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Ice Phenomena in River Mouths

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River outlets located in tideless areas are analyzed in this paper. First, ice processes in the St Clair River mouth are presented. The river mouth, called St. Clair Flats is a typical river delta located on the shore of Lake St. Clair. Based on this example ice jam formation in river delta has been analyzed followed by a presentation of the main mechanism of ice jam formation. The Vistula River mouth is a man-made, artificial channel which was built in the 19^{th} century in order to prevent the formation of ice jams in the natural river delta. The Vistula River releases large amounts of fresh water into the Baltic Sea which freezes in the winter season during which northerly winds prevail causing the drifting ice to move southwards and accumulate to form ice jams in the river mouth. For this reason ice breaking operations are performed. Since the artificial river outlet was constructed, no severe ice related flood risk situations have ever occurred. However, periodic ice-related phenomena still have an impact on the river operation. This paper presents the application of the calibrated mathematical model DynaRICE to perform a series of simulation in the Vistula River mouth for winter storm condition to determine the effects of ice on the water level in the Vistula River and ice jam potential of the river outlet.

1. Introduction

Two typical river outlets can be distinguished. If bed material is deposited at the river mouth it results in the delta shape formation. Noteworthy examples of river outlets of this kind include the Nile Delta and St. Clair Flats. A different process is observed when strong currents remove sediment from the river outlet forming an estuary. River outlets of the letter type are usually located on coasts with a significant tide range (e.g. St Lawrence River, Elbe River).

Over the centuries people have settled along seashores and at river outlets for the reasons of access to convenient transportation, sustenance, energy. This kind of location also ensured sustenance, and a better quality of life. Many estuaries are subject to ice processes the most severe of which are ice jams. The ice jam formation mechanism in river outlets is a complex process affected by many hydraulic and meteorological variables and it still remains unclear.

This paper examines river outlets characterized by no tide effect. An example of ice jam formation in river deltas has been provided and followed by a description of a man made cut-off channel as another type of outlet transformed from a natural delta. The simulation and analysis of the effects of the river ice run during the breakup season on the ice jam formation in the river outlet channel have been presented by means of the two-dimensional river hydro-ice dynamic model DynaRICE together with the main mechanism of the ice jam formation in the two types of river mouths.

2. Ice Jam Formation in River Deltas

A river delta is an accumulative form where the river sediment is deposited and eroded, which leads to the formation of a characteristic fan-shape outlet. The intensity of these processes is associated with sediment size and water hydrodynamics. A number of river outlets of this shape, which deserve attention, have been distinguished. They include St. Clair Flats which is subjected to ice processes. The River of St. Clair is the natural outlet from Lake Huron. During the winter and early spring time large supplies of ice floes can enter the river from Lake Huron. Due to the extensive river delta, (St. Clair Flats) the ice floes may slow down and jam in the river. This situation occurred in April 1984 when a record ice jam was formed in the St. Clair River (USACE, 1984; Derecki and Quinn, 1986). The event was simulated by Kolerski and Shen (2010) basing on all the available evidence and data. The simulation results showed that the ice jam developed in three phases. The first stage of the ice jam formation in St. Clair Flats was reported as a very dynamic process which proceeded upstream of the river with a significant speed. During this stage only one icebreaker operated on the river and it had little or no impact on the ice jam stability in its initial phase. No other man-made activities were reported. Therefore the ice formation process in its first stage may have been regarded as a natural phenomenon, without any human impact. The next two stages of the ice jam development were the upstream progression and shoving of the ice jam in the St. Clair River without any effect on the ice accumulation in the river delta.

