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Vistula River bed erosion processes and their influence on Warsaw's flood safety

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Abstract Large cities have historically been well protected against floods as a function of their importance to society. In Warsaw, Poland, located on a narrow passage of the Vistula River valley, urban flood disasters were not unusual. Beginning at the end of the 19th century, the construction of river embankment and training works caused the narrowing of the flood passage path in the downtown reach of the river. The process of bed erosion lowered the elevation of the river bed by 205 cm over the 20th century, and the consequences of bed lowering are reflected by the rating curve change. Conditions of the flood passage have been analysed by the CCHE2D hydrodynamic model both in retro-modelling and scenario simulation modelling. The high water mark of the 1844 flood and iterative calculations in retro-modelling made possible estimation of the discharge, Q = 8250 $m^3 s^{-1}$. This highest observed historical flood in a natural river has been compared to recent conditions of the Vistula River in Warsaw by scenario modelling. The result shows dramatic changes in water surface elevation, velocities, and shear stress. The vertical velocity in the proximity of Port Praski gauge at km 513 can reach 3.5 m s^{-1}, a very high value for a lowland river. The average flow conveyance is improving due to channel erosion but also declining in the case of extreme floods due to high resistance from vegetation on the flood plains.

Key words Vistula River; Warsaw; erosion; rating curve; hydrodynamic modelling; flood

INTRODUCTION

Flood protection and flood risk management are dynamic issues, as a result of the constant changes in both the natural environment as well as the human built modifications. Flood risk optimization is the rational process by which managers address these hazards, and it forms the basis for water management planning. The consequences of the adopted measures for flood protection have a long-term horizon; for example, in the Rhine River, a training works was started at the beginning of the 19th century by engineer J.G. Tulla, and with the level of available technology and resources at that time, he anticipated that it would be completed in the period of two human generations (Plate, 2002). With today's progress in hydrology, there is access to long observation series, real-time telemetric measurements, and modern computing methods, allowing more precise modelling. In addition, there is a growing notion that hydrotechnical solutions are not absolutely reliable when exposed to extreme hydrological phenomena. Overall, there is now a higher level of interest in finding river regulation strategies that are environmentally sound, and in understanding the role of channel processes in flood risk management. The channel hydraulic conveyance is an important parameter that controls the flood water passage through the given reach of a river. It is not a static property, but a dynamic relationship between river discharge and water surface elevation. An important factor in the stability of the stage–discharge relation is the river channel geometry being a result of erosion or sedimentation process. There are a number of studies showing the influence of river training works on flood conveyance (e.g. Smith & Winkley, 1996; Hudson *et al*., 2008; Bart *et al*., 2009).

One of the methods to estimate the historical flood discharge is retro-modelling, defined as the use of archival hydrological information and geospatial data in state-of-the-art hydrodynamic models to assess historic flow conditions and their subsequent changes (Remo & Pinter 2007; Remo *et al*., 2009). Scenario-modelling is defined as a type of calibrated hydraulic model in which a portion of the characteristics are changed in order to test the sensitivity of the system to specific modifications.

STUDY SITE DESCRIPTION

The north-flowing Vistula River in Warsaw is measured by the water gauge Port Praski, which has been in operation for nearly 200 years. This reach has a drainage area of 84 857 km^2, and it is located at the 513 km of the river chainage, on the right bank of the Vistula River at the inlet canal of the inland harbour. Characteristic discharges are: mean low flow $Q_L = 194$ m^3 s^{-1}, average flow $Q_M = 561$ m^3 s^{-1}, $Q_{p1\%} = 7214$ m^3 s^{-1}, $Q_{p0,1\%} = 9960$ m^3 s^{-1}. Historically, most of the major floods in the Vistula River have been formed by intensive rainfalls in summer months in the Carpathian Mountains, that propagate down the middle and lower reaches of the river.

