closed or at a variety of openings with flow out to the West Sea or into the Incheon Terminal basin. As a result, the skin of the gates will be wetted to a large variation of heights due to dipping into and out of the water, with the potential of ice formation on the skin of the gates during sub-freezing air temperatures. The increased weight on the gates may cause problems with the gate lifting mechanisms and in extreme cases may result in the gates becoming inoperable. Another issue with control gates is ice accumulations on the downstream side of the gates due to splashing and spray from gate seal leakage. This is especially prevalent on tainter gates. The ice may even bridge between the gate lifting arms and the support wall, making gate seal heaters ineffective. The flood control gates at the Incheon Terminal, however, are vertical lift gates that travel in slots within the support walls. This type of gate is less susceptible to gate seal leakage and spray due to the path that water must follow around the sides of the gate. The continual movement of the vertical lift gates to provide the proper water elevation inside the Incheon Terminal will also assist in keeping the lifting mechanisms free from ice accumulations. The level of icing on the skin of the gates, however, cannot be pre-determined and will be thus require observations during the winter to assess the impacts on the lifting mechanisms.

The slide gates at the entrance and exit of the locks of the Incheon Terminal may also be impacted by ice. The slide gates, especially those at the West Sea side of the locks, will experience a large water elevation range, resulting in the potential for gate skin icing similar to the flood gates. The sliding gates seal by seating into recesses within the lock walls. Proper seating will require that the recesses remain free of floating ice pieces as well as ice accumulating on the recess wall surface. Care must also be taken to ensure that ice cannot get into the space behind the gates (the area of the pushing mechanism). Seals, flow inducers, or flushers may be required to keep ice out of the recesses and the gate storage area/pushing mechanism.

The lock itself can be impacted by ice in several ways. During extreme winters, ice accumulations will build up on the lock walls with the potential of reducing the width for vessel passage. The locks are 28.5 m wide with the maximum vessel width of 25.0 m so the closure of the lock due to inadequate width is not likely. The locks are aligned in a nearly east-west direction so the north lock walls will receive sunlight and the south lock walls will be shaded. Ice accumulations will be greater on the south walls and may require some form of ice removal through heating or mechanical means. Another ice issue that can occur in severe winters will be ice pieces that accumulate in the turning basin and which may be pushed into the lock ahead of a vessel (by the vessel). In severe cases, there is not enough room for both the ice and the vessel which requires the vessel to back out of the lock and an "ice lockage" is required. Forcing ice pieces into the lock ahead of a vessel runs the risk of damage to the lock gates and clogging of the lock filling ports.

The final element of the Incheon Terminal that will be impacted by ice conditions is the large turning basin. This large area will generate an ice cover in severe winters, especially in areas where vessel traffic is light. The area near the flood gates should remain ice free when there is significant water flow into the Terminal from the West Sea. The general movement of ice within the Gyeong-In Ara Waterway toward the West Sea will also result in more ice accumulating in the turning basin. Air bubbler screens may be necessary to keep ice out of the lock chambers. Propeller wash from vessels will distribute the ice within the basin and this prop wash may be used to direct the ice where desired (such as toward the flood gates). Ice accumulations along the walls of the docking berths may also need to be addressed.

3.3 Gimpo Terminal

The Gimpo Terminal is located at the Han River. The operational level of the Gyeong-In Ara Waterway will be 2.70 m but the Han River level may vary, resulting in periods when the river will be either higher or lower than the waterway. Generally, the average flow from the Han River into the navigation channel at Gimpo will be 10m3/s in the winter. The structures at the Gimpo Terminal likely impacted by ice only include the lock miter gates and the turning basin. The turning basin at the Gimpo Terminal will experience the same types of problems as the turning basin at the Incheon Terminal. The degree of the problems should be generally less, however, due to the overall ice movement toward the West Sea (out of the Gimpo Terminal). The turning basin does have two side basins (sand port and marina) which may require active ice manipulation to facilitate ice passage out of the turning basin.

The lock at the Gimpo Terminal is a single lock with multiple miter gate configurations (to allow for water levels being either higher in the Han River or the navigation channel). The primary ice issues at the lock will be similar to those of the locks at the Incheon Terminal except that the Gimpo lock has miter gates. Miter gates are more sensitive to ice accumulations in their recesses and care must be taken to ensure that the gates are fully recessed and locked in place prior to the entrance of vessels. Vessel contact with the gates when they are not fully recessed (due to ice accumulations in the recesses) can disable them. Figure 39 shows the miter gate recess of a lock that has significant wall ice accumulations (ice collar) and also floating ice accumulations within the recess. Physical systems are often required for flushing the recess to enable full opening of the miter gates.