The simulation results show that in the first phase, the ice was retarded in the St. Clair Flats and accumulated in the river's delta and branches. Based on the simulated process in the St. Clair River the general mechanism of ice jam formation in a river delta will be described here. In the simulated case the process started in the downstream part of one of the branches where the channel narrows. It was expected that ice would stop in small channels first. Once the ice jammed in one channel, it would be quickly extended upstream and prevented more ice from entering (Fig. 1a). Since the ice could not enter one of the channels, it will be then transported downstream through the other channels with an even higher concentration. This caused another ice jam to start from the area where the channel branches off or bends (Fig. 1b). This ice jam was progressing upstream quickly blocking the next channel (Fig. 1c) and in a short time entire river delta could be jammed (Fig. 1d).

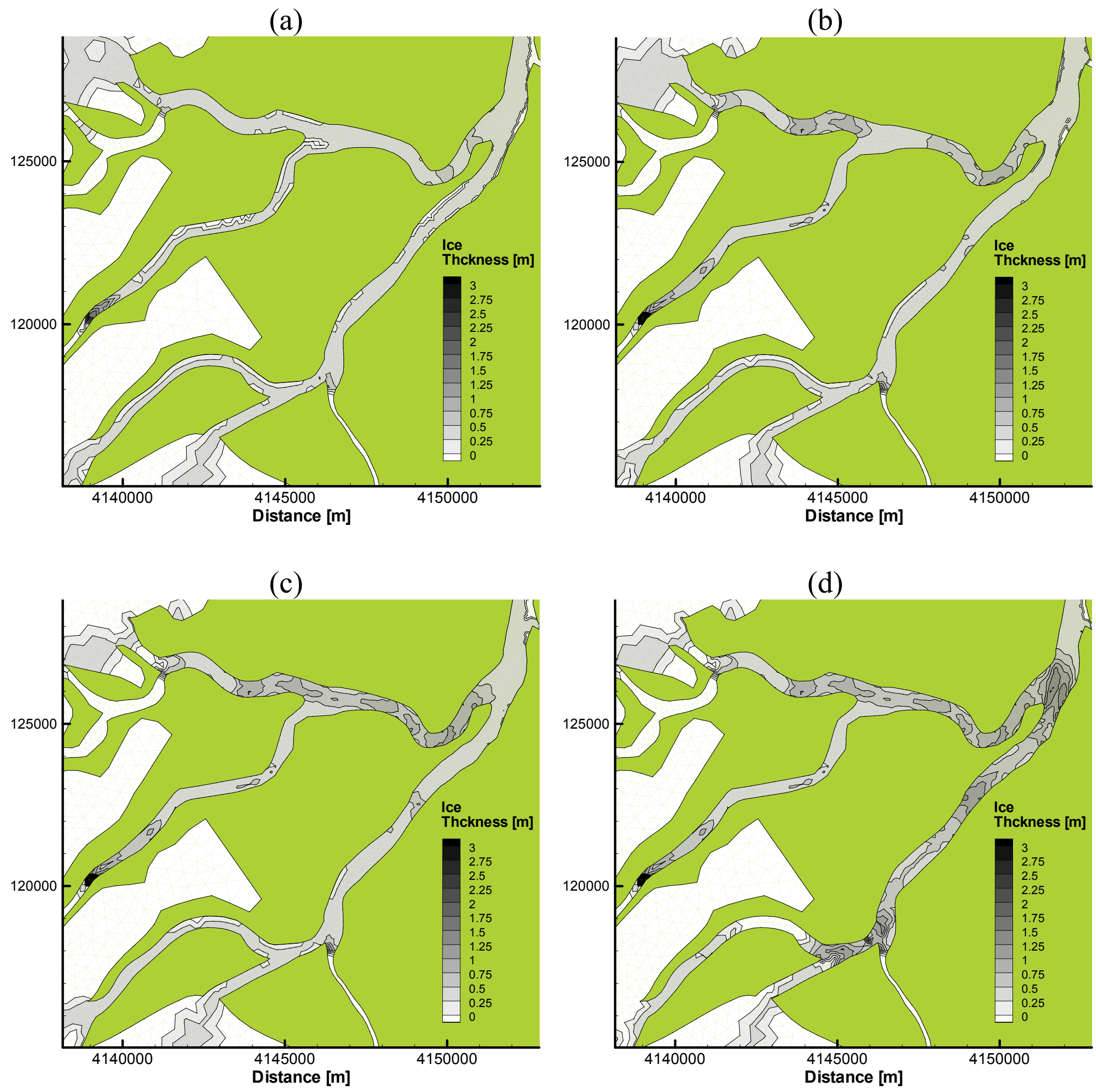

Figure 1. Ice jam formation in a river delta from the initial stage (a) to the jam in the entire delta (d).

