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EFFECTS OF LAND USE CHANGES ON THE RUNOFF IN THE LANDSCAPE BASED ON HYDROLOGICAL SIMULATION IN HEC-HMS AND HEC-RAS USING DIFFERENT ELEVATION DATA

Josef Divín[1], Tomáš Mikita[1]

[1] Department of Forest Management and Applied Geoinformatics, Faculty of Forestry and Wood Technology, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic

Abstract

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The aim of this paper is to determine the effects of land use changes on the runoff in the landscape by means of hydrological modelling. Our partial aim is also to determine the effect of different elevation data and define optimal data sources for this modelling. The research was conducted on the Starozuberský stream experimental watershed.

For comparing elevation models, three scenarios were developed with different input data. Based on a comparison of these models an optimal data source for hydrological modelling was selected. To simulate the change in land use, we have created two scenarios based either upon the current land use and historical data from the fifties of the twentieth century. Comparison was carried out using the HEC-HMS software interface for rainfall-runoff simulation and HEC-RAS for the flooding simulation. Data for the simulation were prepared using the ESRI ArcGIS extensions, namely HEC-GeoHMS and HEC-GeoRAS.

Keywords: ALS, DMR 4G, contour lines, HEC-HMS, HEC-RAS, land use

INTRODUCTION

Floods are one of the most frequent natural disasters that threaten the Czech Republic. Extreme floods are repeated at regular intervals and this implies a certain cyclicality and possible predictability of their occurrence in the future. Floods do not arise only in large river basins, but can also occur on small watersheds of mountain and foothill streams. These floods are mainly caused by extreme rainfall. They are the so called ‘flash floods’ which occur in smaller headwater streams and can cause extensive damage to property and lives.

A wide range of hydrological models is currently available for flood simulations and optimizations and these topics have been addressed by many authors (Knapp, Durgunoglu and Ortel, 1991; Daňhelka, 2003). For the purposes of this study we have selected models from the Hydrological Engineering Center (HEC); model HEC-HMS (Hydrologic Modelling System) for modelling rainfall-runoff relationships, which Daňhelka (2003) considers suitable for watersheds up to 500 square kilometres, and model HEC-RAS (River Analysis System) intended for simulating flooded territory.

The landscape is an ever-evolving and dynamic element, where constant changes occur due to both natural and anthropic influences. The most striking changes are now mainly spreading of human agglomerations, but also grassing or afforestation of arable land. According to Bičík, Jeleček and Štěpánek (2001) the loss of arable land occurs in the longer term, with simultaneous increase in other categories such as permanent grassland and forests in particular. And land use is one of the factors that may affect the hydrological simulations. Unucka and Adamec (2008) determine the effect of forest vegetation cover for the calculation of rainfall-runoff conditions. When using two different scenarios with different land use between 1992 and 2000, the peak flow between these years decreased according to Jeníček (2007).

In addition to the model used to simulate the runoff in the landscape, also the source of elevation data for creating a Digital Terrain Model (DTM) and its accuracy affect the result. The processes of acquiring elevation data for generation of a DTM vary and may be based on methods of geodetic measurement, methods of remote sensing, or may come from a variety of available geodatabases. Casas *et al.* (2006) in their study focused on the comparison of elevation models created using Global Navigation Satellite Systems (GNSS), Airborne Laser Scanning (ALS) system and contour line data of the Fundamental Base of Geographic Data of the Czech Republic (ZABAGED®). Differences in the accuracy of DTMs were tackled by many authors (Uhlířová, 2010; Šilhavý and Čada, 2013). Uhlířová (2010) found that when comparing different ALS data and ZABAGED® contour lines, major differences in elevation were seen especially in the places of streambeds as the ZABAGED® altimetry excludes geometry of smaller streams. Šilhavý and Čada (2013) found the total mean error between altimetry acquired by means of ALS and from ZABAGED® contour lines at the amount of 0.86 m. Mikita, Cibulka and Janata (2013) in their work evaluated the accuracy of digital terrain models of the Czech Republic of 4th and 5th generations in forests. The study demonstrated the accuracy of the new elevation data to be even triple the accuracy of the earlier altimetry in the form of ZABAGED® contour lines. The resulting model has a certain dependence on the pixel size of the created DTM (Podhoranyi *et al.*, 2013; Yang *et al.*, 2014). Yang *et al.* (2014) found in their study that the best model when compared with the reference data is not the model created with the smallest pixel resolution (1 meter per pixel), but they recommend lower resolution of 10 meters. According Podhoranyi *et al.* (2013) the increase in resolution of the input DTM has impact on reducing the extent of the flood area. There was a 14 percent reduction in the extent of a flood-prone area between a DTM created at a resolution of 10 meters per pixel and 1 meter per pixel.

