Modeling of ice phenomena in the mouth of the Vistula River

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Modeling of Ice Phenomena in the Mouth of the Vistula River

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A b s t r a c t

The mouth of the Vistula River, which is a river outlet located in tideless area, is analyzed. The Vistula River mouth is a man-made, artificial channel which was built in the 19th century in order to prevent the formation of ice jams in the natural river delta. 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. In the paper, ice processes in the natural river delta are presented first to refer to the historical jams observed in the Vistula delta. Next, the calibrated mathematical model was applied to perform a series of simulations 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.

Key words: river ice jam, ice dynamics, estuary, SPH, Vistula River.

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. Another process is observed when strong currents remove sediment from the river outlet forming an estuary. River outlets of the latter 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 out-
lets for the reasons of access to convenient transportation, sustenance, ener-
gy. Many estuaries are subjected to ice processes, the most severe of which
being ice jams. The ice jam formation mechanism in river outlets is a com-
plex process affected by many hydraulic and meteorological parameters and
it still remains unclear.

Vistula, which is the largest Polish river, formed typical delta at its
mouth. In the past numerous ice jams occurred on Vistula near Gdańsk caus-
ing significant floods. In 1895 a direct, artificial channel was formed to facil-
itate discharge of Vistula to the Baltic Sea. Since that time, there was no
serious flood caused by ice jam connected with high discharge in Vistula or
high water elevation in the sea caused by storm.

This paper examines river outlets characterized by no tide effect with
special attention paid to the Vistula River mouth. 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 chan-
nel have been presented by means of the two-dimensional river hydro-ice
dynamic model DynaRICE.

2.   ICE JAM FORMATION IN NATURAL RIVER DELTAS

A river delta is an accumulative form where the river sediment is predomi-
nantly deposited and in special condition may be eroded. This process 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 proc-
esses. Due to the extensive river delta, 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
data. 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. Dur-
ing the initial phase of ice jam event, only one icebreaker operated on the
river and it had little or no impact on the ice jam stability. Therefore, the ice
formation process in its initial stage may have been regarded as a natural
phenomenon without any human impact.

Shen *et al.* (2008) showed that the formation of an ice jam is a result of
congestion of ice due to the convergence of ice flow. In a natural river delta
this process started in the downstream part of one of the branches where the
channel narrows. When ice jammed in one channel, accumulation would be

quickly extended upstream and prevented more ice from entering. Since ice could not enter one of the channels, it would have transported downstream through the other channels with an even higher concentration. This would cause another ice jam. It usually started from the area where the channel branches off or bends. This ice jam would progressing upstream quickly blocking the next channel and in a short time entire river delta could be jammed.

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 blocking 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 works. 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 m 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 River 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 (Łomniewski 1960, Cyberski *et al.* 2006). 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 in the river. Based on the historical documentation, the ice jam formation mechanism in the Vistula River delta was similar to that described in above. 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 in the downtown area, the river breached the dunes situated along the sea coast forming a new outlet called Bold Vistula (Fig. 1). Another catastrophic 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.
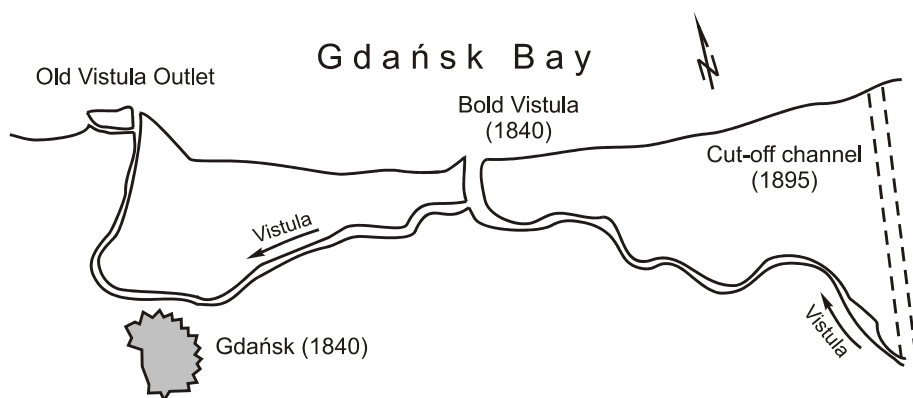
Fig. 1. Vistula River delta in 1840; old river outlet shown on the left side, Bold Vistula is the outlet in the middle, planned cut-off channel is on the right side of the map (from Kossak 1840).

In comparison to natural river delta, 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. Two potentially dangerous situations occurred in March 1956 and February 1994. Both cases were caused by breakup ice jams at Świbno where water level exceeded the flood stage by about 1 m. However, there was no significant flooding reported. The case from March 1956, with elevation of 772 cm (flood stage at Świbno is 680 cm) was the highest historical crest in Vistula outlet operation. The 1994 ice jam caused slightly lower stages, but the better evidence of the water level time series exists, therefore this event was used to calibrate the mathematical model, as presented in Section 4.

