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HOW BIG CAN A FLOOD OF THE VISTULA RIVER BE IN WARSAW – HISTORICAL AND HYDROLOGICAL PERSPECTIVE

1. INTRODUCTION

In the process of city of Warsaw development, an important factor controlling and limiting spatial planning is the flood risk from the Vistula River. The flood risk is understood as a product of flood probability and exposition of the society to the hazard. In spatial planning, it is important to know if the given area is in the range of flood and what would be the consequences of the flood if it occurred. Very important in building the society's awareness of exposure to hazard is the knowledge of probability and range of catastrophic floods recorded in historical data. For this purpose, the common practice in the urban areas is to record high extreme floods by preserving high water marks on important buildings to inform citizens about the range of catastrophic floods. Vistula's high water marks are preserved in Warsaw, for example in Wilanów Park; the levels of summer floods in 1813, 1844 and 1934 are indicated as well as the snow melt floods of 1924 and 1947.

In the classical civil engineering approach, calculations of maximum floods is done with the use of probability distribution functions. The inefficiency of this approach is due to a limited length of time series of the observations and the fact that many rivers are not controlled by the hydrological gauges. Using probability distribution functions we estimate the floods with a recurrence interval of century or millennium using the data representing a few decades. This paper presents alternative methods of estimating the highest possible Vistula River floods in Warsaw.

2. DESCRIPTION OF THE STUDY AREA

High water on the Vistula may occur virtually any time throughout the year. The most common and greatest floods occur in the summer, usually in June and July, and less often in August. They are associated with long-lasting and large scale rainfall covering the greater part of the basin. During rainfall lasting for several days and giving 150–200 mm of rain, flood waves develop on the Carpathian tributaries. Flood water from the source area of the Vistula reaches Krakow within several hours and with a velocity of 10–15 km/h moves down the river.

The Vistula River valley in the city of Warsaw was formed at the end of Pleistocene and through the Holocene period. At the end of the Vistulian glaciation the higher Pleistocene terraces called Otwock terrace and Falenica terrace were formed. At the beginning of Holocene the over-flood Praga terrace was formed. The higher flood terrace (Wawer terrace) was developed in the early Holocene. It stretches along both banks of the river, forming the widest flood plain. The digital elevation model based on SRTM data of the river valley and glacial upland is shown at the figure 1. The foundation of the Warsaw as a city can be explained also by the fact that this place offers a convenient passage across the river valley, due to a close proximity of Praga over flood terrace and safe elevation of the glacial plateau where the old town has been build.

According to historical accounts, the largest flood in Warsaw in terms of its extent was the flood of 1635. During this flood, King Władysław IV traveled down the river to Prussia, as it has been described by A. S. Radziwiłł (1593–1656) in the memoirs contained in his diaries[1] as follows: "On 13th June the king departed from Warsaw entrusted to the Vistula route, and appreciating such a great man she widely opened her womb and, in a way not seen for many years, flooded so widely that Praga showed only the roofs of houses, and over the four miles to Radzymin the villages and fruits of the earth were flooded to the great detriment of the owners".

In the period of 19 c., the biggest flood occurred in 1813. In Warsaw, low-lying neighbourhoods and semirural areas from Wilanów to Kazuń were flooded[2]. At that time the Vistula in Warsaw had no embankments; the water flooded the streets of Solec and its church, Czerniakowska, Fabryczna, Przemysłowa, Dobra, Topiel, Furmańska, Browarna, Sowia and Rybaki with their side streets[3].

Łysiak[4] describes the effects of another catastrophic flood in July 1884 on the basis of reports published in Biesiada Literacka. Over 28 km^2 of the district Saska Kępa was flooded, as well as the districts of Żerzeń and Gocław. Wilanów Park was flooded up to the terrace of the palace. The districts of Morysin, Augustówka, Zawady, Siekierki and Czerniaków were under water. This flood was the impetus to undertake regulatory work on the Vistula in Warsaw, linked with the construction of a water intake for the municipal water supply system in the district of Czerniaków.

[1] A. Przyboś, R. Żelewski (eds.), *Pamiętniki o dziejach w Polsce, 1632–1636, Radziwiłł*, Warsaw 1980, Vol. 1.

[2] J. Grela, H. Słota, J. Zieliński J., *Dorzecze Wisły. Monografia powodzi lipiec 1997*, Warszawa 1999.

[3] F. Galiński, *Legendy o Warszawie*, Warsaw 1937.