Warsaw, the capital of Poland, was developed on the bank of the Vistula River during the 17th century. One of the virtues of this particular location is that it provided a place of convenient crossing through the river and valley. The geological setting of the Vistula valley near Warsaw reflects the fluvial processes taking place during the Quaternary, at the final stages of the Vistulian glaciation and the Holocene. The valley of the north-flowing Vistula River intersects a belt of glacial uplands, and connects Kozienice basin with the Lower Vistula basin. This part has been described by geomorphologists as a trough flow across the southern Mazovian region (Różycki, 1972). Geological constraints of the valley, with the limiting glacial uplands, cause natural narrowing of the river channel, also reflected by the steeper longitudinal slope of the river surface (Zielińska, 1960). After passing the glacial uplands, the Vistula River valley forms a wide alluvial fan formed as a delta in a pre-glacial lake at the margin of Wkra stadial in Riss glaciation (Fig. 1).

For the flood safety of the city of Warsaw, it is important to understand the shape of the flood plain and over-flood terraces, and their changes through time. At the end of the Vistulian glaciation, the lowest over-flood terrace, the Praga terrace, had been formed; the oldest Holocene terrace is called Wawer terrace and shows the pattern of large palaeo-meander bank cuts. The Praga terrace in the downtown area has an elevation of 7–8 m above the average low surface of the Vistula River, and it drops to 5.5 m in the northern districts of the city (Baraniecka & Konecka-Betley, 1987; Biernacki, 2000).

Sediment transported as bedload is mostly sand with the following properties: $d_{50} = 0.35$ mm, density $\rho = 2.654$ t m^{-3}, porosity $p = 0.32$ (Żelaziński *et al.*, 2005). Important for the river bed

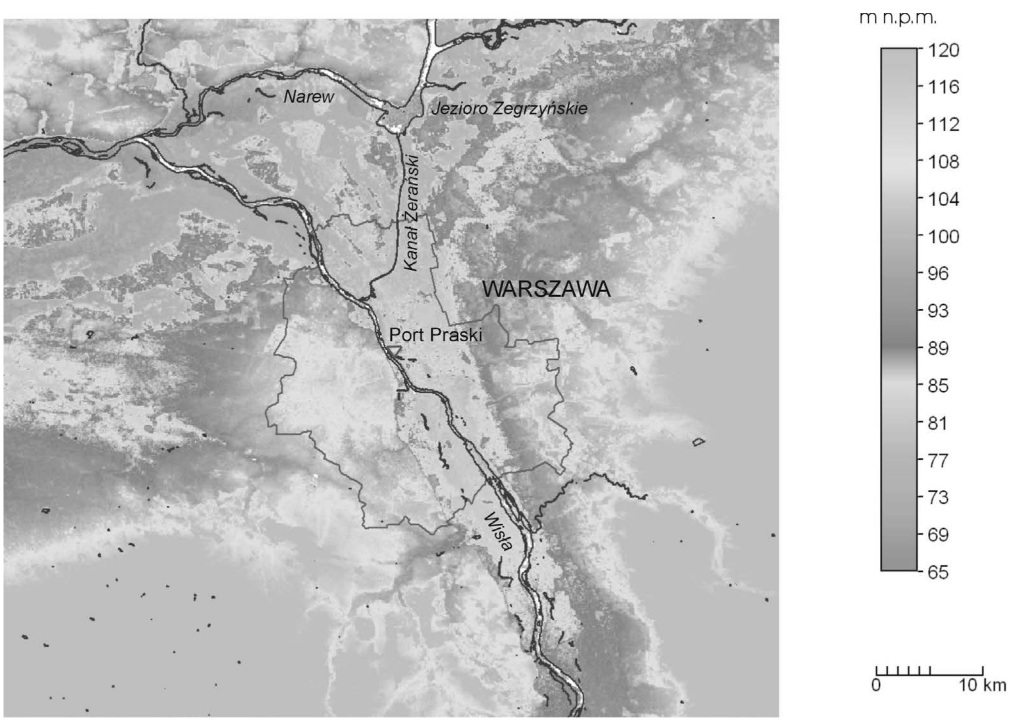

Fig. 1 Hypsometry of the Vistula River valley in Warsaw area (data of SRTM obtained from Global Land Cover Facility, University of Maryland).

morphology are sills made of Tertiary cohesive clays. These older sediments have been disturbed and elevated by the pressure imposed by the Quaternary glaciers. This uneven and complicated run of the Tertiary clays has the name of glacitectonics. The elevated Tertiary clay folds have been covered by a rock pavement from the eroded Quaternary period boulder clays. In the Vistula River channel in Warsaw, these forms act as stone reefs, stabilizing the longitudinal profile.