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 (Pruszak *et al*. 2005). 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 (jetties) which have to be lengthened continually (Gąsiorowski *et al*. 2004). A renovation and extension of the groins was 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.
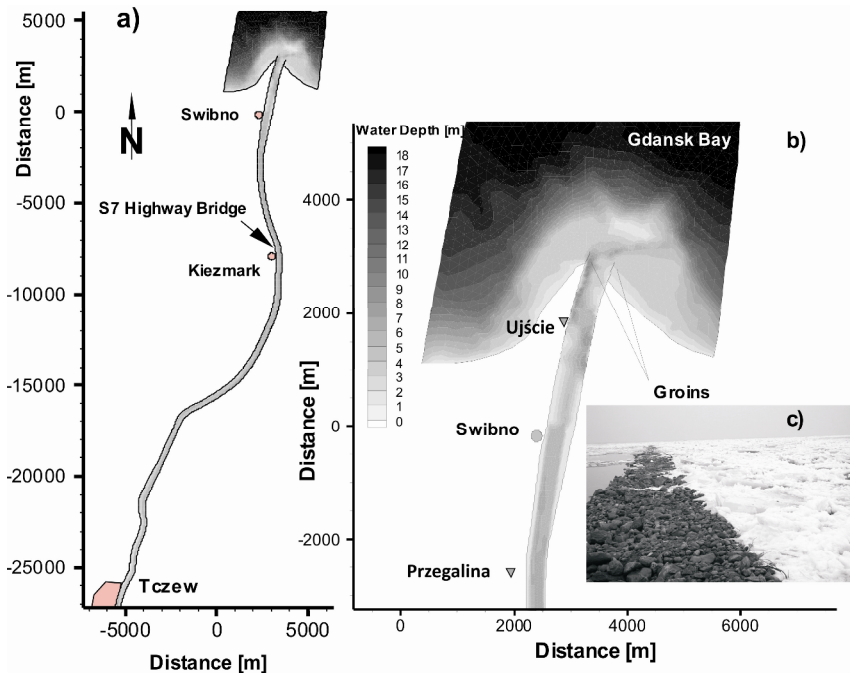
Fig. 2. Water depth for steady state condition (water discharge in Tczew 1000 m^3/s): Vistula River from Tczew to the Gdańsk Bay (a), Vistula outlet (b), and western groin looking downstream, January 2004 (c).

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 (Fig. 2b, c). The other project is concerned with a highway bridge in Kiezmark for a new S7 express road from Gdańsk to Elblag (Fig. 2a). 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 calibrated 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.

4. MATHEMATICAL MODEL

The DynaRICE model is a two-dimensional ice dynamics model for analyz-ing dynamic transport and jamming of surface ice in rivers and lakes (Shen *et al.* 2000). The model simulates the coupled dynamics of ice motion and water flow, including the flow through and under the ice rubble. This model has been successfully applied to many river ice control and ice period opera-tion studies, including Niagara Power Project (Lu *et al.* 1999), ice jam proc-esses in Włocławek reservoir (Kolerski 2011), ice control structure in Notoro Lake (Kolerski *et al.* 2013), ice scour risks at large navigation projects (Carr and Tuthill 2012) and other applications. These studies have shown that the model can accurately simulate dynamic transport and ice jam processes.

In the model, the water depths and unit-width discharges are obtained by solving depth-integrated two-dimensional hydrodynamic equations for shal-low water flows, including effects of surface ice (Shen 2010). Flow in the surface ice layer is included, so that the flow between ice floes and the seep-age flow through thick ice accumulations are considered. The continuity equation for the total water discharge is

$$\frac{\partial H}{\partial t} + \frac{\partial (q_{tx})}{\partial x} + \frac{\partial (q_{ty})}{\partial y} = \frac{\partial}{\partial t}\left(Nt_i'\right) ,\tag{1}$$

where H is the total water depth, $\vec{q}_t$ – unit-width total water discharge, $\vec{q}_t = \vec{q}_u + \vec{q}_l$; $\vec{q}_u$ – unit-width water discharge in the surface ice layer; $\vec{q}_l$ – unit-width water discharge beneath the ice layer, q_{tx} and q_{ty} – components of total unit-width water discharge, t_i' – submerged ice layer thickness, N – ice concentration, x and y – independent variable of space, t – independent time variable. The momentum equations for the flow can be written as:

$$\frac{\partial q_{tx}}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q_{tx}^2}{H_t}\right) + \frac{\partial}{\partial y}\left(\frac{q_{tx}q_{ty}}{H_t}\right) = \frac{1}{\rho}(\tau_{sx} - \tau_{bx}) + \frac{1}{\rho}\left(\frac{\partial T_{xx}}{\partial x} + \frac{\partial T_{yx}}{\partial y}\right) - gH_t\frac{\partial \eta}{\partial x} ,\tag{2}$$

$$\frac{\partial q_{ty}}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q_{tx}q_{ty}}{H_t}\right) + \frac{\partial}{\partial y}\left(\frac{q_{ty}^2}{H_t}\right) = \frac{1}{\rho}(\tau_{sy} - \tau_{by}) + \frac{1}{\rho}\left(\frac{\partial T_{xy}}{\partial x} + \frac{\partial T_{yy}}{\partial y}\right) - gH_t\frac{\partial \eta}{\partial y} ,\tag{3}$$

where: $T_{xx} = \varepsilon_{xy}\left(\frac{\partial q_{tx}}{\partial y} + \frac{\partial q_{ty}}{\partial x}\right)$, ε_{xy} – generalized eddy viscosity coefficients, τ_s and τ_b – shear stresses at ice-water interface and the river bed; H_t – equiva-lent water depth for the total water discharge $\vec{q}_t$, η – water surface elevation above the reference level, ρ – density of water, g – gravitational accelera-tion. The solution of hydrodynamic component of the model is using a finite

element method based on streamline upwind Petrov–Galerkin (SUPG) concept (Liu and Shen 2003). The model is capable of simulating high velocity transitional flows with wet-dry bed conditions.

