Climate Variability and Change—Hydrological Impacts (Proceedings of the Fifth FRIEND World Conference held at Havana, Cuba, November 2006), IAHS Publ. 308, 2006.

Numerical estimation of flood zones in the Vistula River valley, Warsaw, Poland

MAŁGORZATA GUTRY-KORYCKA[1], ARTUR MAGNUSZEWSKI[1], JAROSŁAW SUCHOŻEBRSKI[1], WITOLD JAWORSKI[1], MICHAŁ MARCINKOWSKI[1] & MICHAŁ SZYDŁOWSKI[2]

1 *University of Warsaw, Hydrology Department, Krakowskie Przedmieście 30, 00-927 Warszawa, Poland*
asmagnus@uw.edu.pl

2 *Technical Academy of Gdańsk, Institute of Civil and Environmental Engineering, Narutowicza 11/12, 80-952 Gdańsk, Poland*

Abstract Flood maps (referred to as flood risk maps) are developed for planning purposes and the needs of insurance companies. They usually map the flood with a 100-year recurrence interval (Q_p1%, i.e. discharge of probability of occurrence p = 1%), or flooding during the largest historically recorded flood. Typically these maps identify the zone of highest hazard, the so-called flood path, which is where construction is forbidden, and a zone of high hazard, i.e. the area between the flood path and the edge of the Q_p1% flood. In this study the assessment of the flood waters between the flood protection dykes of a reach of Vistula River was made using a one-dimensional hydraulic model and a Digital Elevation Model (DEM). The ordinates of water level for the Vistula were determined with the HEC-RAS model, assuming conditions of a steady state flow with a given probability of exceedence. The flood zones obtained from the simulations indicate that a significant part of the town is situated in the potentially dangerous flood hazard zone. The simulations also indicate that under present conditions the elevations of the flood protection dykes are sufficient to convey the Q_p1% discharge. However, the dykes would not ensure protection of an important part of the city in the case of a Q_p0.1% discharge.

Key words flood recurrence interval; flood zone mapping; Warsaw, Poland; Vistula River

INTRODUCTION

The creation of flood hazard maps is required by Article 82 of the Polish Water Law. In order to estimate the extent of the flood zones, mathematical models of flood wave propagation and digital models of the river bed and flood plain are usually used. Polish legislation does not specify the models or numerical tools needed to simulate the flood wave propagation for flood hazard mapping. However, some suggestions can be found in the Polish literature (Nachlik *et al*. 2000; Radczuk *et al*. 2001). In general, the flood hazard maps should be prepared for discharges with the probability of occurrence equal to 1%, or for the largest historically recorded flood which is often approximated by the 0.1% probability discharge. These maps are usually made using a one-dimensional mathematical model of open channel flow. For some special cases, for instance levee break analysis, two-dimensional models are suggested. The flood analysis can be done for steady or unsteady water flow depending on the local hydraulic conditions and the availability of hydrological data.

STUDY SITE DESCRIPTION

The geomorphology of the Vistula River valley within the urban area

The valley of the Vistula was developed by fluvial processes throughout the Holocene and during the final stages of the last glaciation. The segment of the Vistula valley studied here (in Warsaw) has a length of 47.05 km (i.e. between 494.76 and 541.81 km of the river course). The width of the lowest over-flood terrace varies between 6 km in the area of Praga, to just several dozen metres on the left bank in the area of the Old Town. The surface of the terrace in the southern parts of the city situated beyond the reach of the flood waters. In the areas of Dolne Łomianki and Kępa Kiełpińska the waters of the most catastrophic floods inundate the surface of the terrace. These floods are typically caused by ice-jams.

The catastrophic flood of July 1884 and the construction of a water uptake for the city water supply were impulses to regulation of the Vistula in Warsaw. In the years 1893–1910, river training work was conducted along both banks of the river. The width of the regulation route of the river was assumed to be 340 m. Between 1923 and 1931, and after the flood of 1924, further stream regulation was carried out to protect the banks and the newly built dykes.

Immediately after World War II, the river channel of the Vistula in Warsaw became a dumping ground for debris. This caused the high-discharge cross-sections in some areas to be reduced by 50% in comparison with the middle Vistula. This resulted in the so-called Warsaw corset which occurs in the segment of 507–517 km. A little upstream of the Śląsko-Dąbrowski Bridge, the channel of Vistula got narrowed down to approximately 350 m. This is the most significant narrowing of the channel in the entire middle and lower course of the river.

