FIELD OBSERVATIONS IN THE TIDAL ZONE OF A FROZEN RIVER

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ABSTRACT
Hydraulic phenomena in freezing waters in the tidal region of a river are difficult to observe, as these occur in the severest part of winter and are obscured by ice sheets. Much about such phenomena remains to be clarified. Our study used field observations to clarify hydraulic phenomena in such a river. Field observations were carried out at a cross-section in the tidal region of the Tokoro River in Hokkaido. Observation was conducted during the freezing period (the day of the full-moon flood tide in February, and the day before and after it) and during the open water period (the day of the full-moon flood tide in August, and the day before and after it), to obtain data for comparison. Water levels were measured immediately upstream and downstream of the cross section. At the observation cross-section, flow velocities were measured using an acoustic Doppler current profiler (ADCP), and salinity was measured. Based on observations and analyses of the data, commonalities and differences between the freezing (ice-covered) and open water periods were identified. One commonality is that the stream centerline shifts with the tide. One difference is that the direction of the primary flow in the freezing period differs greatly from that in the open water period.

INTRODUCTION
Hydraulic studies on the tidal region of a river should address saltwater intrusion, which is a function of morphology, fresh water flow rate and saltwater flow rate. Such intrusion in a river that freezes over is thought to be significantly influenced by the freezing, but that influence is difficult to measure by using the currently employed method, which is the same as that for open water, because ice sheets make it difficult to measure the flow velocity distributions. Much about the complex hydraulic phenomena in the tidal region of an ice-covered river remains to be clarified.

Our study attempted such clarification by field observations of flow and other hydraulic characteristics in winter in the tidal region of the Tokoro River in Hokkaido. For compar-
OUTLINE OF THE FIELD OBSERVATION

Observation sites

Field observations were conducted in the tidal region of the Tokoro River in Hokkaido. The river (channel length of 120 km; catchment area of 1,930 km$^2$) was chosen because there is a station for observing saltwater intrusion and the river freezes over in winter. The river, the observation points, and the kilometer points (at 0.2-km intervals) are shown in Figure 1. The river mouth is the reference point and its kilometer point (KP) is 0. The observation items indicated in Figure 1 are discussed later in this paper. As shown in Figure 1, the observation cross-section is on the upstream side of a large bend. Figure 2 is a top view of the river channel, with color contours showing the river bed elevation. The elevations were obtained in December 2005 using a survey echo sounder and GPS surveying. The channel is shown to have deep spots at the exit (KP0.6), middle (KP1.0) and entrance (KP1.3) of the bend. KP0.6 is extremely deep. It is assumed that these deep spots tend to trap the salt water that intrudes upstream along the riverbed, thereby slowing the upstream progression of intruding salt water.
Observation items

Observations were conducted along the cross-section shown in Figure 1. Flow velocity was measured on nine vertical lines on the cross-section. Water temperature, salinity and density were measured at the thalweg. (The thalweg is the deepest spot in a river-channel cross section.) Water level was measured at one pint upstream and one point downstream of the cross-section. Figure 3 diagrams the measurement method for the freezing period.

Flow velocity In Figure 3, the cross-section is divided by nine vertical lines, on each of which a flow velocity distribution was observed at vertical intervals of 10cm. Equipment used for this included an ADCP (WorkHorse Sentinel 1200kHz Zed-Hed, RD Instruments, high-resolution mode). Measurement was continued for 180 seconds per vertical line, and the measurements were averaged. The measurement accuracy was 0.3 cm/s.

Water temperature, salinity, density and water level Measurements of water temperature, salinity and density were made along the vertical line at the thalweg (Figure 3) using an Alec Electronics Memory STD (ATU100-PK). Water level was measured 250 m upstream and downstream of the cross-section continuously (at 10-minute intervals) using a Koshin Denki Kogyo water level gauge with a data logging feature (MC-1100WA). The measurement range of the water level gauge is 0-10 m, with an accuracy of ±1cm.

Observation period

In 2005, observations were conducted for a period of three tidal cycles each in the ice-covered season and in the open-water season. Each observation covered a cycle of full-moon flood tide. The observations were made 18 times in total: three times each at high tide and low tide for each cycle. Table 1 shows the observation details. The "T.L.D" in the table means the difference between the high and low water levels during the full-moon flood tide.

