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# Application of Digital Elevation Model and Aerial Photographs for Modelling Flood Prone Areas in Small Lowland Rivers

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## 1. Introduction

Floods are one of the most dangerous natural disasters, endangering human life and causing huge economic losses. The frequency of floods has increased in recent times [1]. Environmental changes such as changes in land use, growth of urban areas, and climate changes have a significant impact on the frequency of flooding and the amount of losses [6, 9].

Preparation of uniform guidelines and a common framework of procedures in order to minimize the consequences of flooding began in Europe due to high risk of disasters related to water excess. On 23 October 2007 European Union member states accepted Directive on the assessment and management of flood risks (Floods Directive). Application of hydrological and hydraulic models, integrated with GIS in floodplain mapping, allows for fast calculations and visual presentation of the results. GIS support in such models provides convenience and remarkable value to the performed analyses thanks to eliminating errors that may result from manual data entry [2]. The results obtained from modeling have widespread applications for city planners, environmental planners, flood control administration, policy makers, emergency manager, and eventually will help flood hazard mitigation [1]. One of the most commonly used hydraulic models for the evaluation of flood risk maps is one-dimensional model HEC-RAS [1, 3, 4, 7] with HEC-GeoRAS extension which enables utilization of spatial data for modeling and results visualization in ArcGIS software [8].

The aim of this study was to assess the applicability of Digital Elevation Model developed from aerial photographs to determine the flood hazard zones. This paper attempts to improve the quality of DEM by replacing river geometry based on own field measurements of analyzed reach of the river.

## 2. Study site and available data

The catchment of the Mala Welna River is situated in the central part of Poland, in the Odra River basin (Fig. 1). The 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‰.


**Fig. 1.** Location of the study area
**Rys. 1.** Położenie obiektu badawczego

The Mala Welna river catchment is covered by mineral deposits formed mostly from loamy sands and tills, with predominate to lessivé soils. The catchment has an agricultural character. Agricultural land accounts for around 76.6%, forests 20%, surface water 2% and built-up areas 1.4%.

Mala Welna River has a heterogeneous sequence of stages and discharges measurements. Initially, in 1948 IMGW led hydrometric and periodic water level measurements in the Kiszkowo cross-section and then from 1953 in the Skoki cross-section. In the years 1978–1983 daily water level stages and periodic discharges measurements in the Owcze Glowy cross-section were made. Since 2000, we have lead a comprehensive study on water resources in the catchment to Kiszkowo cross-section. The catchment area is 342 km$^2$ and the river length is 43.5 km. A special study area is the reach with a length of 12.02 km located between Zakrzewo and Kiszkowo villages, were the flood events were observed in details.

## 3. Methodology

The DEM's available in the Polish national geodetic and cartographic database is made on the basis of aerial photographs at 1:26000 scale from 2005, the grid interval is 25 m. The model includes the following layers: planar areas, streams, elevation points, engineering structures and breaklines. The accuracy of DEM estimated from the average RMSE error is 0.5 m. The existing DEM was adjusted on the basis of own measurements of the river cross-sections made using ADCP (Acoustic Doppler Current Profiler) device Stream Pro, developed by Teledyne Instruments. Area directly adjacent to the river was measured using Topcon GPS RTK. All field measurements were made to provide best possible DEM model which is used to obtain geometry data for the hydraulic model.

