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Problems with Modelling Water Distribution in Open Channels with Hydraulic Engineering Structures

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1. Introduction

Exceptional progress has been observed in modelling of open channels flow due to the extensive access to advanced 1-, 2- and 3D hydraulic models integrated with GIS systems [4]. However, the amount of work and costs connected with the preparation of data for the creating of a 2D/3D model does not always yield more accurate results in comparison to simplified models (1D or black-box) [12]. This is connected first of all with low quality of digital elevation models (DEM). In Poland the digital elevation model, developed for the purpose of the Land Parcel Identification System (LPIS) for the entire territory of Poland, is very often used in engineering practice [11]. However, the low spatial accuracy, elevation errors and a lack of river channel geometry force users of hydraulic models to perform time-consuming and costly surveying in order to improve DEM quality and to supplement information on the river channel. At present within the framework of the project implementing the Computerized Information System of Country Protection from Extraordinary Hazards (Polish: Informatyczny System Osłony Kraju przed nadzwyczajnymi zagrożeniami ISOK) a DEM is being developed using LIDAR (Light Detection and Ranging). The DEM is being developed for areas, in which the highest flood risk is found. Within the framework of the Preliminary Flood Risk Assessment (PFRA) prepared in Poland, out of the 39 805 km examined rivers approx. 14 841 km were classified in the first stage to the development of flood risk maps. The DEM prepared with the use of LIDAR within the Computerized Information System of Country Protection from extraordinary hazards will be made in two standards. In one standard it will be the DEM for non-urbanized areas and small towns, where measurement point density is 4 per 1 m^2 and 6 per 1 m^2, the area covered in the study is 182 403 km^2 and 8 148 km^2, respectively [9]. A separate DEM will be prepared for 94 bigger towns, where the measurement point density is going to be 12 per 1 m^2 and the total area covered by measurements will be 13 769 km^2. Preparing a DEM with the use of LIDAR will make it possible to improve accuracy of calculations, since at present the mean elevation error DEM LIPS is below 1.5 m, while in the case of the DEM of the Computerized Information System of Country Protection from extraordinary hazards it is going to be below 0.1 m. However, applied measurement techniques do not make it possible to take bathometer measurements of the river channel with the same spatial accuracy [7]. For this reason it is necessary to take detailed surveying of the river channel bathymetry and to integrate it with the existing DEM. Measurements taken with a lower spatial accuracy result in a situation when intermediate sections have to be generated using different interpolation algorithms. While DEM accuracy has a significant effect on modelling of flows in the high flow zone, it has no practical importance in the modelling of water distribution in the river channel in the low and mean flow zones. In such a situation the quality of modelling results is determined only by the quality of the digital model of the river channel. A significant problem is also connected with hydroengineering structures, determining water distribution at low and mean flows. Thus it is necessary to provide their highly accurate description, i.e. the schedule of works and curves of discharge of sluices.

The aim of this study was to construct a model of the Kalisz Hydrotechnical System with hydroengineering facilities and next to simulate water flows with a 1% exceedance probability. As a result of the analyses and simulations a digital flood risk map was prepared for the town of Kalisz and adjacent areas.

2. Materials and methods

Modelling of water distribution at the Kalisz Hydrotechnical System (Kaliski Węzeł Wodny – the Kalisz Hydrotechnical System) was based on the DEM prepared within the project of the Computerized Information System of Country Protection from extraordinary hazards purchased from the Central National Geodetic and Cartographic Inventory in Warsaw (Centralny Ośrodek Geodezji i Kartografii w Warszawie – CODGIK). Individual files correspond in their range to 27 map sheets at a 1:5 000 scale. Due to the fact that the available DEM does not contain information on river bathymetry it was necessary to prepare cross-sections of the channels for the Prosna River, the Bernardyński Canal, the Rypinkowski Canal as well as the Swędrnia and the Pokrzywnica. On the Prosna measurements were taken at the segment from the Piwonice section (69 km +800 according to the Regional Water Management Board data) to the section located 300 m below the weir at Nowa Wieś Kościelna.

