NUMERICAL MODELING OF ICE JAM FORMATION IN THE WŁOCŁAWEK RESERVOIR

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Abstract: Ice jam formation in a run-of-the-river reservoir and the effects of ice jam on water levels and water velocity were simulated using a two-dimensional model for simulating river ice dynamics (DynaRICE). The record ice jam of January 1982 in the Włocławek Reservoir is also examined here. The simulation showed that the ice jam in question was formed by surface ice produced in the Vistula River, upstream of the reservoir. The effect of thermal production of suspended frazil in the reservoir on ice jam was negligible. The simulated water level as well as the ice jam profile were in agreement with the observed data. The ice discharge upstream of the reservoir and the volume of ice in the Włocławek Reservoir were calculated. The results showed that there was less ice in the reservoir than claimed in previous literature. Suspended frazil and the undercover transport mechanism were not taken into account in this study.

1. Introduction

The Włocławek Project, which was completed in 1970, is located in the Lower Vistula River. The barrage of the Vistula River forms the Włocławek Reservoir, a water body with a volume of 400 million m^3 and a length of about 50 km. Its essential 42-km long section is situated between two cities, Włocławek and Płock. During the last forty years, since the Włocławek Reservoir was put into operation, several flood risks occurred in the vicinity of the reservoir. The most severe one was related to an ice jam which formed upstream of the reservoir. In the winter of 1982, due to meteorological and hydrological conditions, an ice jam formed at the point situated at 655 km causing the flooding of Płock. Several papers and reports describe this flood [1–3]. However, the mechanism of ice jam formation during this event remains unclear. Neither of the models used to simulate this record ice jam included the dynamic effects of ice on the river hydrodynamics. Majewski [4] developed a steady-state model for simulating a backwater profile in the reservoir with a static ice cover. Kolerski [5] developed an unsteady flow model with a constant ice cover and applied it to the Włocławek Reservoir. Neither of the models, however, involved ice dynamics. In all the cases static ice cover was simulated and the only interaction between ice and water was due to ice thickness and roughness of the underside of the cover. Ice jam formation cannot be simulated with a static ice cover model. Thus, in order to reproduce the situation from 1982 and to understand the ice jam formation in the Włocławek Reservoir, a two-dimensional DynaRICE model was used in this paper.

2. Mathematical model

The DynaRICE model is a two-dimensional ice dynamics model for analyzing dynamic transport and jamming of surface ice in rivers and lakes [6]. The model simulates the coupled dynamics of ice motion and water flow, including the flow through and under ice rubble. This model has been successfully applied to various studies of river ice control and ice period operation, including the Niagara Power Project [7, 8], St. Clair River ice jam effects on possible bed changes [9], ice formation in the Missouri-Mississippi River confluence [10], and the breakup jam in the Shokotsu River in Japan [11]. The aforementioned studies have shown that this model can accurately simulate dynamic transport and ice jam processes.

In this model, hydrodynamics is simulated by solving the depth-integrated two-dimensional hydrodynamic equations for shallow water flows, including the effects of surface ice. The flow in the surface ice layer, $\vec{q}_u$, is taken into account so that the flow between ice floes as well as the seepage flow through thick ice accumulations are considered. The continuity equation for the total water discharge is:

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

where H is the total water depth; $\vec{q}_t$ is the total unit-width water discharge; $\vec{q}_t=\vec{q}_u+\vec{q}_l$; $\vec{q}_u$ is the unit-width water discharge in the surface ice layer; $\vec{q}_l$ is the unit-width water discharge beneath the ice layer; q_{tx} and q_{ty} are the components

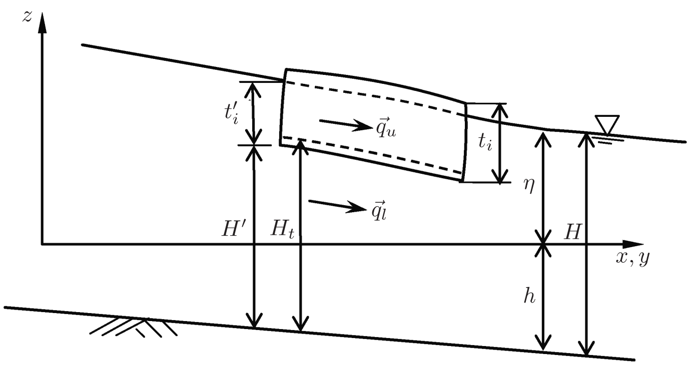

Figure 1. Definition sketch of hydrodynamics

of the total unit-width water discharge; t_i' is the thickness of the submerged ice layer; N is the ice concentration. The momentum equations for the flow can be written as:

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

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

where $T_{xx}=\varepsilon_{xy}\left(\frac{\partial q_{tx}}{\partial y}+\frac{\partial q_{ty}}{\partial x}\right)$; ε_{xy} are the generalized eddy viscosity coefficients; τ_s and τ_b are the shear stresses at the ice-water interface and in the river bed, respectively; H_t is the equivalent water depth of the total water discharge q_t (Figure 1). The hydrodynamic component of the model has recently been improved using a finite element method based on the streamline upwind Petrov-Galerkin (SUPG) concept [12]. The model is capable of simulating high-velocity transitional flows under wet-dry bed conditions.