<table>
<thead>
<tr>
<th>Period</th>
<th>Start</th>
<th>End</th>
<th>T.L.D(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freezing</td>
<td>09:00 on 2/22</td>
<td>11:50 on 2/25</td>
<td>1.00</td>
</tr>
<tr>
<td>Open water</td>
<td>04:40 on 8/18</td>
<td>07:30 on 8/21</td>
<td>1.33</td>
</tr>
</tbody>
</table>

During both periods, observation covered three tidal cycles.

Observation dates and times

Figure 4 shows the observation dates and times, river bed elevations, water levels, and rates of water level fluctuations during the ice-covered and open water observation periods. Dates and times, transverse distances, elevations and rates of water level fluctuations are respectively indicated on the bottom horizontal axis, the top horizontal axis, the left vertical axis and the right vertical axis. Observation hour in the figure represents the mean time for each observation session. Each observation session is indicated as a successive number, in order of the sessions, with "w" for sessions during the ice-covered water and "s" for those during the open-water summer. The average change in bed elevation at the cross-section was -0.02 m for the ice-covered water and for the open water. As that value is considered negligible, bed fluctuation was excluded from the list of variables to be considered in our comparison of the two observation periods.
OBSERVATION RESULTS

Tidal and water levels

Figure 5 shows the correlation between the tidal level measured at the Abashiri observatory and the water level at the observation cross-section. The data are hourly data and the data points are connected with lines to indicate the time order. The relationship shown in Figure 5 can be summarized as follows.

Falling tide... The data points are along the line of Y=X
Rising tide... Water level rises

This indicates that there is a clockwise bivalent relationship between the two periods, with tidal and water levels roughly equal except during saltwater intrusion, when the river water level rises. This suggests that, barring any significant change in flow rate, the river water level can be estimated based on the tidal level.

3-dimensional flow velocity

Saltwater-intrusion-induced changes in flow velocity were measured using an ADCP at 6w, 9w and 12w (ice-covered period) and at 2s, 5s and 8s (open-water period), and were then resolved into three-dimensional components. Figure 6 shows the three-dimensional components of flow velocities for ice-covered and open-water periods. The horizontal axis represents transverse distance, and the vertical axis represents elevation. Flow velocity and direction are shown using a color contour plot, and the flow velocities in the transverse and vertical directions are shown using vectors. The graphs for high tides include a horizontal line indicating the boundary between fresh and salt water. Legends used for the graphs are the same for the ice-covered water and open-water periods. The downstreamward bearing was obtained by averaging the bearings measured with ADCP, which are in the ranges of 0 to 90 degrees and 270 to 360 degrees. The obtained bearings are in the direction of the river mouth. The downstreamward bearings obtained for observations shown in Figure 6 were 356 degree for the freezing period and 348 degree for the open water period. The boundaries between fresh and salt water in Figure 6 were obtained by calculating the echo intensity of ADCP at a salinity of 15 psu, and connecting the elevations (m) on the nine vertical lines at which the salinity was 15 psu.
At low tide, the stream centerline is located on the left-bank side of the channel, at rising tide, the stream centerline is located in the middle of the cross section, and flow velocities and directions suggest that the stream centerline changes its location with flow velocity and direction. Initially, the stream centerline at the observation cross-section was thought to be constantly on the left-bank side of the channel, because the thalweg in the bend is on the left-bank side of the channel. However, the observed flow velocities and directions suggest that the stream centerline changes its location with changes in tidal level. The stream centerline shows the following changes (Figure 6).

1) At low tide, the stream centerline is located on the left-bank side of the channel, the same side as the thalweg (forced vortex). (See 6w and 2s in Figure 6)

2) At rising tide, the stream centerline is located in the middle of the cross section, with the overall flow velocity across the cross-section having slowed down.

3) At high tide, the stream centerline shifts on the right-bank side of the channel. The water is divided into the upper layer of freshwater single-section flow and the lower layer of salt water. The flow velocity of salt water at the boundary between the salt and fresh water is greater that at the lower portion of the salt water layer (free vortex). (See 9w and 5s in Figure 6)

4) At falling tide, the stream centerline is at the midpoint of the cross-section, and the flow velocity increases at all points in the cross-section.