The two-dimensional ice dynamic model was developed based on the discrete parcel method with smoothed particle hydrodynamics (SPH) algorithm presented below. In the ice transport equations, the term "particle" was replaced by "parcel" to avoid the confusion of particle with a single ice pan or ice piece. A parcel is considered as material element defined as a collection of ice pieces. The ice dynamic equations consider all the external and the internal forces which act on ice parcel. These forces include water drag, gravity, internal resistance of ice, and bed friction on grounded ice. The momentum balance of parcel k at the location of $\vec{r}_k$ can be written in Lagrangian form as:

$$(M_i)_k \left(\frac{D\vec{V}_i}{Dt} \right)_k = (\vec{R})_k + (\vec{F}_a)_k + (\vec{F}_w)_k + (\vec{G})_k , \qquad (4)$$

where $\left(\dfrac{D\vec{V}_i}{Dt} \right)_k$ is acceleration of ice parcel k, M_i is ice mass per unit area, $\vec{V}_i$ is ice velocity, $\vec{R}$ is internal ice resistance, $\vec{F}_a$ is wind drag force, $\vec{F}_w$ is water drag force, and $\vec{G}$ is gravitational force component due to water slope. In addition, both the boundary effects of ice friction along river banks and the bed friction on ice movement when ice grounding occurs are considered. A viscoelastic-plastic (VEP) constitutive law was used to formulate internal ice resistance, which is governed by the material behavior of ice rubble (Ji $et\ al.$ 2004). The two-dimensional internal ice resistance force, $(\vec{R})_k = \vec{i}(R_x)_k + \vec{j}(R_y)_k$, can be calculated as the following (Shen $et\ al.$ 2000):

$$(R_x)_k = \frac{\partial}{\partial x}(\sigma_{xx} N t_i)_k + \frac{\partial}{\partial y}(\sigma_{xy} N t_i)_k , \qquad (5)$$

$$(R_y)_k = \frac{\partial}{\partial x}(\sigma_{yx} N t_i)_k + \frac{\partial}{\partial y}(\sigma_{yy} N t_i)_k , \qquad (6)$$

where σ_{xx} and σ_{yy} are normal stress components and $\sigma_{xy} = \sigma_{yx}$ are shear stress components of internal stresses at $\vec{r}_k$ where parcel k is located ($\vec{r}\ ^2 = x^2 + y^2$), N is ice concentration, and t_i is an ice thickness. Similarly, all the external forces including wind and water drag as well as gravitational force are calculated as the follows (Shen $et\ al.$ 2000):

$$(\vec{F}_a)_k = \vec{i}\left[\rho_a c_a \left|\overrightarrow{WV}\right|_k (WV_x)_k N_k\right] + \vec{j}\left[\rho_a c_a \left|\overrightarrow{WV}\right|_k (WV_y)_k N_k\right], \tag{7}$$

$$(\vec{F}_w)_k = \vec{i}\left[\rho c_w \left|\vec{V}_w - \vec{V}_i\right|_k (V_{wx} - u)_k N_k\right] + \vec{j}\left[\rho c_w \left|\vec{V}_w - \vec{V}_i\right|_k (V_{wy} - v)_k N_k\right], \tag{8}$$

$$(\vec{G})_k = -\vec{i}(M_i)_k g\left(\frac{\partial \eta}{\partial x}\right)_k - \vec{j}(M_i)_k g\left(\frac{\partial \eta}{\partial y}\right)_k, \tag{9}$$

where $(\overrightarrow{WV})_k$ is the wind velocity at the location of parcel k, ρ_a is density of air, c_a is wind drag coefficient, which incorporate both the frictional and form drag effects; in a study was set as $c_a - 0.0015$, $(\vec{V}_w)_k$ is water current velocity at $\vec{r}_k$, and u_k, v_k are components of ice velocity of parcel k in x and y directions, and c_w is water drag coefficient on ice, which varies with ice concentration and ice floe geometry.

Even though the DynaRICE model is able to include all the thermal processes involved during ice formation and cover decay, this module was not included in a current study. The effect of ice decay due to the thermal melting is much smaller in comparison to the ice dynamic during the breakup. Therefore, the thermodynamics was neglected in the study. This assumption was also made to get insulated condition for a sensitivity study proceeded.

5. SPH FORMULATION

Smoothed Particle Hydrodynamics (SPH) is a pure Lagrangian method introduced by Lucy (1977) and Gingold and Monagham (1977) to simulate fluid dynamics in astrophysics and cosmological gas dynamics. SPH method has been adopted by wide range of disciplines including open surface flow (Takeda *et. al* 1994), wave dynamics (Staroszczyk 2010), dam-break flow (Wang and Shen 1999) and hydraulic jump dynamics (De Padova *et al.* 2013).

A Lagrangian discrete-parcel method based on the smoothed particle hydrodynamics is used to solve the ice dynamic equations in DynaRICE model (Shen *et al.* 2000, 2008). The basic concept of the discrete-parcel method is that the ice, considered as a continuum, can be represented by a sufficiently large number of individual parcels carrying mass, momentum and energy. In a flow field, the mass density at any point is obtained by summing up the contribution from all the particles surrounding that point, *i.e.*, a function $f(\vec{r})$ in the solution domain D is approximated by

$$\bar{f}(\vec{r}) = \int_D W(\vec{r} - \vec{r}', h) f(\vec{r}') d\vec{r}', \tag{10}$$

where $\vec{r}$ and $\vec{r}'$ are position vectors for specified point and its neighboring points. The function W is a kernel with normalization of $\lim_{l \to 0} \int_D W\left(\vec{r} - \vec{r}', h\right) d\vec{r}' = 1$, and l is a smoothing length which determines the range of influence of the kernel. In a current model the Gaussian function

$$G\left(\vec{r}, \vec{r}', l\right) = \frac{1}{l^2 \pi} \exp\left(-\frac{\left(\vec{r} - \vec{r}'\right)^2}{l^2}\right) \tag{11}$$

and suggested by Monaghan (1982), B-spline kernel (M_4) were tested.