According to the designs of the Central Water Management Bureau from the 1960s, the city should be protected against the flood that has a recurrence of 1000 years (Q_p0.1%) by the protection dykes that are built at distances of 400–600 m from the channel. Upstream and downstream of Warsaw, the protection dykes are located at 1000 to 1700 m and shield agricultural areas against the inundation caused by the Q_p1% flood.

Hydrological conditions

The channel elevation decreased on average by 1.5 cm year^{-1} between 1921 and 1953 and by 9 cm year^{-1} between 1953 and 1959 (Bogdanowicz *et al.*, 2000). The narrowing of the high discharge channel has also increased of the height of the flood, increased the water flow velocity and its eroding force. During mean high discharges the bottom of the river can be scoured to a depth of as much as 3 m. The mean annual discharge of the Vistula at the Warsaw Haven cross-section in the years 1951–1995 was 561 m^3 s^{-1}.

In the 19th and 20th centuries, the catastrophic floods in the middle reaches of the Vistula occurred every few or a dozen years (1813, 1838, 1839, 1844, 1845, 1855, 1867, 1884, 1889, 1891, 1903, 1924, 1947, 1960, 1962). The largest flood in the 19th century occurred in 1844. During this flood the lower elevation areas of the city and the suburban areas between Wilanów and Kazuń were inundated. The highest water level in Warsaw noted during this flood was 84.71 m a.s.l. The highest discharge of the March 1924 flood was 5860 m^3 s^{-1} and is the largest discharge measured in the period 1921–1997 (Bogdanowicz *et al.*, 2000). The Q_p1% discharge is estimated at to 7210 m^3 s^{-1} (Wierzbicki, 2001). Fal & Dąbrowski (2001) established, on the basis of the 200-year series of maximum water levels and the historical discharge curve, that the Q_p0.1% discharge is 9960 m^3 s^{-1}.

METHOD

The extent of flood waters was determined by jointly using a one-dimensional hydraulic model and a Digital Elevation Model (DEM). While similar approaches have been used in natural river conditions, this study concerns urban area. The ordinates of water level in the Vistula valley were determined with the HEC-RAS one-dimensional model, assuming conditions of a steady-state flow with a given probability of exceedence. The HEC-RAS (River Analysis System) model was developed by the US Army Corps of Engineers Hydrologic Engineering Center. In the study reported here the assessment of flood zone was done assuming steady-state flow conditions by the solution of the one-dimensional energy (Bernoulli) equation. Energy losses are evaluated by friction (Manning's equation). The limitations of 1-D hydrodynamic modelling in the urban area are discussed by Mark *et al*. (2004). Our approach does not take in to consideration the underground pipe system, flow by the street system, areas with stagnant water, and water entry into houses. A useful overview of problems related to urban flood modelling is given by Haider *et al.* (2003).

Data for the model

The data needed for the description of the channel geometry were obtained from the echo-sounder measurements carried out on 24–30 September 1998 on the reach of the Vistula River between 490.760 and 541.800 km (Wierzbicki, 2001). Using these profiles, contour lines were drawn on the map by hand and considering the river bed forms and the more important water engineering structures.

The data on the elevations of the crests of the dykes came from the Hydroprojekt design office in Warsaw. These elevations were originally in the form of a table, in which the elevations of the dykes crests are provided for the consecutive kilometres of the river's course. These values were transferred to the system of orthogonal cartographic coordinates by interpolation. The calculations result in a set of coordinate values (x,y,z) describing the distribution of the dyke crest elevations on both sides of the river.

The data on the relief of the area between the flood protection dykes and behind them were acquired from photogrammetric processing of the aerial photographs by the District Geodesic and Cartographic Department. The relief of the over-flood terraces and higher terrain were from a digital elevation model obtained from the Office of the Surveyor of the Mazowieckie Voivodship. The spatial resolution of that DEM is in the range of 100 m.

The data describing the course of the dyke crests, the relief of the area between and behind the dykes, and the bottom of the river, were merged to one file which contained around 0.77 million points. On the basis of this data set the digital model of relief (DEM) was interpolated using the procedure of inverse distances and a resolution of 20 m (Fig. 1).