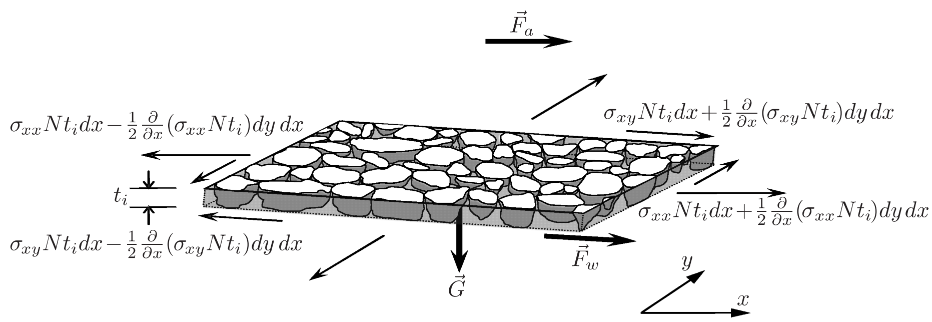

Figure 2. Definition sketch of ice dynamics; σ_{xx}, σ_{yy} are the normal stress components and σ_{xy} is the shear stress component

A Lagrangian discrete-parcel method based on smoothed-particle hydrodynamics [13] is used to simulate the ice dynamics. The basic idea behind 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. The ice dynamic equations take into account all external and internal forces. These forces include water drag, gravity, internal resistance of ice, and bed friction on grounded ice. The momentum equation of the surface ice can be written in Lagrangian form as:

$$M_i\frac{\partial \vec{V}_i}{\partial t}=\vec{R}+\vec{F}_a+\vec{F}_w+\vec{G} \quad (4)$$

where, $\frac{\partial \vec{V}_i}{\partial t}$ is the acceleration of ice parcels; M_i is the ice mass per unit area; $\vec{V}_i$ is the ice velocity; $\vec{R}$ is the internal ice resistance; $\vec{F}_a$ is the wind drag force; $\vec{F}_w$ is the water drag force; $\vec{G}$ is the gravitational force component due to the water slope (Figure 2). In addition, both the boundary effects of ice friction along river banks and the bed friction on ice movement when ice grounding occurs were considered. The visco-elastic-plastic (VEP) constitutive law was used in order to formulate the internal ice resistance, which is governed by the material behavior of ice rubble [14]. The pressure term was formulated by a modified Coulomb law.

3. River bathymetry and finite element mesh

The model domain covers the 42.35 section of the Włocławek Reservoir from the Włocławek Dam (km 674+850) at the downstream boundary to the Płock Bridge gauging station at km 632+500 where the model upstream boundary conditions were set up (Figure 3).

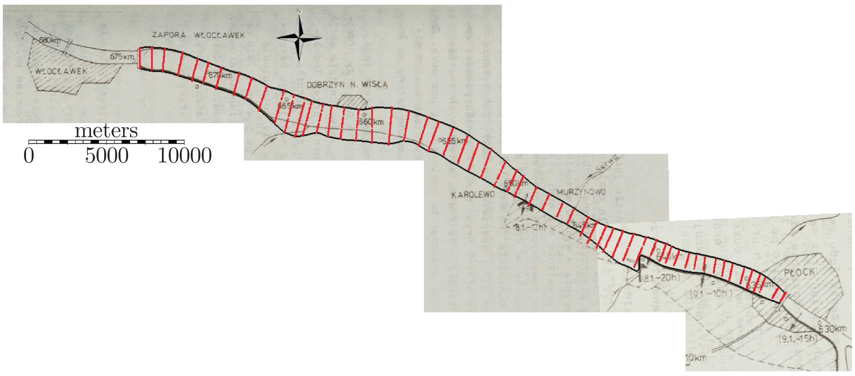

Figure 3. Cross-section spacing of the Włocławek Reservoir

The bathymetry of the reservoir was based on survey data provided by Hydroprojekt Włocławek SA (personal communication). These include the post-jam bathymetry data surveyed in 1993 for the Włocławek Reservoir from the Włocławek Dam up to the Płock Bridge gauging station. The data pertains to 57 cross-sections spaced at distances of 500 m to 1000 m (Figure 3). Each cross-section includes 50 or more survey data points, which were used to reproduce the detailed reservoir bathymetry. The water depths of the reservoir for the water discharge in Płock $Q = 1000\,\mathrm{m}^3/\mathrm{s}$ are shown in Figure 4.

