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Ice Phenomena on the Lower Vistula

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Abstract

The Vistula River is the largest Polish river, which flows from the south to north and discharges into Baltic Sea. Flow direction has strong influence on the formation and decay of ice phenomena and ice cover. The final section of the Vistula is the Lower Vistula from the confluence of the Narew River to the sea. This section has variable character and is very prone to ice jams of various characteristics. It is important to forecast or even foresee first appearance of ice phenomena (frazil ice, border ice, bottom ice, ice floes or ice pans) and formation of permanent ice cover. Such observations were carried out in several cross-sections of the Lower Vistula. Analyses of these data for the cross-section Toruń starting from 1860 to the present time clearly indicate the decreasing number of days with ice phenomena and solid ice cover. This situation strongly depends on the meteorological parameters as well as river discharge and water temperature. The paper presents information on the duration of ice phenomena and ice cover, water temperature and air temperature in several cross-sections of the Lower Vistula. It appears that the idea of NDD factor (cumulative freezing-degree-days) can be a good indicator for the formation of ice phenomena along the Lower Vistula.

Key words: Lower Vistula, ice phenomena, thermal regime, ice jam floods, frazil ice

1. Introduction

Vistula is the largest Polish river (total length 1 047 km) and the longest river in Baltic Sea catchment. As concerns discharge it is second largest after Neva (Russia). Vistula discharges 7% of all fresh water to the Baltic Sea. Vistula flows from the south to north and discharges to the Baltic Sea. The source of Vistula is in Carpathian Mountains at the elevation of 1060 m above sea level (Barania Mountain). The average multiannual discharge of Vistula is 1060 m^3/s. Maximum recorded discharge was 7840 m^3/s and minimum 253 m^3/s. The highest average multiyear discharges appear in March (1500 m^3 /s) and April (1850 m^3/s), while the lowest in December (*Fal*, 2000). Lower Vistula is the final section (390 km long) and is very prone to the formation of ice phenomena. Most of the floods, which appeared along this section, were caused by ice jams. Therefore it is very important to have forecast of the appearance of ice phenomena (frazil ice, boarder ice, bottom ice, ice floes, frazil pans), formation of permanent ice cover (whole width of the river covered with ice), and ice break-up date.

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This situation is complicated by the fact that break-up on the rivers in the south of Poland is about 10 days earlier than in the north and it is important to arrange flow of ice to the sea through the frozen downstream Vistula section. This is usually accomplished by means of ice-breakers, which form the ice free channel. There are many factors, which determine the flow of broken ice downstream along the final Vistula section. These are: river discharge, wind speed and direction, and water level in the sea. Further complication along the Lower Vistula is caused by variable hydro-meteorological conditions. During one winter season it is possible to have one ice period, while in the other two or even three ice periods appear. By means of ice period we understand situation from ice formation with solid ice cover till ice break-up and ice-run.

The paper presents general characteristics of the Lower Vistula section, ice phenomena along this river section, application of NDD factor for the forecast of ice phenomena. The paper ends with general conclusions.

2. Characteristics of the Lower Vistula

The section of Lower Vistula is highly variable from hydro-morphological point of view. It is possible to distinguish four different sections of the Lower Vistula (*Majewski*, 2009a) going from the upstream point (Fig. 1).

- From the confluence of the Narew River to the upstream part of Włocławek reservoir. This section is very close to natural river with lots of shoals, islands and side channels.
- Włocławek reservoir (commissioned in 1970), which was formed by the barrage damming the Vistula River. The reservoir is run-of-river type and is about 70 km long.
- Downstream from the barrage Włocławek to the place Silno the Vistula River is degraded by the operation of the barrage Włocławek and hydraulic power plant.
- From the place Silno to the Bay of Gdańsk (Baltic Sea) the Vistula was trained for navigation purposes in the XIX century. This section has flood dykes on both sides of the river protecting against discharge of 1% probability.

Differentiated character of the Lower Vistula results in different time and character of the formation of ice phenomena and permanent ice cover. In 1829 a very severe ice jam close to the mouth of Vistula resulted in flooding of Gdańsk up to the second floor. In 1840 another ice jam caused the breach of coastal dunes and formation of new outlet of Vistula to the sea. Formation of ice jams, especially along final section (30 km long) lead to substantial changes in the river mouth which was developed in 1895 in the form of direct channel to the sea.