Geodetic measurements were taken using a GRX-1 device by SOKKIA. Measurement accuracy of this device for X and Y coordinates is 10 mm + 1 ppm, while for the Z coordinate it is 20 mm + 1 ppm, respectively. The applied communication and control software was the Sokkia Spectrum Field ver. 8.1 installed at the SHC-250 controller, while post-processing was performed using the Topcon Link ver. 8 and Spectrum Survey Office ver. 8.2 programmes.

Measurements of river channel bathymetry, velocity and flow were taken using an ADCP StreamPro probe by Teledyne RD Instruments. The probe is used for measurements on small and medium-sized rivers with a depth of 0.1–6.0 m and velocity is measured at the range of $\pm 5\ m{\cdot}s^{-1}$. Velocity measurement is accurate to $\pm 2\ cm{\cdot}s^{-1}$ and flow rate is approx. 2%. Measurements were taken on a total of 42 cross-sections on the Prosna, 14 cross-sections at the Bernardyński Canal, 2 at the Rypinkowski Canal and 6 at the Swędrnia. The gauging sections were situated at locations facilitating detailed analyses of water distribution at the Kalisz Hydrotechnical System, as shown in Fig. 1.

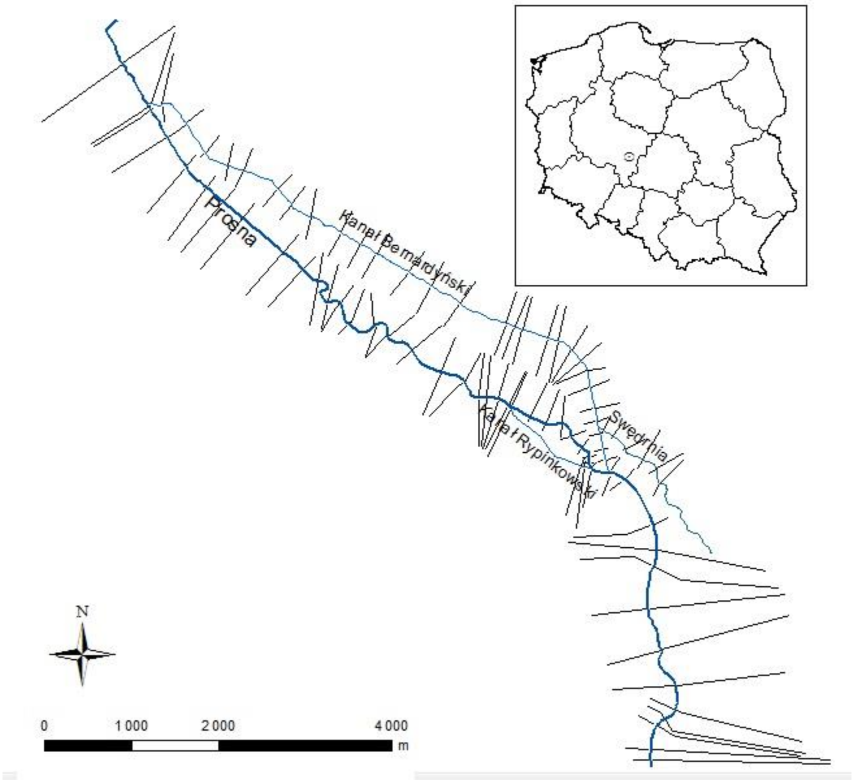


Fig. 1. Study site location
Rys. 1. Lokalizacja obiektu badań

Geodesic measurements and river channel bathymetry supplemented the purchased DEM with the river channel data according to the methodology proposed by [8]. The applied method provided better results when constructing the DEM of the river in comparison to conventional methods using linear interpolation algorithms, which have limitations in case of meandering rivers.

In the course of field work a detailed survey was also performed for hydroengineering structures (weirs and drop falls) and clearance measurements were taken at bridge sections in the Kalisz Hydrotechnical System. The study was also based on data supplied by the Regional Water Management Board on the characteristics of hydroengineering structures.

