date and estimated ice duration were averaged for each grid cell. The analysis of results by grid cell summarized the spatial patterns of lake ice formation, melt, and duration across years.

# 4. Results And Discussion

## 4.1 Compile MODIS Browse Imagery

The most complete MODIS time series was constructed by combining data from several sources, using the best data available for each time period (Table 3). Publically available MODIS browse imagery archives were available from summer 2005 through present (GINA) and from fall 2007 through present (MODIS Rapid Response southwest Alaska subset). These data were generally available at a frequency of daily or higher. The MODIS Rapid Response data also included multiple band combinations which improved the accuracy of estimates; therefore these were used whenever available.

For earlier winters the only readily available MODIS browse imagery was the time series developed by ABR for assessing snow cover depletion (PLP, 2011a). These data were coarser (500-m pixels) and only included dates from late winter through early summer (the snowmelt season). The ABR time series selected dates with limited cloud cover over the mine study area; some dates with good viewing conditions over the lake study area may have been excluded because the time series was compiled with the primary objective of estimating snow cover on land. The ABR time series could readily be refined to include more dates (including freeze-up) and higher spatial resolution; however, the current effort used only pre-existing browse imagery.

## 4.2 Interpret MODIS Browse Imagery

When available (i.e., for all seasons analyzed except freeze-up in winter 2005/2006 and winter 2006/2007), false color infrared composites of MODIS bands 7/2/1 were used to discriminate clouds from snow and ice. The color and texture of snow and ice are generally easy to distinguish from clouds using this band combination. Snow and snow-covered ice are light blue while clouds are usually bright white. Clouds with high snow content may have a light blue color but generally have a diffuse texture distinct from ground snow. Open water, wet ice, snow-free ice, and cloud shadows can all be very dark with the 7/2/1 band combination. Cloud shadows may be distinguished from the other classes by context (location and shape of nearby clouds). Ice fractures may help distinguish snow-free ice from open water. However, it was often difficult to distinguish wet ice and snow-free ice from open water using this combination alone.

The natural color composite of MODIS bands 1/4/3 was reviewed to improve discrimination of snow-free ice, wet ice, and open water. In general, snow-free ice and wet ice were brighter than open water. Textural and time series cues also provided information that was useful to distinguish open water from snow-free or wet ice. For example, water pooling on ice would result in dark areas with decreasing darkness towards edges. Snow-free ice often had some small, bright textural features that remained at a fixed location across multiple time steps. These were likely associated with fractures or pressure ridges trapping snow. In these cases, the earliest image with a fixed location for the feature represented the observed lake ice formation date. Snow-free ice would also abruptly and uniformly turn from dark to bright white across a very large area after a snow event occurred; this was interpreted as a cue that freeze-up had likely occurred at an earlier date. Some examples illustrating the lake ice interpretation of false color MODIS imagery were prepared for the Environmental Baseline Document chapter that discussed seals in Iliamna Lake (PLP, 2011b); the figure is reproduced here (Figure 2). Additional examples illustrating the lake ice interpretation of natural color and false color MODIS imagery may be provided on request.

## 4.3 Summarize Lake Ice Data

The plot of estimated ice cover by date (Figure 3) depicts a summary of ice cover for each winter. Freeze-up imagery was not available for winter 1999/2000 through winter 2004/2005, so those winters show only the break-up season, starting in March. The plots include data for three scenarios: maximum ice (dark blue), midpoint ice (medium blue), and minimum ice (light blue). These scenarios bracket the uncertainty in freeze-up and break-up dates due to cloud cover. The midpoint ice scenario provides the most unbiased estimate as it assumes that freeze-up occurs in each grid cell at the date midway between the last ice-free date and the first ice date, and that break-up occurs at the date midway between the last ice date and the first ice-free date. However, break-up and freeze-up could have occurred at any of the dates in the range.

No break-up was observed in the study area during winter 2000/2001 and winter 2002/2003, so no ice cover profile is plotted. Patchy ice was observed within the study area during March during those winters but it did not harden into permanent winter ice; it dispersed soon after forming. These finding indicate that permanent winter ice formed during ten of the twelve winters observed; eastern Iliamna Lake freezes in 83% of winters during the study period.

Ice cover profiles with narrow bands of medium and dark blue represent periods with smaller uncertainty in ice cover. For example, the dates of freeze-up during winter 2008/2009 and winter 2010/2011 and the dates of break-up during winters 2000/2001, 2005/2006, and 2008/2009 have little uncertainty due to cloud cover.

Wide bands of medium and dark blue indicate high uncertainty. There was very high uncertainty in the initial stages of freeze-up for winter 2006/2007 and winter 2009/2010, and high uncertainty in the latter portion of freeze-up in winter 2005/2006. Uncertainty was very high during portions of break-up in winters 2003/2004, 2004/2005, and 2010/2011.

Despite the uncertainty due to cloud cover, it is clear that there are substantial variations in both the dates and rates of freeze-up and break-up across years. Freeze-up was earliest in winter 2006/2007 and later in winter 2005/2006, 2009/2020, and 2010/2011. Freeze-up may occur rapidly (in less than a week, as in winter 2008/2009) or gradually (over more than three weeks, as in winter 2010/2011). In most winters, the rate of freeze-up was ambiguous due to cloud cover. Similarly, break-up was early in winter 2004/2005 and late in winter 2005/2006. Break-up was more gradual during winter 2006/2007 and was rapid in winter 2005/2006.

The standardized freeze-up, break-up, and ice duration metrics (Table 3) were calculated for six freeze-up seasons and ten break-up seasons. The start of freeze-up (first date with ≥ 10% permanent winter ice) based on the midpoint ice scenario ranged from December 18 to January 14; the average date was December 29. The final freeze-up date (first date with > 90% permanent winter ice) ranged from December 23 to February 1, with an average date of January 9. On average, it took 11 days to proceed from the start of freeze-up to final freeze-up. The uncertainty in the start of freeze-up ranged from 2 to 20 days with an average uncertainty of 9.7 days. The uncertainty in the date of final freeze-up was 6 days or less in five years but was 29 days in winter 2005/2006, resulting in an average uncertainty of 7.5 days. Limited imagery that was reviewed for winter 2004/2005 was consistent with other years, with freeze-up occurring sometime between January 18, 2005 and February 3, 2005 (Figure 2). The latest imagery from winter 2011/2012 indicates that freeze-up had not occurred yet, as of December 15, 2011.

