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Impact of Digital Terrain Model Uncertainty on Flood Inundation Mapping

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1. Introduction

Significant technological progress in recent years caused that the process of determining the flood hazard zones is relatively easy. There are many available hydrological and hydraulic models, both commercial and public. Note, however, that all of them, even the most advanced, are useless if the input data are subject to large errors. In the process of determining flood zones, all input data uncertainties and the uncertainty of the model itself is transferred to the final result of calculations. The final product in the form of flood hazard maps does not contain information about the quality of data used in its preparation, so it is impossible to determine the reliability degree of the maps by the user. The problem of data uncertainty and its impact on modeling is recently noticed by scientists around the world [1, 9, 12].

Nowadays, there are two approaches for flood modeling, first engineering (classical method – deterministic) and other researches (probabilistic). In the classical method of determining the flood hazard zones, the result of a simulation is one zone of the assumed flood flow, which does not include the uncertainties of input data. Another approach is used in the probabilistic methods for flood hazard mapping in which it is assumed that the input data are subject to error. The result is a probabilistic flood hazard map [10].

Great technological advances in computer modeling in recent years, allows you to include more factors in calculations. So far, the problem of uncertainty in hydrological and hydraulic modeling is not sufficiently noticed especially in engineering practice, there is no regulatory requirement to consider uncertainties in determining flood zones.

2. The aim of the researches

The aim of this study was to analyze the impact of digital terrain model (DTM) uncertainty on the size of the flood risk zones. Uncertainty assessments were performed using Monte Carlo method. Computer simulations were carried out using a hydraulic model HEC-RAS with HEC-GeoRAS extension on Mala Welna river on the reach from Kiszkowo 1 cross-section to Kiszkowo 2 cross-section, where floods were observed and documented in the years 1998–2012 by Land Reclamation and Environmental Engineering employees. Analysis and discussion of the results was carried out in relation to the flood hazard zone designated by the classical method, which does not take into account the impact of data uncertainty on the size of the flood risk zones and a probabilistic method, in which the final result was a probabilistic flood hazard map.

3. Materials and methods

Digital Terrain Model, developed on the basis of aerial photographs in the scale of 1:26 000, with 25 m spatial resolution, in the form of Triangulated Irregular Network (TIN) and raster topographic map obtained from the Central National Geodetic and Cartographic Inventory no. N-33-131-Ba-3 scale of 1:10 000 were used to determine the flood hazard zones. DTM obtained from Polish database is not suitable for modeling flood hazard zones because it does not contain information about the river bathymetry. Therefore, it was necessary to carry out own field measurements, which included probing depth of the river and performing additional surveying using the Doppler probe ADCP (Acoustic Doppler Current Profiler) Stream Pro developed by Teledyne Instruments and Topcon GPS RTK module [11]. Collected data allowed to include the river channel into DTM. Improvement of DTM was performed using ESRI's ArcGIS software according to the methodology proposed by Merwade [7].

DTM, made for the Polish database is loaded with errors, that can significantly affect the size of the designated flood hazard zones. This study assumes that the DTM of the Mala Welna River analyzed section is charged with the same errors as in the Hejmanowska studies [5]. Empirical distribution of error presented by Hejmanowska was described by the distribution function using Mathwave's EasyFit software.

In the first stage of assessing the impact of DTM uncertainty on the size of the flood risk zones, TIN nodes were extracted. The resulting points had X and Y geographic coordinates and altitude H. Total amount of 221 points were extracted within the Mala Welna River valley from section Kiszkowo 1 to section Kiszkowo 2. According to the Monte Carlo methodology, height of nodes were modified with the approved theoretical distribution of error. Total of 1000 new digital elevation models were made, which were the input data for HEC-RAS with HEC-GeoRAS extension model.

Mala Welna River flood zone from section Kiszkowo 1 to section Kiszkowo 2 has been determined for the maximum flow with the probability of occurrence of 0.2%, $WQ_{0.2\%} = 18.21$ m^3/s [11]. Geometric data for the model were developed in ArcGIS software with HEC-GeoRAS extension which allows to prepare input data, and export them into hydraulic model HEC-RAS. After calculations, the final results are imported back to geographic information system for their spatial visualization.