The annual maximum discharges with probability of exceedance 10%, 1% and 0.2% were conducted with the use of Floods Analysis software developed in 2001 by Institute of Meteorology and Water Management (Poland). The calculations were made on the basis of maximum discharges form winter and summer hydrologic half years from the years 1965–1975, 1978–1983 and 2000–2010. In the first stage an examination of homogeneity of maximum discharge series using genetic methods and statistical methods with the use of the Grubbs-Beck test, the test of series, the Kruskal-Wallis and the Sperman rank correlation coefficient test for trend in mean and variance was worked out. Selection of the best fitted distribution function of maximum half year discharges for the following four types most commonly used in Poland such as: Gamma, log-Normal, Weibull and log-Gamma. Estimation of distribution function parameters was carried out with the use of the maximum likelihood method. Goodness of fit of theoretical probability distribution function with the empirical distributions on the basis of $\chi^2$ Pearson test, at $\alpha = 0.05$ significance level was tested. The most credible function of probability distribution was selected with the use of Akaike Information Criterion (ACI). The probabilities of exceedance of annual maximum discharges were calculated like an alternative of two non-eliminated independent events, based on the most credible function of probability distribution of the maximum discharges of the winter and summer season.

Water surface levels and size of the flooded area on the analyzed river section during 10%, 1% and 0.2% probable discharges was calculated using HEC-RAS model (Hydrologic Engineering Center's River Analysis System) developed by the U. S. Army Corps of Engineers (U.S. Army Corps of Engineers, 2006). HEC-RAS is one-dimensional hydraulic model that allows to perform simulations assuming steady and unsteady flow. HEC-RAS is public-domain software, so it is widely used around the world to determine flood hazard zones. In this project all calculations were performed assuming a steady flow, where the water surface levels and water velocity in individual cross-sections were calculated by solving one-dimensional energy equation. Energy losses were evaluated using Manning's roughness coefficient and contraction/expansion. All geometry data necessary to perform calculation were obtained from digital elevation model in ArcGIS software by ESRI with HEC-GeoRAS extension.

Calibration of the HEC-RAS model was performed using Manning roughness coefficients. Field observations and discharge measurements in the bridge cross-sections and aerial photographs, made during the flood in 2008, were used in the calibration process. Verification of the model was made on the basis of field measurements taken during 2009 flood. Flood hazard zones calculated in HEC-RAS model were compared with the actual zones using the measure of fit *F* [5]:

$$F = \frac{Num(S_{mod} \cap S_{obs})}{Num(S_{mod} \cup S_{obs})} \quad (1)$$

$S_{mod}$ represent the set of pixels located under water identified using hydraulic modeling, $S_{obs}$ is the set of pixels located under water identified in the time of actual flood using aerial photographs and field measurements, and *Num* gives the number of members of these sets. Measure of fit *F* is the quotient of the number of cells correctly identified by the model as being flooded and the total number of flooded cells defined on the basis of modeling and measurements. In the case of perfect compliance between predicted and actual flood hazard zone $F = 1$.

# 4. Results and discussion

The first stage of this study was to improve the existing DEM's. River geometry was removed from the model and then replaced by the geometry based on own measurement of the river cross-sections. Riverbed ordinates identified on the basis of the existing DEM's did differ from those measured in the field in the range from 0.3 to 0.9 m. An accurate numerical model of the study site is very important especially in the lowlands areas without levees. Calibration of hydraulic model HEC-RAS was based on the observed flood in 2008 on the section from Gorzuchowskie Lake to Owieczki cross-section. Discharges measured in March 2008 in the bridge cross-sections located along the river were the input data to the hydraulic model. A total of 500 simulations were made assuming different Manning's roughness coefficient for main channel and adjacent areas in 61 cross-sections (Fig. 2). In the calibration process the Manning's values were divided into 0.005 interval from the selected rough scale values such as 0.02 to 0.05. The maximum value of measure of fit F calculated using Horrit's and Bates formula (2001) between modeled and actual flood area was 0.87 (Fig. 3). The model has been verified on the basis of independent data collected during the 2002 flood which was used to reconstruct flood hazard zone in ArcGIS software. It was compared to modeled flood zone. This time the measure of fit equals F = 0.73. Calibrated and verified model was used to determine the extent of flood hazard zones at 10%, 1% and 0.2% probable discharges.

Maximum annual discharges with probability of exceedance 10%, 1% and 0.2% shown in Figure 4 are calculated with the use of Floods Analysis software on the basis of half years maximum discharges. The best fitted functions of probability distribution on the basis of ACI have occurred the Gamma (ACI = 133.25) and the log-Gamma (ACI = 72.76) distribution functions for winter and summer hydrologic half years respectively Table 1.