4 RIVER ICE MANAGEMENT PLAN

A river ice management plan is a system-wide analysis of a waterway to account for issues that may arise from winter operation during periods of sub-freezing temperatures. The river ice management plan has three objectives: navigation during periods of ice should be conducted with the highest possible efficiency, approaching that of the non-ice affected season; interruptions due to ice impacts should be kept to a minimum and their duration should be as short as possible; and if a specific ice issue does arise, all technically feasible and reasonable ice-problem solutions will have already been identified and implemented. A successful river ice management plan usually addresses problems through a combination of structural and operational solutions.

4.1 Structural Solutions

Structural solutions generally include those solutions that entail some type of engineered construction and are usually operated on a seasonal basis. The US Army Corps of Engineers (2006) describes structural and operational solutions to ice problems, which usually evolve over time based on the severity, duration, and economic impact of the problem. For a new system such as the Gyeong-In Ara Waterway, some ice problems may be expected while others may not occur until a particularly severe winter. For this reason, it may not be prudent to expend a considerable amount of resources on potential solutions initially, preferring to gain experience through one or two winters in order to decide which problems to address.

Some solutions are meant to either prevent ice from forming on surfaces or to assist in removing that ice. Gate heaters are used to maintain gate operation when ice accumulations may render the gates inoperable. Gate seal heaters are often used for tainter gates to ensure that seal leakage is kept to a minimum, preventing spray icing of the tainter gate arms. Gate skin heaters, typically electrical powered, provides heat to the skin of the gate resulting in the prevention of ice buildup. Since the skin of the gates represents a large area, heating the entire gate skin is often not an efficient solution. Combining operational solutions to minimize the area of the gate skin that is exposed to ice accumulation will greatly reduce the energy requirement for gate skin heating. Steam generators are used to supply heat directly to the ice accumulations by a steam lance, a long pole with several jets at the end to effectively slice the accumulations off from the gates or lock walls. Lock wall deicing by using electrical heaters is also very energy intensive. The heaters may be embedded into the concrete walls, attached onto the wall surface with epoxy, or bolted to the walls in the form of heater panels. Again as with the gate skin heaters, determining the minimum amount of area requiring heating is necessary. Another method for deicing or preventing icing on lock walls is through the use of coatings to reduce the adhesion strength of ice to the lock wall.

Other structural solutions are meant to either move floating ice out of or into areas where it can be dealt with. Gate recess flushing can be accomplished through the use of compressed air released at the bottom of the gate recess near the lock wall or through the use of a propeller-type flow inducer. Gate recess flushers are most often used in miter gate recesses and their effectiveness can be increased by pulsing their operation or by partially opening the miter gate and then turning the flusher on. Line bubblers are utilized for limiting ice movement, such as keeping ice out of a lock approach or placed diagonally across the entrance to the lock, it can actually deflect ice that is moving toward the lock, deflecting it toward a spillway or dam gate for passage through the dam. A bubbler screen can also be used to induce vertical mixing of the water column, using any thermal reserve in the deeper water to provide heat for melting the surface ice. Vertical mixing of the water column could also improve water quality or redistribute pollutants by dilution.

4.2 Operational Solutions

Operational solutions include schemes such as convoying of vessels, maintaining a single vessel track in the ice, ice flushing operations at the terminals, and ice maintenance on lock gates and walls. Operational solutions are modifications to standard procedures with the intent of reducing the problems associated with ice during sub-freezing weather conditions. Ice accumulations or ice collars on lock walls and miter gate recess walls can result in width restrictions. By keeping the pool elevation in the chamber high (except during lockages), the chamber wall temperature will be near the water temperature and less likely to form ice collars. To clear fragmented ice pieces from around miter gates and their recesses, vessel propeller wash, miter gate fanning, pike poles and ice rakes, or gate recess flushers are used. If additional techniques used to deflect floating ice away from the upper lock approaches are effective, then the task of dealing with fragmented ice in the lock chamber and gate recesses will be reduced.