The start of break-up (for the ten winters when break-up occurred in the study area) based on the midpoint ice scenario ranged from April 2 to May 20 with an average date of May 5. Final break-up was observed between April 27 and May 22, with an average date of May 14. On average, 9 days passed between start of break-up and final break-up. The uncertainty in break-up dates was lower than for freeze-up dates, since cloud cover is less during spring. For start of break-up, uncertainty ranged from 1 to 8 days with an average of 4.0 days, and for final break-up uncertainty ranged from 1 to 15 days with an average of 5.0 days.

Ice duration (number of days between final freeze-up and final break-up) under the midpoint ice scenario ranged from 110 days to 149 days with an average duration of 129.5 days. The shortest ice duration occurred during winter 2005/2006 when the date of final freeze-up was late (February 1) but also highly uncertain (29 days). Uncertainty in the ice duration ranged from 4 to 30 days with an average uncertainty of 14.0 days.

Lake ice spatial patterns were assessed by calculating summary statistics for each grid cell across all of the years with data (Figure 4). The average freeze-up date varied over 12 days in the study area, with the earliest ice occurring in shallow, sheltered water. Lake ice formed later towards the center of the lake, and along the north shore. Average break-up dates ranged over 13 days with later break-up to the west and in areas where islands trap ice. As ice breaks up on Iliamna Lake, large ice masses are often observed moving across the lake, usually from east to west due to prevailing winds. Average ice duration by grid cell ranges from 124 to 141 days with the most persistent ice in sheltered shallows and to the west.

# 5. Summary

Satellite imagery was reviewed for eastern Iliamna Lake (from the mouth of the Newhalen River east to Pile Bay). Permanent winter lake ice has formed during ten of the previous twelve winters (83% of winters), and generally persisted from late December or January through late April or May. Late winter and spring observations indicated that permanent lake ice did not form in the study area during two winters (winter 2000/2001 and winter 2002/2003). Cloud cover often prevented precise estimates of freeze-up and break-up dates. Uncertainty of estimates was on average 8–10 days for freeze-up and 4–5 days for break-up.

Freeze-up timing was estimated for six winters (winter 2005/2006 through winter 2010/2011). During these winters, freeze-up started (≥ 10% ice) at dates ranging between December 18 and January 14 (average date December 29). Final freeze-up (> 90% ice cover) occurred on dates between December 23 and February 1 (average date January 9). Uncertainty in date estimates as a result of cloud cover averaged 9.7 days for start of freeze-up and 7.5 days for final freeze-up.

Ice break-up timing was estimated for twelve winters (winter 1999/2000 through winter 2010/2011). For the ten winters when permanent winter ice formed in the study area, start of break-up (≤90% ice cover) occurred at dates ranging between April 2 and May 20 (average date May 5). Final break-up (< 10% ice cover) occurred at dates between April 27 and May 22 (average date May 14). Uncertainty in date estimates as a result of cloud cover averaged 4.0 days for start of break-up and 5.0 days for final break-up.

Ice duration for the six winters (winter 2005/2006 through winter 2010/2011) ranged from 110 days to 149 days. The average ice duration was 129.5 days.

Analysis of spatial patterns of lake ice across years indicated that the average ice-on date varied by up to 11 days within the study area, with deeper water and the northern shore freezing later. Average break-up dates varied by up to 13 days within the study area, with break-up occurring latest at the western edge of the study area, where wind-blown ice floes often accumulated.

# 6. References

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Reed, B., Budde, M., Spencer, P., and Miller, A.E. 2009. Integration of MODIS-derived metrics to assess interannual variability in snowpack, lake ice, and NDVI in southwest Alaska. Remote Sensing of Environment, 113, 1443–1452.

# Tables

TABLE 1
Sources of MODIS Browse Imagery Available for Interpretation of Lake Ice, Eastern Iliamna Lake, Alaska, 2000–2011

| Source | Date Range | Band Combinations | Pixel Size | Compression |
|---|---|---|---|---|
| GINA MODIS Browse | Summer 2007–present | Natural Color and False Color Infrared (7/2/1) | 250 m | Lossy |
| MODIS Rapid Response Southwest Alaska subsets | Summer 2005–present | Natural Color | 250 m | Lossy |
| ABR/Pebble Partnership Snow Study | March–June, 2000–2008 | Natural Color and False Color Infrared (7/2/1) | 500 m | None |

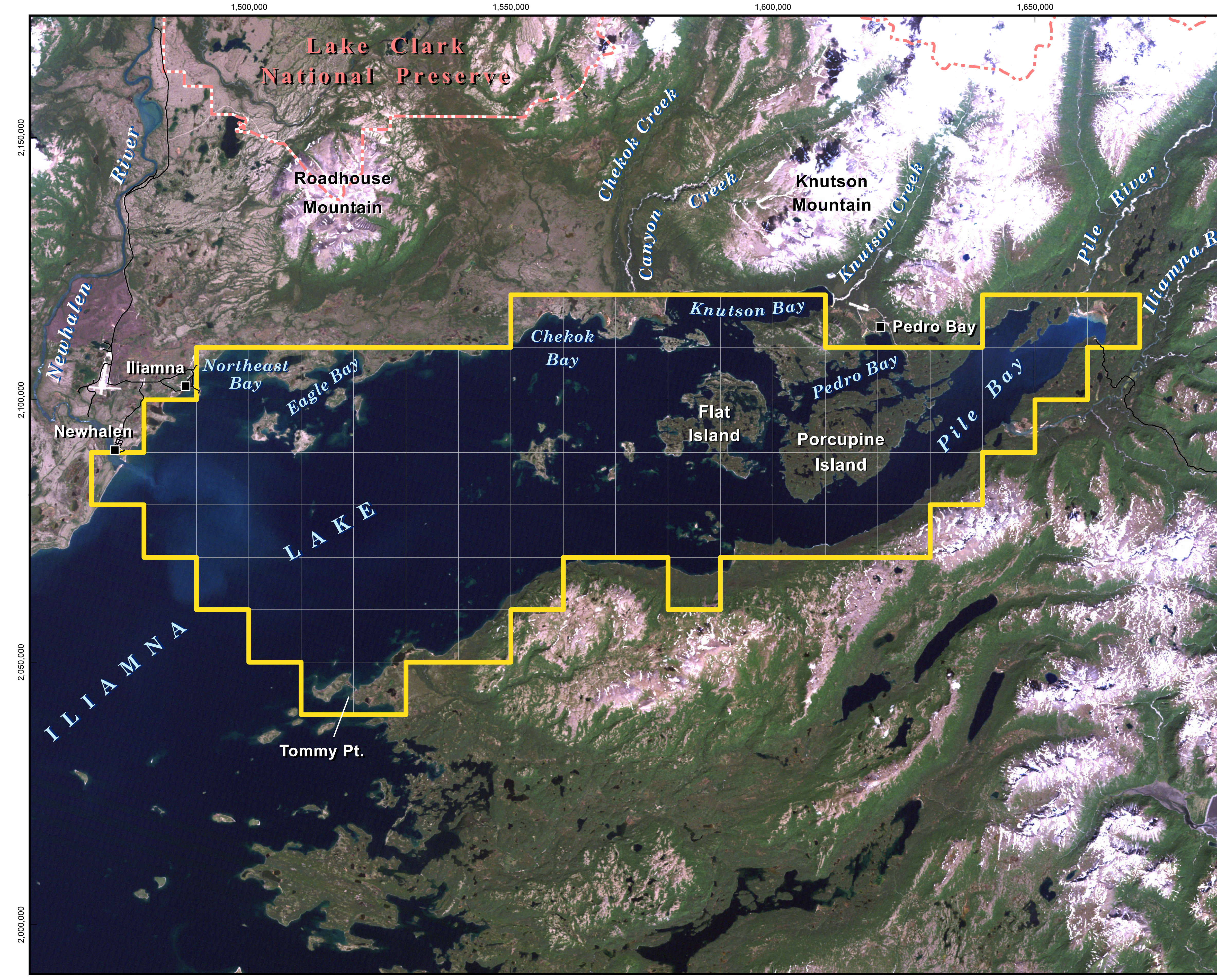
TABLE 2
MODIS Browse Data Imagery used for Lake Ice Interpretation, Eastern Iliamna Lake, Alaska, 2000–2011