HEC-RAS model developed by the U.S. Army Corps of Engineers is one-dimensional hydraulic model, used to calculate the water level heights in open channels. Calculations can be performed for steady and unsteady flow, including the influence of hydraulic structures on the flow conditions [2, 3, 6, 13]. HEC-RAS model enriched with HEC-GeoRAS extension allows to enter geometry data of an object in ArcGIS software. This requires additional data in the form of digital terrain model, but eliminates the possibility of making mistakes during manual data entry and greatly speeds up the work [4]. HEC-GeoRAS allows for entry such objects as streams, banks, flow paths, bridges and culverts, Leeves, blocked obstructions, Landuse areas (manning coefficients), storage areas and others.

The end result of a single simulation is vector flood hazard zone, which then, in order to automate the calculation was converted into a raster (grid size of 1.0 to 1.0 m) with value of 1. Each session was performed for 50 simulations, and the results obtained after the subsequent sessions were compared. It was assumed that the process of simulations will be completed when the surface of flood zone with likelihood of appearance of 100% and 1% of the i-th session of the simulation will vary by less than 0.5% of the surface of flood zone of the j-th session simulation by the following formula:

$$\frac{\boldsymbol{A}_{\boldsymbol{z_i}} - \boldsymbol{A}_{\boldsymbol{z_j}}}{\boldsymbol{A}_{\boldsymbol{z_j}}} < 0{,}5\% \tag{1}$$

where:

$\boldsymbol{A}_{\boldsymbol{z_i}}$ – surface of flood zone of i-th simulation session
$\boldsymbol{A}_{\boldsymbol{z_j}}$ – surface of flood zone of j-th simulation session

Flood inundation maps made by the classical method based on original DTM, and flood probability maps made with Monte Carlo method were the final result of the performed simulations.

4. Results and discussion

The catchment of the Mala Welna River is situated in the central part of Poland, in the Odra River basin. Total area of the Mala Welna catchment equals 688 km^2. The length of the river Mala Welna is 83.8 km, the source of the river is situated at an altitude of about 119 m asl and the outlet is located at an altitude of 65 m asl. Mala Welna is a typical lowland river, and its mean slope equals 0.64 ‰ [11].

A special study area is the reach with a length of 0.54 km located between Kiszkowo 1 and Kiszkowo 2 cross-sections, were the flood events were observed in details. Kiszkowo 1 and Kiszkowo 2 cross sections were determined at the intersection of Mala Welna River and roads connecting Kiszkowo and Gniezno and Pobiedziska (Fig. 1). Free surface slope of the river on analyzed section equals 0.05%. River valley on the analyzed area is asymmetric, the right side of the river valley floodplain width varies from 125 m to 180 m, and the left side of the river valley is wider, and its width varies from 600 m up to 1000 m. Valley is limited from the north west by side with slopes varies between 2–40%. Southeast edge of the Mala Welna valley is less steep, slopes range from 0 to 8%. The average height of land on the analyzed area equals 94.6 m asl while the lowest point is situated on the height of 91.8 m asl and the highest point reaches 102.6 meters asl.

Fig. 1. Study site, Mala Welna River
Rys. 1. Lokalizacja obiektu badań, rzeka Mała Wełna

Accuracy analysis of DTM available from Central National Geodetic and Cartographic Inventory made by Hejmanowska [5] based on 149 tachimetric measurements showed that the model is loaded with mean error of 0.19 m and the error value of the individual points of measurement errors ranged ± 2,0 m (Fig. 2).

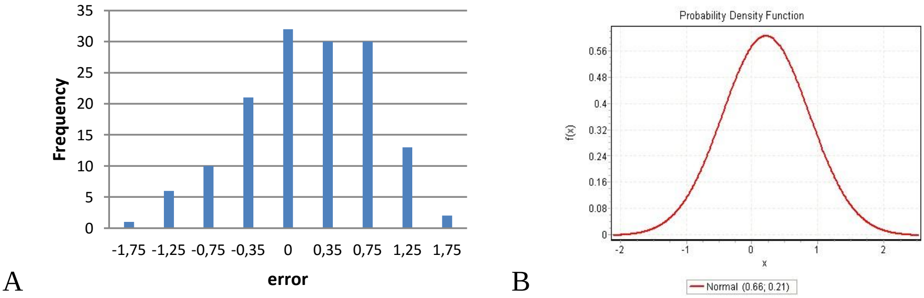


Fig. 2. DTM error distribution [4]
Rys. 2. Histogram rozkładu błędu NMT [4]