The natural narrowing of the Vistula River valley due to geological constraints has been further limited by the flood protective dikes built at the end of 19th century and through the 1950s. The location of the dikes and the sequence of their construction are shown in Fig. 2. The spacing of the dikes in the rural area out of the Warsaw border is in the range 1500 m at km 501, while in the inner city it drops to 470–480 m at km 511–514 of chainage. Such a narrowing of the flood water passage route by the flood protective dikes was designed at the end of 19th century as a method to concentrate water flow near the water supply intake. This change in the river cross-section geometry was accommodated by increasing the height of the flood protective dikes.

The Vistula River in Warsaw was used intensively for inland navigation in the 1950s–1960s. These works continued in 1962–1963 and 1968–1976; structures added include groins, longitudinal dams, and waterfront boulevards. The narrowing of the river due to flood protective dikes and river training structures has been called the "Warsaw corset."

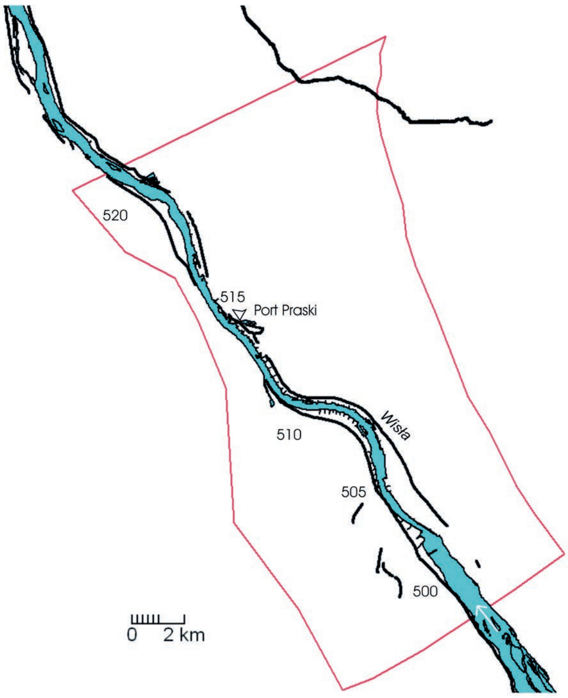

Fig. 2 Outline of the modelled area and location of the flood protective dikes along the Vistula River valley in the Warsaw area.

Another factor contributing to the erosion of the river bed is the dredging of sand and gravel for the post war reconstruction of the city. In 1950, the volume of dredged sediments reached 500 000 m^3, rivaling the natural bedload transport rate (Skibiński, 1963). During 1952–1959, the volume of dredged bed material increased to 850 000 m^3 per year, and in 1978, peaked at nearly 2 000 000 m^3 (Wierzbicki, 2001). During the 1990s, the volume of the dredged sand decreased, finally stabilizing at 1 200 000 m^3 (Żelaziński *et al*., 2005).

Exploitation of the river sediments together with the narrowing of the channel by the training works resulted in rapid bottom erosion. This process was first predicted by Pomianowski (1938) who anticipated the channel deepening by 2 m. The channel erosion became more visible after the completion of the river training works in the 1960s. Zielińska (1960) forecast that the process of erosion would slow down or even reverse to sedimentation, but the existing trend continues.

Intensive erosion has exposed the stone reefs at the top of the cohesive clays elevations, impeding navigation. To improve navigational safety, a dredging operation conducted from 1989 to 1991 at the reach 509–520.5 km removed 3000 m^3 of stones, maintaining a transit depth of 1.2–1.5 m (Kowalski *et al*., 2013).