| Winter | Freeze-Up | Break-Up |
|---|---|---|
| 1999–2000 | Pre-launch, No Imagery | ABR MODIS |
| 2000–2001 | Browse Imagery not Processed | ABR MODIS |
| 2001–2002 | Browse Imagery not Processed | ABR MODIS |
| 2002–2003 | Browse Imagery not Processed | ABR MODIS |
| 2003–2004 | Browse Imagery not Processed | ABR MODIS |
| 2004–2005 | Browse Imagery not Processed | ABR MODIS |
| 2005–2006 | GINA Browse | ABR MODIS and GINA Browse |
| 2006–2007 | GINA Browse | NASA Rapid Response Browse |
| 2007–2008 | NASA Rapid Response Browse | NASA Rapid Response Browse |
| 2008–2009 | NASA Rapid Response Browse | NASA Rapid Response Browse |
| 2009–2010 | NASA Rapid Response Browse | NASA Rapid Response Browse |
| 2010–2011 | NASA Rapid Response Browse | NASA Rapid Response Browse |

TABLE 3
Lake Ice Metrics for Eastern Iliamna Lake, Alaska, 2000–2011

| Winter | Start Freeze-Up (>=10% Ice Cover) | | | | Final Freeze-Up (>90% Ice Cover) | | | | Start Break-Up (<=90% Ice Cover) | | | | Final Break-Up (<=10% Ice Cover) | | | | Ice Duration (Final Freeze-Up to Final Break-Up) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Max. Ice | **Midpoint** | Min. Ice | Uncertainty | Max. Ice | **Midpoint** | Min. Ice | Uncertainty | Max. Ice | **Midpoint** | Min. Ice | Uncertainty | Max. Ice | **Midpoint** | Min. Ice | Uncertainty | Max. Ice | **Midpoint** | Min. Ice | Uncertainty |
| 1999/2000 | No MODIS Data | | | | | | | | 4/22/2000 | **4/23/2000** | 4/25/2000 | 3 | 5/2/2000 | **5/4/2000** | 5/6/2000 | 4 | Not Calculated | | | |
| 2000/2001 | Not Assessed | | | | | | | | No Permanent Winter Ice | | | | | | | | | | | |
| 2001/2002 | | | | | | | | | 5/13/2002 | **5/13/2002** | 5/14/2002 | 1 | 5/20/2002 | **5/20/2002** | 5/21/2002 | 1 | | | | |
| 2002/2003 | | | | | | | | | No Permanent Winter Ice | | | | | | | | | | | |
| 2003/2004 | | | | | | | | | 4/26/2004 | **4/30/2004** | 5/4/2004 | 8 | 5/5/2004 | **5/6/2004** | 5/7/2004 | 2 | | | | |
| 2004/2005 | | | | | | | | | 4/1/2005 | **4/2/2005** | 4/4/2005 | 3 | 4/25/2005 | **4/27/2005** | 4/29/2005 | 4 | | | | |
| 2005/2006 | 1/8/2006 | **1/14/2006** | 1/17/2006 | 9 | 1/18/2006 | **2/1/2006** | 2/16/2006 | 29 | 5/18/2006 | **5/20/2006** | 5/22/2006 | 4 | 5/22/2006 | **5/22/2006** | 5/23/2006 | 1 | 95 | **110** | 125 | 30 |
| 2006/2007 | 12/11/2006 | **12/18/2006** | 12/25/2006 | 14 | 12/21/2006 | **12/23/2006** | 12/25/2006 | 4 | 5/5/2007 | **5/8/2007** | 5/12/2007 | 7 | 5/20/2007 | **5/21/2007** | 5/22/2007 | 2 | 146 | **149** | 152 | 6 |
| 2007/2008 | 12/28/2007 | **1/1/2008** | 1/5/2008 | 8 | 1/5/2008 | **1/6/2008** | 1/9/2008 | 4 | 5/11/2008 | **5/12/2008** | 5/14/2008 | 3 | 5/11/2008 | **5/14/2008** | 5/18/2008 | 7 | 123 | **129** | 134 | 11 |
| 2008/2009 | 12/27/2008 | **12/28/2008** | 12/29/2008 | 2 | 12/29/2008 | **12/30/2008** | 12/30/2008 | 1 | 5/12/2009 | **5/13/2009** | 5/15/2009 | 3 | 5/18/2009 | **5/19/2009** | 5/21/2009 | 3 | 139 | **140** | 143 | 4 |
| 2009/2010 | 12/24/2009 | **1/3/2010** | 1/13/2010 | 20 | 1/14/2010 | **1/17/2010** | 1/20/2010 | 6 | 5/10/2010 | **5/13/2010** | 5/16/2010 | 6 | 5/10/2010 | **5/15/2010** | 5/21/2010 | 11 | 110 | **118** | 127 | 17 |
| 2010/2011 | 12/15/2010 | **12/18/2010** | 12/20/2010 | 5 | 1/10/2011 | **1/11/2011** | 1/11/2011 | 1 | 5/14/2011 | **5/15/2011** | 5/16/2011 | 2 | 5/16/2011 | **5/22/2011** | 5/31/2011 | 15 | 125 | **131** | 141 | 16 |
| Mean | 12/24 | **12/29** | 1/2 | 9.7 | 1/5 | **1/9** | 1/13 | 7.5 | 5/4 | **5/5** | 5/8 | 4.0 | 5/11 | **5/14** | 5/16 | 5.0 | 123.0 | **129.5** | 137.0 | 14.0 |