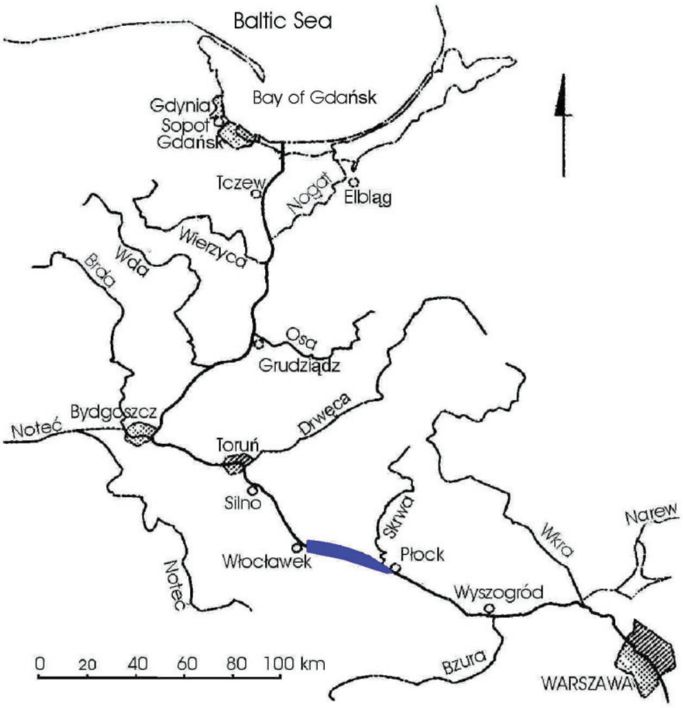

Fig. 1. Layout of the Lower Vistula.

Fig. 2. Final section of Vistula River with permanent ice cover.

In 1982 there was a very important flood in the region of upper part of Włocławek reservoir caused by exceptional hydraulic and meteorological conditions, which resulted in large ice jam (Fig. 3). The main reason of this flood was the formation of considerable amount of frazil ice on the river upstream from the reservoir and inflow of this ice to the reservoir, where permanent ice cover already existed. Frazil ice caused hanging dams and considerable decrease of flow cross-sections, which resulted in very high water stages. They exceeded the crest of side dams, overtopping them and breaching. Large areas of the city Płock and agricultural land were flooded.

Fig. 3. Ice cover on the upper part of the Włocławek reservoir in winter 1982.

3. *Ice phenomena along the Lower Vistula*

Lower Vistula is 390 km long and extremely differentiated as indicated in p. 58. Frazil ice is very common especially upstream from Włocławek reservoir. On the Włocławek reservoir due to lower flow velocities permanent ice cover forms earlier than on the other river sections. The thickness of ice very often exceeds 0.5 m. Frazil ice presents special problems on the reservoir, when permanent ice cover formed and upstream from the reservoir there is free water surface where large amounts of frazil ice develop and flow into the reservoir forming hanging dams and increase of water level even during low water discharge. Final section of Vistula downstream from Tczew (Fig. 1) shows large ice thickness exceeding 0.6 m (Fig. 2). This happened during winter 2005/6. Similar situation was also during 2009/10. Construction of Włocławek project and reservoir resulted in ice jam problems, which appeared during ice formation and later during ice break-up. Comparison of ice phenomena on the river and nearby lakes shows that when ice formed on the lake it stayed there till spring when higher temperatures caused melting of ice. On Vistula River changes of the state of ice cover depends very much on dynamic conditions caused by the changes of discharge. Winter 2010/2011 was one of the most severe seasons of the last 10 years. The whole Lower Vistula was covered with thick solid ice, which in some places exceeded 0.5 m. In spring before ice-break-up the assistance of ice-breakers was necessary. They moved from the river mouth upstream. This way broken ice could float from the river to the Bay of Gdansk.

Development of ice cover on the Lower Vistula usually begins on Włocławek Reservoir, where flow velocities are smaller than on the river upstream or downstream form the reservoir. Next ice cover forms upstream from the reservoir due to the operation of ice booms, which are installed every year in the upper part of the reservoir.