$$W\left(r, l\right) = \begin{cases} \dfrac{1}{l^2}\left(\dfrac{3}{2} - R^2 + \dfrac{1}{2} R^3\right) & \text{for } R \in \langle 0,1 \rangle \\[2mm] \dfrac{1}{6l^2}\left(2 - R\right)^3 & \text{for } R \in (1,2) \\[2mm] 0 & \text{for } R \in (2, \infty) \end{cases} \tag{12}$$

where $R = \left|\vec{r} - \vec{r}'\right|/l$ and $\vec{r}^2 = x^2 + y^2$. The Gaussian function is the smoothest one; however, it cannot provide accurate interpolation, unless the search area is sufficiently large. It can be easily proved that for Gaussian function with a searching area of $2l \times 2l$ the error in mass balance (ice volume) is in a range of 4%. If the searching area will be increased to area of $4l \times 4l$, the error will be reduced to only $7 \times 10^{-5}\%$. There is no such a problem with M_4 spline function, because the mass is always conserved within the range of $2R$. Therefore, in the study the M_4 kernel is used. If m_j and $M_j = m_j n_j$ is defined as the mass and mass density of particle j located at $\vec{r}_j$ distance, Eq. 10 can be modified to

$$\bar{f}\left(\vec{r}, l\right) = \sum_{j=1}^{N} \frac{f_j}{n_j} W\left(\vec{r} - \vec{r}_j, l\right) = \sum_{j=1}^{N} f_j \frac{m_j}{M_j} W\left(\vec{r} - \vec{r}_j, l\right), \tag{13}$$

where n_j is a number of particles per unit volume of area. The two-dimensional mass density at the location of $\vec{r}_k = \vec{i}x + \vec{j}y$ can be obtained from Eq. 13 as

$$\bar{f}\left(\vec{r}, l\right) = \sum_{j=1}^{N} \frac{f_j}{n_j} W\left(\vec{r} - \vec{r}_j, l\right) = \sum_{j=1}^{N} f_j \frac{m_j}{M_j} W\left(\vec{r} - \vec{r}_j, l\right), \tag{14}$$

in which W_{kj} denotes the average of interpolation kernels of parcel k and j:

$$W_{kj} = \frac{W\left(\vec{r}_k - \vec{r}_j, l_k\right) + W\left(\vec{r}_k - \vec{r}_j, l_j\right)}{2}. \tag{15}$$

6. RIVER BATHYMETRY AND MODEL CALIBRATION

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 3000 m into the Gdańsk Bay at the downstream boundary. Figure 2a shows the model domain and the bathymetry and the finite element mesh is shown in Fig. 3. 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).

As mentioned above, there were only two cases related to ice phenomena with flood stage at Świbno. Both cases were affected by ice jam in Vistula cut-off channel. The case from March 1956 was caused by breakup ice interacting with thick ice floes on Gdańsk Bay. The next case was freeze up ice jam which formed at sediment accumulation in the near-shore zone with Gdańsk Bay free from the ice. Although the case from March 1956 caused record high water level at Świbno, there was more data recorded during the February 1994 case, and this event was used for model calibration. Water levels from four gauge stations located at Vistula outlet (Fig. 4) as well as air and water temperature data (Figs. 5 and 6) were published by Dziaduszko
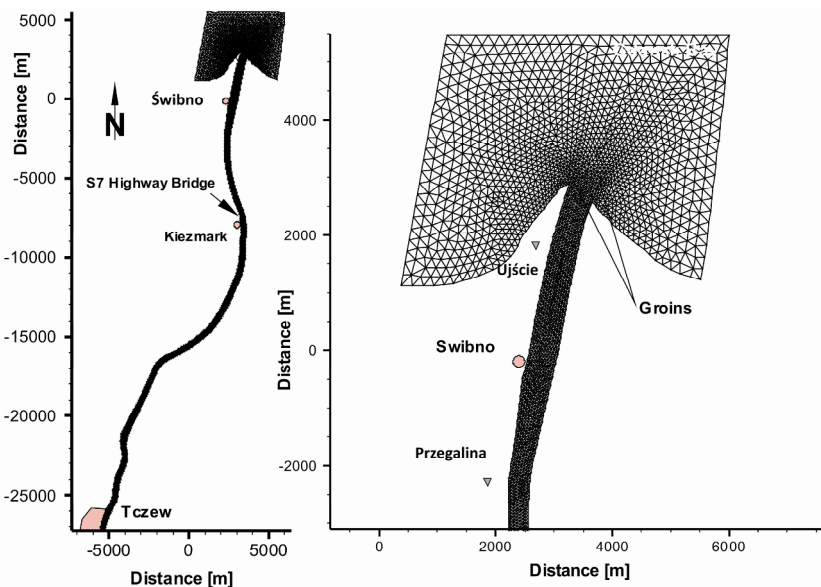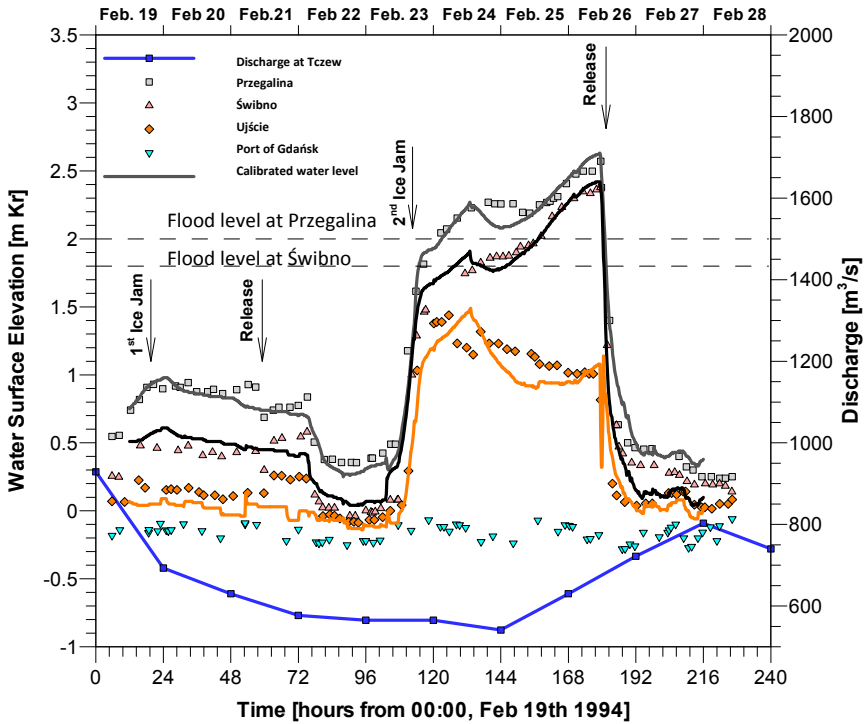

Fig. 3. Finite element mesh.