The finite element mesh was set up in a local coordinate system using the surface-water modeling system (SMS), version 10. The SMS software was developed for surface water modeling and can be used to generate a two-dimensional finite element mesh with scattered data points. In order to capture the channel-bed surface in more detail, and to improve the computational efficiency of the DynaRICE model, the finite element mesh was set up in a specific way. In the downstream part of the domain, the mesh consisted of triangular elements with nodes spaced 45 meters apart in the streamwise direction and 40 meters across the width of the channel (Figure 5). The size of the elements varied along the domain. In the upstream part of the domain, the size of the finite elements increased to about 150–100 m. The mesh consisted of about 14000 elements and 7500 nodes.

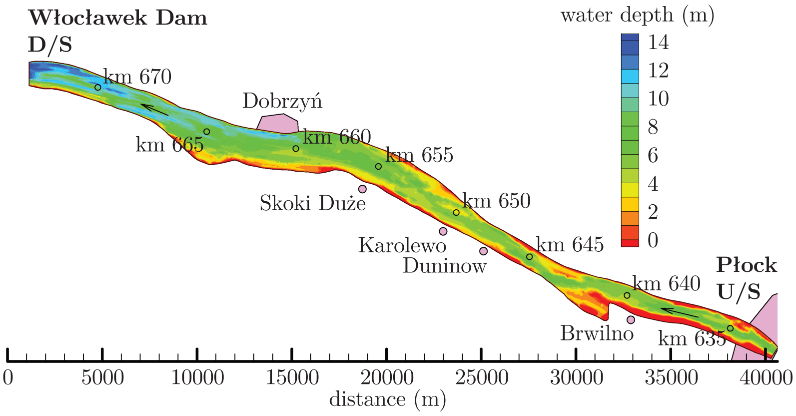

Figure 4. Water depth for a steady-state condition (water discharge in Płock $1000\,\mathrm{m}^3/\mathrm{s}$)

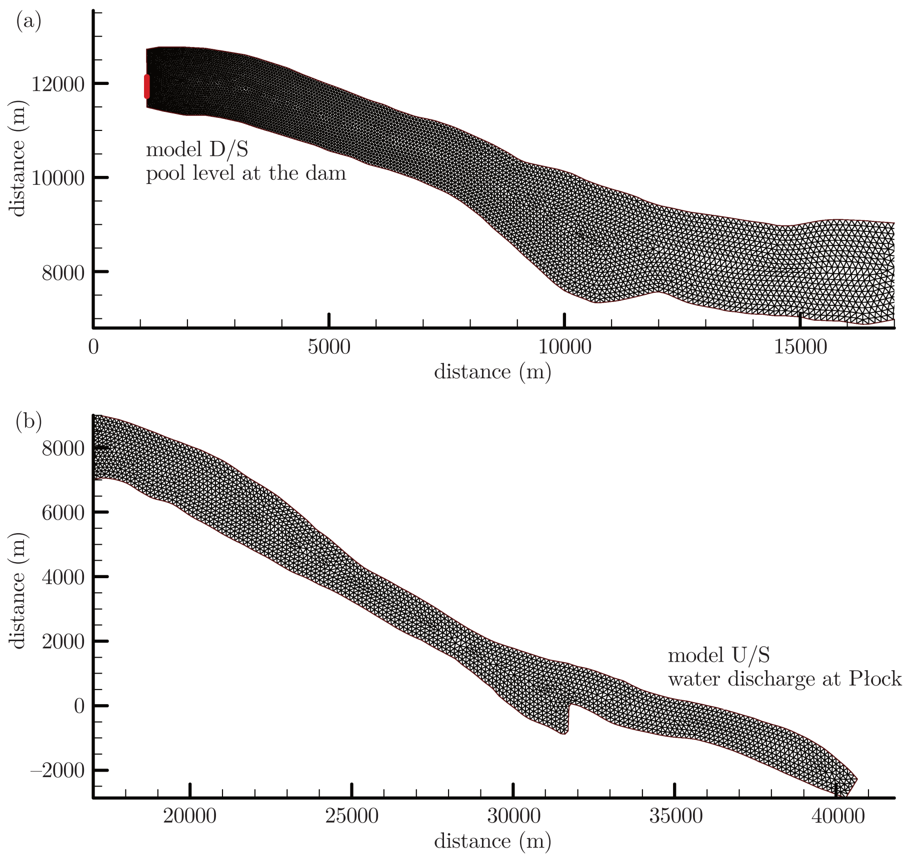

Figure 5. Model domains and finite element mesh: (a) downstream part: km 667 – 674; (b) upstream part: km 630 – 667

The finite element mesh of the domain is shown in Figure 5. The purpose of a decrease in the element size in the lower part of the domain was to simulate the Włocławek Project spillway (200 m wide) and the power plant intakes (150 m wide). Both the spillway and the adjacent power plant intakes take about 30% of the width of the cross-section. This portion of the river is used as a downstream open boundary, as shown in red in Figure 5.