[4] W. Łysiak, *Historia Saskiej Kępy*, Warsaw 2008.

On 27 March 1924 a transit of the snowmelt flood wave was recorded in Warsaw. Flooding in Warsaw was caused by an ice jam created at km 541; the embankments in Buraków and Jabłonna were breached and the dammed water flooded Czerniaków[5].

On 22 July 1934 a flood wave of a discharge Q = 5460 m^3/s passed through Warsaw. Despite the existing system of embankments, it caused damage in Czerniaków and Wilanów, as well as in Łomianki.

Until almost the end of the 19th century the Warsaw stretch of Vistula river remained in its natural state. The catastrophic flood of July 1884 sparked regulation of the river and construction of the flood protective dikes. In the years 1923–1931 further regulation work was carried out, after the flood of 1924. Immediately after World War II, the river channel of the Vistula in Warsaw became the debris dumping ground, so that the cross sections of the river got narrowed down, forming the so-called Warsaw corset over the segment of 507–517 km (figure 2).

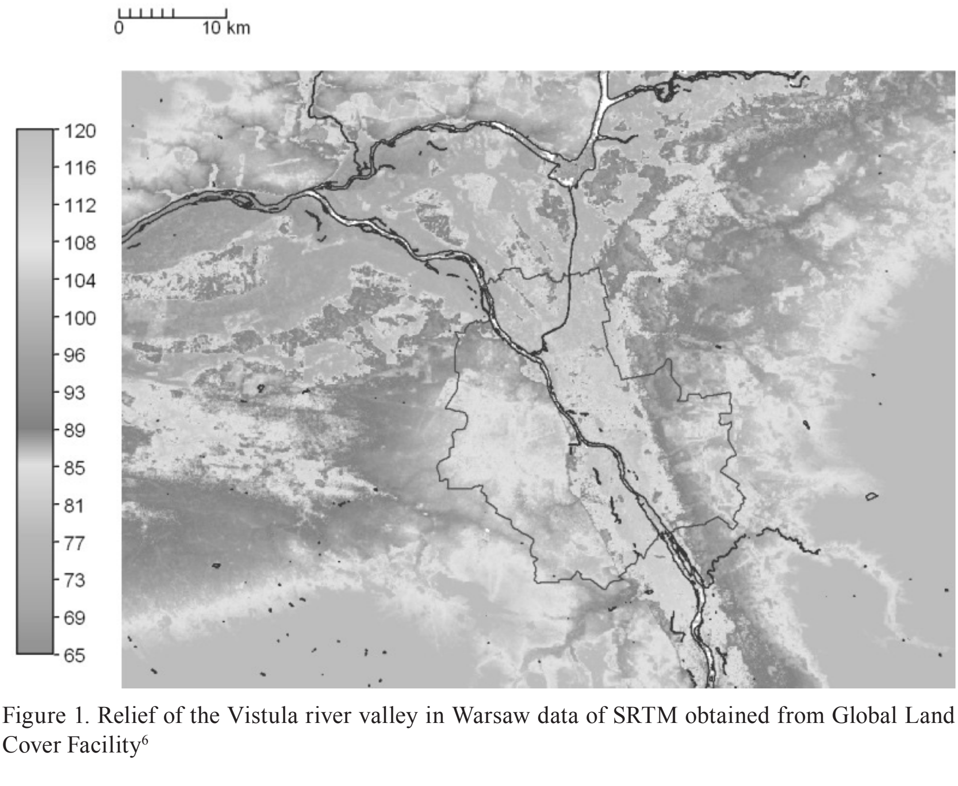

Figure 1. Relief of the Vistula river valley in Warsaw data of SRTM obtained from Global Land Cover Facility[6]

[5] J. Kobendzina, *Powodzie na Wiśle w okolicach Warszawy*, Gospodarka Wodna 1954, R. XIV, Vol. 4, pp. 156–157.

[6] A. Magnuszewski, M. Gutry-Korycka, Z. Mikulski, *Historyczne i współczesne warunki przepływu wód wielkich Wisły w Warszawie cz. I i II*, Gospodarka Wodna 2012, No. 1, pp. 9–17, and No. 2, pp. 58–63.