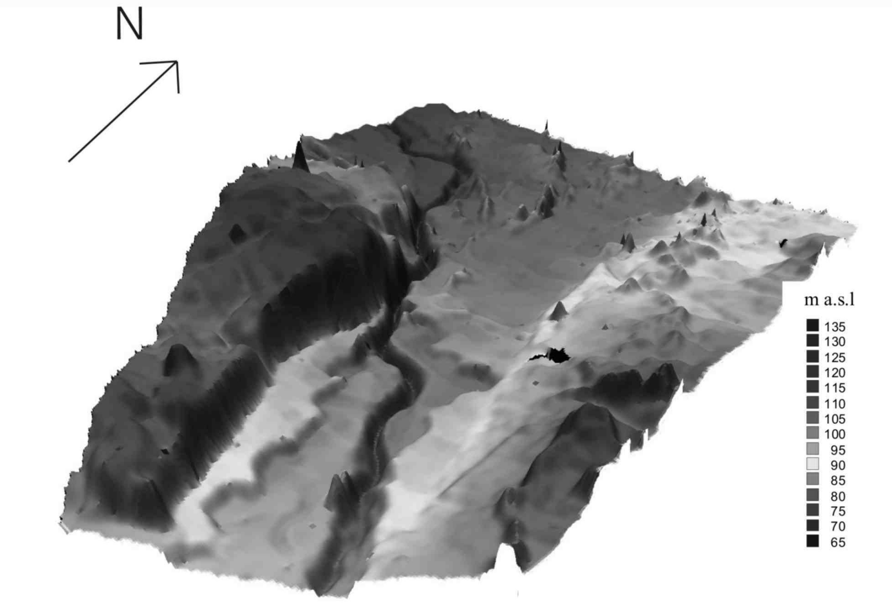

Fig. 1 Digital elevation model of the Vistula valley in Warsaw showing the city “corset” imposed on the river channel (river flows from south to north).

The Manning roughness coefficient values were estimated on the basis of land-use maps and air photographs for the area between the dykes. The following values of the roughness coefficient adopted were: Vistula River channel: 0.03; meadows: 0.04; single trees: 0.045; arable land: 0.05; orchards: 0.055; forests: 0.12; osiers and bushes: 0.15; roads and boulevards: 0.02. Roughness coefficients have been verified during model calibration, to match up to flood level ordinates obtained from HEC-RAS calculations on field measurements from 1998 (Wierzbicki, 2001).

RESULTS

Flood zone ranges for the discharges Q_p1% and Q_p0.1% have been obtained by imposing the flood level models on the DEM using the map algebra function of the ILWIS 3.3 software (Figs 2 and 3). Simulations indicate that a significant part of town is situated in the potentially dangerous zone of the flood hazard. Our results are different from previous studies by Jacewicz (1999) and have a closer fit to the morphology of the flood plain. In the present condition, the flood protection dykes are sufficient to convey the Q_p1% discharge. However, the results indicate that the channel segment between 514 and 515.5 km on the right-hand bank have an inadequate dyke that poses a threat to the Zoological Garden. Likewise, Praga Haven and its hinterland are not properly protected against the Q_p1% flood. This suggests that the entry to the port should be controlled by a flood gate, if more intensive construction activity in this area is undertaken.