# FIGURES

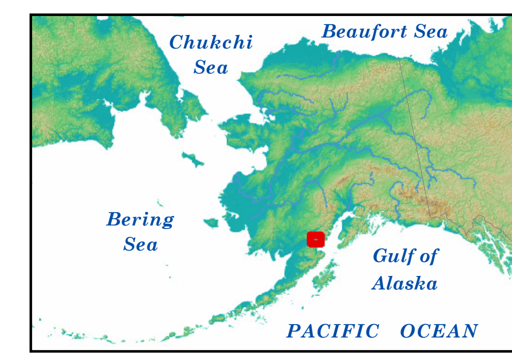





# Figure 1
## Lake Ice Study Area, Eastern Iliamna Lake, Alaska

**Legend**

- Study Area
- Analysis Grid Cells
- Existing Road

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Kilometers: 0 2 4 6 8 10 12

Scale 1:226,000

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**Alaska State Plane Zone 5 (units feet)**
**1983 North American Datum**

| | |
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| Version: 1 | Author: ABR-AZC |

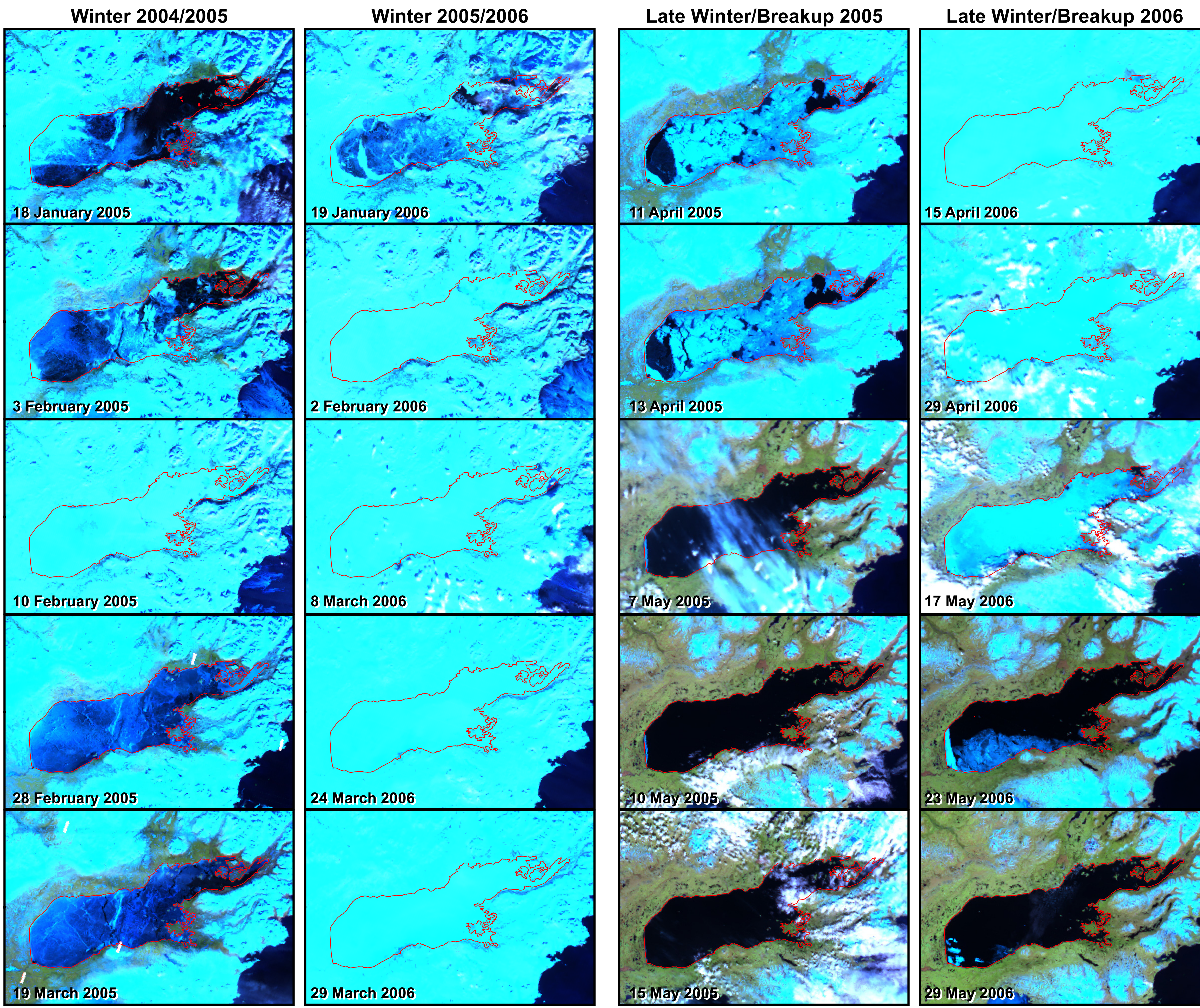


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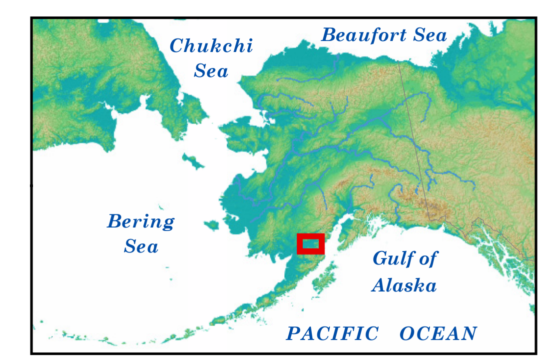
**Figure 2**
**False Color Infrared MODIS Satellite Imagery of Ice Cover on Iliamna Lake, Alaska, Winter 2004/2005 and 2005/2006**

**Legend**

- Iliamna Lake Outline
- Open Water
- Snow-covered Land or Snow-covered Lake Ice
- Snow-free Lake Ice
- Snow-Free Land (Vegetated)
- Clouds

Images are 500-m false color composites (Bands 6/2/1) produced from corrected reflectance swaths acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard the NASA Terra platform. Data acquired from the Goddard Earth Sciences Data and Information Services Center.