Vessels are often used in operational solutions both for moving ice using their propeller wash and by physically blocking ice movement into an area. Within the turning basins, vessels waiting for lockage will often assist in positioning themselves to block ice movement into the upper lock approach or by using their propeller wash to direct ice pieces toward the dam or spillway gates. For large ice accumulations in the upper lock approach, it may be necessary to conduct an "ice lockage". In some cases, the lower lock gate can be opened and the filling valves adjusted to provide a flushing action of the ice out of the lock chamber. This technique might be utilized through the fish passage gates at the Gimpo Terminal.

During severe winters, the ice thickness that can develop on the navigation channel and continuous vessel traffic could result in significant volumes of brash ice in the channel and turning basins. Heat transfer is greatest from the open water surface and ice growth is fastest when ice is thin. By maintaining a minimum open water surface width, the heat loss will be minimized. A single vessel track in an otherwise intact ice surface would represent the minimum open water area and minimum heat loss and ice generation. It is unknown how the vessel traffic will impact the ice cover when it is initially forming or whether vessel wakes will break up thin ice covers. Based on predicted traffic levels, there may be areas required for two-way vessel passage during these severe ice conditions. Research has resulted in some prototype ice prows that are attached to towboats for cutting a defined path into an ice cover. These prows cut a clean edge in the ice cover and push the pieces down under the prow and out to the sides, beneath the intact ice cover, leaving an open ice-free path through the ice cover. Prior to the consideration of developing an ice prow for the Gyeong-In Ara Waterway, experience must be gained as to the ice-vessel interaction of the sea-river vessels for which the waterway was designed.

5 RECOMMENDATIONS

There is no operational history during open water or ice periods for the newly designed and constructed Gyeong-In Ara Waterway. Thus, the goal of the river ice management plan is to be aware of potential ice issues, develop potential solutions to issues that may arise, and to identify those options that might be undertaken if significant ice forms. Many solutions to ice formation develop over a period of time as personnel who must operate the waterway system become more proficient in identifying them before they occur, learn specific precursor conditions prior to the development of ice, and gain the experience of the operating the system during the winter. Many components should be built into the system since they are almost certain to be of value in the winter operations of the waterway. In average winters, ice pieces may move around the system and may become lodged in the miter gate recesses, low flow areas of the turning basins, and along the shoreline of the canal. The maintenance of the gates will be of particular interest and importance during the winter season. The miter gates will require monitoring for ice accumulation on their skin surface and if accumulation does occur, the availability of steam for clearing ice may be necessary. Pike poles can be used to maintain the recesses ice-free during gate operation. Monitoring and measurement of the ice accumulation on the lock walls and miter gate recess walls will provide an indication of whether additional heating is required. Particular care should be taken in the operation of the slide gates when ice is present, monitoring any ice buildup on the gate skin, in the gate seats, and the seal areas protecting the pushing mechanisms. The continual operation of the vertical lift flood gates during sub-freezing weather is very important to the success of the project. These gates should be monitored for ice accumulation, mechanical operation (force required for lifting), and the opening and head differential required for passage of ice through the gate opening. The performance of the proposed vessels with respect to their impact on the formation and growth of ice in the waterway but also their performance in moving through sheet and brash ice should be monitored. These key components generally relate to increased levels of personnel for the first few winters with much hands-on operation with respect to gate operation (pike poles, steam lances, etc.). Operational experience developed over the first few winters will determine whether additional measures are necessary, such as skin heaters on gates and lock walls to prevent ice buildup, flow inducers and bubblers to assist with ice movement and mixing, and line bubblers for keeping ice out of the Incheon Terminal locks and diverting the ice toward the flood gates. Finally, under rare conditions when ice accumulations adversely impact navigation, operational options include convoying vessels, introducing warm water sources from the Han River or sewage treatment plants, or flushing the system from the Han River toward the West Sea.

The proposed river ice management plan is based on an analysis that suggests ice formation on the Gyeong-In Ara waterway will be modest. Even under "extreme" winter conditions, the estimated ice formation should not cause significant problems. In general, vessel traffic and lock navigation can be maintained with the types of vessels identified for use, perhaps with some of the modest efforts to address ice described above. Because the estimated ice formation is modest and does not suggest the need for large up-front expenditures on specific ice equipment, we have recommended an adaptive management approach. We recommend that K-water invest in simple ice equipment before the first winter of operation, such as pike poles and steam hoses. The operators should measure actual ice formation on the various elements of the system for at least the first few years of operation, prepare an action plan for severe ice conditions, have contingencies in place to combat and deter ice formation, and adjust the winter operational procedures as conditions dictate. The discussion in the previous sections can be used as a basis for addressing various ice conditions.