The dynamics of the river channel changes are illustrated by the instability of the rating curves reflecting the relationship between water stage and discharge. We can analyse rating curves from the Port Praski gauge from the following years: 1919, 1960, and 2010. Lowering of the rating curve from 2010 (with respect to the 1919 curve) in the low flow range indicates channel bottom erosion by 205 cm. However, comparison of the curves in the high flow range indicate that the initial flood conveyance has declined. The rating curve of 2010 is lower than the curve of 1960 but still higher than the initial curve of 1919. This relation is visible also when we compare the stage of the floods from 1960 and 1962, which was higher than the stage of the last flood (2010), with a highest ever measured discharge (Table 1). That can be explained by the influence of the river training works from the 1960s, as well as the subsequent channel erosion. The first response of the channel to the river training works was to produce a new flood plain between the groins, which was sheltered by the dense vegetation cover. More recently, erosion processes in the channel have lowered the position of the newest rating curve.

The Vistula river channel erosion with time is depicted in Fig. 3, showing the position of the water stage corresponding to mean low flow during 1919–2010 at the Port Praski gauge station. The intensity of channel erosion shows acceleration during the post war period which can in turn be explained by the dredging and intensification of river training works.

Table 1 High water stages and corresponding discharge of the Vistula River in Warsaw profile (Port Praski) 1813–2010: 1 – obtained from retro-modelling by CCHE2D; *value from retro-modelling

Water stage H (cm)	Year	Origin of the flood S – snow melt/R – rainfall	Discharge Q ($m^3 s^{-1}$)
849 (863)	1844	R	8 250 *
808	1813	R	7 430 *
787	1960	R	5 650
780	1962	R	5 520
777	2010	R	5 899
758	1924	S	5 860
749	1934	R	5 460
728	1980	R	4 720
706	2001	R	4 780
646	1997	R	4 170

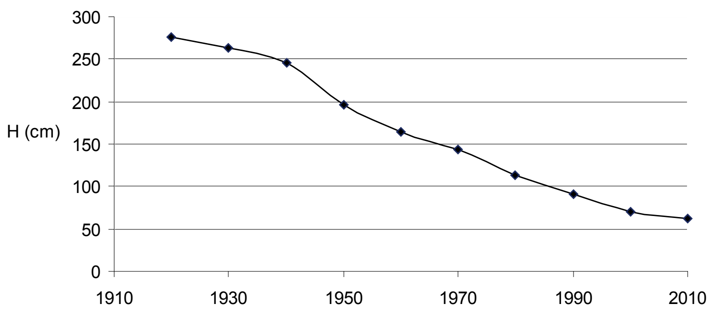

Fig. 3 Water stage of the Vistula River in Warsaw corresponding to long-term average low flow.

RETRO- AND SCENARIO MODELLING

The retro- and scenario modelling presented herein was completed using the hydrodynamic 2D model called CCHE2D, developed at the National Center for Computational Hydroscience and Engineering (NCCHE) at the University of Mississippi, USA. The model simulates free surface flow, and it is based on the depth-averaged Navier-Stokes equations. Turbulent shear stresses were estimated using Boussinesq approximation, with the introduction of turbulent eddy viscosity. The set of equations is solved implicitly by the control volume approach and the efficient element method. This model has been applied successfully to simulate flow in natural channels, and has proven to be an effective tool for hydraulic research (Jia *et al*., 2002).

The numerical calculations are carried out at the nodes of an irregular rectangular mesh. Data needed in the modelling comprise geometric data of the channel and flood plain, as well as Manning roughness values. The geometric information was obtained from a DEM of 20 m resolution based on river soundings and digital stereoscopy representing the flood plain and higher terraces. For retro-modelling of the flood passage, the recent river training structures, flood protection dikes and bridges narrowing were removed from the DEM by editing elevation values. The retro-modelling also used the geometry and location of the recent river channel, assuming that for the extreme flood passage, the geometry of the flood plain is most important. A Manning roughness coefficient n was assigned to land-use classes according to the literature values: river channel 0.03, open area with a low vegetation 0.04, settlement area 0.06, forest and tall vegetation 0.11. The spatial distribution of the values was obtained from recent topographic maps and an early topographic map (from 1832) representing natural flow conditions. The computing mesh for the retro-modelling used $i = 200 \times j = 400$ lines, and the computing mesh for scenario modelling contained $i = 50 \times j = 400$ lines. Both computing domains covered the space between 501–521 km of the river chainage. The DEM from which elevation points have been calculated contains 1.95 million (x, y, and z) coordinates. The model assumed steady-state flow conditions and parabolic eddy viscosity.