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Kilometers: 0 10 20 30 40 50 60 70 80 90

N

Scale 1:1,900,000

**Alaska State Plane Zone 5 (units feet)**
**1983 North American Datum**

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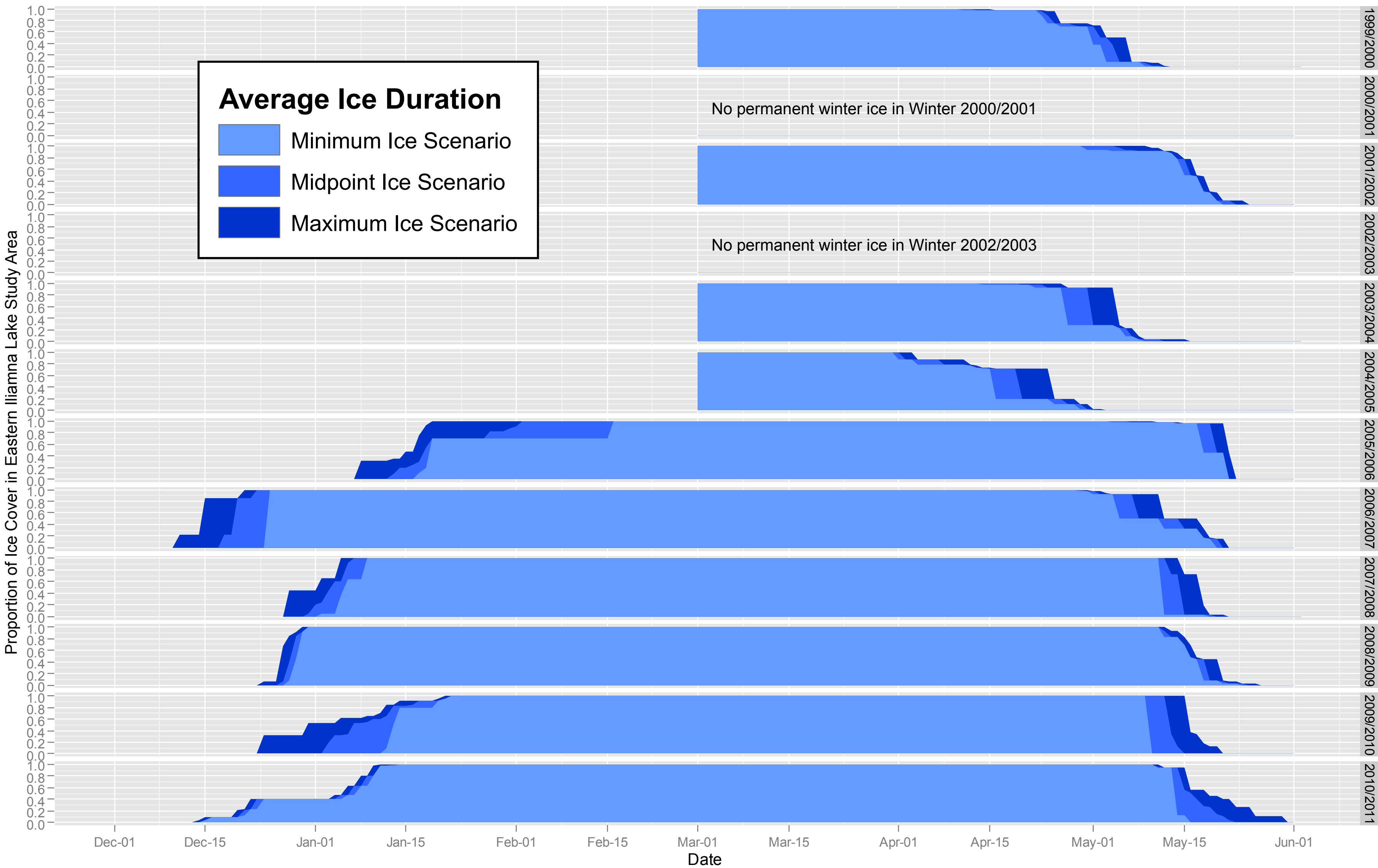
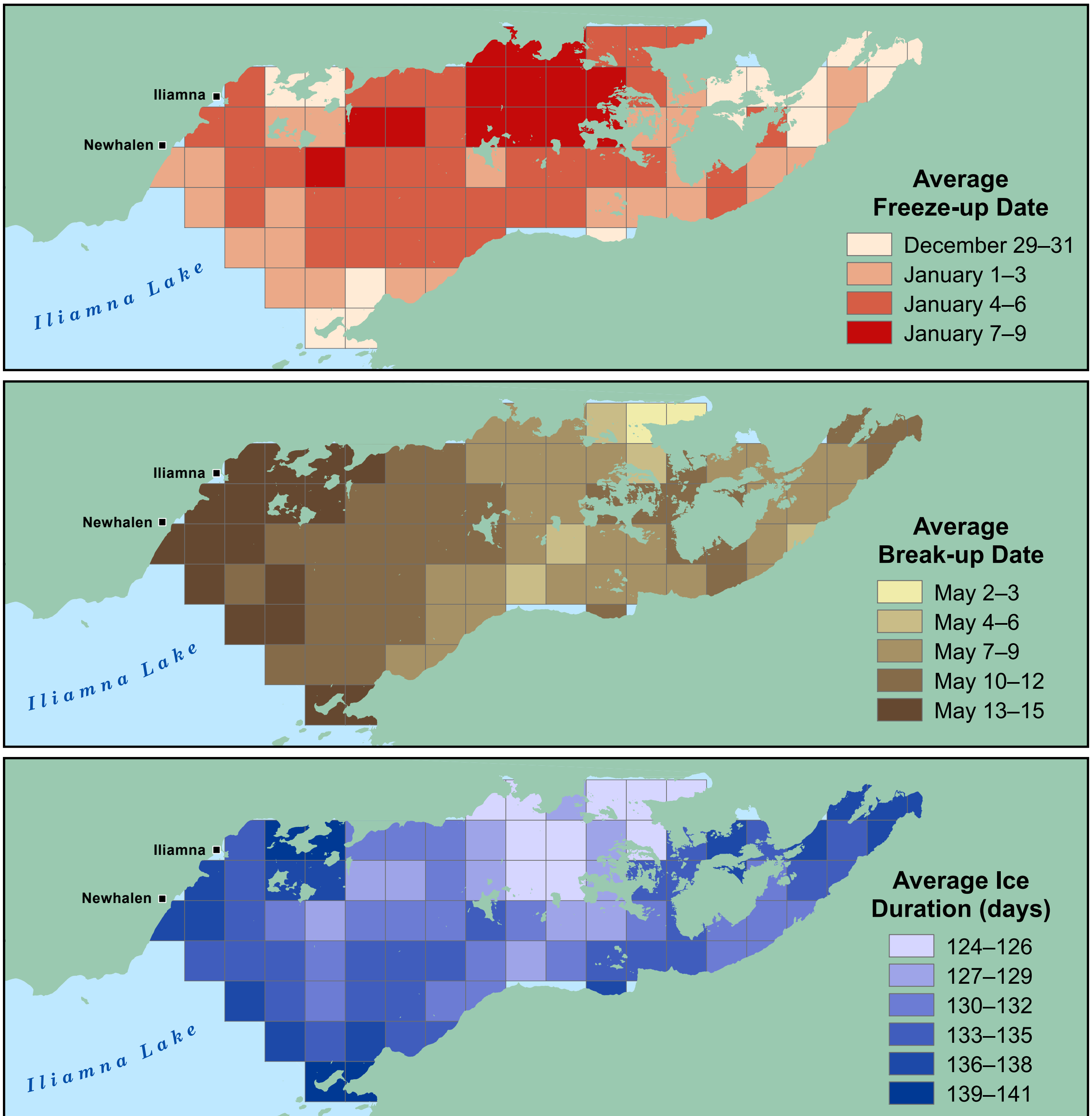
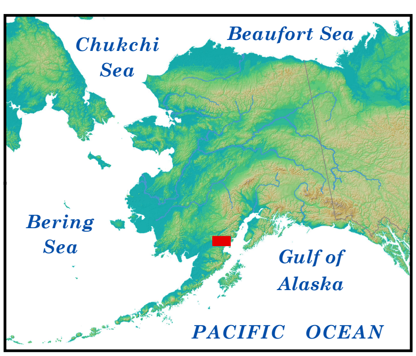