4. Flood of January 1982

Meteorological and hydrological conditions during the winter of 1982 were the most severe in the exploitation history of the reservoir. In the lower Vistula River, two ice periods are typically observed during any one season. During the winter season of 1981/1982, the first ice cover was formed in December 1981 when the air temperature dropped down to −20°C.The thickness of the ice cover reached 15 cm. At the end of December 1981, the air temperature rose significantly, which together with rainfall caused the breakup of the ice cover. Due to wind blowing from the west, the velocity of ice flows in the lower part of the reservoir decreased and ice could not get sluiced down the spillway. However, an ice-free channel made by icebreakers allowed the ice to move down the reservoir without stoppage or accumulation.

On 6$^{\text{th}}$ January 1982, the air temperature dropped rapidly to −8.8°C and reached a minimum of −23.2°C on 9$^{\text{th}}$ January. Such a low air temperature led to the production of ice in the Vistula River upstream of the reservoir. An ice cover started to form in the reservoir on 6$^{\text{th}}$ January. In the morning of 8$^{\text{th}}$ January, an ice jam formed in the vicinity of the village of Karolewo (km 650). The ice jam toe was located between km 650 and km 655. The ice accumulation developed upstream and reached Płock during the night of 9/10$^{\text{th}}$ January. The ice cover in the downstream section of the reservoir (from the dam, up to km 657) was about 0.5 m thick and consisted mostly of frozen ice floes. The survey data concerning the thickness of the ice jam were collected in a number of cross-sections along the reservoir. Since all the measurements were performed after the ice jam was fully formed, *i.e.* between 23$^{\text{rd}}$ January and 15$^{\text{th}}$ February, the jam profile from the period of formation does not necessarily coincide with the observed data. The range of the ice jam can be reproduced using an air photograph made on 12$^{\text{th}}$ January 1982. This suffices to determine the formation of ice jam in the reservoir between 6$^{\text{th}}$ and 10$^{\text{th}}$ January.

5. Model calibration and boundary conditions

Open-water calibration was carried out for the ice-free period right before the ice jam of 6$^{\text{th}}$ January 1982. Manning's roughness coefficient for the bed can be calibrated based on water level data measured along the model domain. However, there was only one available station located at the model upstream boundary. Another possibility is to vary the roughness base of the bed with respect to the water depth and bed material. Since we are not familiar with the characteristics of the reservoir bed, one value of bed roughness ($n_b = 0.025$) was assumed for the entire model domain in order to avoid misinterpretation.

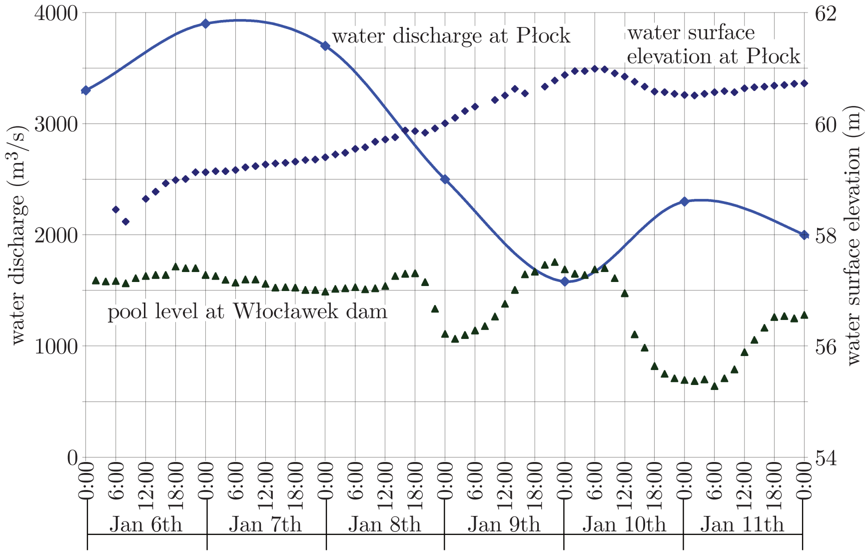

Figure 6. Observed water levels and water discharge for the ice run in January 1982