DTM empirical error was described with distribution function using maximum likelihood method in Mathwave's EasyFit software. The best match was obtained for the normal distribution function, in which the mean value is μ = 0.21 and the standard deviation equals σ = 0.66 m

In the next step nodes were extracted from DTM in the form of TIN. Height of nodes ranged from 93.16 to 99.51 m asl (Fig. 3). Then, according to the adopted methodology (Monte Carlo), altitude coordinate of points were modified with the approved theoretical distribution of error. This resulted in a 1000 new DTM, which were input data for HEC-RAS model with HEC-GeoRAS extension.

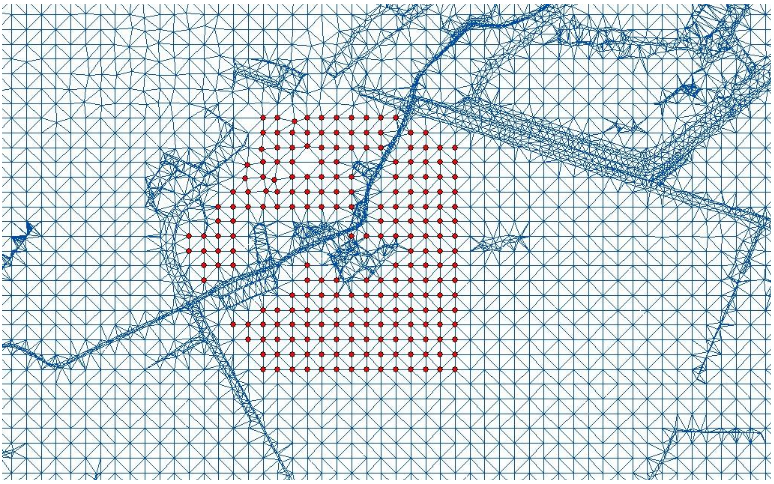
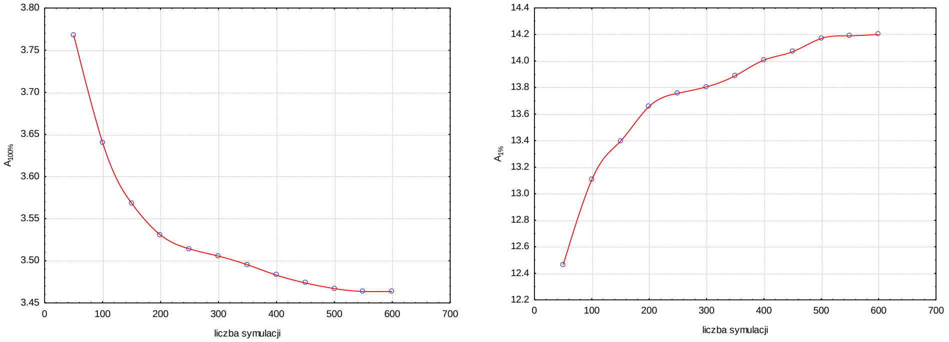


Fig. 3. DTM structure with highlighted modified nodes
Rys. 3. Struktura NMT z zaznaczonymi punktami poddanymi modyfikacji

The results of simulations are presented on the flood hazard maps after successive sessions of simulation, which were made of 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550 and 600 simulations. Detailed analyzes were performed within the 1% probability flood zone and the zone in which the probability of flooding is greatest and equals 100%.

The results of calculations showed that the maximum range of the flooded area (probability of 1%) varies from 13.1 ha to 14.2 ha. After the 500 simulations, size of the flooded area reached its maximum, and after another 50 simulations its size increased only about 0.01 ha. In case of the 100% likelihood flood risk map, flooded area varied from 3.64 ha to 3.45 ha, respectively after 100 and 550 simulations (Fig. 4).

Performed analysis showed that 550 simulation allows to develop a reliable probabilistic flood hazard map for the analyzed Mala Welna River section from section Kiszkowo 1 to section Kiszkowo 2. Finally, the flood risk area with 100% probability (raster cell values equal to 550) was equal to 3.45 ha, while the maximum range of the flood zone can be more than four times larger with the area of 14.2 ha (Fig. 5). Note, however, that in case of the maximum flood zone, its range is determined with areas flooded only 5 times in 550 performed simulations (5/550·100% = 1%). The probability of such a large inundation zone at the assumed maximum flow $WQ_{1\%}$ is very low.