Warsaw has been affected quite often by floods, and the range of extreme high water levels has been documented by high water marks that were carved in stone or commemorated with iron plates. After the catastrophic flood of 1844, a total of 10 flood marks were placed, but only one remains, located on the right bank of the Vistula, close to Port Praski water gauge. The elevation of other flood marks has been reconstructed from historical documents by Kuźniar (1997). Information on historical floods relates only to their elevation in a longitudinal profile, and the discharge is not known. However, by retro-modelling and iterative computations and comparison of the calculated water surface elevations to recorded high water marks, the discharge of the 1844 flood is estimated as 8250 $m^3 s^{-1}$. The comparison of the water surface elevation and DTM shows that in the period of extreme historical floods, before river embankment, there was possible flow over the Praga terrace in a shortcut leading to the Narew River, a Vistula River tributary located north of Warsaw. The flow was carried out in a topographic lowering, used today by the Zegrzynski and Bródnowski canals (Magnuszewski & Gutry-Korycka, 2009).

The difference between the natural and recent conditions of catastrophic flood passage makes the width of the flood plain available for a high water flow. In the natural conditions at the time of the 1844 flood there was no limit for flow, but by the end of the 19th century, high flow was concentrated by the flood protection dikes. For the scenario modelling, a computing mesh limited to the area constrained by the recent flood protection dikes was prepared. The model was calibrated and verified by comparison of calculated velocity and water elevation to real current meter measurements performed by the Institute of Meteorology and Water Management (IMGW) during the flood of 10 June 2006 (Table 2).

In the scenario modelling, as an upper boundary condition, we applied the discharge of the 1844 flood, Q = 8250 m^3s^{-1} and an open lower boundary condition. For comparison of the results

Table 2 Comparison of the observed and calculated hydraulic parameters obtained by IMGW from current meter hydrometric measurement at Świętokrzyski Bridge and the CCHE2D model.

Date of discharge measurement by current meter	Q ($m^3 s^{-1}$)	H (cm)	Maximum vertical velocity v_h ($m s^{-1}$) in the hydrometric cross-section		Elevation of the water surface in the water gauge profile (m)	
			Observed	Calculated	Observed	Calculated
2006 VI 10	3059	576	2.15	2.36	81.84	82.03

from retro and scenario modelling, a sequence of monitoring points was designed, located in a river channel thalweg. The values of the hydraulic parameters channel width, water surface elevation, velocity of flow, and shear stress, from both modelling results, are shown in Fig. 4.