METHODOLOGY

Description of Watershed

The Starozuberský stream watershed (Fig. 1) is located in the cadastral area of the town of Zubří in the Zlín Region. It is placed under the competency of water authorities of Rožnov pod Radhoštěm and Frenštát pod Radhoštěm. The hydrological order number is 4-11-01-111 (Povodí Moravy, 2015). Starozuberský Stream is the right tributary of Rožnovská Bečva River and empties into it at the divide of Zubří and Rožnov pod Radhoštěm towns. Catchment area is 11.25 square kilometres, while the area of simulated region under hydrodynamic conditions is 0.418 square kilometres. The length of backbone watercourse is 8.3 kilometres. The altitude range of the watershed studied is 350 to 650 metres. The stream rises on the slopes of Kamenárka Mountain (862 metres above sea level). Tab. I shows the overview of N-years flows of Starozuberský Stream (Zubří, 2015).

Comparison of Elevation Models

As a first step we address different reactions of the watershed to the rainfall-runoff and hydrodynamic processes based on different elevation models (contour lines, DMR 4G, ALS).

Fundamental Base of Geographic Data (ZABAGED®) is a digital model of the territory of the Czech Republic. Currently it comprised 116 types of geographic objects included in the planimetric or altimetric part. The ZABAGED® database was founded upon the Base Map of the Czech Republic 1: 10 000 (ZM 10). For the purpose of this study we have used its altimetric part, which is represented by a 3D set of contours. The altimetric part of ZABAGED® consists of three types of contour objects with a basic interval of 5, 2 or 1 m depending on the nature of the terrain.

The accuracy of contour lines reaches 0.7 to 1.5 m in the open terrain, 1 to 2 metres in urban areas and 2 to 5 m in forested terrain (ZABAGED, 2015).

Digital Terrain Model of 4th generation (DMR 4G) represents a display of natural or man-modified land surface in the digital form as elevations in a regular grid (5×5 m) of points with X, Y, H coordinates, where H represents an altitude in the elevation reference system "Baltic – after adjustment". The model shows a total mean error of elevation 0.3 m in the open terrain and 1 m in the forested terrain. The model was created from data acquired by airborne laser scanning of altimetry of the Czech Republic between the years 2009 and 2013 (DMR 4G, 2015).

Airborne laser scanning (ALS) is one of the modern methods of remote sensing. The history of its use is not long whether in the Czech Republic or abroad. ALS makes use of the so-called LIDARs, which measure distances by laser beams. The world LiDAR is an acronym made from the initial letters of the English words "Light Detection and Ranging" (Dolanský, 2004). The ALS data after classification of points of the bare land surface without vegetation

I: *Table of N-years flows m³/s (Zubří 2015)*

N	1	2	5	10	20	50	100
	4.40	8.52	15.5	22.0	29.4	40.8	50.8

1: *Starozuberský stream experimental watershed (catchment area for rainfall-runoff simulation)*

and buildings amounted to an average density of about one point per square metre.

For these available data sources digital terrain models were created with a resolution of one meter per pixel. They were interpolated by Topo To Raster tool of ArcGIS software to the form of a raster DTM and also into triangulated irregular network (TIN). TIN model was used for profile creation in hydrodynamic simulations and raster model was used for rainfall-runoff simulations. Simulation of rainfall-runoff conditions on the created DTMs took place in the HEC-HMS software model and its ArcGIS extension (HEC-GeoHMS). Actual overflows in the given watershed were calculated using the HEC-RAS software and its ArcGIS extension (HEC-GeoRAS).

Hydrologic Data

The data was collected from water levelling gauging station which measured water level in half-hour intervals on the Starozuberský stream. Used data are from 16 May 2014 when maximum water level was measured. Data were taken from the auxiliary observation profile category C, which consists of the level measuring sensor with automatic data transmission. GPS coordinates of the gauging station are 49.48904° N 18.10405° E (Fig. 1). Total precipitation from May 15 to 16 was used for the actual simulation of the model for temporal distribution of rainfall (see Fig. 3). Precipitation measurements were acquired from the rain gauge station WH1080, which is located in the village Zašová. GPS coordinates of the weather station are 49.471667° N 18.043333° E, altitude of the station is 331 m above sea level. Sensors for rainfall measurement are located 2 meters above the ground; minimal distance is 6 m from surrounding buildings and 10 m from surrounding trees. Precipitation and flow measurements were acquired in 30 minute intervals.