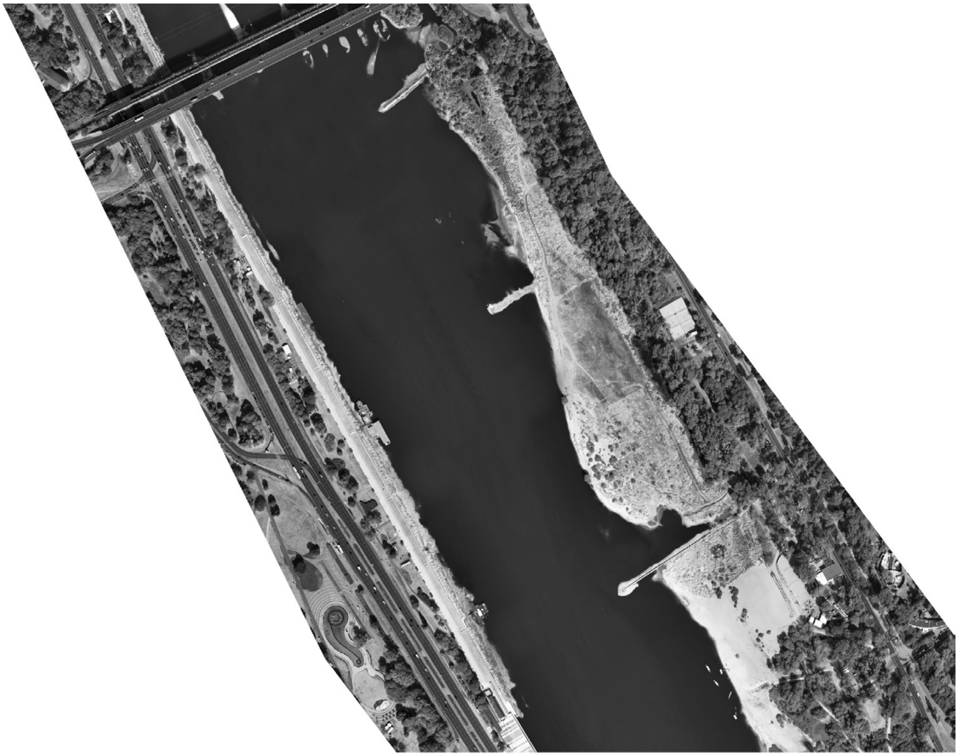

Figure 2. Aerial photo showing part of of the Vistula river "corset" in Warsaw near Gdański Bridge (photo by MGGP Aero)

The hydrological regime of the Vistula River in Warsaw is represented by the water gauge Port Praski, which has been in operation for nearly 200 years. Gauge controls the catchment area of 84 857 km^2, and it is located at the 513 km of the river chainage. Most of the major floods in the Vistula River have been formed in summer by intensive rainfalls in the Carpathian Mountains. The highest recorded by hydrological measurements floods occurred in summer – years 1960, 1962, 2010.

3. METHOD OF FLOOD MAGNITUDE ESTIMATION

Flood risk optimization is the rational process by which managers estimate the level of hazards, and use that knowledge for water management and spatial planning. The estimation of flood risk is done usually in relation to extreme floods levels. There are number of information sources on extreme floods levels. The available approach includes:

1) estimation of maximum flood from hydrological observations and measurements using probability distribution functions;

2) estimation of maximum flood range from geological evidences such as fluvial deposits and river channel forms;

3) 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.

The **first approach** needs long time series of hydrological observations both stage and discharge. Having long time observations, it is possible to use probability methods to calculate the discharge of given recurrence. Vistula is measured in Warsaw at gauge Port Praski. The length of discharge observations is reaching 100 years. Characteristic discharges are[7]: mean low flow QL = 194 m^3/s, average flow QM = 561 m^3/s, Qp1% = 7214 m^3/s, Qp0.1% = 9960 m^3/s. The maximum flood of p0.1% is used for the design of flood protective dikes in Warsaw. Flood protective dikes in the rural area out of Warsaw boundaries are lower and designed for a flood of p1%. Having the value of maximum discharge, it is possible to estimate the potential reach of the flood by comparing digital elevation model altitudes with an altitude of high water.

Having hydrological measurements data it is also possible to find a relationship between catchment area and magnitude of flood. It can be expressed as flood potential index – *k*, calculated after J. François[8] as

$$k = 10 \cdot \left(1 - \frac{\log QH - 6}{\log A - 8}\right),$$

where, QH – highest measured discharge (m^3/s), A – river catchment area (km^2).

Highest *k* values in Poland are common for the mountain rivers such as Dunajec, Soła, Raba, Skawa, all being Carpathian tributaries of the Vistula River. It is possible to draw an envelope line on a maximum values of *k* (figure 3). From this line the maximum possible flood in Warsaw can be estimated as $Q_{max} \approx 9000$ m^3/s.