The pool level at the Włocławek Dam was used to set up the downstream boundary condition of the model. The upstream boundary condition was defined to coincide with the water discharge at the Płock Bridge (Figure 6). Ice was supplied from the upstream boundary and both its concentration and thickness varied with time. Ice discharge and ice parameters were calibrated so as to match the water level data from the Płock gauging station. For the ice-covered water surface, the surface shear stress components acting on the water can be written as:

$$\tau_{sx} = \rho c_w \left|\vec{V}_i - \vec{V}_w\right| (u - V_{wx}) \tag{5}$$

$$\tau_{sx} = \rho c_w \left|\vec{V}_i - \vec{V}_w\right| (v - V_{wy}) \tag{6}$$

where $\vec{V}_w$ is the water current velocity beneath the ice cover; $\vec{V}_i = u\vec{i} + v\vec{j}$ is the ice velocity; c_w is the water drag coefficient on the ice, which varies with ice concentration and ice floe geometry. This coefficient can be related to Manning's coefficient for the underside of the cover, n_i, as follows:

$$c_w = \frac{n_i^2 g}{(\alpha_i H')^{1/3}} \tag{7}$$

where α_i is the fraction of the total water flow depth affected by the ice friction; H' is the water depth under the ice.

The DynaRICE model uses Manning's coefficient for ice, which varies with the ice thickness. The minimum value is used for single ice floes, increasing with an increase in ice thickness due to ice accumulation or ice jam formation. The roughness coefficient for the underside of the ice cover reaches its maximum in the case of an ice jam. Both the minimum and maximum value of Manning's coefficient for ice are subject to calibration. In the current study, a minimum value of 0.03 was used for a single layer of ice. A value as high as 0.1 was used as the maximum value of this coefficient, corresponding to an ice jam.

During the calibration of the model, the position of the ice jam toe and of the ice jam head were compared with observations. Since the thickness of the ice jam was measured about one month after the ice formed, these data cannot be directly compared with the simulation results. The backwater profile was measured along the reservoir during the ice jam formation on 9$^{\text{th}}$ January. However, due to certain inconsistencies in the data, the backwater profile is not used here for the comparison of water levels.

6. Simulation results

Ice jam formation started on 6$^{\text{th}}$ January when a rapid decrease in air temperature was observed. Until then the ice was moving downstream the reservoir without any stoppage. The first stage of the process was the formation of an ice cover in the lower part of the reservoir. In order to simulate this stage, we assumed that a cover with a constant thickness of 0.5 m formed between the Włocławek Dam and km 652 (in the vicinity of the village of Skoki Duże). The rest of the reservoir was covered with ice moving downstream at a speed of about 1.0 m/s. The hydrodynamic conditions at 10 am on 6$^{\text{th}}$ January were used as the initial conditions for the model (Figure 7). The simulation was set up so as to reproduce these initial conditions. The steady-state conditions (the pool level of 57.3 m and the discharge at Płock equal to 1500 m^3/s) were simulated until the simulation reached a steady solution (the water level and the water discharge were constant in the entire domain).

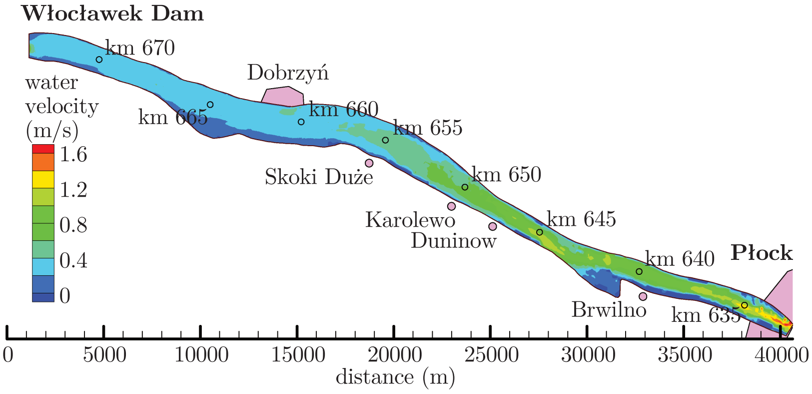

Figure 7. Simulated water velocity at the beginning of the simulation (6$^{\text{th}}$ January 1982, 10 am, water discharge in Płock equal to 1500 m^3/s)

Since the ice supply in Płock was unknown, it was calibrated in order to obtain correct water levels. Over 40 trial simulations were set up in order to reach the final ice discharge in the model upstream. The ice discharge used in the final run is presented in Figure 8, which also shows the total ice volume in the reservoir.