A B

Fig 4. Size of 100% (A) and 1% (B) flood risk map depending on the number of performed simulations.
Rys. 4. Powierzchnia strefy zagrożenia powodziowego o prawdopodobieństwie wystąpienia 100% (A) i 1% (B) w zależności od liczby wykonanych symulacji.

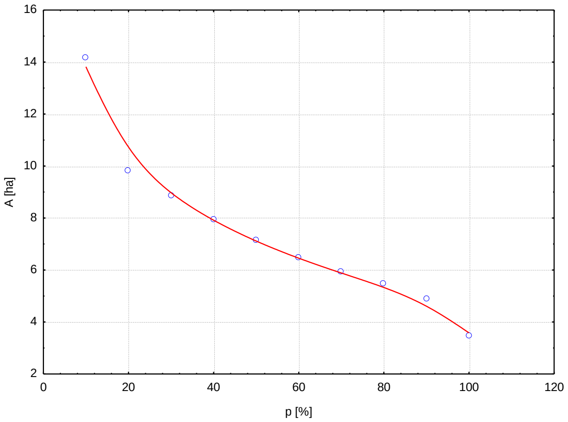


Fig. 5. Variation of flood inundation extent after taking account the DTM uncertainty
Rys. 5. Zmiana powierzchni zalewu po uwzględnieniu niepewności NMT

In the last stage of researches, the size of flood hazard zones designated by probabilistic and classic method based on the original

DTM supplemented with the river bathymetry were compared (Fig. 6). Flood hazard zone determined without taking into account the DTM uncertainty equals 8.8 ha. Comparison of so designated area with probabilistic flood hazard map showed that it corresponds to the area of the likelihood of occurrence of 30% (Fig. 6). This is probably due to the fact that DTM analyzed by Hejmanowska [5] was charged by systematic error equals to 0.21 m, while the random error were 0.66 m, which affected the result of simulation and the size of the flood risk zone.

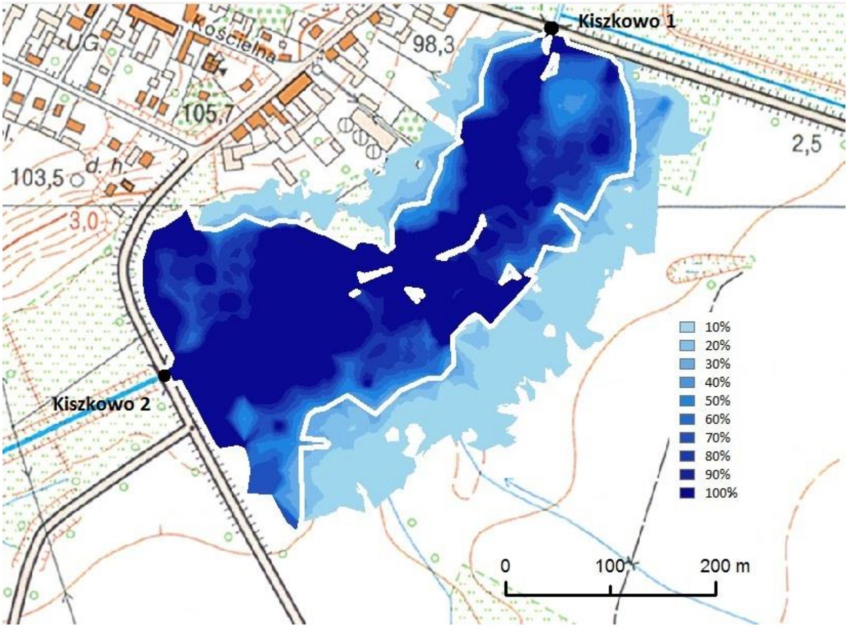


Fig. 6. Probabilistic flood hazard map of Mala Welna River from Kiszkowo 1 to Kiszkowo 2 at maximum flow $WQ_{0.2\%}$

Rys. 6. Probabilistyczna mapa zagrożenia powodziowego rzeki Małej Wełny na odcinku od przekroju Kiszkowo 1 do przekroju Kiszkowo 2 przy przepływie maksymalnym $WQ_{0.2\%}$

The results of the researches showed that it is impossible to precisely determine the range of the flood zone, due to the uncertainty of the measurement input data for a model. A better solution seems to be presentation of flood hazard zones using fuzzy boundaries, which is associated with data and the model uncertainties [10]. Significant impact on the results of hydraulic calculations are also placed on the boundary conditions of the model [8]. Including uncertainties factors we can get a broader picture of the flood risk, which is particularly important in the case of catastrophic floods, which threaten the peoples lives.