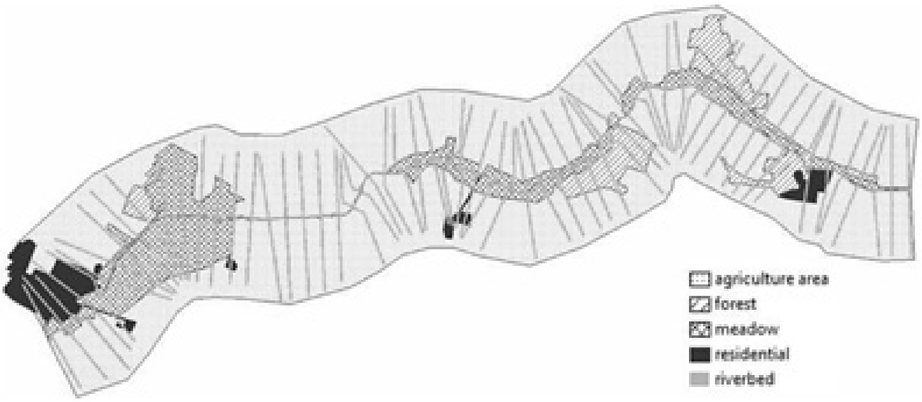


**Fig. 2.** Map with cut-lines and classification results
**Rys. 2.** Przekroje poprzeczne wraz użytkowaniem terenu


**Fig. 3.** Observed and modeled flood extens
**Rys. 3.** Rzeczywiste i modelowane strefy zalewowe

Such calculated maximum annual discharges were used to delineate flood prone areas by means of HEC-RAS model.

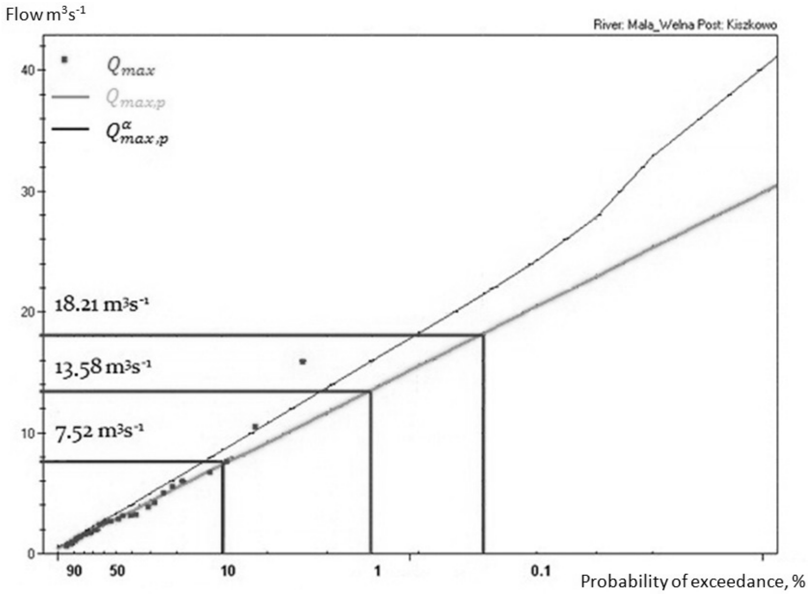


**Fig. 4.** Probability curve of the maximum annual discharge for Mala Welna River at the Kiszkowo cross-section

**Rys. 4.** Krzywa prawdopodobieństwa przewyższenia przepływów maksymalnych rzeki Małej Wełny w przekroju Kiszkowo

**Table 1.** Results of Chi-square test and ACI for given distribution types

**Tabela 1.** Analiza statystyczna dopasowania przyjętych funkcji rozkładu prawdopodobieństwa

| Distribution type | Winter season | | Summer season | |
|---|---|---|---|---|
| | Chi-square | ACI | Chi-square | ACI |
| Gamma | 2.65 | 133.25 | 1.57 | 77.90 |
| Weibull | 2.73 | 133.52 | 2.14 | 78.07 |
| log-Normal | 3.22 | 134.90 | 0.69 | 73.00 |
| log-Gamma | 5.87 | 142.59 | 0.79 | 72.76 |