Fig. 4. Comparison of simulated (line) and observed (symbols) water level for ice event for February 1994, together with water discharge in Tczew (line with symbols). Colour version of this figure is available in electronic edition only.
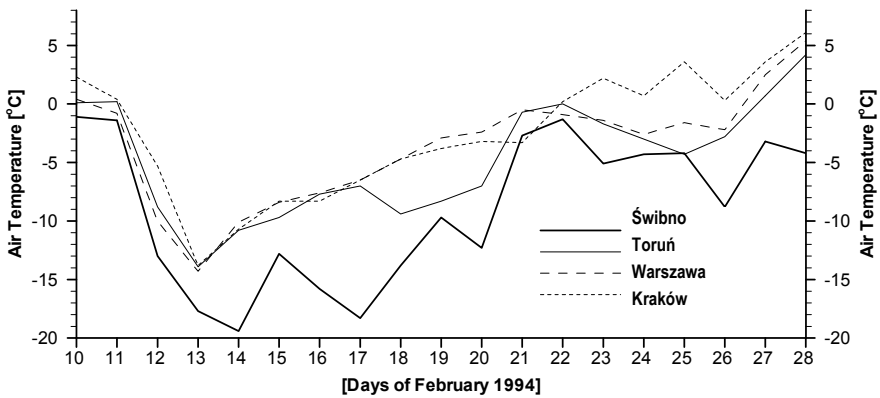
Fig. 5. Air temperature in Poland in February 1994 from meteorological stations along the Vistula River from North (Świbno) to South (Kraków).
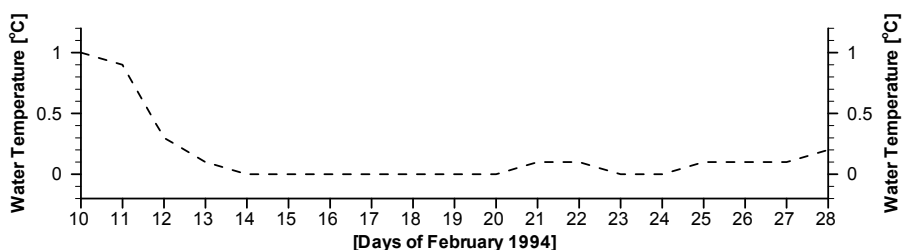
Fig. 6. Water temperature in Świbno measured during the ice event in February 1994.

and Malicki (1994). Other necessary data such as water discharge at Tczew and wind velocities and directions from Gdańsk harbor were provided by Institute of Meteorology according to the agreement between the Institute and Gdańsk University of Technology.

The ice jam was caused by the air temperature oscillations in the second decade of the February 1994. The relatively high air temperatures during the first ten days of February (mean average from Gdansk Airport was –1.8° C) caused little or no ice events on the Vistula River. According to the data from Świbno hydrological station, the water temperature on 10 February 1994, was +1° C (Fig. 5). The situation changed on 12 February when a high pressure area from south-eastern Europe started to move in the north-west direction. In the middle of February, the center of anticyclone was located on southern Baltic Sea with the extraordinarily high pressure of 1050 hPa. Cold arctic air masses were dragged from Belarus and Ukraine causing significant air temperature drop to –10° C daytime and –18° C at the night over the entire Vistula basin (Fig. 5). At this condition, ice started to form intensively over the entire length of the Vistula River. The first ice floes were observed in Vistula Outlet on 13 February with the concentration of 30%. Base on the observations, ice was stopped at Świbno ferry on 19 February (Dziaduszko and Malicki 1994). This is confirmed by observation data which indicated a rise of water level between Świbno and Przegalina gauging stations (Fig. 4). The evidence showed that the first ice stoppage caused moderate jamming which was released spontaneously in next two days. The most probable mechanism of the ice jam release was ice cover collapsing due to exceeding ice cover equilibrium stage, which is commonly known as "shoving". Shoving occur if the internal resistance of ice accumulation is be unable to resist the increasing streamwise forces as the cover progresses upstream (White 1999). This mechanism is common for the Lower Vistula River (Grześ 1991) and leads to mechanical thickening of ice cover downstream. In the Vistula outlet the effect of ice shoving may actually lead to ice jam releasing due to pushing ice mass to the Gdańsk Bay. Water level data indicated that

the ice cover collapsed on 21 February, but this was followed by a more severe ice jam formed upstream of Świbno. This jam was again shoved downstream and its toe was probably stopped at fan-delta in the near-shore zone, in front of the river mouth. The ice jam developed quickly and caused an increase of water level over the entire length of the Vistula cut-off channel. Due to intense icebreaking, the ice jam was released on 26 February which caused water level drop by about 2 m.

It is worth to notice that during the entire ice event the observed water discharge at Tczew was not higher than 855 m^3/s, and over the four days did not exceeded 600 m^3/s (Fig. 4). The low flow conditions caused ice settling on the river bed, but from the other side, due to the reduced discharge, water level did not raised significantly above the flood level. In case of rapid increase of water discharge during the ice jam event, the situation may become more severe and cause flooding.