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Seasonal and long-term within-channel permafrost and its effect on northern river navigation

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ABSTRACT: Frozen ground within river channels is widely observed on most Russian Arctic rivers with sand-clay alluvium. Within-channel permafrost determines high long-term stability and site-specific trends in channel development, affecting northern rivers navigation conditions. Extensive field studies on 200-km reach of Lena River in Central Yakutia, largest in the region, show that navigation conditions are majorly impaired by permafrost-affected narrowing, increasing length and curvature of fairways. Economical effects of such impairment, including gross operational costs, dredging operation and new fairways development expenses, were estimated based on statistic data provided by Lena Basin State Waterways & Navigation Authority. Average additional gross operating costs (per 1 km of fairway length) were estimated about US $60 to $100 per ship passage, including ship maintenance costs, fuel and crew expenses. Furthermore, above 1.5 M m^3 of bed material were excavated within the studied reach during years 2003-2007 to maintain safe ship operations, adding another us $6 M to the total expenses. Study results reveal, that permafrost and related channel dynamics add to the northern navigation costs. Facilitation of the latter includes forecasts of permafrost-induced channel alterations. A probabilistic model using hydrological data was developed in order to assess the spatial extent of within-channel permafrost and its potential impact on channel dynamics. Modeling results for the studied 200-km Lena river reach appear to be consistent with field observations, thus allowing introduction of the model in forecasting and decision-making processes during waterway development planning.

KEY WORDS: Seasonal permafrost, channel dynamics, northern navigation.

1 INTRODUCTION & BACKGROUND

Within-channel seasonal and long-term permafrost gained little attention in Arctic hydrology research, probably due to the common opinion that open taliks generally exist under large water bodies. Following the well-known simplified empirical rule, a major condition for a talik to be formed is that the width of the water object exceeds its depth by at least twice (Kudryavtsev, 1975).

Due to instrumentation and methodological issues, the permafrost formation process occurring within northern river channels is currently poorly understood. Yet it is renowned that permafrost brings substantial alterations to the rates of channel development, both in terms of lateral and vertical deformations (Scott 1978). Specifics of fluvial dynamics affect all aspects of water use and management in the North, including northern navigation. Rivers still play an important role in transportation schemes of the northern regions, and navigation conditions are commonly impaired by shallow navigable depths of these rivers, high sinuosity of the fairways and long low-flow periods. Permafrost formation within channels, encouraged by low winter temperatures and high soil moisture environments, adds to the complications of the northern navigation, yet its main spatial features and influence on navigation conditions and channel dynamics, is still poorly studied.

Evidences of within-channel permafrost existence and dynamics are given in a limited number of publications, based on both empirical studies and field observations. First evidences of permafrost existence in the middle Lena River reach near Yakutsk are given in (Chistyakov, 1952), and related to the stability of a large point bar in the vicinity of the Yakutsk Permafrost Research Station observation point in the Tabaga settlement. The phenomenon was further observed on rivers of Western Siberia (Zernov, 1989), Yakutia (Kartashov 1958, Tolstov 1966, Tananaev 2007) and Alaska (Scott 1978, Walker 1983). These publications mostly discuss the existence of frozen layer within the river channels, based on occasional observations of the phenomenon rather than special studies on the topic. The work by Zernov (1989) shows the dynamics of frozen layers in sandy material, but it uses observations obtained on man-made sand dams rather than within-channel areas.

The general purpose of this paper is to evaluate the overall effect of within-channel permafrost on navigation conditions of northern rivers. This requires a brief overview of the effects that the existence of within-channel permafrost casts on channel dynamics, combined with some preliminary estimates of its economical effect.

2 STUDY AREA

The Lena River is one of the largest Eurasian rivers in terms of both watershed area and total freshwater flux. The 200-km reach of the Lena River that was studied is situated between the city of Yakutsk and Aldan River mouth, in the middle reach of the river (Figure 1). Approximately ¼ of the total Sakha (Yakutia) Republic population is concentrated within this studied reach, and the river section itself is one of the most heavily exploited Lena River reaches, including navigation activities.