This results in the stoppage of frazil ice, which subsequently freezes and forms permanent ice cover. This prevents further formation of frazil ice along this river section. Downstream from the reservoir there is always ice free river section. Further downstream ice cover forms gradually from border ice. Discharge of ice floes in the downstream direction in spring requires always assistance of ice-breakers.

Multiyear changes of the duration (amount of days) of ice phenomena and permanent ice cover for the Lower Vistula in cross-section Toruń in the form of 10-year consecutive movable average are shown in Figure 4. Trends of these phenomena are also presented in the same figure. Data show that in the second half of XIX century ice phenomena along the Lower Vistula appeared during about 100 days, while at the beginning of XXI century this amount decreased to about 50 days. Number of days with permanent ice cover decreased from about 70 nearly to zero. Both trends have similar character and inclination. They indicate systematic decrease of the amount of days with ice phenomena and permanent ice cover. This may indicate the influence of climate warming. Despite these indications we are faced with more frequent appearance of extremes in the form of very mild winters but also severe ones. E.g. in winter 2005/6 along final section of the Vistula there was permanent ice cover 0.6 m thick. During several previous years there was no permanent ice cover over this river section. Similar situation happened during winter 2009/10, which has very low air temperatures.

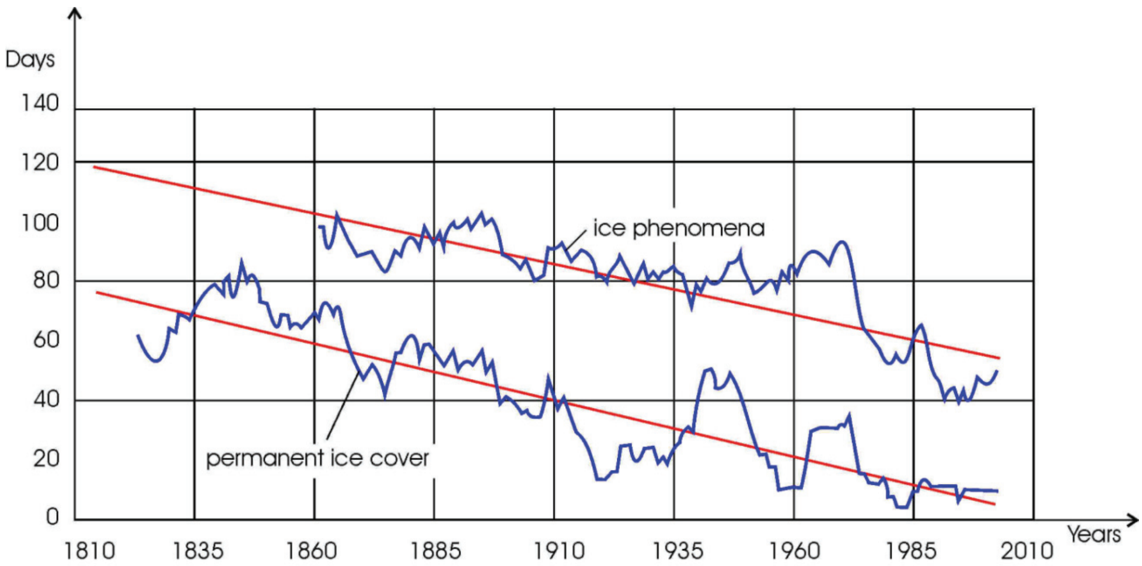

Fig. 4. Duration of ice phenomena and permanent ice cover in Vistula cross-section Toruń (*Pawłowski*, 2008).

Observations concerning the appearance of various forms of ice on the Lower Vistula were carried out in 22 cross-sections. In some cross-sections there are long series of data and some of them exceed even hundred years. Interesting data concerning the beginning and termination of ice phenomena in the cross-section Toruń are from the years 1860/1 till 2003/4. They are shown in Figure 5.