The entire ice jam event of February 1994 was reproduced by mathematical model. Due to the complex evolution process of the ice jam and the lack of detailed information on ice condition, it is difficult to re-establish what occurred in the field. Ice floe thickness together with ice concentration is used to define the ice discharge boundary condition. Since there was no data on ice discharge from the Tczew gauging station, ice supply was calibrated against observed data on ice jam initiation and progression together with water level data. Daily water discharge data from Tczew (Fig. 4) were used as upstream boundary condition. Water level data obtained from Port of Gdańsk were applied at model downstream. The initial condition for the calibration period was water depths obtained by solving steady, gradually varied flow equation for water discharge of 19 February 1994.

Approximately 80 trials with different temporal distribution of the ice supply were made in order to match observed water level and jam conditions (Fig. 4). During the simulation, ice was supplied with the floe thickness of 0.3 m and the concentration varied from 20 to 55%. The calibrated ice jam profile from 23 to 26 February is presented in Fig. 7. It is important to mention that all model parameters calibrated during the 1994 ice jam case are within the range of typical values presented in the literature. The ice roughness is assumed to vary between a minimum value, n_{imin}, corresponding to a single layer ice cover thickness, *i.e.*, ice floe thickness, and a maximum value, n_{imax}. The Manning's roughness coefficient varies linearly with increasing ice thickness. In this study, values of the calibrated ice roughness were $n_{imin} = 0.02$ and $n_{imax} = 0.09$, which is consistent with values provided for the Vistula River by Majewski (2007). Bed roughness of the channel was calibration using water level data during an open water period from four gauging stations shown in Fig. 3 (Tczew, Przegalina, Świbno, Ujście). The bed Manning's coefficients are presented in Table 1.
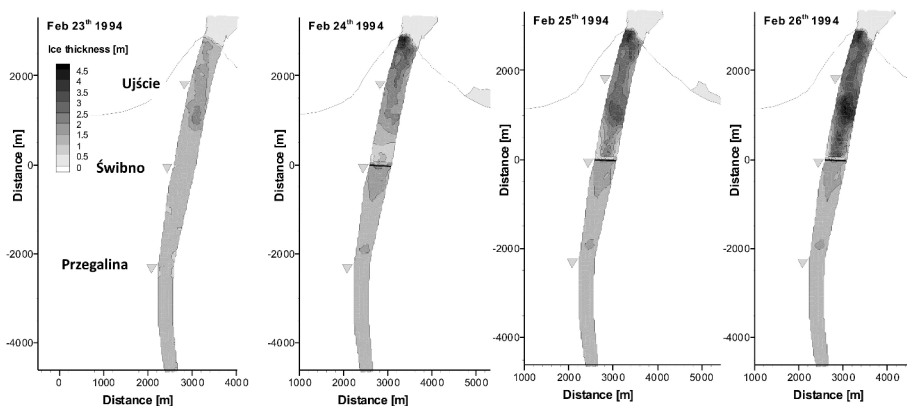
Fig. 7. Ice jam development in Vistula River outlet during the four days of February 1994.

Table 1

Bed Manning's coefficients

Vistula River Gauges	Bed Manning's coefficient
Gdańsk Bay–Ujście	0.052
Ujście–Świbno	0.025
Świbno–Przegalina	0.050
Przegalina–Tczew	0.035

7. SENSITIVITY STUDY

Sensitivity studies were conducted using both steady state (cases R, 1-2) and unsteady flow conditions (cases 3-8). A total of 9 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 nine 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 2. 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 used in the simulation are the 10- and 100-year and long-term average water levels (Fig. 8) which are based on the measured data of 6 storm events measured at the Gdańsk Harbor. These water levels are referred to the Kronstadt 86 sea-gauge datum. The Baltic is a tideless sea; however, water level

Table 2

Sensitivity analysis cases (R – reference case);
for all cases Gdańsk Bay is covered with broken ice

	Q Tczew [m^3/s]	H Gdańsk Bay [m Kr.]	Wind velocity [m/s]	Remarks
Case R	1080	0	10	Reference case Long term average discharge
Case 1	10 000	R	R	100 year discharge
Case 2	600	R	R	Low discharge
Case 3	R	100 yr[1]	R	
Case 4	600	100 yr	R	
Case 5	R	100 yr	20	
Case 6	600	100 yr	20	
Case 7	R	10 yr[2]	R	
Case 8	600	10 yr	R	

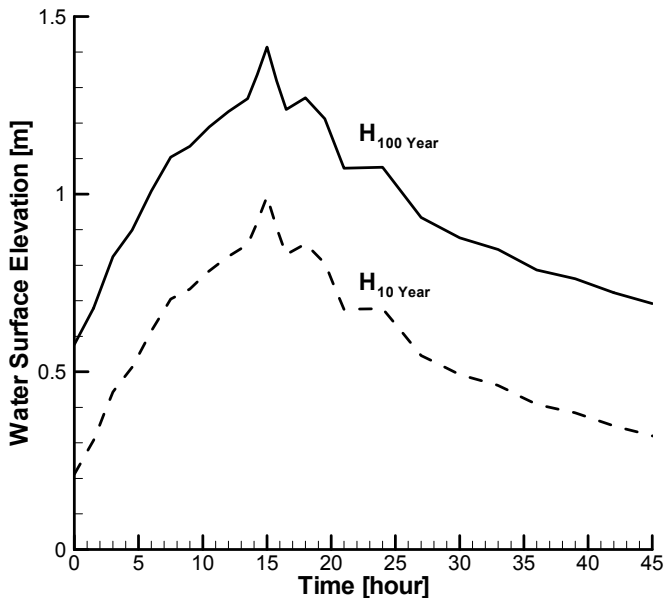[1]$H_{100\ Year}$ – see Fig. 8,
[2]$H_{10\ Year}$ – see Fig. 8.