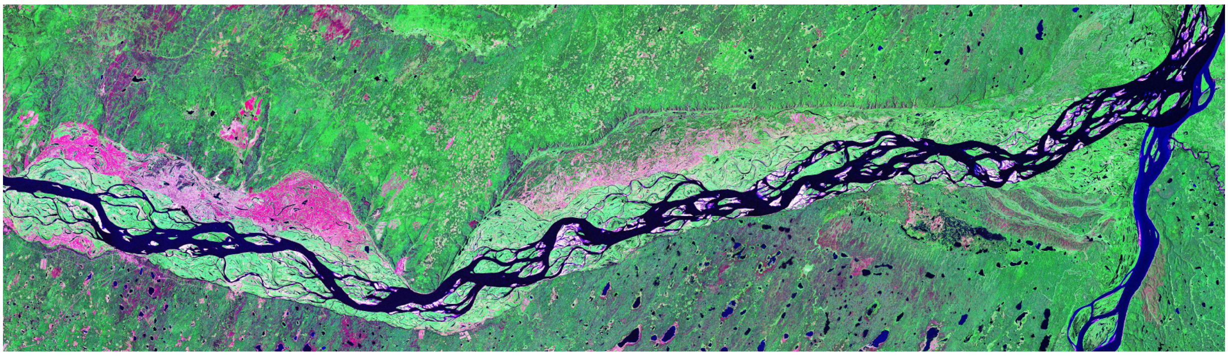

Figure1: Studied Lena River reach (flow direction is left to right), image derived from Landsat 7 ETM+ mosaic imagery.

The mean annual discharge at the Tabaga gauging station (20 km upstream of Yakutsk) is 7 070 m^3 s^{-1}, and it is quite unevenly distributed throughout the year. The high spring freshet generally contributes 75% to 90% of total water flux, with average daily peak discharges about 35 000 m^3 s^{-1} and the observed peak exceeding 51 700 m^3 s^{-1} (May 27, 1966). The following low-flow period dominates summer and autumn, interrupted usually by several (generally no more than 2 or 3) major high-flow events, originating from heavy orographic rains in the upper part of the basin. Winter flow is negligible, average discharges rarely exceed 1 000 m^3 s^{-1}, and the river flows under a thick – up to 2.5 m – ice layer.

Due to relatively high valley bottom slopes and the excessive amount of bed material carried, braiding is the dominating channel pattern throughout the high-flow period, while during low-flow periods most side channels dry out, leaving the main channel meandering. Massive alluvial fields, represented by point and side bars, totalling about 55% to 65% of the channel area, stay above the water level during winter (Tananaev 2007), thus allowing direct cooling of the channel surface (Figure 2). Negative thermal balance on the surface (and at least the first few meters below) is the main prerequisite of permafrost formation.

Figure 2: Meandering of winter low-flow channel near Yakutsk.

3 RESULTS & DISCUSSION

3.1 Permafrost-affected channel dynamics

Analysis of satellite imagery and consecutive bathymetric surveys shows that the presence of permafrost within the studied river reach affects the Lena River channel dynamics in terms of stabilizing the position of large alluvial bedforms. Permafrost-affected bedforms further attach to floodplains, islands and other large bedforms, with further development being dependent on its position within channel. Generally, permafrost-affected bedforms have relatively stable upstream positions, and are associated with excessive accumulation at their downstream ends. The entire form will gradually increase its length due to accumulation, but it also increases its width by growing to the opposite bank, thus narrowing the low-flow channel (and reducing the available navigable fairway; see Figure 3).

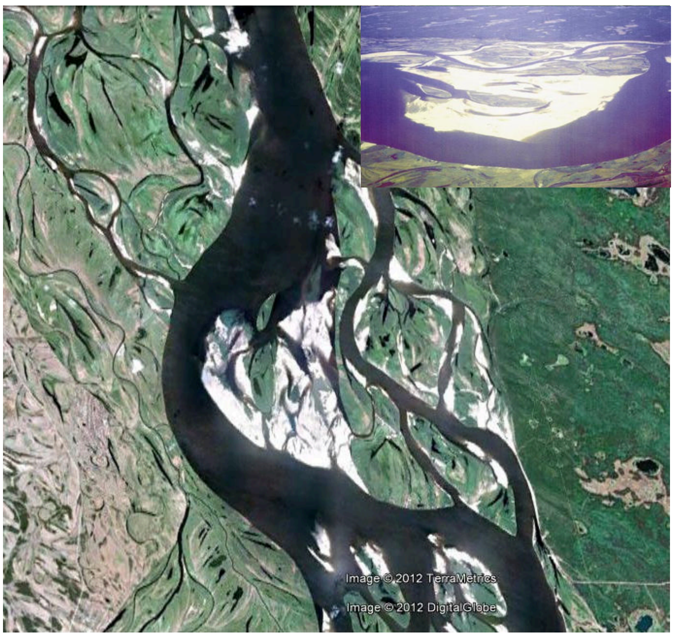

Figure 3: Typical channel morphometry affected by over-developed side-bar (At-Aryta meander, 40 km downstream of Yakutsk), Google Earth satellite imagery; upper right is the aerial photo of the same river reach.