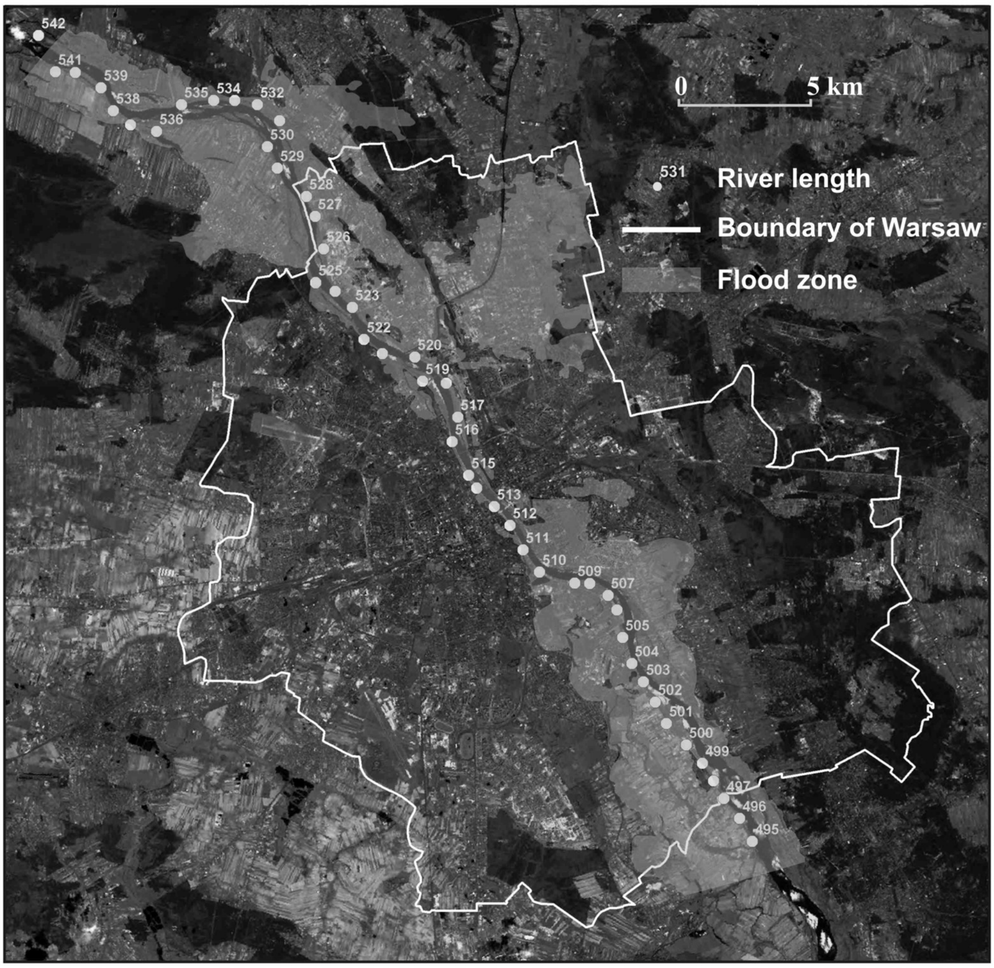

Fig. 2 Range of Qp1% flood zone represented on the background of a Landsat 7 image.

In the case of the occurrence of the Q_p0.1% discharge, the dyes would not ensure protection of important parts of the city. This is especially true on the right bank between 512.5–521 km and 523–535 km, and on the left bank in the segment 525–533.5 km.

The area downstream of 526 km is a not urbanized and so the potential flood losses are lower than in nearby urban areas. Nevertheless, the left bank between 511 and 514 km is not protected by the dykes at all and the elevation of the artificially raised flood terrace does not secure a safe passage of the Q_p0.1% waters. At the same time, this area is attractive for the potential investment projects within Powiśle district, including the extensions to the campus of the University of Warsaw. A similar situation exists over the segment between 517 and 521 km, where the Olympic Centre was established and further developments are planned. A very sensitive area also occurs along the 510–511 km fragment of the left bank, where the flood dykes end, and entry to the area behind the dykes is protected with Czerniaków Head flood gate. Other stretches of the river, where a risk of topping the dikes by the Q_p0.1% flood exists are: 517–521 km on the left bank and 512–523 km on the right bank.

Acknowledgements The authors thank the Global Land Cover Facility, Institute for Advanced Computer Studies, University of Maryland, College Park, USA for making available the Landsat 7 imagery. This research has been financed by the European Commission under the Fifth Framework Programme for Scientific Research: project URBS Pandens, and grant PZB-KBN-086/PO4/2003 – Extreme meteorological and hydrological events in Poland.