[7] B. Fal, P. Dąbrowski, *Dwieście lat obserwacji i pomiarów hydrologicznych Wisły w Warszawie. Przepływy Wisły w Warszawie*, Gospodarka Wodna 2001, No. 12, pp. 503–510.

[8] J. A. Rodier, M. Roche, *World Catalogue of Maximum Observed Floods*, Wallingford 1984.

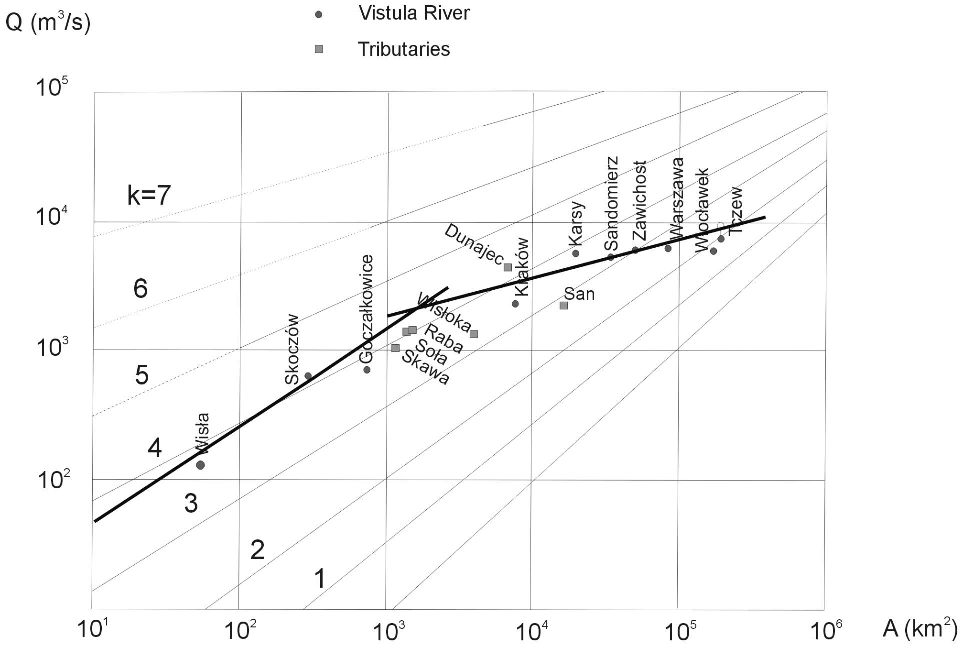

Figure 3. Maximum discharge as a function of the Vistula catchment with selected tributaries[9], on Françou's *k* index and the functions *QH*(*A*): 1 – rivers according to the World Catalogue (2003), and 2 – rivers of Poland[10]

The **second approach** has been used by Polish Geological Institute in the map covering the whole country and representing maximum range of floods in the river valleys[11]. The map has been created using information from the accurate geological maps in the scale 1:50000. It has been assumed that the range of Holocene deposits related to fluvial processes are good indicators of the maximum possible range of contemporary floods. These deposits comprise fluvial sands, silt, peats. Fluvial forms are also analyzed like oxbow lakes, flood cones, river flood terraces. The range of flood estimated from geological evidences for Warsaw is shown at figure 4. About 23% of the city area is located in the potential catastrophic flood range. This method is not giving the value of the discharge but indirectly informs about the reach of the maximum possible flood range. It can be used for spatial planning and first effort to delineate the flood risk. The area of the flood range and the area of the buildings standing on it can be useful characteristic to be considered in the decision making at flood risk management processes.

[9] A. Magnuszewski, *Procesy korytowe rzek nizinnych a bezpieczeństwo powodziowe*, WGSR UW, Warsaw 2013.

[10] B. Fal, *Maksymalne przepływy rzek polskich na tle wartości zaobserwowanych w różnych rzekach świata*, Gospodarka Wodna 2004, No. 5, pp. 188–192.

[11] PIG, *Mapa obszarów zagrożonych podtopieniami w Polsce*, Warsaw 2007.