A 1D model of analysis and forecasting of unsteady flows SPRUNER [5] was applied in modelling of water distribution in the low flow zone.

The model was calibrated based on high flow WQ = 130 $m^3 \cdot s^{-1}$ measured during the flood of 2010 at the Piwonice profile – variant 0. Moreover, traces of high water from the year 2010 were also used, as well as archival photographic documentations of the flooded areas. Computer simulations were prepared for 3 adopted variants, i.e. variant I – full opening of the Rypinkowski Weir for the flood of 2010, variant II – optimal control of the operation of the Rypinkowski and Franciszkański weirs, and variant III – passage of high water with a 1% exceedance probability.

3. Results and discussion

3.1. Study area

The Prosna River is the biggest left-side tributary of the Warta River, with the total catchment area of 4924.7 km^2. From the river-head located at an altitude of 272 m a.s.l. to confluence to the Warta located at 70 m a.s.l. the river travels 216.8 km, which gives the mean slope of 0.7‰.

Detailed studies and field observations were conducted at the Kalisz Hydrotechnical System, which according to the Regional Water Management Board comprises the Prosna River at the segment from the bridge at the Księżna Jolanta street at 70+050 km to the bridge above the town of Warszówka 63+570 km, with its tributaries in the town of Kalisz. However, from the hydraulic point of view the analysed hydratechnical system comprises the Prosna from the section located above the Bernardyński Canal (km) to the section located below the Bernardyński Canal (km) together with the Rypinkowski and Bernardyński Canals, the Pokrzywnica and Swędrnia rivers as well as the other small tributaries flowing the Prosna in the town of Kalisz.

The Prosna catchment area to the Piwonice gauging station is 2938,2 km^2, while to the section located immediately below the confluence of the Bernardyński Canal is 3999.44 km^2, which corresponds to approx. 60% and 80% total catchment area. In Kalisz the Pokrzywnica flows into the Prosna at km 69+300 km and the total catchment area is

482.59 km^2. Next at 66+550 km the river branches and there the Bernardyński Canal starts, which main task is to carry high waters through the town. The total length of the Bernardyński Canal is 7.5 km. At 7+050 km the Swędrnia River flows to the Bernardyński Canal and the total catchment area of that river is 551.91 km^2. At 66+200 km of the Prosna the Rypinkowski Canal starts, which again flows to this river at 64+850 km, with the total length of the canal of 1.2 km. The Kalisz Hydrotechnical System is completed with the gauging station located below the confluence of the Bernardyński Canal to the Prosna.

3.2. Hydrological conditions

Hydrological measurements on the Prosna have been conducted since 1922 at the Piwonice profile at 69+800 km. The total catchment area of the Prosna to the Piwonice profile is 2938,2 km^2, the zero of the gauging station is set at an altitude of 101.98 m a.s.l. The Prosna is characterised by the snow-rain regime. The highest flows on the river are recorded in the period from February to April, while the lowest from August to September. The analysed catchment has a limited water storage capacity, while the extreme flow variation coefficient calculated as a quotient of SWQ and SNQ is 22. Water resources of the Prosna catchment are low, with the mean specific yield of approx. 4 $dm^3 \cdot s^{-1} \cdot km^{-2}$. Mean flow of the Prosna in the Piwonice profile in the years 1951–1990 was SSQ = 11.5 $m^3 \cdot s^{-1}$ at minimum flow NNQ = 1.26 $m^3 \cdot s^{-1}$ and maximum flow WWQ = 189 $m^3 \cdot s^{-1}$ (tab. 1).