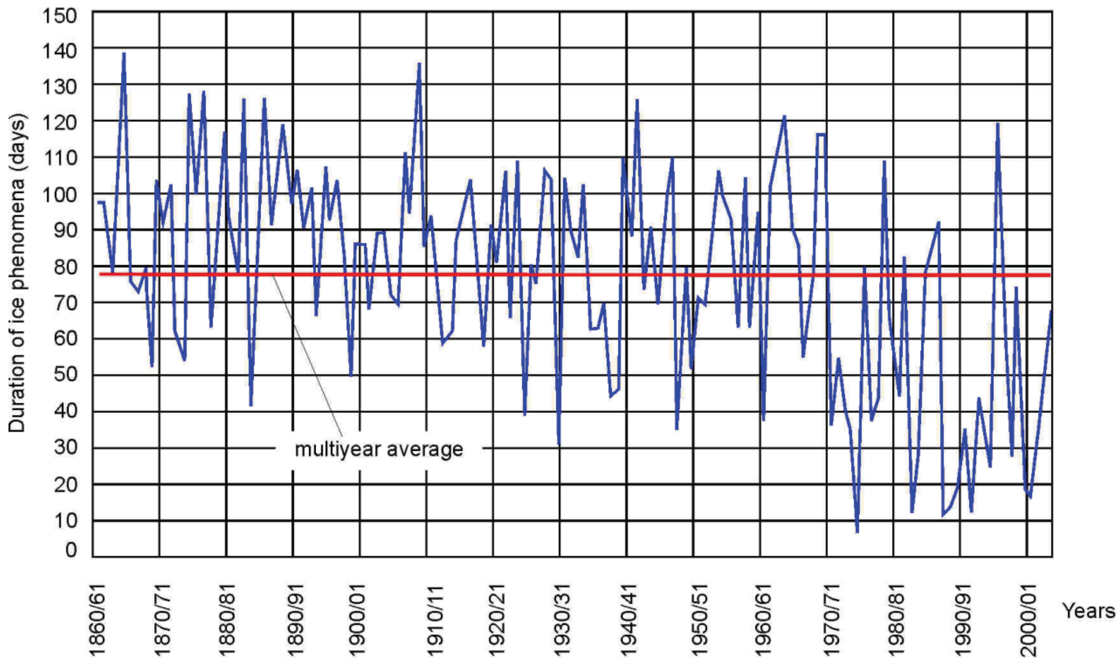

Fig. 5. Number of days with ice phenomena in cross-section Toruń during 1861–2000 (*Mroziński*, 2006)

This graph shows considerable variations in the amount of days with ice phenomena in cross-section Toruń. These variations began to increase at the end of XX century. The range is from 11 to 120 days within only several winter seasons. The red line shows the multiyear average amount of days with ice phenomena, which is 78 days per year.