Issue of modeling flood hazard zones, with considering the uncertainties of the input data such as altitude, roughness coefficient and the flow value has recently become very popular in scientific research around the world. However, it seems that the inclusion of these elements in engineering practice is quite remote. This is mainly due to the fact that probabilistic methods are much more complex, requires large amounts of data together with an identification of their uncertainties. Preparation of probabilistic flood maps requires also a large number of simulations, which is very expensive and time consuming. There are way much more sources of uncertainty, however, with the progress of one, two and three-dimensional hydraulic models integrated with geographic information systems it seems that taking into account the impact of measurement data uncertainties on the simulation results will be much easier and faster in the future.

5. Conclusions

1. DTM uncertainty significantly affect the size of the flood zone. Size of the flood hazard zones with maximum flow $WQ_{0.2\%}$ ranged from 3.45 ha to 14.2 ha respectively for flooding probability of 100 and 1%.
2. Flood zone determined by the classical method, without taking into account the uncertainty of digital terrain model, equals 8.80 ha and respond as 30% probable area of probabilistic map.
3. The proposed method for visualizing probabilistic flood hazard maps can be very useful in determining the amount of insurance premiums in areas with a higher and lower probability of flooding.

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Wpływ niepewności numerycznego modelu terenu na wyznaczanie stref zasięgu zalewu powodziowego

Streszczenie

Celem pracy była analiza wpływu niepewności numerycznego modelu terenu (NMT) na wielkość stref zagrożenia powodziowego. Ocenę niepewności wykonano metodą Monte Carlo. Symulacje komputerowe prowadzono przy wykorzystaniu modelu hydraulicznego HEC-RAS z rozszerzeniem HEC-GeoRAS na przykładzie rzeki Małej Wełny na odcinku od przekroju Kiszkowo 1 do przekroju Kiszkowo 2, na którym obserwowano i dokumentowano występowanie zalewów w latach 1998–2012. Analizę i dyskusję wyników przeprowadzono w odniesieniu do stref zagrożenia powodziowego wyznaczonych metodą klasyczną (twardą), w której nie uwzględnia się wpływu niepewności danych na wielkość stref zagrożenia powodziowego oraz metodą miękką, w której efektem końcowym była probabilistyczna mapa zagrożenia powodziowego.

Przeprowadzone analizy wykazały, że wykonanie 550 symulacji pozwala na opracowanie wiarygodnej probabilistycznej mapy zagrożenia powodziowego na 0,54 kilometrowym odcinku rzeki Małej Wełny. Symulacje wykazały, że strefa zagrożenia powodziowego o prawdopodobieństwie wystąpienia 100% miała powierzchnię równą 3,45 ha, natomiast maksymalny zasięg zalewu może mieć powierzchnię ponad czterokrotnie większą tj. 14,2 ha Należy jednak pamiętać, że w przypadku maksymalnej strefy zalewowej, o jej zasięgu decydują obszary na których zalew występował tylko 5 razy podczas przeprowadzonych 550 symulacji. Prawdopodobieństwo wystąpienia tak dużego zalewu przy założonym przepływie maksymalnym $WQ_{0.2\%}$ jest więc niskie.

Wyniki przeprowadzonych analiz wykazały, że nie można w sposób dokładny określić zasięgu strefy zalewowej, co wynika z niepewności danych pomiarowych wprowadzanych do modelu. Lepszym rozwiązaniem wydaje się być przedstawienie zasięgu powodzi poprzez zastosowanie rozmytych granic, co związane jest z niepewnością danych oraz niepewnością samego modelu. Wprowadzając czynniki niepewności uzyskujemy szerszy obraz zasięgu zalewu, co jest szczególnie ważne w przypadku katastrofalnych powodzi, gdzie zagrożone jest życie ludzi.