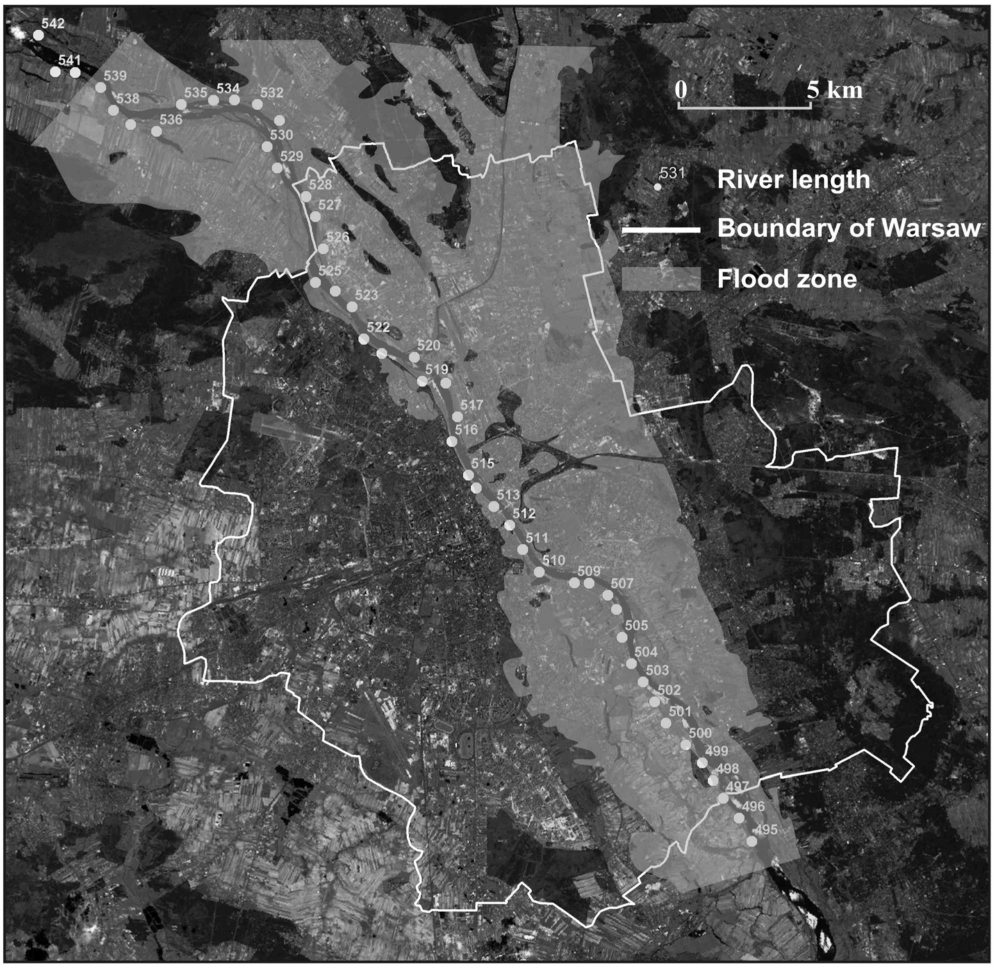

Fig. 3 Range of Qp0.1% flood zone represented on the background of a Landsat 7 image.

REFERENCES

Bogdanowicz, E., Fal, B. & Dobrzyńska, I. (2000) Charakterystyki hydrologiczne (Hydrological characteristics. In: *Wisła w Warszawie*, 9–13. Biuro Zarządu m.st. Warszawy. Wydział Planowania Przestrzennego i Architektury, Warszawa, Poland (in Polish).

Haider, S., Paquier, A., Morel, R. & Champagne, J. Y. (2003) Urban flood modelling using computational fluid dynamics. *Proc. Institution of Civil Engineers: Water and Maritime Engineering* **156**(2), 129–35.

Jacewicz, A. (2000) Ocena i propozycja zabudowy hydrotechnicznej koryta Wisły (The assessment and the proposal of hydro-engineering development of the channel of Vistula River. In: *Wisła w Warszawie,* 154–171. Wydział Planowania Przestrzennego i Architektury, Warszawa, Poland (in Polish).

Fal, B. & Dąbrowski, P. (2001) Dwieście lat obserwacji i pomiarów hydrologicznych Wisły w Warszawie: Obserwacje stanów wody (Two hundred years of hydrological observations and measurements of Vistula in Warsaw. Observations of water levels). *Gospodarka Wodna* **11**, 461–467 (in Polish).

Mark, O., Weesakul, S., Apirumanekul, C., Aroonnet, S. B. & Djordjevic, S. (2004) Potential and limitations of 1D modelling of urban flooding. *J. Hydrol.* **299**(3–4), 284–299.

Nachlik, E., Kostecki, S., Gądek, W. & Stochmal, R. (2000) *Strefy zagrożenia powodziowego* (Flood hazard zones). Wydawnictwo Profil – Biuro Koordynacji Projektu Banku Światowego, Wrocław, Poland (in Polish).

Radczuk, L., Szymkiewicz, R., Jełowicki, J., Żyszkowska, W. & Brun, J. F. (2001) *Wyznaczanie stref zagrożenia powodziowego* (Determination of the zones of flood hazard). Wydawnictwo Safege – Biuro Koordynacji Projektu Banku Światowego, Wrocław, Poland (in Polish).

Wierzbicki, J. (2001) Stałość pionowego układu koryta Wisły oraz położenia zwierciadła wód małych i wielkich na odcinku miejskim w Warszawie (Stability of the vertical setting of the channel of Vistula and the position of the low and high discharges on the urban segment in Warsaw). *Gospodarka Wodna* **4**, 143–149 (in Polish).