The ice jam process described above could take place in any river delta where ice phenomena occur during the winter season. Different river deltas may have its own character, but in general it is expected that ice will stop in channels which are narrow or those which change their direction, or else in areas where they branch off. Ice jam formation in river deltas is a gradual process leading to block one channel after another.

3. The Mouth of the Vistula River

Due to the human activity aimed at preventing cities and farms from flooding, natural river outlets were often transformed into artificial man-made channels and other engineering structures. This was the case with the Delta of the Vistula River where the new cut-off channel was built. At the end of the 19th century a new outlet of the Vistula was constructed by cutting off all the river's distributaries and building an artificial channel which directed the river flow right to the Baltic Sea. The cut-off channel is approximately 500 meters wide at the top, which is about the same size as the winding river channel that it replaced. The reason for that enterprise was to avoid further ice jams in the region of the Vistula Delta and to regulate the river flow. Before the new cut-off channel was built, the Vistula, which is a typical alluvial river, formed its delta at the Baltic Sea shore from the river-bed material. Over the centuries ice jams formed in the western arm of the Vistula Delta, predominantly due to its complicated layout. Those ice jams caused frequent floods which inundated the city of Gdańsk. They occurred every 3 to 4 years and were connected with storms in the Baltic Sea resulting in the raise of water elevation. The ice jam formation mechanism in the Vistula river delta was probably similar to that simulated in St. Clair Flats. In the complicated network of the channels ice floes were retarded and may have stopped eventually forming an ice jam. In 1840, due to an ice jam near the city of Gdańsk, with its toe located probably in the downtown area, the river breached the dunes situated along the sea coast forming a new outlet called Bold Vistula (Fig. 2). Another significant ice jam occurred after 50 years causing a flood in the entire town. The flood was the signal for the authorities that the Vistula's outlet had to be regulated.