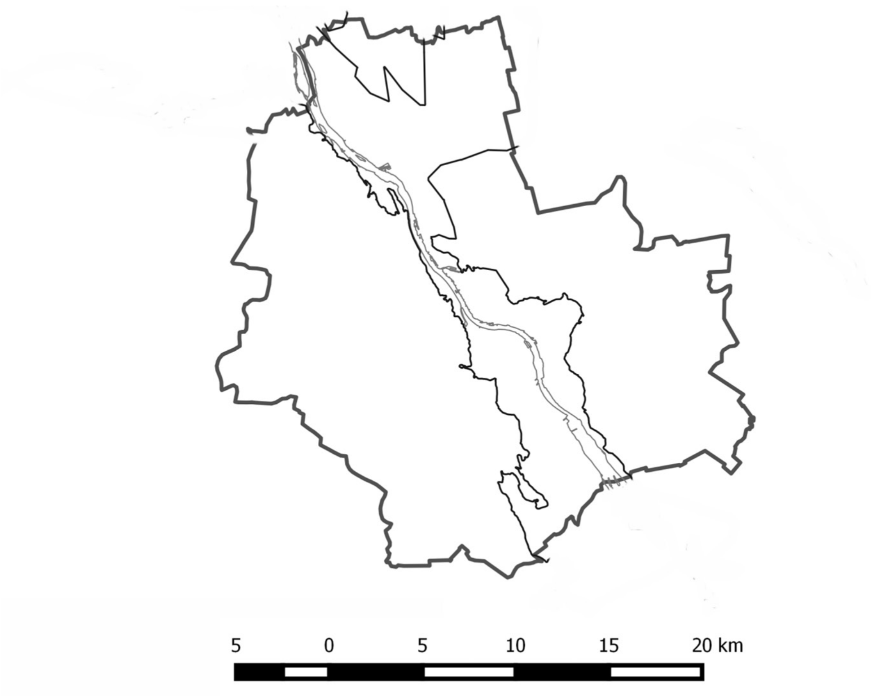

Figure 4. Vistula river reach 500–521 km: range of potential flood of Qp1%

The **third approach** makes use of the retro modeling 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. 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[12].

The level of catastrophic floods is known from high water marks. The flood levels of 1813 and 1844 were commemorated by a cast iron plate on the wall of a building on Klopotowskiego Street in the Warsaw district of Praga (figure 5). High water marks for 1888 and 1891 can also be found on the cover of the spring flowing out at the foot of the hill near the Camaldolese church in the Warsaw district of Bielany.

[12] Y. Jia, S. S. Wang, Y. Xu, *Validation and application of a 2D model to channels with complex geometry*, Int. J. Computational Engng Sci. 2002, pp. 57–71.

Figure 5. Metal plate showing high water mark of the floods from 1813 and 1844 years at Kłopotowskiego street in Warsaw

The numerical calculations are carried out at the nodes of an irregular rectangular mesh. Data needed in the modeling comprise geometric data of the channel and flood plain, as well as Manning roughness values. For retro modeling 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 modeling 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[13]. An example of the retro modeling approach is shown at figure 6, representing flow in a natural conditions (without the flood protective dikes). Using retro modeling, it was possible to estimate the discharge corresponding to the high water marks of the catastrophic floods from 1813 and 1844 years (table).

[13] P. Kuźniar, A. Magnuszewski, *Przepływ wód wielkich Wisły w Warszawie – rekonstrukcja powodzi historycznych*, (in:) A. Magnuszewski (eds.), *Hydrologia w ochronie i kształtowaniu środowiska. Monografie Komitetu Inżynierii Środowiska*, Warsaw 2010, No. 69, pp. 109–118.