Fig. 8. Hypothetical hydrographs for the Gdańsk Bay for 10- and 100-year events based on the Kronstadt 86 sea-gauge.

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 of 20 m/s from NW and N directions.

8. SIMULATION RESULTS

Nine 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 including the worst case scenario.

In general, all the cases with the low discharge produced thicker ice accumulation (Fig. 9). For both cases with average water level in the Gdańsk Bay (reference case and case 2 – Fig. 9a, b) ice piled up at the river mouth. At the river mouth, ice floes were stopped by the ice drifting on 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. Case 2 where the low river flow was simulated ($Q = 600$ m^3/s), produced more severe condition compared to the reference case with average discharge. In this case, ice slowed down and accumulated in the area between jetties decreasing channel conveyance. For case with the long term average water discharge (reference case, $Q = 1080$ m^3/s) the higher drag force from the water to the ice floes was observed and the accumulation was shoved to the Gdańsk Bay. However, the associated water levels for case 2 were lower than in case R because of the smaller discharge. The maximum water levels were observed for case 1, where the 100 was simulated but the high water levels were not caused by the ice phenomena. For this case, all ice was flushed from the river down to the Gdańsk Bay and no severe ice accumulation was observed.

For cases with the high water level in the Gdańsk Bay (Figs. 9c and 10) ice accumulated in two locations: at the river mouth and in the vicinity of the proposed highway bridge. At the river mouth, the mechanism is identical with this described above. 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 (Fig. 9c *versus* Fig. 10). 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
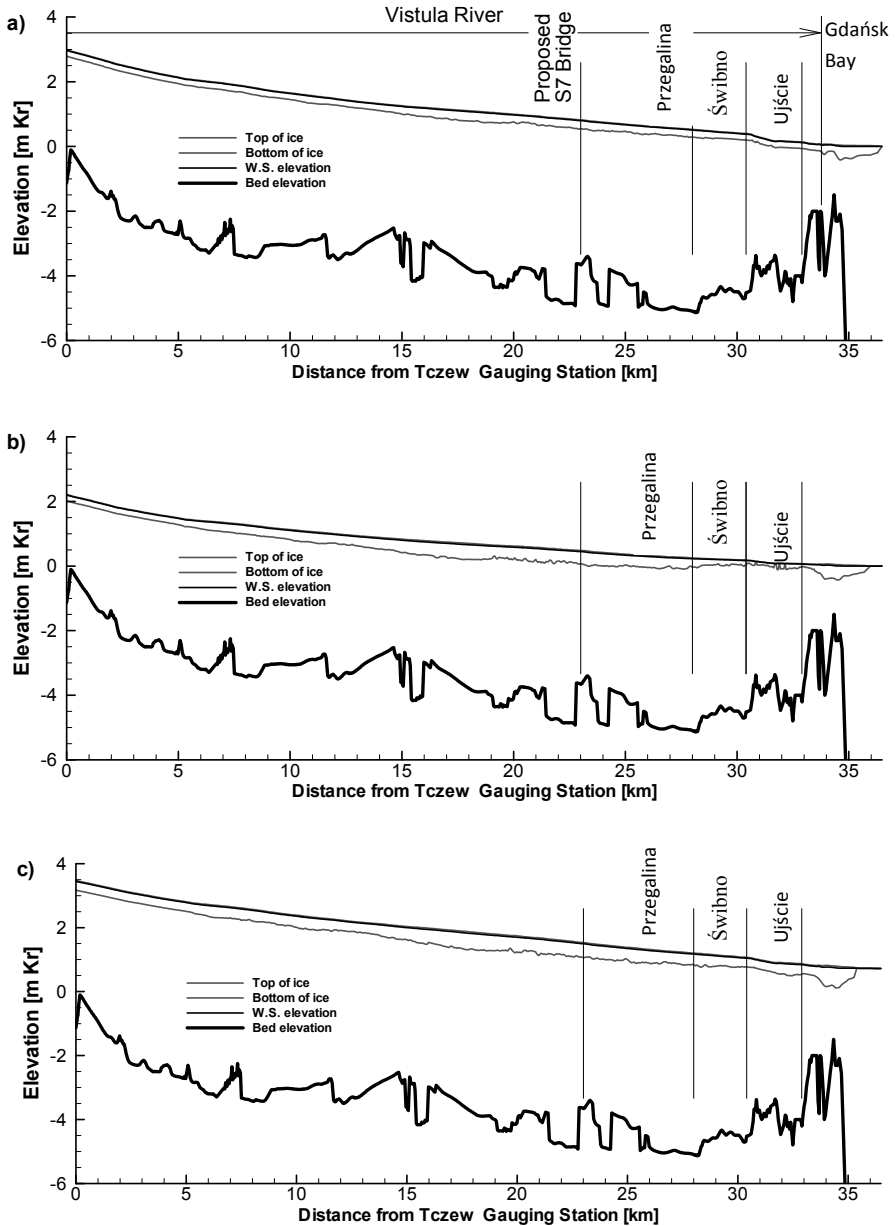
Fig. 9. Longitudinal profile of water surface elevation and ice thickness for case R (a), case 2 (b), and case 5 (c).
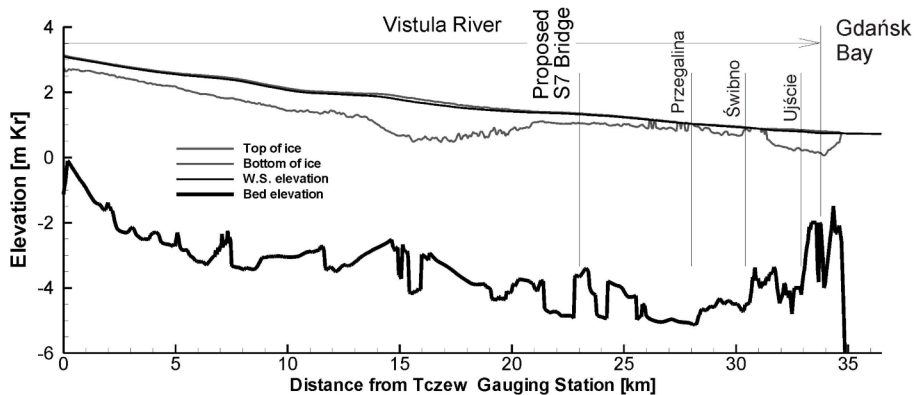
Fig. 10. Longitudinal profile of water surface elevation and ice thickness for case 6 (low discharge in the river, 100 year storm in the Gdańsk Bay, and high wind velocity).
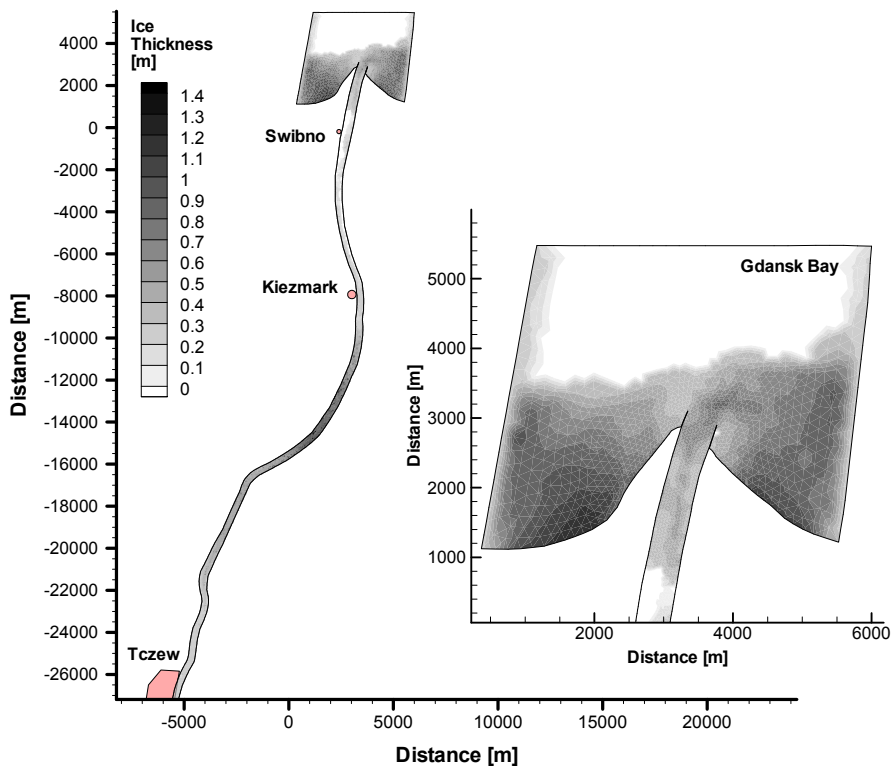