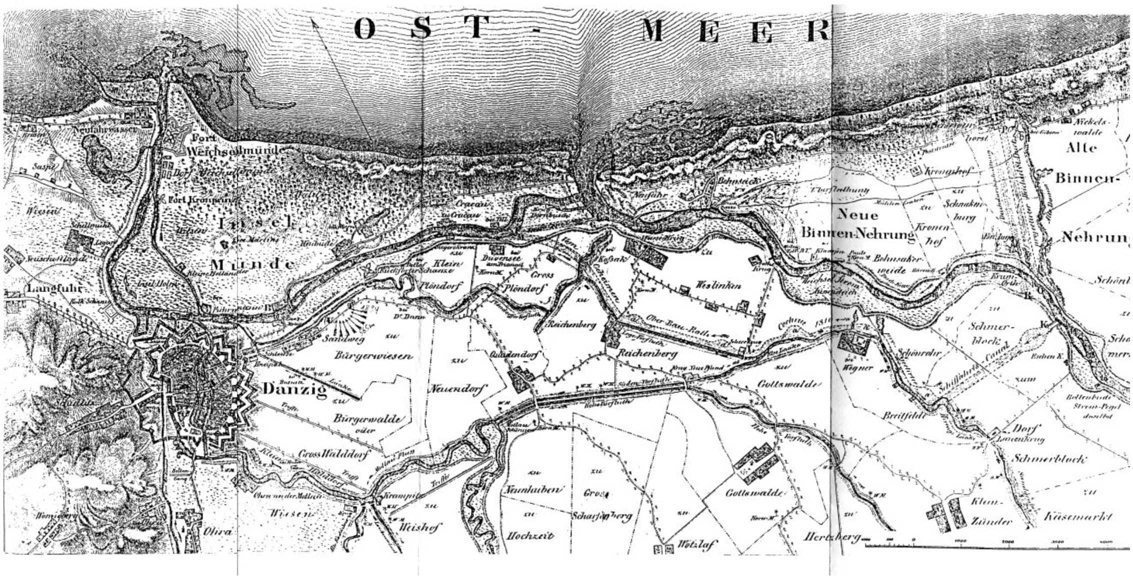

Figure 2. Vistula River Delta in 1840; old river outlet shown on the left side, Bold Vistula is the outlet in the middle, planned cut-off channel is on the right side of the map (Kossak 1840).

The artificial channel shortened significantly the natural river outlet (from 18 to 9 km) and increased the river slope in consequence. Since the new river outlet was put into the operation, no significant ice jam formation has been observed in that section of the river. The reason for this situation is the correct design of the river outlet as well as the ice breaking operations performed in that area. During the last 115 years of the channel's existence an accumulative form known as a fan-delta has been building up in the near-shore zone, in front of the river mouth. The changes in the main mouth of the Vistula are associated with the estuarine sedimentation of sand carried by the river. The maintenance of the outlet requires groins which have to be lengthened continually. A renovation and extension of the groins is planned for the summer of 2012. The regulation of the river mouth with the use of groins has been approved of as the only efficient way of concentrating the river current at the land-sea transition point, thus taking advantage of the river's natural capacity to erode a channel in the near-shore shoals.