Table 1. Characteristic flows of rivers in the Kalisz Hydrotechnical System [1, 2, 3]
Tabela 1. Przepływy charakterystyczne rzek KWW [1, 2, 3]

	Name of river	Profile	Years	Catchment area A [km^2]	Characteristic flows [$m^3 \cdot s^{-1}$]				
					NNQ	SNQ	SSQ	SWQ	WWQ
1	Prosna	Piwonice	*	2938.2	1.37	3.18	11.5	65.1	127.0
			51-70		1.26	2.67	10.2	63.2	152.0
			51-90		1.26	3.16	11.5	69.1	189.0
2	Pokrzywnica	Kalisz	*	476.1	0.042	0.26	2.03	15.0	28.0
3	Kanał Bernadyński	-		-	-	-	-	-	-
4	Kanał Rypinkowski	-		-	-	-	-	-	-
5	Swędrnia	Kalisz	*	544.0	0.11	0.25	1.92	14.7	46.9
6	Piwonka	-		14.4	-	-	-	-	-
7	Krępica	-		17.5	-	-	-	-	-

The slight storage capacity of the Prosna catchment results in a situation when in the summer flows in the river are very low, while during the spring thaw there are flows which may cause floodings or floods in Kalisz. The base flow of the Prosna at the Piwonice profile, as specified by the Institute of Meteorology and Water Management, the State Research Institute, Branch in Poznań, amounts to $WQ_{1\%} = 199\ m^{3} \cdot s^{-1}$, while the control flow $WQ_{0,3\%} = 242\ m^{3} \cdot s^{-1}$ (tab. 2).

Table 2. Maximum flows as defined by the exceedance probability of the Prosna at the Piwonice profile (source: IMGW Poznań**)**
Tabela 2. Przepływy maksymalne o określonym prawdopodobieństwie przewyższenia rzeki Prosny w profilu Piwonice (źródło: IMGW Poznań)

Probability [%]	WQ [$m^{3} \cdot s^{-1}$]
0.1	280
0.3	242
0.5	224
1	199
2	174
3	160

3.3. Hydraulic analysis

In the course of field studies a total of 64 cross-sections were performed on site, at which measurements of flow rates were also recorded. On the Prosna 42 cross-sections were identified, which were characterised by variable geometry and hydraulic parameters. The width of the water table at cross sections during measurements ranged from 9.08 to 167.95 m, while surface area ranged from 8 to 102 m^2. Additionally, on the Prosna and the Bernardyński and Rypinkowski Canals weirs were constructed, which task was to provide optimal water distribution in the Kalisz Hydrotechnical System (Tab. 3). Mean water table slope of the Prosna in the segment from the Księżna Jolanta bridge to the Franciszkański weir is 0.47‰, while from the Franciszkański weir to the weir at Nowa Wieś Klasztorna it is 0.55‰. Slightly higher mean water table slope are found at the Rypinkowski and Bernadyński Canals, amounting to 0.74‰ and 0.64‰, respectively.

Table 3. Major hydroengineering structures in the Kalisz Hydrotechnical System
Tabela 3. Wykaz ważniejszych budowli hydrotechnicznych KWW

No.	Type and name of structure	[km]	Number of spans	Clearance of spans	Net clearance of structure	Water rise head
1	Franciszkański weir	65+040	4	3.80m; 3.82m; 3.80m; (2.45m+1.39m	15.26m	2.23m
2	Rypinkowski weir	1+150	5	3.94m; 3.93m; 4.00m; 3.95m; 4.05m	19.87m	2.75m
3	Weir at the Bernardyński Canal	7+550	2	2 x 16.0m	16.0m	2.50m
4	Weir at Kościelna Wieś	69+000	8	8x3.25	26	2.5
5	Fascine and stone sill at Piwonice	69+550	-	-	22.0 m	0.5 m

3.4. One-dimensional unsteady flow analysis and prediction system

The analysis of flow conditions for the Prosna river on the channel reach in question was carried out using a one-dimensional unsteady flow analysis and prediction system called SPRUNER [5]. This system was used to perform several simulations of flow through the Kalisz Hydrotechnical System for historical waves having various probabilities of occurrence. The SPRUNER was developed in the framework of the research project carried out at the Faculty of Land Reclamation and Environmental Engineering, the Poznań University of Life Sciences, from mid-1993 to 1995. The program is based on the Saint-Venant equations [6]:

The mass conservation equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial (A_C + A_O)}{\partial t} = q \qquad (1)$$

The momentum equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial(\beta Q^2/A)}{\partial x} + gA(\frac{\partial h}{\partial x} + S_f + S_{ec}) + W = 0 \qquad (2)$$

where: Q – flow rate [m^3/s], h – water table ordinate [m], x – cross-section position coordinate [m], t – time [s], g – acceleration due to gravity [m/s^2], q – unitary lateral inflow on the length of the watercourse [m^3/s/m], β – momentum coefficient [-], S_f – hydraulic gradient [-], S_{ec} – term representing loss due to the cross-section getting narrower or wider [-], $W = qQ/A_c$ – term representing the unitary lateral inflow in the equation of motion [m^3/s^2].

Boundary and initial conditions must be determined in order to solve the above equations. An implicit weighted four-point, finite difference solution technique was applied in SPRUNER system to solve the equations.

3.5. Water distribution in the Kalisz Hydrotechnical System

Simulation calculations showed that during the flood of 2010 water distribution at the Kalisz Hydrotechnical System was as follows. The Bernardyński Canal carried approx. 49% total flow, while the Prosna at the section within the town limits carried 26% and the Rypinkowski canal – 25%, respectively. Control of the operation of the Rypinkowski and Franciszkański weirs changed the percentage distribution of water between the analysed flood relief channels and the Prosna (Tab. 5). The amount of water carried by the Bernardyński Canal increased to 55% and in the Prosna within the town limits it increased to 28%, while flows in the Rypinkowski Canal decreased to 17%. Weir control in the Kalisz Hydrotechnical System would have made it possible to reduce flood damage caused during the flood of 2010.

At the final stage of the study simulation calculations were performed for high water with exceedance probability of 1%. Calculations showed that optimally water distribution at the Kalisz Hydrotechnical System, in order to minimize flood damage, should be as follows: the Prosna within the town limits should carry approx. 47.95 $m^3 \cdot s^{-1}$ (24%), the Rypinkowski Canal 51.01 $m^3 \cdot s^{-1}$ (26%), while the other 101.05 $m^3 \cdot s^{-1}$ (50%) should be carried by the Bernardyński Canal. Such a water distribution at a 1% flow will not assure a safe passage of high water through the town of Kalisz. We need to take into consideration the occurrence of flood in areas located above the bridge at the street Ulica Piłsudskiego (over the Prosna) and above the bridge in the direction of the town of Warszówka at the Bernardyński Canal. As a result of damming of the Swędrnia considerable flooding occurred in the Rajsków district as well as the sports and leisure facilities in the street Ulica Sportowa.

Table 4. Water distribution in the Kalisz Hydrotechnical System
Tabela 4. Wykaz ważniejszych budowli hydrotechnicznych KWW

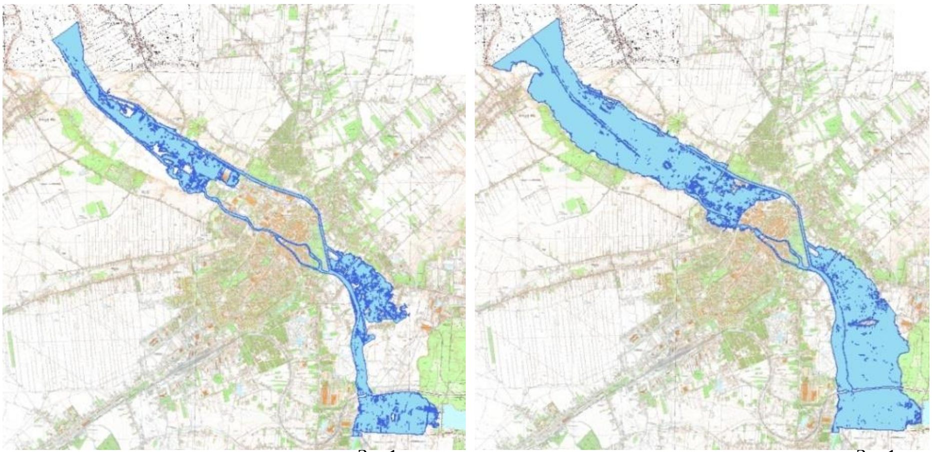
Variant	Prosna Miejska [m^3/s]	Rypinkowski Canal [m^3/s]	Bernardyński Canal [m^3/s]	Bernardyński Canal – below the confluence of the Swędrnia [m^3/s]
0	36.12	34.26	67.62	93.62
I	33.88	37.76	66.36	92.35
II	38.18	23.42	76.4	102.39
III	47,94	51.01	100.05	126.06