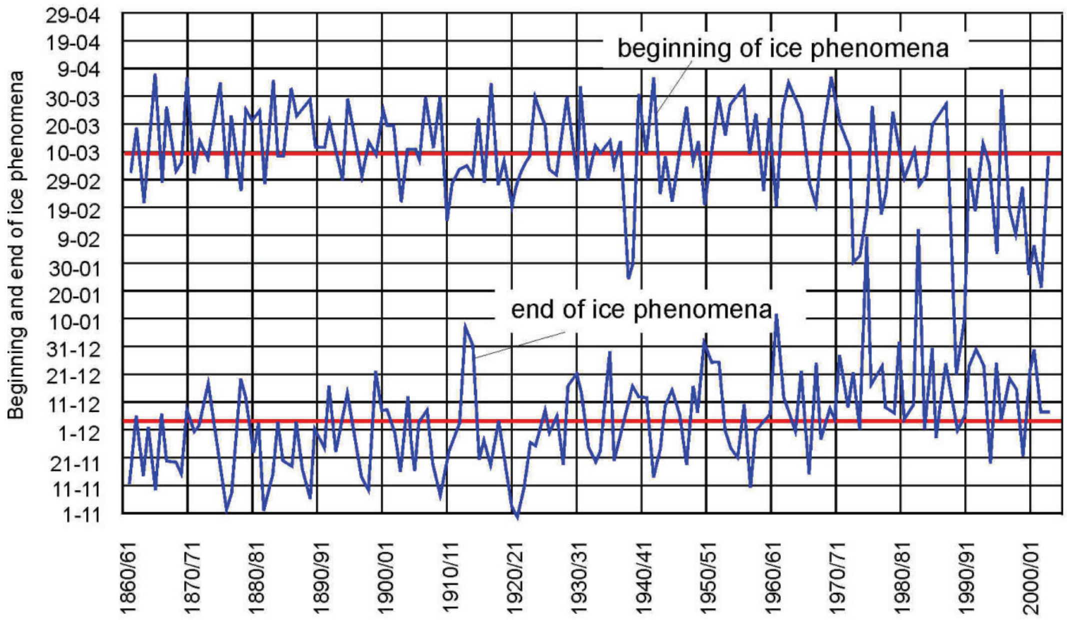

Fig. 6. Beginning and termination of ice phenomena in the cross-section Toruń (Mroziński, 2006)

It was also interesting to observe the dates of the beginning and termination of ice phenomena at a given cross-section. This record is shown in Fig. 6. The average multiyear date for the beginning of ice phenomena in cross-section Toruń is the 5th December and the termination on the 9th of March. Graph shows considerable variations both in the date of beginning and terminating of ice phenomena. It can be observed that after 1970 the beginning of ice phenomena was later. Also the end of phenomena started earlier. Similar presentations were carried out for other cross-sections of the Lower Vistula.

4. Application of NDD factor

The Negative Degree Days (NDD) factor is often used in ice engineering for the estimation of the amount of frazil ice formation (*Ice Engineering*, 1982), growth of the ice thickness (*Majewski*, 2009) or the appearance of ice phenomena (*Mroziński*, 2006). By means of NDD factor we understand the sum of average daily negative air temperatures.

Any forecast of the appearance of ice phenomena or permanent ice cover is very difficult because of many factors which influence this physical process. The application of NDD factor requires forecast of air temperatures, which is now becoming more and more accurate. It is possible now to forecast air temperature with good accuracy for one week in advance. At present there is, however, no forecast of ice phenomena on the Lower Vistula.

Ice and thermal characteristics in winter 2005/6 in cross-section Toruń are shown in Figure 7. These include: cumulative curve of NDD, average daily air and water temperature. Vertical lines show the beginning and termination of ice phenomena as

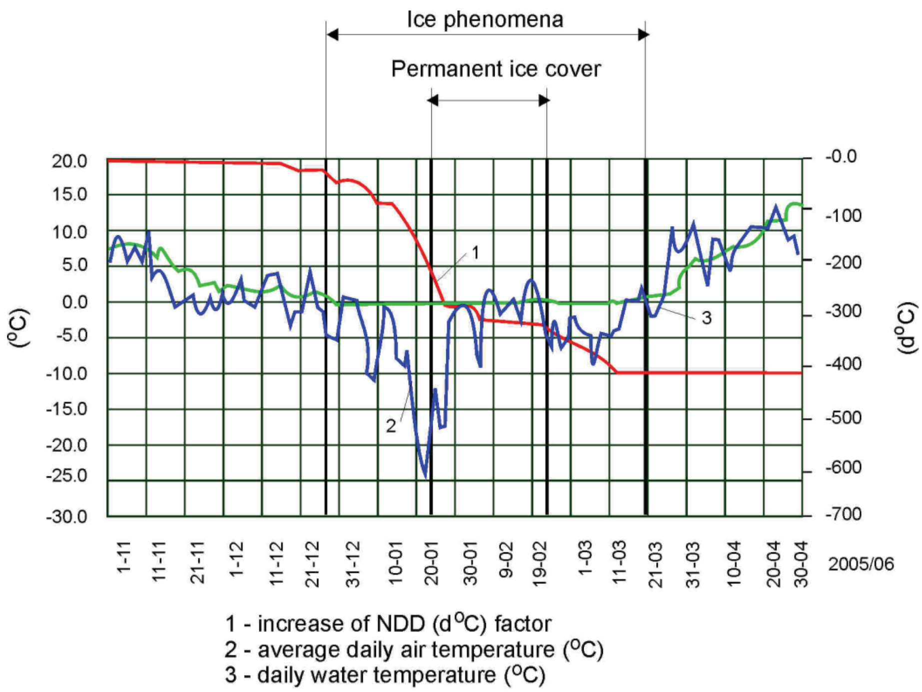

Fig. 7. Ice and thermal characteristics in cross-section Toruń, winter 2005/6.