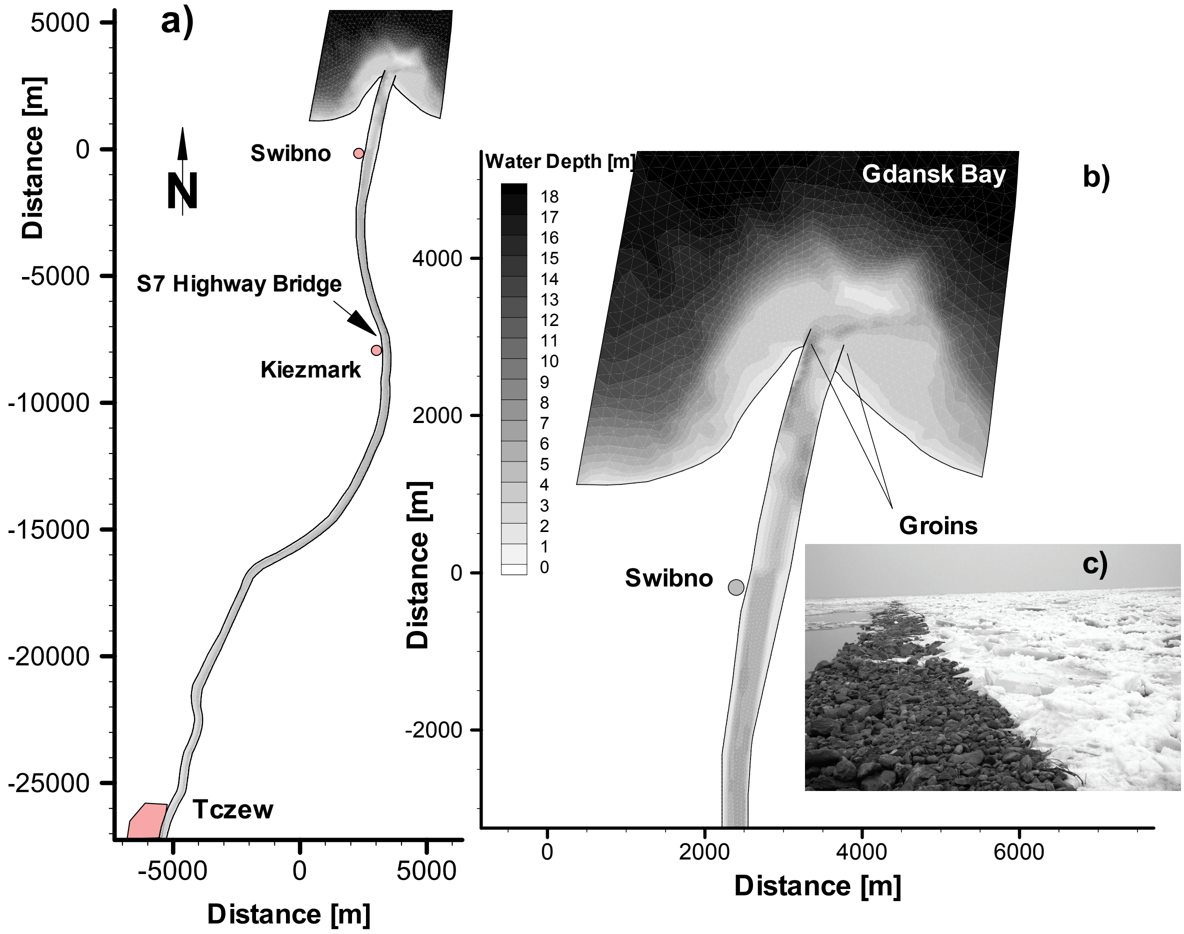

Figure 3. Water depth for steady state condition (water discharge in Tczew 1000 m^3/s); Vistula River from Tczew to the Gdańsk Bay (a); Vistula outlet (b); western groin looking downstream, Jan 2004 (c).

Even though the flood risk was significantly reduced, there is still a need to understand river ice processes in the outlet of the Vistula River. This becomes especially important in view of two major engineering projects planned in this area. One is the extension and renovation of the groins in order to prevent sediment from accumulation in the near-shore zone (Figs. 3b and 3c). Whereas the other project is concerned with a highway bridge for a new S7 express road from Gdańsk to Elblag (Fig. 3a). This critical section of the river was never analyzed for prediction reasons related to ice formation for a variety of meteorological and hydrological conditions. Thus to understand the ice jam formation in the Vistula outlet, a two-dimensional DynaRICE model has been used here. Sensitivity analysis on ice jam conditions in the lower Vistula River was performed with varying model parameters based on the average, 10 and 100 year return period condition. These parameters were the wind speed, water level in the Baltic Sea and water discharge at the gauging station of Tczew. In addition to the high river flow, low discharge, typically observed in the winter period, was simulated. In the study nine scenarios with varied parameters were evaluated, and the most severe scenario was found.