Table 5. Water stages in the Kalisz Hydrotechnical System during passage of high waters
Tabela 5. Stany wody w KWW podczas przejścia wód wielkich

	Stages					
va-riant	Weir Ry-pinkowski GW [m a.s.l.]	Weir Bernar-dyński GW [m a.s.l.]	Weir Fran-ciszkański GW [m a.s.l.]	Chopin bridge [m a.s.l.]	Wojska Polskiego bridge [m a.s.l.]	Swędrnia – Trasa Bursztyno-wa bridge [m a.s.l.]
0	102.83	102.78	102.50	102.28	102.07	102.751
I	102.80	102.75	102.51	102.31	102.10	102.729
II	103.01	102.94	102.72	102.07	101.88	102.904
III	103.42	103.37	103.14	102.89	102.63	

Distributions of water stages obtained over the length of individual canals of the Kalisz Hydrotechnical System were introduced to the DEM in order to determine the range of floodings for flows from variants 0 and III (Fig. 2). Determination of the flooding range for variant 0 was to verify the adopted methodology by comparing the obtained results with aerial photographs ordered by the Town Office of Kalisz on 23 May

2010. Aerial photographs confirmed the area consistency of the range of flooding for variant 0. Next the range of flooding for a 1% flow (variant III) was determined. Analysis of this variant indicates the risk of flooding for urbanized areas located close to the town centre caused by the backwater overspill through a depression of Piłsudskiego street (63+270 km). The Prosna overflows to the right bank in the depression below the sections at 63+270 km and initially the range is based on the escarpment of Ulica Piłsudskiego. With an increase in filling the altitude of water exceeds the altitude of the depression in Piłsudskiego street and water flows into areas located above this street. Also the Bernardyński Canal will exceed altitudes of the escarpments on the left bank above the bridge in the direction of Warszówka.



Variant „0", Q=130 m^3s^{-1} Wariant „III", $Q_{1\%}$=199 m^3s^{-1}

Fig. 2. Flood hazard zone for variant "0" and "III"
Rys. 2. Zasięg zalewu dla wariantu „0" i „III"

4. Conclusions

The constructed model of the Kalisz Hydrotechnical System makes it possible to conduct analyses of high water ranges and the distribution of flow over an entire range of stages and flows. Its construction required a combination of a highly accurate DEM with measurements of watercourse bathymetry. An important element was to determine hydraulic parameters of hydroengineering structures having a considerable influence on the distribution of stages and flows during the passage of high waters and determining these distributions for medium and low waters. The application of results obtained from a 1D model of flow made it possible to determine flood risk zones with no need to construct a highly time and work consuming 2D model.

Preliminary analysis of results indicates a considerable flood risk for the town of Kalisz and the need to improve the flood protection system in all its aspects. It is necessary to construct levee of the Swędrnia in order to protect the district of Rajsków, levee of the right bank of the Prosna below Ulica Piłsudskiego, as well as reconstruct embankments of the Bernardyński Canal. Another solution would be to initiate the construction of the Wielowieś Klasztorna reservoir, which would reduce maximum flows to the level of approx. 105 $m^3 \cdot s^{-1}$, constituting at present the flow level causing no flood damage.