The simulation results showed that about 25 million m^3 of ice were supplied into the reservoir during the ice jam formation. The remaining 22 million m^3 of ice were in the reservoir from the beginning of the simulation in the form of ice floes moving on the surface; border ice and ice cover formed in the lower part of the reservoir. During the first day of ice formation (6^{th} January), the simulated ice discharge in the model upstream was almost constant and equal to about $50\,m^3/s$. After about 30 h into the simulation, the ice discharge was increased to about $150\,m^3/s$ in order to match the increasing head loss along the reservoir. This was preceded by increasing the concentration of the ice supply at the model upstream boundary. During the following days, ice discharge decreased as a consequence of ice accumulation in the upper part of the reservoir. The ice accumulation in the reservoir caused an increase in the water level and a decrease in the water velocity. Since the water velocity is the main force Niezręcznie: wyszło, że „prędkość jest siłą”. behind the ice movement, the ice discharge also decreased. After 86 h into the simulation, ice was no longer supplied from the upstream part of the river. ???
This was in agreement with the observed data. During the night of $9/10^{th}$ January, an ice cover formed at the Płock Bridge, which is the model upstream [1]. This means that the surface ice was no longer supplied into the model domain. In the following days, the ice was still able to move under the solid cover, as well as to change its profile along the reservoir. However, this was not simulated in this study.

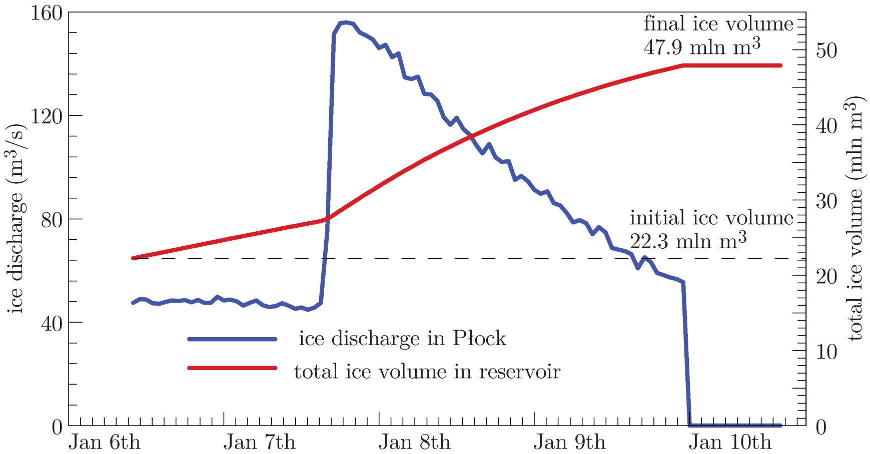

Figure 8. Simulated ice discharge at the model upstream and the ice volume in the Włocławek Reservoir

Based on the simulated results of ice discharge, the maximum volume of the ice during ice formation was about 4% of the total water volume in Płock. The ice supplied to the reservoir was formed upstream of the reservoir and entered the reservoir in the form of surface ice. In this study, it was assumed that there was no thermal production of ice in the reservoir. Based on Majewski [1], highly concentrated ice was observed on the surface of the reservoir during the entire period of ice formation. The layer of the surface ice prevented water from being supercooled and thus thermal ice could not be formed in the water body. Moreover, the volume of ice which may have been produced over the stretch of 20 km, *i.e.* from Skoki Duże to Płock, is negligible compared to the volume of ice produced upstream of the reservoir (about 500 km).

The ice discharge was calibrated in order to match the observed water levels at the Płock Bridge gauging station. The data from the observations showed that the ice jam formation began around 6$^{\text{th}}$ January. In the following days, the head loss along the reservoir increased and reached a maximum at noon on 10$^{\text{th}}$ January (Figure 9). The pool level was relatively stable over the time of ice formation. More importantly, the observations showed that water levels at the power dam decreased by about 40 cm, from 57.4 to 57.0 m (Figure 9). This was due to the additional head loss caused by the accumulation of surface ice. A similar situation was observed during the ice study for the St. Lawrence/FDR Power Project [15]. All the cases simulated in Shen's study indicate that the water level at a power dam decreases with the accumulation of ice. This was in agreement with the observed data for the Włocławek Reservoir.