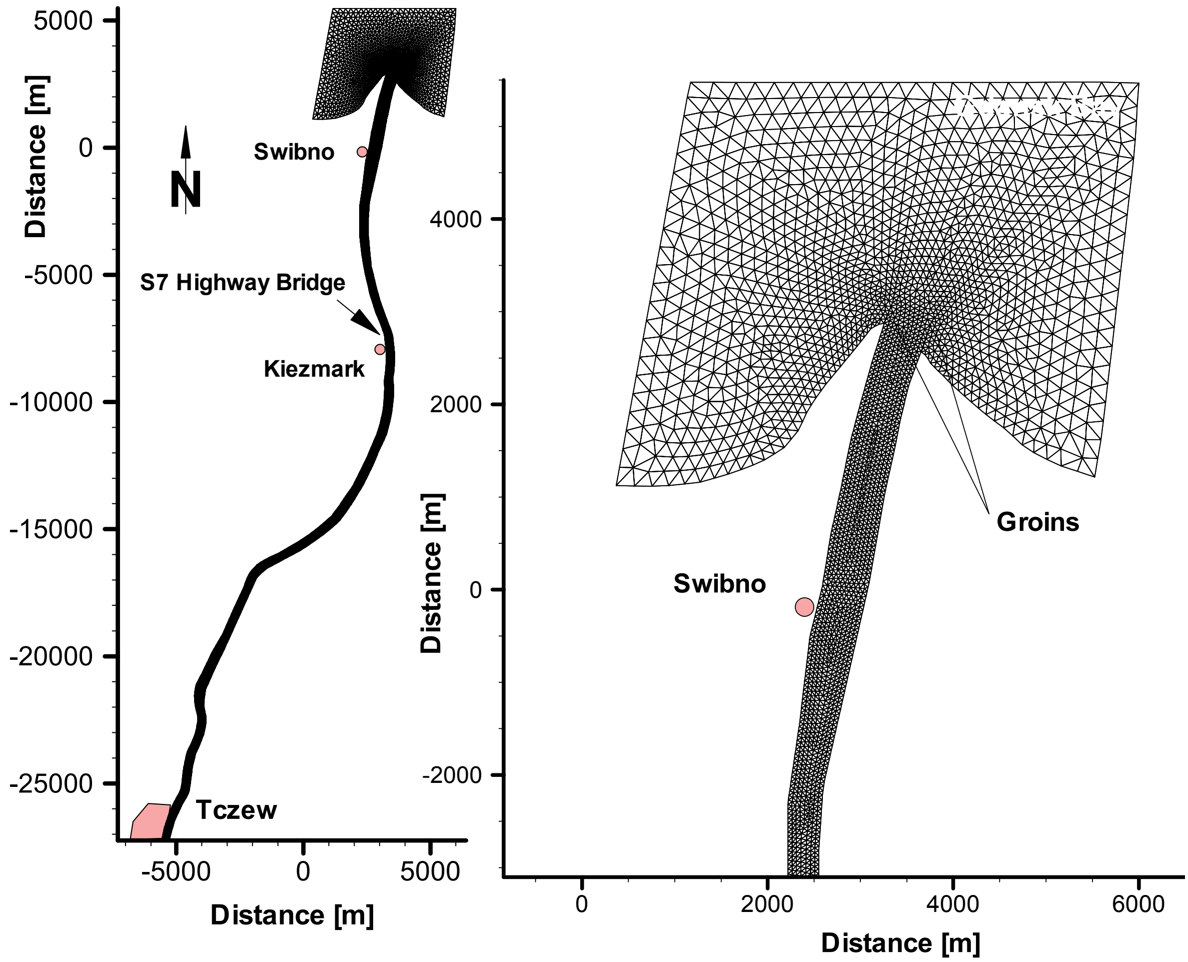

Figure 4. Finite element mesh

4. River Bathymetry and Input Data

The model domain covers the 35 km section of the Vistula River from the Tczew gauging station (km 908.6) at the upstream boundary down to the river mouth (km 944.0) and continues about 3,000 m into the Gdańsk Bay at the downstream boundary. Fig. 3a shows the model domain and the bathymetry. This river section has been trained for navigation purposes and has regular cross sections limited by the river dykes on both sides. The bathymetry of the river from Tczew to the mouth has been described by means of the geometry of 50 cross sections. The bathymetry of the near-shore zone was measured in 2003 for the Regional Water Board in Gdańsk (Majewski et al., 2003).

Sensitivity studies were conducted using steady state flow conditions. A total of 11 cases with different combinations of flow and downstream sea water levels were simulated to determine the range of the effects the ice would have on the water level and the flow velocity in the Vistula River mouth. These eleven cases are combinations of three different steady flow conditions, three different water levels at the Baltic Sea downstream and the wind velocity. The three upstream flow conditions are the 100-year flood, long-term average and long term low flow conditions as summarized in Table 1. The long-term average discharge at the Vistula mouth is 1080 m^3/s, while the minimum recorded discharge was 253 m^3/s and the maximum amounted to 7840 m^3/s. The downstream water levels are the 10- and 100-year and long-term average water levels measured at the Gdańsk Harbor (Fig. 6). These water levels are based on the Kronstadt Sea-gauge. The Baltic is a tideless sea, however, water level variation in the Bay of Gdańsk, due to storms, is from +1.14 m to -0.86 m in relation to the average water elevation. The maximum wave height of 2.7 m was measured during the winds blowing at the speed 20 m/s from NW and N directions.