Figure 3. Annual Ice Cover Extent by Date, Eastern Iliamna Lake, Alaska, 2000–2011. Scenarios characterize uncertainty caused by cloud cover obscuring the exact dates of ice formation and melt.




**Legend**

Background

Iliamna Lake (outside study area)

N

Miles 0 2 4 6 8

Kilometers 0 2 4 6 8 10 12

Scale 1:480,000

**Alaska State Plane Zone 5 (units feet)**
**1983 North American Datum**

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**Figure 4. Multi-Year Spatial Patterns of Ice Formation, Ice Melt, and Ice Duration, Eastern Iliamna Lake, Alaska, 2000–2011**

| | |
|---|---|
| File: Fig04_Iliamna_Lake_Ice_Patterns_v01.mxd | Date: Dec. 16, 2011 |
| Version: 1 | Author: ABR-MJM |

**Image Analysis Preliminary Summary Report**

Project:

**Pebble Project Area Iliamna Lake Ice Study**

**P.O. Box 80410**
**Fairbanks, AK 99708**

1 August 2018

Prepared for:
**Tim Havey**
Pebble Limited Partnership
3201 C Street, Suite 505
Anchorage, Alaska 99503

Prepared by:
**Matthew J Macander**

## INTRODUCTION

Iliamna Lake is the largest freshwater lake in Alaska, with a total surface area of 2,622 square kilometers, a volume of 115 cubic kilometers, a mean depth of 44 meters, and a maximum depth of 301 meters (Anderson, 1969). Lake ice forms on Iliamna Lake during most winters (Macander 2011). The timing of ice establishment and ice melt affects the regional climate, wildlife habitats (PLP, 2011), subsistence activity (Gaul, 2007), and could constrain the proposed barge traffic on the lake during winter and spring. Lake ice integrates weather (primarily temperatures) over a time period of several months, and trends in lake ice cover over decades or centuries have been used as one line of evidence for climate change (Magnuson et al., 2000).

Remote sensing provides an opportunity to retrospectively quantify the ice cover on Iliamna Lake. The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor provides daily coverage since March 2000 with an appropriate spatial resolution (250 to 500-m pixels) and spectral bands suitable for distinguishing ice, snow, open water, clouds, and shadows.

## METHODS

We compiled a georeferenced time-series of MODIS imagery covering the dates of ice formation and ice melt during each winter. The dates compiled were December 1 through June 1 for winters 1999/2000 through 2017/2018. The record began in February 2000.

The study area was divided into 340 square grid cells, with each cell 10,000 feet to a side (Figure 1). We reviewed the daily images for each winter and interpreted ice cover, open water, or unknown for selected images from each winter that provided information on changing ice conditions. Then, the cells that were unknown were filled using other dates from that winter for the same cell using three approaches to characterize uncertainty: last observation carried forward, midpoint filling, or next observation carried back.

The time-series of ice cover was then plotted for each winter. The plots showed the timing and speed of ice cover formation as well as the range of uncertainty due to cloud cover.

The ice duration (number of days with ice) was calculated for each cell and each winter using the midpoint-filling approach. The median ice duration for each cell for the full time-series was then calculated.

## PRELIMINARY RESULTS

The analysis covered 19 winters (Figure 2). 15 of the winters had prolonged periods of complete or nearly complete ice cover. 4 winters (2000/2001, 2002/2003, 2014/2015, and 2015/2016) had minimal or no observed periods of complete ice cover. Winter 2015/2016 had only trace ice cover observed through the entire winter. Often there were several weeks of uncertainty in ice-on and ice-off dates due to cloud cover, as seen in the range between the maximum ice scenario and the minimum ice scenario.

A map of median ice duration (Figure 3) shows a strong spatial pattern with the shortest ice duration (<105 days) in the eastern portion of the lake, as far west as Iliamna. Median ice duration is intermediate across the lake to Kohkanok (96–110 days), except along the shore and in the complex of bays and islands east of Kohkanok. Farther west, the median ice duration increases gradually, ranging from 106-140 days. This pattern is likely due to prevailing winds concentrating lake ice in the western side of the lake; often accumulations of ice near the western shore persist for weeks after the rest of the ice has melted.

The data have not yet been summarized to estimate the annual date of ice onset and melt for each cell and winter.

## ATTACHMENTS

Attachment A: Study area map, annual ice cover plots, and ice duration map as figures 1–3.