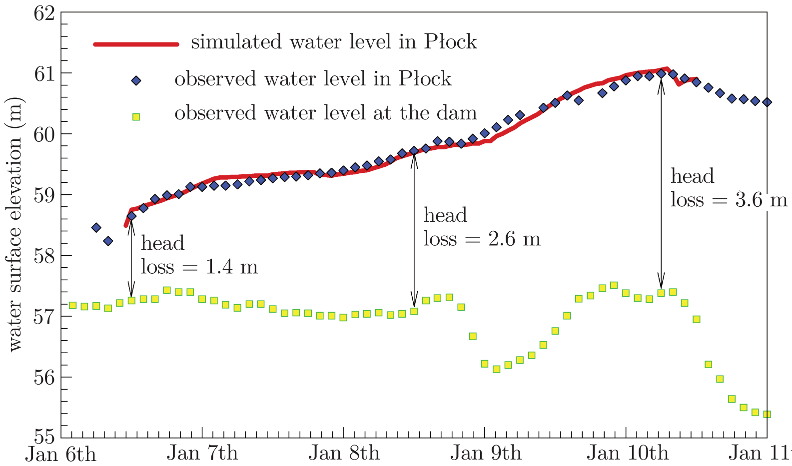

Figure 9. Comparison of the simulated and observed water level for the January 1982 ice run

During the night of 8$^{\text{th}}$ January, the pool level was lowered by about 1.0 m. The decision to do so resulted from misinterpretation of the river hydrodynamics. It was expected that lowering the water level at the dam would cause a decrease in the water level in the upstream part of the reservoir. However, this actually increased the flow resistance together with the head loss along the reservoir which in turn led to an increase in the water level at the model upstream. The simulation results confirmed that the upstream water level also increased, which is in agreement with observations.

Finally, we compared the simulated and observed ice thickness along the reservoir. The measurements of ice thickness were performed after the complete formation of the ice jam. This means that the simulated ice thickness may not necessarily match the observed data exactly. The water level and ice jam profile at the time when the jam was fully formed (10^{th} January 1982 at 12 pm) are presented in Figure 10. Figure 11 shows the contour plot of the ice thickness at the same time. Figure 12 compares the observed and simulated ice thickness in the upstream part of the reservoir. Figure 13 shows a cross-sectional view of the simulated and observed ice thickness in the ice jam toe at km 652.5.

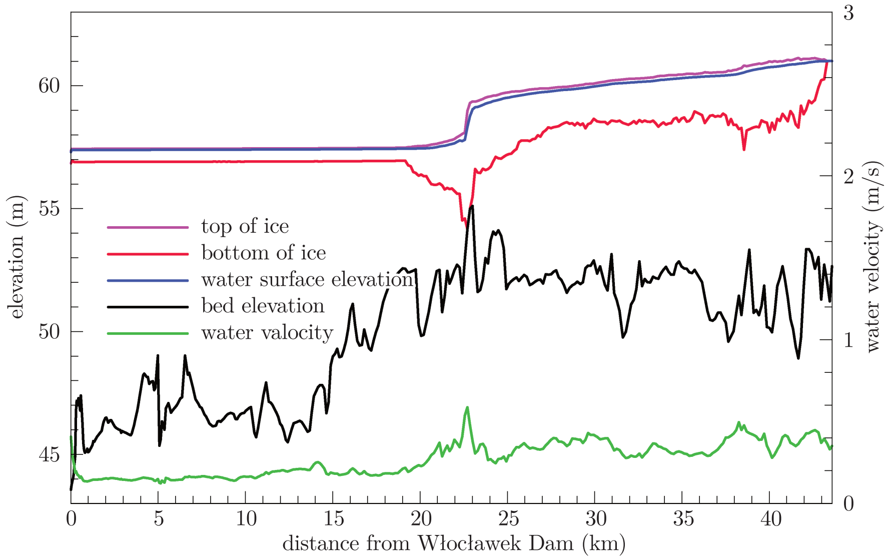

Figure 10. Simulated longitudinal profiles of the water surface, ice jam, channel bed and water velocity 90 h into the simulation (10^{th} January 1982, 12 pm)

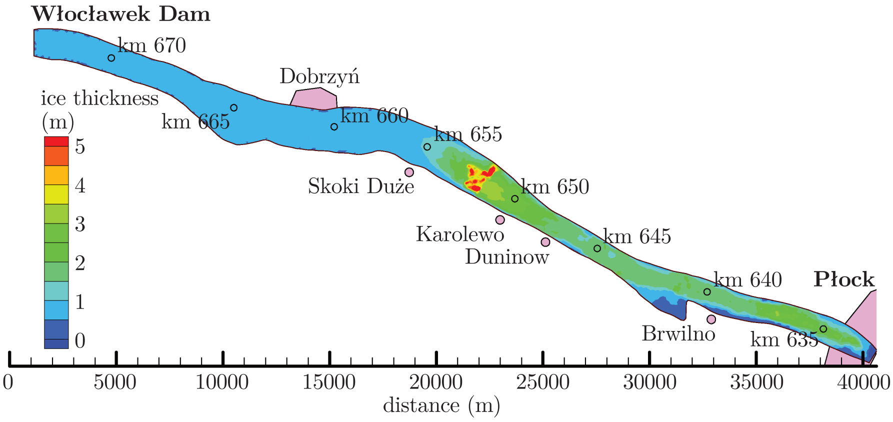

Figure 11. Simulated ice thickness 90 h into the simulation (10^{th} January 1982, 12 pm)