well as beginning and termination of permanent ice cover. Left vertical axis indicates air and water temperatures. Right hand vertical axis shows NDD. Period of ice phenomena included 78 days, while permanent ice cover lasted about 32 days. Beginning of ice phenomena was when water temperature dropt to 0 °C and NDD reached the value of about -25 d °C. When NDD reached -200 d °C period of permanent ice cover started. This was accompanied by low air temperatures. The end of ice phenomena was around 20th March when air and water temperature increased above zero and the amount of NDD was not increasing with maximum value of NDD- 400 °C.

The red line in Fig. 7 actually represents the total change of NDD factor, which increases from zero to reach the value of about 400. There is no further change of NDD factor because average daily air temperature is no more negative.

It is also interesting to calculate the *intensity of frost*, which is the ratio of NDD divided by the amount of days with negative air temperatures. This can be interpreted as the average negative daily air temperature during time of negative air temperatures. In cross-section Toruń maximum NDD was -584.3 d °C (112 days with negative air temperatures winter 1995/96), and minimum -106.2 d °C (46 days with negative air temperature in winter 1999/2000). Thus *intensity of frost* was -5.2 in 1995/96 and -2.3 °C in 199/2000 respectively.

One of the essential parameters during ice formation is river discharge, which appears during that period of time. It is shown in Figure 8. During the existence of ice phenomena Vistula discharge in this cross-section varied around 400–800 m^3/s, while during permanent ice cover its value ranged from 600 to 800 m^3/s. Average multi-annual discharge in this cross-section is about 750 m^3/s.

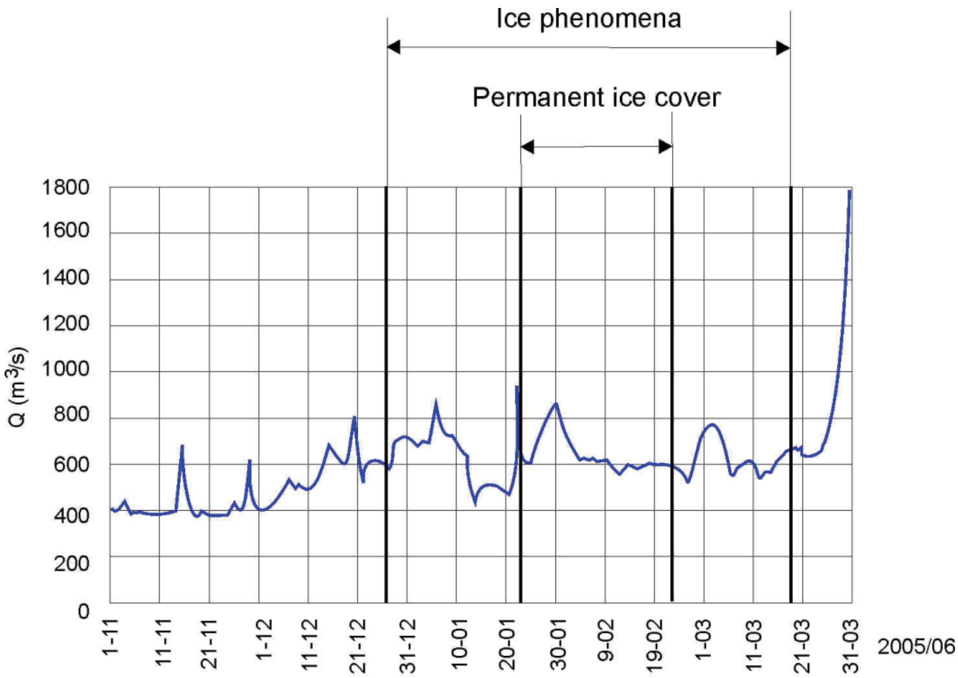

Fig. 8. Changes of discharge in cross-section Toruń, winter 2005/6.