Fig. 11. Ice thickness distribution for case 6 (low discharge in the river, 100 year storm in the Gdańsk Bay, and high wind velocity).

blowing from the north with velocity of 20 m/s. For the case with low flow velocity, the ice forms a jam with a thickness of 1.2 m (Figs. 10 and 11). The toe of this ice jam is located about 8 km upstream of the proposed bridge. It is a potentially dangerous situation which, if 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.

9.   SUMMARY AND CONCLUSIONS

River deltas are especially 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. As shown on the presented example of St. Clair River, 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.

Two historical cases of March 1956 and February 1994 have shown the potential flood risk associated with the ice jam processes in the Vistula outlet channel. The 1994 case produced a severe situation in the river mouth which was only resolved due to the intense icebreaking. According to the results from calibrated mathematical model, this case would lead to much higher water levels within the next days if ice had not been released. Moreover, if during the described ice jam event the water discharge increased, the situation in the river outlet might cause flooding.

Results of the sensitivity analysis have shown that ice was jamming, if during the ice run the water discharge was low. The two locations where the ice accumulated were in the vicinity of the highway bridge and the direct river outlet. Ice jam formation upstream of the bridge is caused by river geometry and piers which are the obstacles for the ice run. In the river outlet, the ice jam is caused by slope change and sediment accumulation in the near-shore zone. Efficient ice runoff is hampered by the sediment allocation in fan-delta which reduces river conveyance in the entire section. Northern wind and associated high water level on the Gdańsk Bay can make the situation more serious. From nine analyzed cases, 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 as well as in the river mouth. If the ice formation is not released, it may create potential flood. The only effective way of ice jam release in the river outlet is a mechanical breakup using icebreakers. The mouth of the Vistula River should be maintained by icebreakers during the breakup and the ice run.

Keeping proper channel condition and appropriate water depth will help to prevent ice from stopping. Proposed spur dykes, planned in the river outlet section, may reduce ice jam hazard. Spur dykes will case flow concentration and water velocity increase in the central part of the channel which is designed to push ice downstream. As shown before, the main force that causes ice to move is the drag force from water; therefore, the increasing flow velocity will lead to a smoother ice transport on the water surface. Construction of extended jetties will cause flushing away the sediment accumulation into the deeper part of the Gdańsk Bay. This may temporarily resolve the ice jam potential in the direct vicinity of the Vistula outlet.

The new piers of the proposed bridge will interact with ice. Therefore, they should be designed with particular care to not increase the jam potential of this section of the river. Most probably, ice will accumulate upstream of the bridge which will cause significant load on piers. This force must be considered in the design process of the new bridge.

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