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References

1. *Atlas hydrologiczny Polski*. Wydawnictwo Geologiczne, Warszawa, 1986.
2. *Atlas posterunków wodowskazowych dla potrzeb Państwowego Monitoring Środowiska*. Państwowa Inspekcja Ochrony Środowiska, Warszawa – Katowice, 1996.
3. **Galuba M., Pancewicz M.:** *Kaliski Węzeł Wodny i zarządzanie wodami*. Kalisz, 2005.
4. **Knebl M.R., Yang Z.-L., Hutchison K., Maidment D.R.:** *Regional scale flood modeling using NEXRAD rainfall, GIS, and HEC-HMS/RAS: a case study for the San Antonio River Basin Summer 2002 storm event*. Journal of Environmental Management 75, 4, 325–336 (2005).
5. **Laks I**., **Kałuża T.:** *Modelowanie nieustalonych przepływów w rzekach nizinnych na przykładzie Warty*. Wydawnictwo Uniwersytetu Przyrodniczego w Poznaniu, 2012.
6. **Maidment D.R.(editor):** *Handbook of Hydrology*. McGRAW-HILL INC, New York, 1992.
7. **Marks K., Bates P.:** *Integration of high resolution topographic data with floodplain flow models*. Hydrol. Process. 14, 2109–2122 (2000).

8. **Merwade V., Cook A., Coonrod J.:** *GIS techniques for creating river terrain models for hydrodynamic modeling and flood inundation mapping.* Environmental Modelling & Software 23, 1300–1311 (2008).
9. **Projekt ISOK:** *Informatyczny system osłony kraju przed nadzwyczajnymi zagrożeniami*. Warszawa, 2012.
10. **Smemoe C., Nelson E., Zundel A., Miller A.:** *Demonstrating floodplain uncertainty using flood probability maps*. Journal of the American Water Resources Association vol. 42, No. 2, 359–371 (2007).
11. **Sojka M., Murat-Błażejewska S., Wróżyński R.:** *Application of digital elevation model and aerial photographs for modelling flood prone areas in small lowland rivers.* Rocznik Ochrona Środowiska (Annual Set the Environment Protection), 14, 172–181 (2012).
12. **Szymkiewicz R.:** *Modelowanie matematyczne przepływów w rzekach i kanałach*. Wyd. Nauk. PWN, Warszawa, 332 (2000).

Problemy modelowania rozrządu wody w kanałach otwartych z zabudową hydrotechniczną

Streszczenie

W pracy przedstawiono zagadnienia modelowaniu rozdziału przepływu w sieci rzecznej z zabudową hydrotechniczną na przykładzie Kaliskiego Węzła Wodnego. Jednowymiarowy model Kaliskiego Węzła Wodnego został utworzony z wykorzystaniem systemu modelowania przepływów nieustalonych SPRUNER. Dane o geometrii obszaru przepływu zostały opracowane na podstawie pomiarów bezpośrednich batymetrii i parametrów budowli hydrotechnicznych oraz numerycznego modelu terenu bazującego na pomiarach LIDAR. Wykonano procedurę tarowania modelu dla fali powodziowej z 2010 roku. Przeprowadzono symulacje rozdziału przepływu dla 4 wariantów. Wyniki symulacji zostały naniesione na numeryczny model terenu w celu wyznaczenia zasięgu zalewu dla fali z 2010 roku oraz dla przepływu o prawdopodobieństwie 1%.

Przeprowadzone badania wykazały, że Numeryczny Model Terenu wpływa istotnie na modelowanie przepływów w strefie przepływów wysokich, to praktyczne nie ma znaczenia przy modelowaniu rozrządu wody w korycie w strefie przepływów niskich i średnich. Wtedy, o jakości uzyskanych wyników z modelowania decyduje tylko, jakość numerycznego modelu koryta rzeki. Istotny problem stanowią także budowle hydrotechniczne, które decydują o rozrządzie wody przy przepływach niskich i średnich. W związku z tym konieczny jest ich bardzo dokładny opis tj. harmonogram pracy oraz krzywe wydatku urządzeń upustowych.