Table 1. Sensitivity analysis cases (R = Reference case).

	Q Tczew	H Gdańsk Bay	Wind Velocity	Ice Condition on Gdańsk Bay	Remarks
	[m^3/s]	[m Kr.]	[m/s]	[-]	
Case R	1,080	0	10	Broken Ice	Reference Case Long Term Average Discharge
Case 1	R	R	R	No Ice	
Case 3	10,000	R	R	R	100 Year Discharge
Case 4	600	R	R	R	Low Discharge
Case 5	R	100 yr	R	R	
Case 6	600	100 yr	R	R	
Case 7	R	100 yr	20	R	
Case 8	600	100 yr	20	R	
Case 9	R	10 yr	R	R	
Case 10	600	10 yr	R	R	

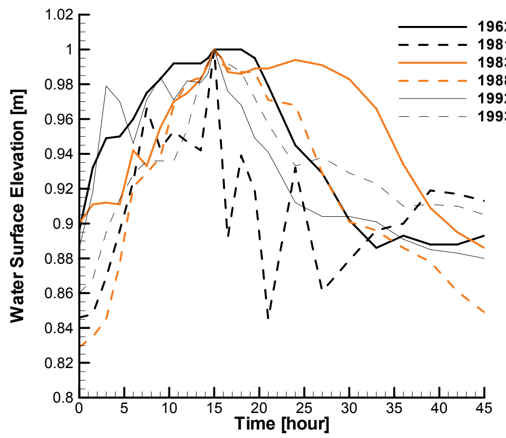

Figure 5. Storm surges for the Gdańsk Bay based on the Kronstadt sea-gauge.

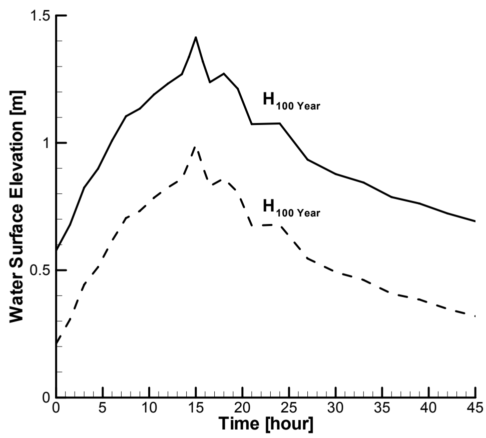

Figure 6. Hypothetical hydrographs for the Gdańsk Bay for 10- and 100-year events.

5. Simulation Results

Eleven scenario cases were studied as summarized in Table 1. Throughout the entire ice breakup and run on the Vistula River all available icebreakers usually operated in the analyzed section of the river. These activities could have had effects on the stability of portions of ice jam in the river. However, the possible effect of the icebreakers on the ice conditions was not included in the current model. This assumption leads to more severe conditions for all the analyzed cases. A brief discussion of the simulated cases will be presented in this section, followed by the results of the simulations of the worst case scenario.

In general, all the cases with the low discharge produced thicker ice accumulation. However, the associated water levels were lower because of the smaller discharge. For cases with the high water level in the Gdańsk Bay ice accumulated in two locations: at the river mouth and in the vicinity of the proposed highway bridge. At the river mouth ice floes were stopped by the ice covering the bay and the low flow velocity in the deep sea. For the case with the low river flow the ice piled up easily in this area, but for the cases with the long term average flow or 100 year flow, all the ice was flushed down into the deep sea. The ice stoppage in the vicinity of the highway bridge was affected by the river geometry (mild river band). Again larger ice accumulation was observed for the low river flow. For higher water discharge the ice was moving down continuously without stoppage.