Even though the survey of ice thickness was performed 10 days after the ice jam was fully formed, the simulation results are in good agreement with these observations (Figure 12). The ice jam formed a sharp toe at km 652.5, which was

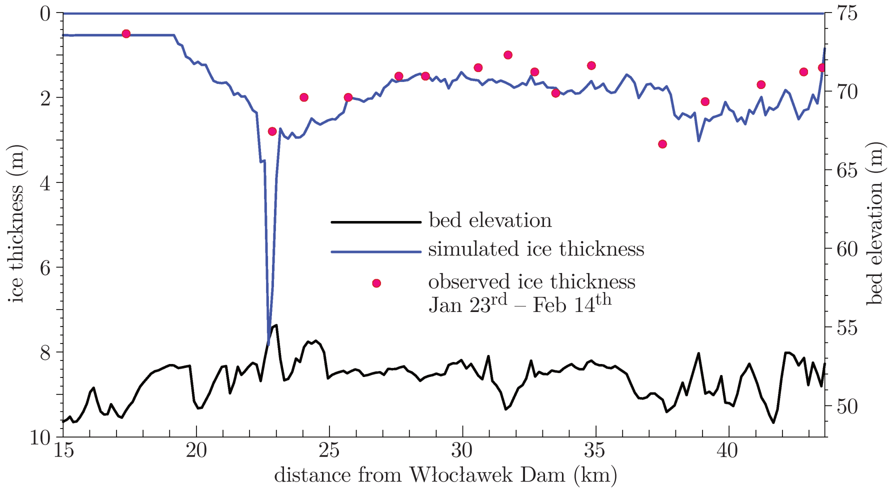

Figure 12. Simulated longitudinal profiles of ice thickness and channel bed 90 h into the simulation (10th January 1982, 12 pm)

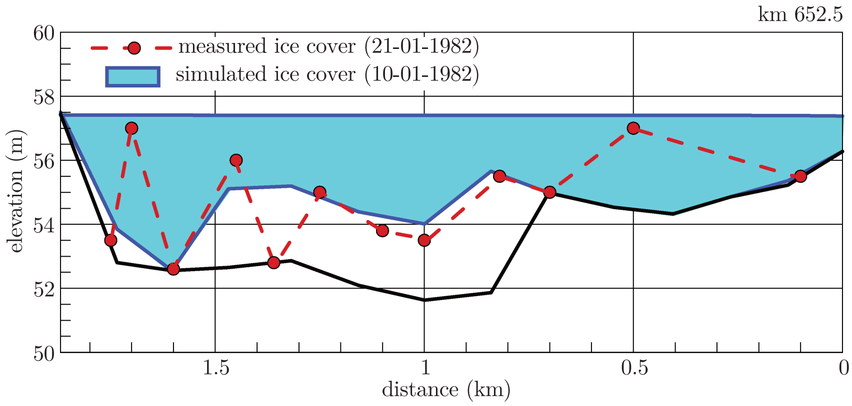

Figure 13. Simulated and measured profile of the ice jam toe at km 652.5

partly grounded. This was consistent with the survey data showing grounded ice at km 652.5, see Figure 13 [4]. The ice thickness was measured in the-cross section at km 652.5 on 21st January. According to these measurements, there was less ice on the river banks than predicted from the simulation. Since an ice jam thickens near the toe, the water flow area decreases, increasing water velocity and drag on the ice underside. The water velocity may become large enough to erode ice pieces from the jam underside and transport them downstream. A similar process may have taken place here between 10th and 21st January, when the ice thickness was measured.

7. Summary

The ice jam of 1982 in the Włocławek Reservoir had a major impact on the level and flow of the Vistula River upstream of the reservoir. The DynaRICE model was used here to simulate the formation of this jam. The simulated results were in good agreement with the observed water levels at the Płock Bridge gauging station. The simulated ice jam profile along the reservoir and across the ice jam toe were also in good agreement with the field data. The results of the DynaRICE simulations indicated that the ice jam formed from surface ice run. The thermal ice production in the reservoir was negligible and the suspended frazil ice was not the primary cause of ice jam formation. Moreover, the total volume of the ice supplied into the reservoir was equal to ca. $25\,\mathrm{m}^3$. This value is significantly lower than the values previously reported in the literature [1]. The simulations also confirmed that lowering the pool level causes an increase in the backwater effect of the jam.

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