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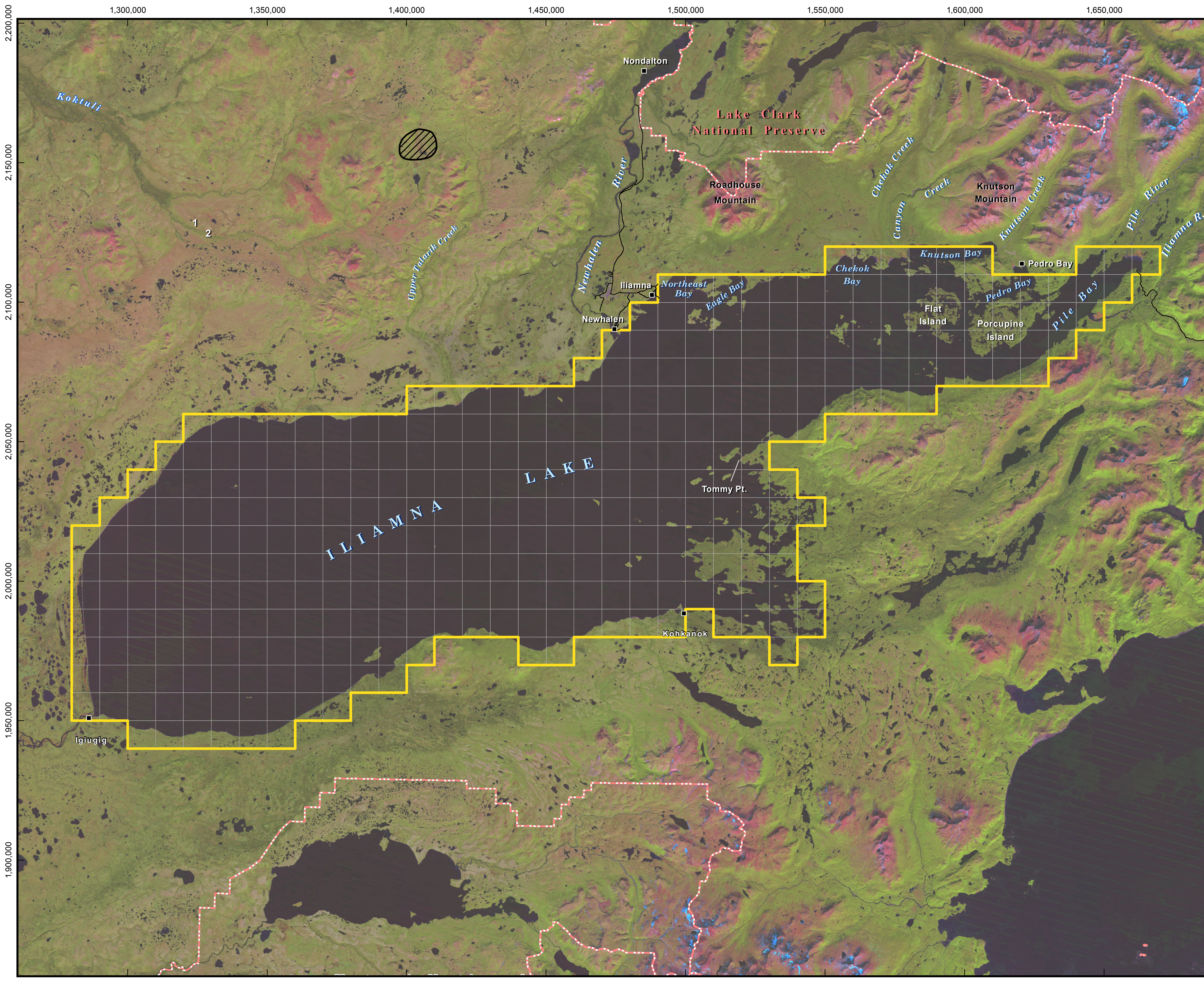


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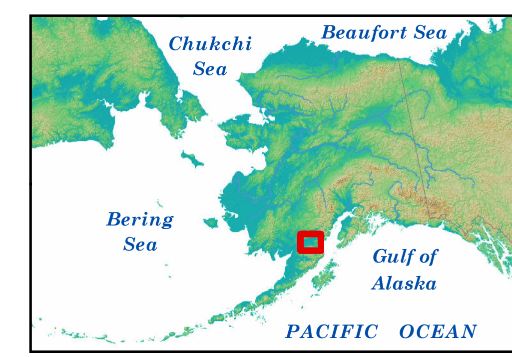
# Figure 1
# Lake Ice Study Area, Iliamna Lake, Alaska

## Legend

Study Area

Analysis Grid Cells

Existing Road

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Kilometers
0 2 4 6 8 10 12

Scale 1:424,577

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**Alaska State Plane Zone 5 (units feet)**
**1983 North American Datum**

| | |
|---|---|
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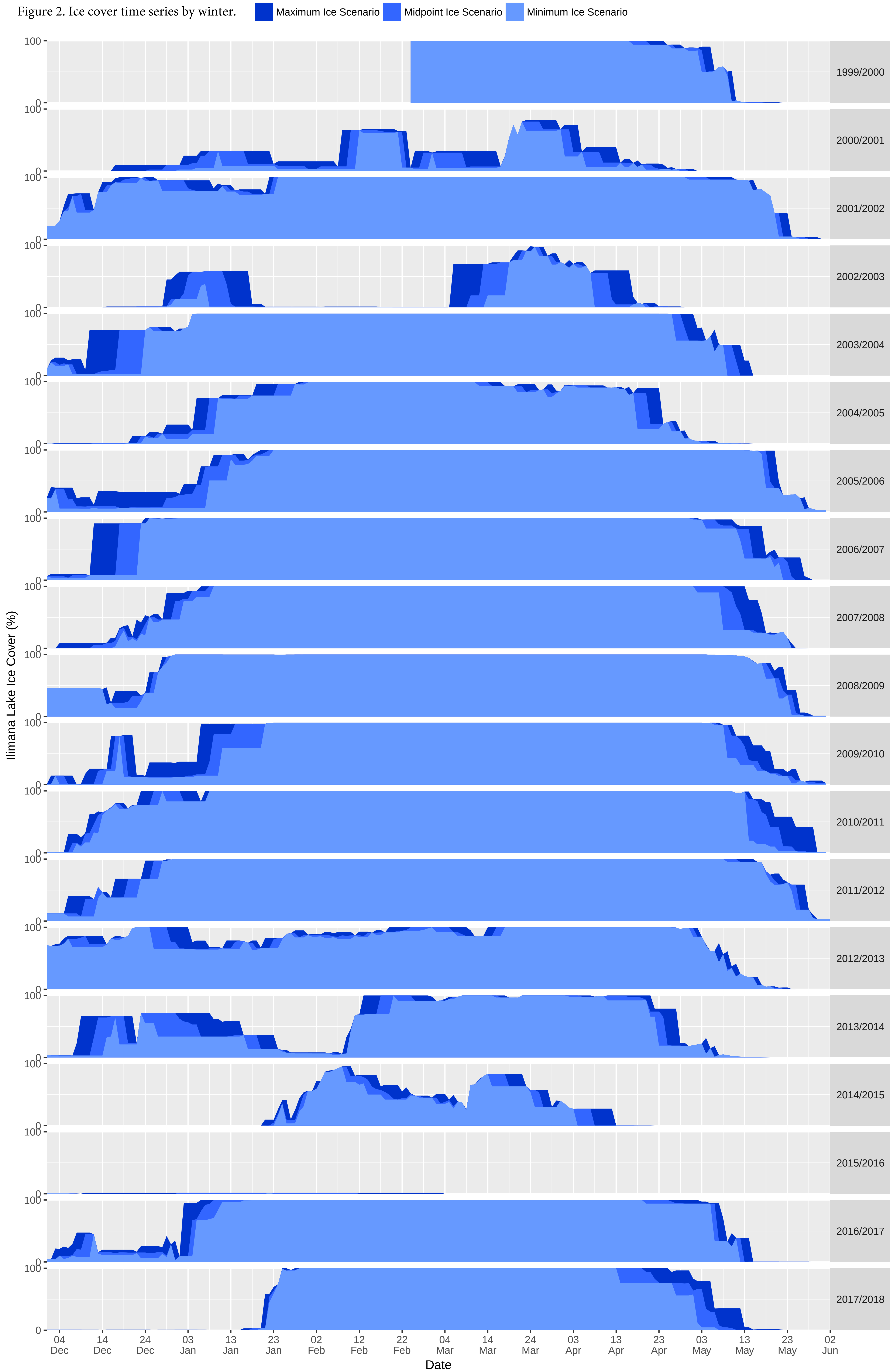
| Version: 1 | Author: ABR-MJM |