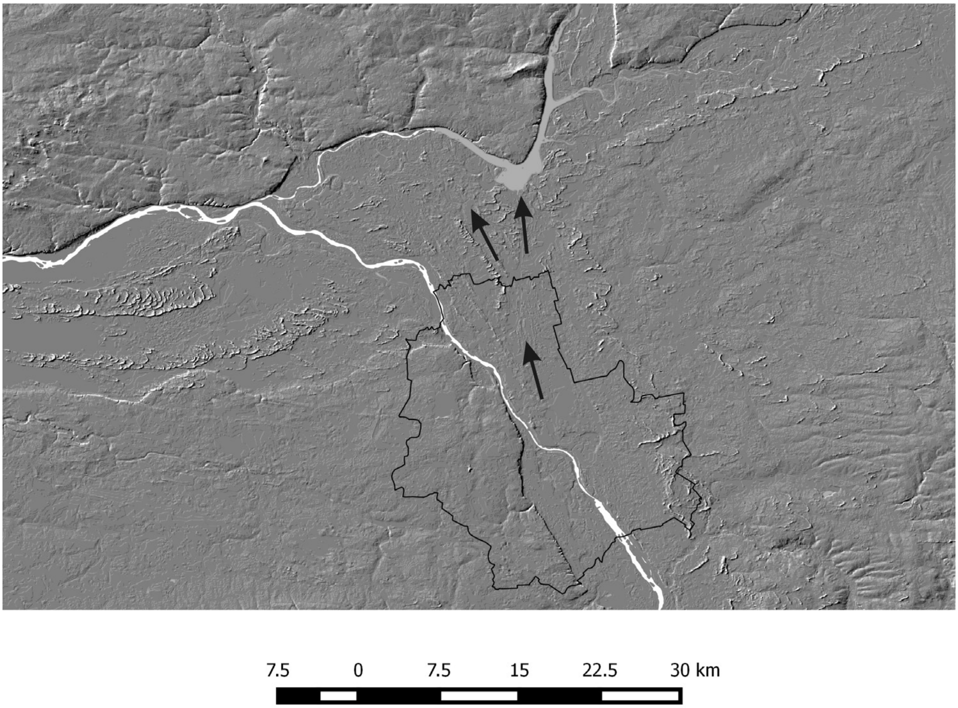

Figure 6. Flow of one thousand years recurrence flood Q $p_{0,1\%}$ calculated by CCHE2D hydrodynamic model across the city of Warsaw in natural conditions without the flood protective dikes

It has been proved also that in a natural state the extreme floods could flow over Praga terrace finding a shortcut directly to Narew tributary of Vistula.

Table

High water stages and corresponding discharge of the largest historical floods of the Vistula River in Warsaw profile (Port Praski) obtained from retro modelling by CCHE2D

Water stage H (cm)	**Year**	**Origin of the flood S – snow melt/R – rainfall**	**Discharge Q (m^3/s)**
849 (863)	1844	R	8 250
808	1813	R	7 430

4. DISCUSSION

Presented methods of extreme flood estimation can be seen as a complementary. The classical approach based on probability distribution functions has many inadequacies resulting from limited length of hydrological observations, changing climate conditions and changes caused by river training and embankment structures. The flood range estimation by retro-modeling is interesting due to the fact that we have a record of high water marks and other proxy data such as press reports. The retro modeling can also be used for verification of the historical floods range. In this way the flood range of 1635 is evidently overestimated. The maximum width of the flooded valley could be 5 km in the borders of Warsaw, while in the report of Radziwiłł we read about the distance to Radzymin which is about 28 km.

In the design stage of water engineering many structures such as bridges, flood protective dikes, and boulevards, there is an important unknown about the maximum possible flood magnitude. Presented methods can give the approximation of such a maximum flood. This information is also very important for flood risk management. One of the important aspects is lowering the flood risk exposition which can be done by proper spatial management. Warsaw is a very fast growing metropolis characterized by urban sprawl. The knowledge about the historical floods range is very important for proper decisions in spatial planning.

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Summary

Flood risk management is the recent methodology of lowering flood hazard in the urban areas. One of the important aspects of the flood risk is the exposure to the flood risk due to an improper settlement location. The spatial planning and estimation of the exposure to flood can be done on the basis of proper information of extreme floods. Three methods of maximum historical floods range and discharge estimation has been discussed. The example of the Vistula River in Warsaw has been used as a case study.

ZASIĘG POWODZI W WARSZAWIE – PERSPEKTYWA HISTORYCZNA I HYDROLOGICZNA

Streszczenie

Zarządzanie zagrożeniem powodziowym to nowa metodologia zmniejszania niebezpieczeństw dla przestrzeni miejskiej. Jednym z ważnych aspektów zagrożenia powodziowego jest ekspozycja na zalanie spowodowana niewłaściwą lokalizacją zabudowań. Planowanie przestrzenne i ocena zagrożenia powodziowego mogą być dokonane na podstawie właściwej informacji o ekstremalnych powodziach. W niniejszym artykule

dokonano analizy studium przypadku powodzi Wisły w Warszawie w różnych okresach historycznych, biorąc pod uwagę trzy metodologie oceny wielkości powodzi ekstremalnych w miastach.

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KEYWORDS

Vistula river, Warsaw, flood risk, spatial planning, retro modeling

SŁOWA KLUCZOWE

Wisła, Warszawa, zagrożenie powodziowe, planowanie powodziowe, modelowanie historyczne