5) At low tide, the stream centerline returns to the left-bank side of the channel, the same side as the thalweg (forced vortex). (See 12w and 8s in Figure 6)

**Flow velocity and direction** Initially, the stream centerline at the observation cross-section was thought to be constantly on the left-bank side of the channel, because the thalweg in the bend is on the left-bank side of the channel. However, the observed flow velocities and directions suggest that the stream centerline changes its location with changes in tidal level. The stream centerline shows the following changes (Figure 6).

Freezing period (bearing of primary flow: 356 degree) Open period (bearing of primary flow: 348 degree)

**Figure 6** 3-dimensional flow velocity during freeing and open periods
This shift of the stream centerline was observed both in the ice-covered and open-water periods; therefore, it is concluded that ice sheets have almost no impact on this shifting of the stream centerline. It is assumed that this shift of centerline is caused by a shift from forced vortex to free vortex, and the shift appears to be induced by the decrease in flow velocity caused by saltwater intrusion and the changes in resistance structure caused by the formation of fresh water single-section flow. (See 9w and 5s in Figure 6)

**Transverse and vertical flow velocity distribution** During the open-water period, counterclockwise helical flow was observed near the stream centerline at low tide. Helical flow was also observed at high tide in the upper layer near the stream centerline, although there was almost no flow in the lower layer. During the freezing period, no helical flow was observed concurrently with fast flow towards the outside of the bend at low tide. At high tide, flow towards the inside of the bend was observed in the upper layer, with the flow being faster nearer the stream centerline, concurrently with flow towards the left bank in the lower layer.

The downstreamward bearings were examined, focusing on the flow toward the outside of the bend at low tide and the downstream flow near the inside of the bend at high tide during the freezing period. Table 2 shows the average values, the bearing of each flow at the observation cross-section. The table also shows the downstreamward bearings.

<table>
<thead>
<tr>
<th></th>
<th>Low tide</th>
<th>High tide, Downflow</th>
<th>High tide, Upflow</th>
<th>Low tide Downstreamward bearings(average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freezing period</td>
<td>327</td>
<td>14</td>
<td>176</td>
<td>327</td>
</tr>
<tr>
<td>Open period</td>
<td>343</td>
<td>349</td>
<td>171</td>
<td>343</td>
</tr>
</tbody>
</table>

The difference between the bearing of each flow and the downstreamward bearings at low tide during the open period was 5 degree, while it was 29 degree in the freezing period. This suggests that there was a substantial shift in the direction of primary flow during the freezing period. To clarify this shift, the bearing of the primary flow at low tide was examined. A line was drawn between the thalweg at KP1.05 and that at KP1.20, the two points on either side of the observation cross-section. The bearing of the line was 339 degree. From Table 2, it is suggested that the direction of the primary flow is from the thalweg towards the outside of the bend during the freezing period while it is from the thalweg towards the inside of the bend during the open period.

Downflow at high tide had the following direction. Downflow was from the thalweg towards the inside of the bend during the freezing period, which is opposite to the direction of the downflow at low tide, and it was towards the inside of the bend during the open water period. The direction of the upflow at high tide was nearly the same during the ice-covered and open-water periods.

From this, it was concluded that the shift in the direction of the downflow from inside of the bend to the outside of the bend at low and high tides during the freezing period is due to substantial change in the direction of the primary flow component. Although transverse and vertical flow distributions are complex, the observation and analysis conducted for this study was able to determine that the direction of downflow during the freezing period changes far greater than during the open period; thus, helical flow is considered less likely to occur during the freezing period.
SALTWATER INTRUSION
Flow velocity of fresh and salt water

Using an experiment-derived **formula (1)** for calculating the flow velocity of fresh and salt water, the resistance encountered by a fluid is discussed.

\[ V_1 = K_1 \sqrt{\epsilon g H_0} \quad \text{and} \quad V_2 = K_2 \sqrt{\epsilon g H_0} \] (1)

\( V \): flow velocity \([m/s]\), \( K \): coefficient, \( g \): 9.8 \([m/s^2]\), \( H_0 \): water depth \([m]\), \( \epsilon : (\rho_2 - \rho_1)/\rho_2 \), \( \rho \): density \([t/m^3]\). Suffixes "1" and "2" respectively refer to fresh water and salt water. Based on the above, \( K_1 \) and \( K_2 \) were obtained (**Table 3**). For this, the maximum flow velocities were used.