The most severe condition for all the simulated cases is the case with high water set up in the Gdańsk Bay (100 year recurrence interval) and wind blowing from the north with velocity of 20 m/s. For the case with low flow velocity ice form a jam with a thickness of 1.2 m (Fig. 7). The toe if this ice jam is located about 8 km upstream of the proposed bridge. It is potentially dangerous situation which not monitored can result in breaching of flood dykes. The new bridge piers located in the main channel may increase the risk of ice jam associated with high water set up in the Gdańsk Bay.

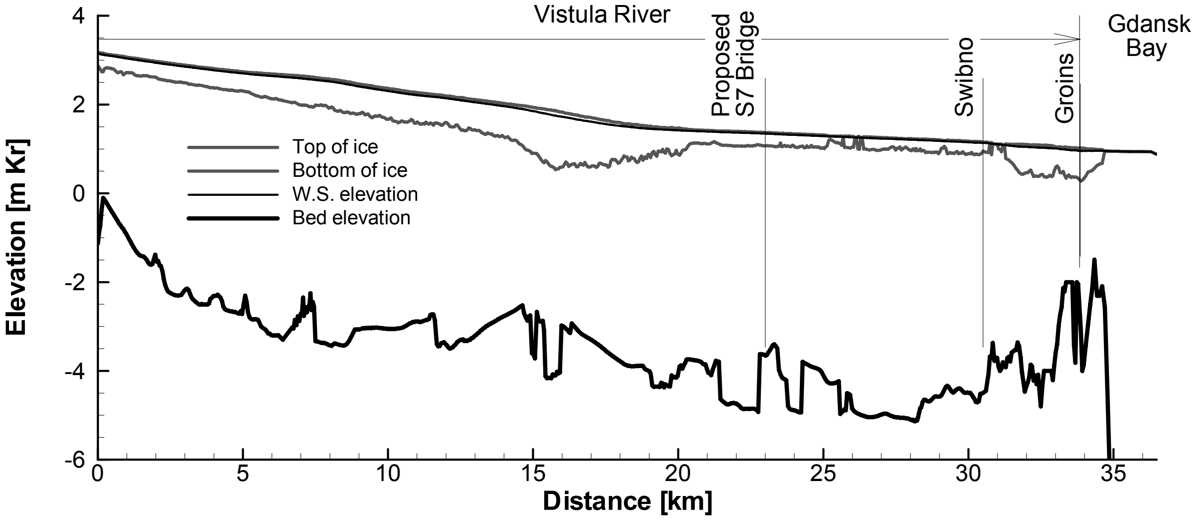

Figure 7. Longitudinal profile of water surface elevation and ice thickness for case 8 (low discharge in the river, 100 year storm in the Gdańsk Bay and high wind velocity).

6. Conclusions

River deltas, especially, are prone to ice jam formations. In these locations ice movement is usually retarded and may result in jamming due to the slope change and water level effect. Sediment allocation in river deltas contributes to the formation of the complicated channel layout in the river mouth. In such a channel system ice can accumulate easily. This is a complex and gradual process where an ice jam is formed in channels, one after the other. A direct channel to the sea is an effective way to reduce a flood hazard caused by ice jams in river deltas. The construction of a direct cut-off channel in the Vistula is a good example of such a solution. However, it has not eliminated the flood hazard completely. Simulation results have shown that the worst case scenario is one in which there is low water discharge in the river, high water level in the Gdańsk Bay and a strong wind blowing from the north. In this very case an ice jam will form upstream of a proposed highway bridge. If the ice formation is not released, it may create potential flood. The mouth of the Vistula River should be maintained by icebreakers during the breakup and the ice run. Fortunately, a regular river channel along the final section of the Vistula allows for the operation of icebreakers which require appropriate water depth.

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