3.2 Economical Effect Estimates

Gross operational costs differ depending on the commercial ship type, movement direction (up- or downstream), and cargo weight. While no detailed data are available, rough estimates were used based on statistical data provided by the Lena Basin State Waterways and Navigation Authority, regional branch of Federal Marine and River Transportation Agency. Average gross operational costs were estimated based on data on: fuel consumption per 1 km of fairway, crew salary per hour, and ship amortization period and result in about \$60 to \$100 per ship passage (per 1 km of fairway length). Ship passage was based on a passage of a large tugboat (Russian R153 project) with a still-water speed of about 20 kph, running a standard four-cylinder diesel engine (800 kW power) and an auxiliary engine, 17 crew members and a degraded technical state of the fleet. Total costs were estimated to be about $240,000 to $400,000 per 1 km of fairway length (for 4000 ship passages during the navigation season). The actual number of passages is not directly available, but it is taken into account as a best guess based on personal communications. Total fairway length increases due to permafrost-affected channel dynamics and is about 10 km for the studied 200-km river reach, thus leading to substantial additional expenses, up to $4 M per navigation.

Furthermore, the Lena Basin State Waterways and Navigation Authority spent another $6 M on dredging operations within the studied reach, excavating more than 1.5 M m^3 during years 2003-2007. Major dredging operations were conducted within the river reaches, where the over-development of alluvial forms led to the significant impairment of waterways quality. As an example, closing of the navigable Arbyn branch by the over-developed side bar in the final stage of 2004 navigation (Figure 4) led to a fairway transfer in 2005 to a narrow hardly navigable shallow reach. About 0.36 M m^3 of material was relocated during extensive excavation in 2006 and 2007, totaling in costs around $ 2 M.

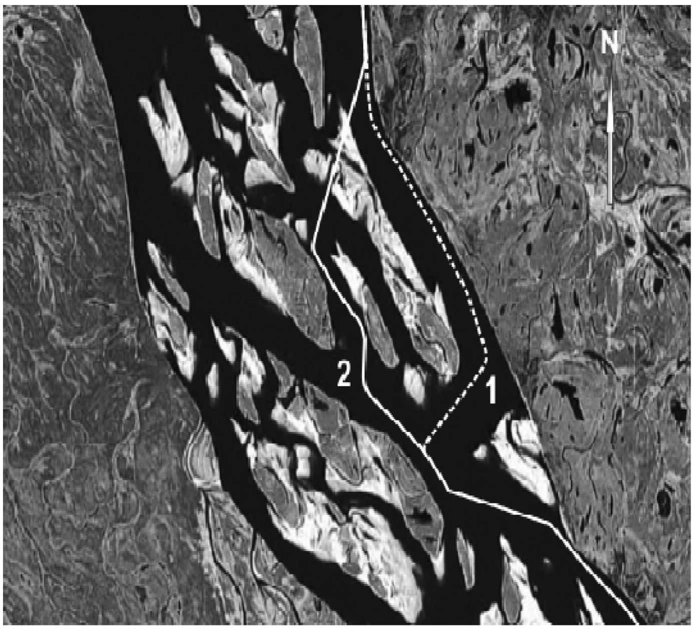

Figure 4: Navigable fairway position on Arbyn shallow, 150 km downstream of Yakutsk, in the years 2003 (1) and 2006 (2).

3.3 Permafrost Spatial Distribution Modeling

In order to address the negative consequences of permafrost-affected channel dynamics, adequate information on spatial distribution of potentially frozen alluvium is needed. Such information can be obtained directly, but requires extensive drilling including underwater. Mathematical modeling of within-channel permafrost formation by channel-atmosphere interaction and heat transfer is also not feasible because of the methodological flaws and complexity of reproducing the water movement in freezing sandy channel alluvium.