For comparison the run of the thermal and ice phenomena in cross-section Tczew during winter 2005/6 is shown in Figure 9. This cross-section is located about 120 km north from cross-section Toruń. In cross-section Tczew nearly identically as in cross-section Toruń duration of ice phenomena was similar and amounted 77 days.

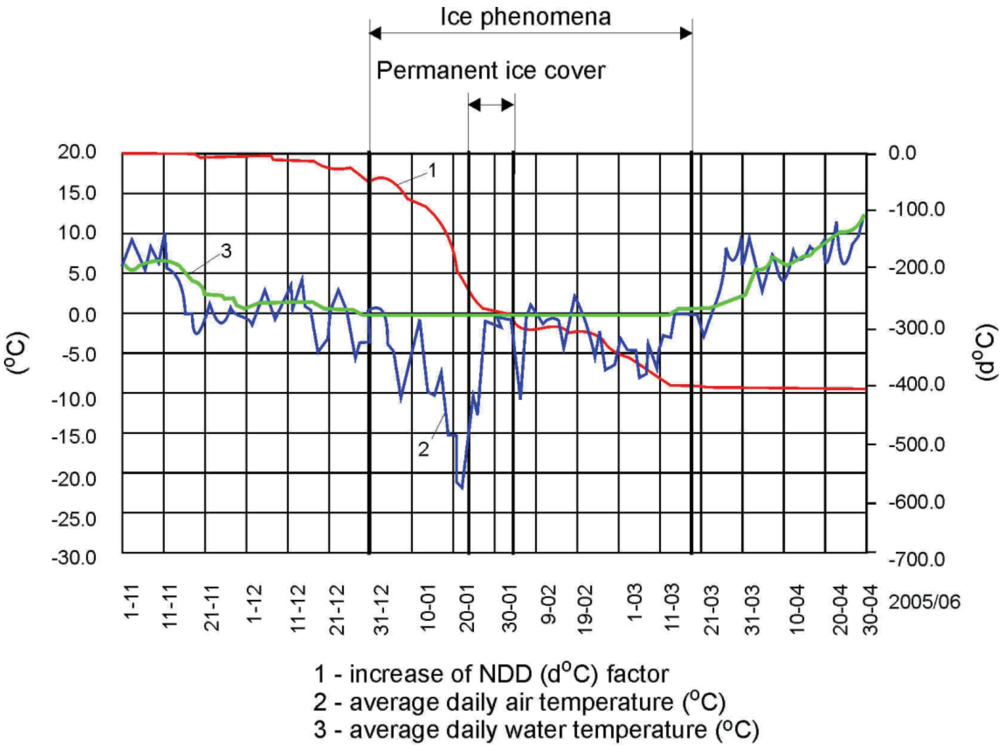

Fig. 9. Ice and thermal characteristics in cross-section Tczew, winter 2005/6.

However, permanent ice cower lasted only 12 days, while in Toruń was 32 days. Run of the increase of NDD was similar in Tczew and Toruń and reached about -400 d °C. In cross-section Tczew ice phenomena appeared when NDD reached the value -50 d °C, and the permanent ice cover appeared when NDD reached the value about -230 d °C. In cross-section Tczew discharge was above 600 m^3/s, and twice reached the value 1000 m^3/s (Fig. 10). This may explain shorter period of permanent ice cover.

Discharges in the Vistula River in cross-sections Toruń and Tczew shown in Fig. 8 and 10 are somewhat lower than average values. There is very small influence of ice phenomena on the discharge. Influence of ice cover is evident on the water stages. With permanent ice cover water stage will be higher for the same discharge than for free water surface.

Cross-section Toruń is located in the middle of the Lower Vistula and quite well represents flow and meteorological conditions. Thus it can be considered as good representative for this type investigations. There are plans to construct next hydraulic project downstream from the existing project Włocławek. It will be a typical run-of-river reservoir with hydraulic power plant, navigation lock and fish pass. It must be expected that ice conditions along the Lower Vistula downstream from Włocławek will change, however, no change in flow conditions can be expected.