The smaller the \( K \), the greater the resistance encountered by a fluid. Looking at fresh water, the average value of \( K_1 \) is 0.19 during the freezing period and 0.30 during the open period. As the value is smaller in winter, this indicates that fluid meets greater resistance in winter than in summer. This is assumed to be due to frictional resistance of ice sheets, which is thought to reduce the velocity of fresh water. Looking at salt water, the average value of \( K_2 \) is -0.13 during both the freezing and open periods, which means that salt water meets the same resistance with or without ice sheets.

Flow rates of fresh water and saltwater

Saltwater intrusion causes both fresh water (river water) and saltwater (tide water) to alternate downstreamward and upstreamward, and to have flow rates that change with time. To compare the flow of river water and tide water during the ice-covered period and open water period, flows were put into four categories based on the observed flow rates and salinity. Flow rates and directions (upflow, downflow) for river water and tidal water were determined.

**Behavior of flow rates** Figure 7 shows the combined flow rate, the flow rate of river water and the flow rate of tide, as well as the water level at the observation cross section. Positive (+) means downstreamward flow; negative (-) means upstreamward flow. The upper graph shows data collected during the freezing period; the lower graph shows data collected during the open water period. The flow rate of river water is indicated by dots; the flow rate of tide is indicated by squares. The horizontal axis represents dates. The left-hand vertical axis represents water level, negative flow rate of river water, and positive and negative flow rate of tide. The right-hand vertical axis represents the combined flow rate and positive flow rate of river water. Based on this, the graphs tell us the following about the flow rates.

<table>
<thead>
<tr>
<th></th>
<th>( V_1 )</th>
<th>( V_2 )</th>
<th>( H_0 )</th>
<th>( \epsilon )</th>
<th>( K_1 )</th>
<th>( K_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>9w Winter</td>
<td>0.17</td>
<td>-0.14</td>
<td>2.9</td>
<td>0.022</td>
<td>0.22</td>
<td>-0.18</td>
</tr>
<tr>
<td>14w Winter</td>
<td>0.12</td>
<td>-0.06</td>
<td>2.7</td>
<td>0.021</td>
<td>0.16</td>
<td>-0.08</td>
</tr>
<tr>
<td>5s Summer</td>
<td>0.26</td>
<td>-0.11</td>
<td>3.3</td>
<td>0.022</td>
<td>0.31</td>
<td>-0.13</td>
</tr>
<tr>
<td>11s Summer</td>
<td>0.25</td>
<td>-0.11</td>
<td>3.1</td>
<td>0.023</td>
<td>0.30</td>
<td>-0.14</td>
</tr>
</tbody>
</table>
1) When the water level is high, saltwater intrudes (the tide flow rate is negative) and tracts river water upstreamward (the river water flow rate also becomes negative). This causes the overall flow velocity of the stream to decrease, and the combined flow rate to decrease.

2) As the water level falls, positive flows of river water and tide (remaining in the river channel) occur, allowing the water that has been retained upstream by saltwater intrusion to flow downstream all at once, which causes the combined flow to increase.

The analysis has shown that these behaviors commonly occur in both the freezing and open periods.

CONCLUSIONS

Similarities and differences between freezing and open periods were identified based on field observations and analyses. Common to both periods were a relationship between tidal and river water levels that plots as a clockwise increase-decrease cycle, and a tide-related change in the stream centerline position. The direction of primary flow differs significantly between the ice-covered and open-water periods, the disappearance of helical flow during the freezing period, and a decrease in flow velocity of fresh water in the saltwater intrusion phase of the freezing period due to frictional resistance of ice sheets. Dividing the total flow rate of an observation cross-section of the river into four flows enabled clarification of the complex phenomena of saltwater intrusion.

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REFERENCE