Floods maps for three different return periods are shown in figure 5. Maximum annual discharges of given return periods were used for creating flood hazard maps by dividing them into three water depth representing low – 0–0.5 m, moderate 0.51–1.0 m and high risk – more than 1 m (Table 2). The results obtained from HEC-RAS model were used to overlay with land use and land cover maps from the year 2010. Flood hazard zones have occurred mainly in arable land and meadows. The width of the flood zones ranged from 10 to 360 m.

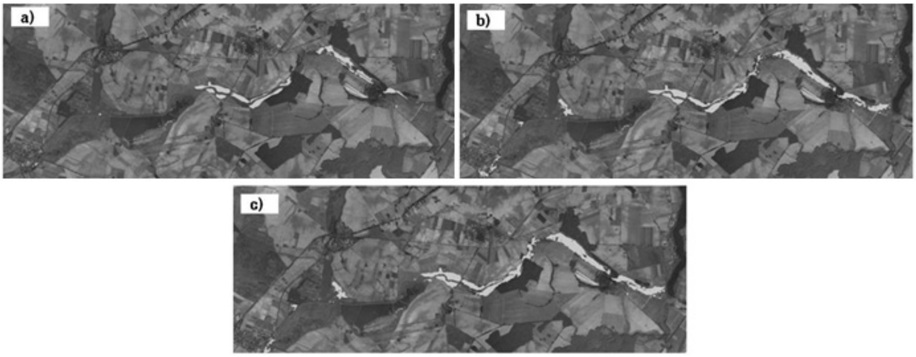

**Fig. 5.** Flood risk map for given probabilities $Q_{10\%}$(a), $Q_{1\%}$(b) and $Q_{0.2\%}$(C)
**Rys. 5.** Mapa zagrożenia powodziowego dla przepływu $Q_{10\%}$(a), $Q_{1\%}$(b) i $Q_{0.2\%}$(C)

**Table 2.** Flood hazard area depending on water depth h for various return periods
**Tabela 2.** Rozkład głębokości w wyznaczonych strefach zagrożenia powodziowego

| Return period years | Low (h < 0.5 m) km$^2$ | Moderate (h = 0.5–1.0 m) km$^2$ | High (h > 1 m) km$^2$ | Total area km$^2$ |
|---|---|---|---|---|
| 10 | 0.419 | 0.048 | 0.005 | 0.472 |
| 100 | 0.721 | 0.132 | 0.030 | 0.883 |
| 500 | 0.763 | 0.258 | 0.040 | 1.061 |

## 5. Conclusions

The study showed the usefulness of the hydraulic model HEC-RAS and geographic information system ArcGIS integration to predict flood hazard areas in accordance with requirements of the Directive 2007/60/EC (2007). However, the use of hydraulic models should be preceded by calibration and validation process based on the past observed floods. To achieve satisfying results in flood risk modeling it is important to use DEM loaded with the smallest possible error which optimally reflects the land relief and has the appropriate spatial resolution. The main conclusions of this paper are as follows:

1. Quality of DEM available in Polish resources developed from 1:26000 scaled aerial photographs is not satisfactory enough in case of hydrological modeling.
2. DEM can be improved by adding a specific river geometry obtained from field measurements.
3. The improved DEM and hydraulic model HEC-RAS allow for accurate estimates of flood hazard zones in the small and medium-sized river catchments.