Figure 2. Ice cover time series by winter.



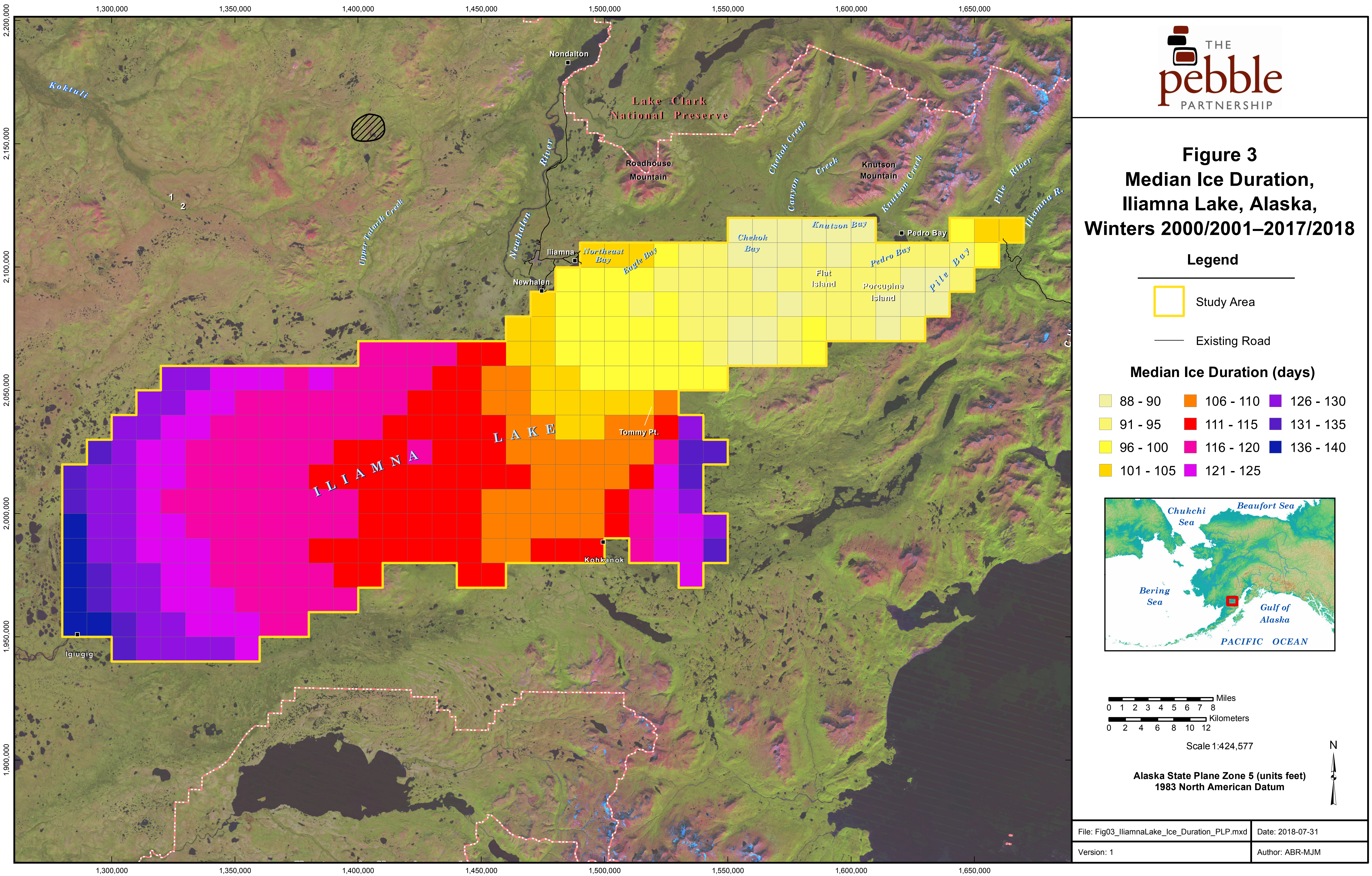

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Figure 3
Median Ice Duration,
Iliamna Lake, Alaska,
Winters 2000/2001–2017/2018
Legend
Study Area
Existing Road
Median Ice Duration (days)
88 - 90
91 - 95
96 - 100
101 - 105
106 - 110
111 - 115
116 - 120
121 - 125
126 - 130
131 - 135
136 - 140
Chukchi Sea
Beaufort Sea
Bering Sea
Gulf of Alaska
PACIFIC OCEAN
Miles
0 1 2 3 4 5 6 7 8
Kilometers
0 2 4 6 8 10 12
Scale 1:424,577
N
Alaska State Plane Zone 5 (units feet)
1983 North American Datum
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Version: 1
Author: ABR-MJM
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1,650,000
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2,050,000
2,000,000
1,950,000
1,900,000
Koktuli
Nondalton
Lake Clark National Preserve
Roadhouse Mountain
Newhalen River
Upper Talarik Creek
Chekok Creek
Canyon Creek
Knutson Mountain
Knutson Creek
Pile River
Iliamna R.
Iliamna
Newhalen
Northeast Bay
Eagle Bay
Chekok Bay
Knutson Bay
Pedro Bay
Flat Island
Porcupine Island
Pile Bay
Tommy Pt.
ILIAMNA LAKE
Kokhanok
Igiugig
1
2