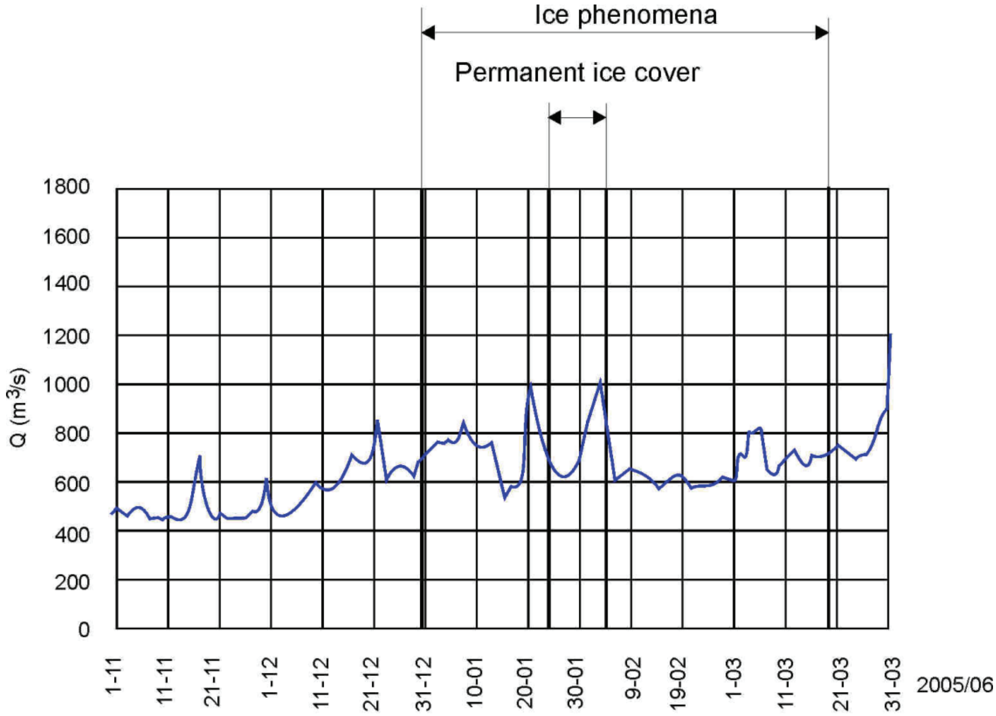

Fig. 10. Changes of discharge in cross-section Tczew, winter 2005/6.

5. *Flow and climatological conditions along the Lower Vistula*

The section of Vistula River called Lower Vistula 390 km long has only few small tributaries, which do not change flow conditions along this section. Discharge is actually formed along the upper and middle section. The catchments of these Vistula sections have very often different weather conditions, which govern flow and ice conditions. The catchment of the upper Vistula section includes mountains, which usually have large amounts of snow and result in high discharge during spring when snow is melting. Increase of the discharge during spring usually causes ice break-up and ice-run. These very often result in ice jams causing increase in water elevation.

6. *Conclusions*

Vistula River is divided into three sections and catchments. They represent different climate, flow and ice conditions. Lower Vistula is very important in this respect because flow and ice conditions on the upstream sections have very strong influence. Results presented in this paper allow to formulate the following conclusions.

1. Lower Vistula is the section with intensive appearance of ice phenomena and permanent ice cover. This caused very often ice jams and important floods.

2. Since many years observations of ice phenomena along Lower Vistula, together with meteorological observations (mainly air temperatures) are carried out.
3. These data indicate that the amount of days with ice phenomena and permanent ice cover is constantly decreasing, however, large irregularities are present.
4. The beginning of ice phenomena is nearly similar in all Lower Vistula cross-sections and takes place when water temperature decreases to zero degrees and the value of NDD reaches the value about -50 d °C.
5. Beginning of permanent ice cover takes place when NDD reaches the value around -200 d °C.
6. Duration of ice phenomena is similar during particular winter season in all Lower Vistula cross-sections, however, duration of permanent ice cover is different and probably depends on the value of discharge, which changes along this river section due to consecutive tributaries.

Long period of the observations concerning ice phenomena indicate that they are constantly decreasing. This concerned both ice phenomena as well as permanent ice cover. However, last two winters indicate certain reverse of this trend. It is difficult to conclude whether it is permanent change or only temporary situation. Therefore further studies concerning this problem are necessary.

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