## References


1. **Ahmad B., Kallem M. S., Butt M. J. and Dahri Z. H.:** *Hydrological modeling and flood hazard mapping of Nullah Lai*. Proc. Pakistan Acad. Sci. 47(4): 215–226 (2010).
2. **Gül G.O., Harmancioglu N. and Gül A.:** *A combined hydrologic and hydraulic modeling approach for testing efficiency of structural flood control measures*. Nat Hazards 54, 245–260 (2010).
3. **Gunasekara I. P. A.:** *Flood hazard mapping in lower reach of Kelani river*. Engineer, Vol. XXXXI, No. 05, 149–154 (2008).
4. **Hicks F.E.A and Peacock T.:** *Stability of HEC-RAS for flood forecasting*. Canadian Water Resources Journal, Vol. 30(2), 159–174 (2005).
5. **Horritt M.S. and Bates P.D.:** *Effect of spatial resolution on a raster based model of flood flow*. Journal of Hydrology 253, 239–249 (2001).
6. **Kjeldsen T.R.:** *Modelling the impact of urbanization on flood frequency relationships in the UK*. Hydrology Research Vol 41.5 391–405 (2010).
7. **Myronidis D., Emmanouloidis D., Stathis D. and Stefanidis P.:** *Integrated flood hazard mapping in the framework of the E.U. Directive on the assessment and management of flood risk*. Fresenius Environmental Bulletin, Vol. 18, No 1, 102–111 (2009).
8. **Ozcan O., Musaogul N., Seker D.Z. and Tanik A.:** *Determination of flood risk in Sakarya sub-basin using remotely sensed data and GIS*. Fresenius Environmental Bulletin, Vol. 17, No 11b, 1964–1970 (2008)
9. **Sole A., Giosa L., Nole L., Medina V. and Bateman A.:** *Flood risk modeling with LiDAR technology*. Flood Recovery, Innovation and Response I, Ecology and the Environment, Vol. 118, 2008.

# Zastosowanie Numerycznego Modelu Terenu oraz zdjęć lotniczych przy wyznaczania stref zagrożenia powodziowego w małych zlewniach rzek nizinnych

## Streszczenie

Celem pracy była ocena możliwości zastosowania numerycznego modelu terenu opracowanego na podstawie zdjęć lotniczych do wyznaczenia stref zagrożenia powodziowego. Wiele prac koncentruje się na ocenie ryzyka powodziowego w zasięgu dużych rzek pomijając aspekty niepewności wyznaczania stref dla rzek małych i średnich, gdzie jakość numerycznego modelu terenu wywiera zdecydowanie większy wpływ na wyniki modelowania.

W pracy podjęto próbę poprawy jakości NMT na podstawie własnych pomiarów terenowych prowadzonych na analizowanym odcinku rzeki Małej Wełny. Pozwoliło to na precyzyjne odzwierciedlenie koryta rzeki, a co za tym idzie możliwości zastosowania takiego modelu bez konieczności opracowania nowych modeli przy pomocy LIDAR. W pracy wyznaczono strefy zalewowe na 12 kilometrowym odcinku rzeki Małej Wełny. Do obliczeń rzędnych zwierciadła wody przy trzech scenariuszach powodziowych (10%, 1% oraz 0,2%) zastosowany został model HEC-RAS oraz program ArcGIS z rozszerzeniem HEC-GeoRAS, który zapewnia kompatybilność obu programów. Model został skalibrowany i zweryfikowany na podstawie dostępnych zdjęć lotniczych i pomiarów terenowych wykonanych podczas powodzi w latach 2008 i 2009. Badania wykazały, że dostępny w Polsce numeryczny model terenu opracowany na podstawie zdjęć lotniczych w skali 1:26000 może być z powodzeniem stosowany w procesie wyznaczania stref zalewowych pod warunkiem uzupełnienia go o dane pochodzące z własnych pomiarów terenowych koryta rzecznego. Badania potwierdziły użyteczność korzystania ze zdjęć lotniczych podczas procesu kalibracji i weryfikacji obliczeń hydraulicznych podczas modelowania powodzi.