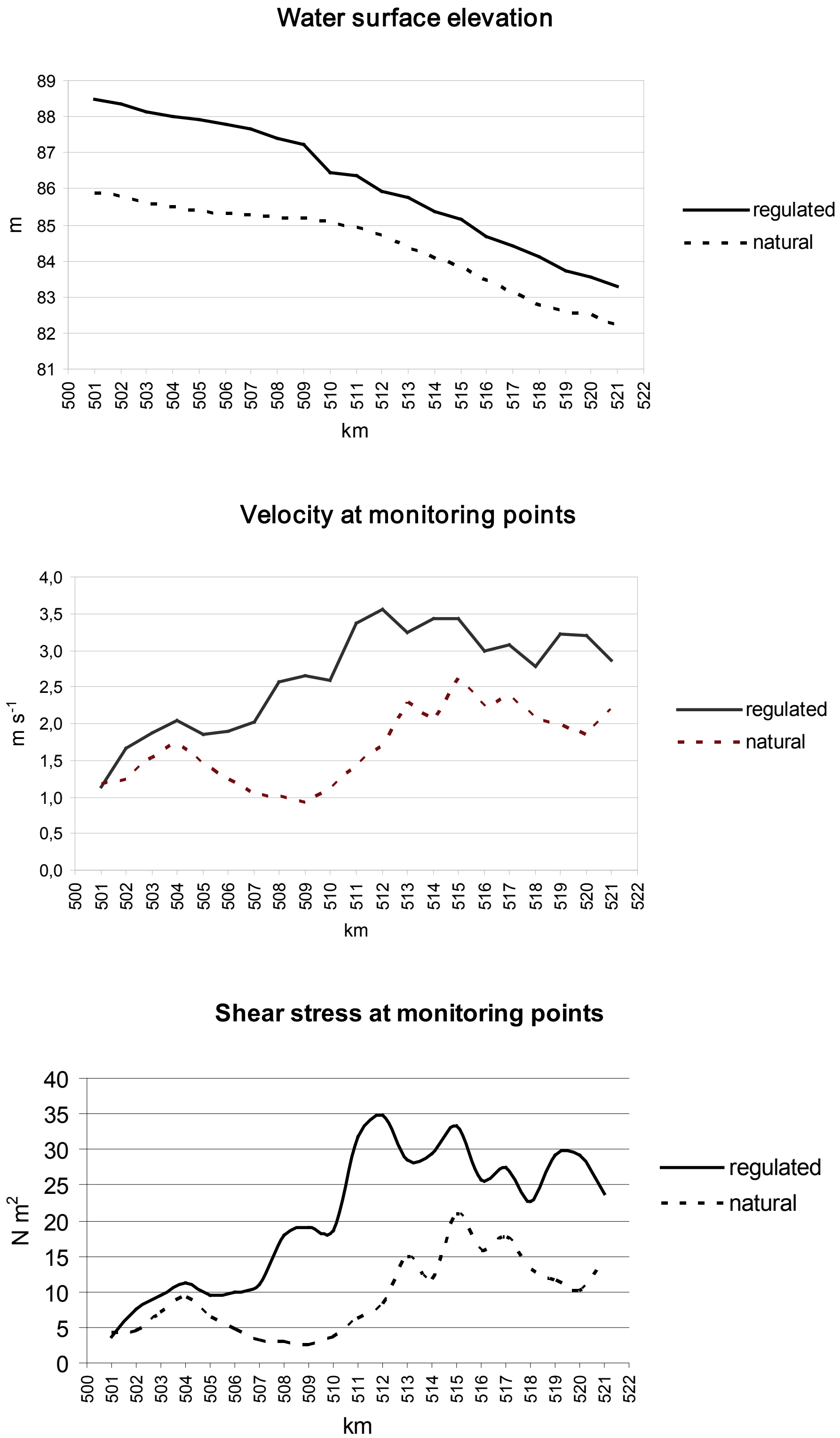

Fig. 4 Comparison of the hydraulic parameters of the Vistula River in Warsaw, corresponding to natural and regulated flow conditions

DISCUSSION OF THE RESULTS

The method of retro-modelling can be used for the reconstruction of historical floods for which only limited data are available. The flood of 1844 is important since it set the record for the highest water level ever measured in the Vistula River in Warsaw. During an extreme flood in a natural river valley without flood protection dikes, the first over-flood terrace could be inundated. The 1844 flood with a peak discharge of 8250 $m^3 s^{-1}$ is an important reference value for Warsaw's flood protection planning; a flood of such magnitude may still propagate down from the upper Vistula River.

The consequence of river embankment and regulation is a water surface higher by 2 m during the extreme flow. The longitudinal profile shows that the highest increase of the water level is observed in the reach km 501–509 which approaches the narrowest part of the channel.

In the conditions of extreme flood passage, the velocity of the flow in the Vistula River reach km 505–515 can reach speeds of 3.5 m s^{-1}. This is very high velocity for a lowland river, and the region of highest velocities is situated close to the Port Praski gauge at km 513. Erosion of the river bottom is partly caused by the river dredging works, but the high energy of flowing water during the floods also plays important role. The CCHE2D model provides very valuable information on spatial distribution of water velocity and shear stress.

River channel erosion will continue, improving flood conveyance, but also creating problems for navigation during low flow periods. One additional problem is the land cover of the new flood plains in the space between flood protection dikes. Dense vegetation on the new flood plains creates additional resistance to high flows and needs to be controlled by periodic pruning. In light of the interdependent relationship between the natural and built environment in the Vistula River valley near Warsaw, hydrodynamic modelling is an important tool for understanding the processes shaping erosion and deposition.

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