Hydrodynamic Modelling

For the hydrodynamic simulation we have chosen calculations on the basis of steady flow, which is one of the components of the HEC-RAS model.

Steady Flow Analysis

This component of the model system is intended for calculating the profiles of surface water for steady flow. Steady flow can be modelled in supercritical, subcritical as well as mixed flow regimes. The basic calculation is based on solving one-dimensional energy equation (USBR 2015), see below.

$$H = z + y + \frac{\alpha \bar{v}^2}{2g},$$

where

α .... kinetic energy correction factor,

g .... gravitational acceleration (m/s),

H ...... energy head (m),
v .... average velocity in the transverse profile (m/s),
y .... flow level height in the transverse profile (m),
z .... height of the streambed bottom in the transverse profile (m).

Energy losses are evaluated on the basis of friction (Manning's equation below). Roughness coefficient for the purpose of this study was determined according to Keršl (2001).

$$v = \frac{1}{n} \times R^{\frac{2}{3}} \times i^{\frac{1}{2}},$$

where
v .... velocity (m/s),
n .... Manning's roughness coefficient,
R....... hydraulic radius (m),
i .... slope of the streambed.

This model also includes methods for calculating flow regime (i.e. hydraulic jumps), hydraulics of bridges and evaluation of profiles at river confluence (river nodes).

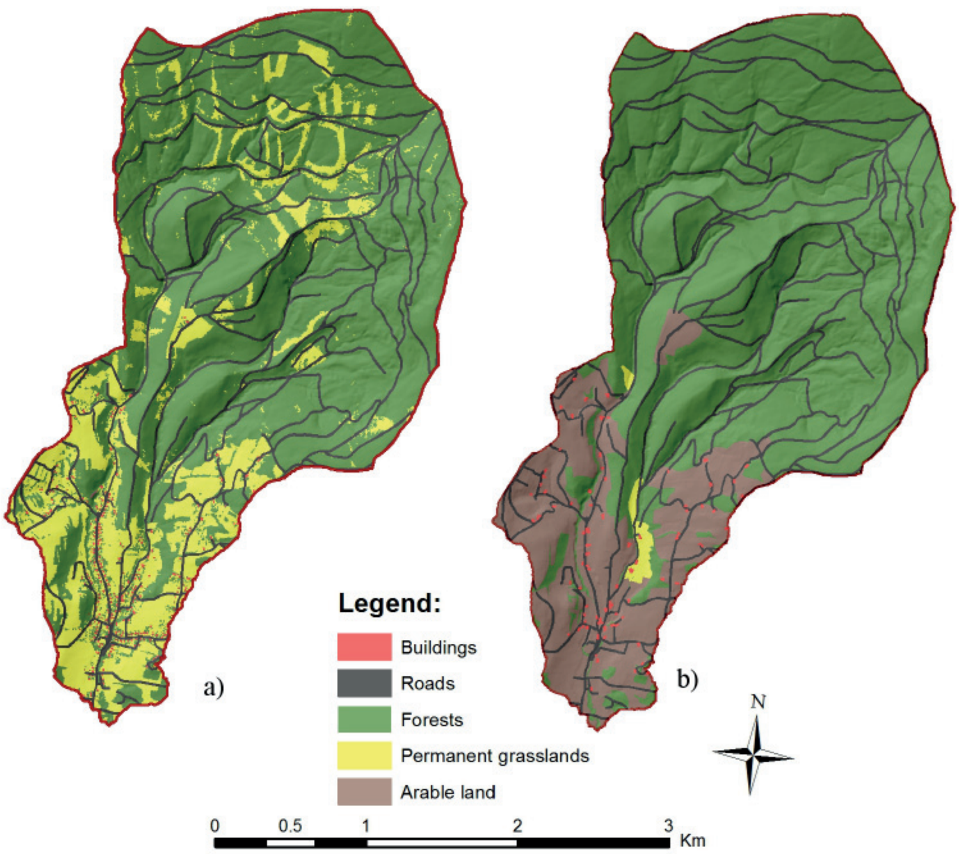
The calculation can also count on the effects of various obstructions such as bridges, culverts, weirs and buildings in the flood-prone area (HEC-RAS, 2015). For the purposes of this study, these values were neglected.

Analysis of Land Use Changes

Based on the selection of optimal source of elevation data we have examined the effect of land use changes on the resulting rainfall-runoff and hydrodynamic simulations. We have classified the input land use data taken from the above data sources into five basic classes: buildings, roads,

II: *The size of land use category for two scenario (Current land use, Land use of 50th years of 20th century)*

Land use category	Land use 50th years of 20th century. Area (km²)	Current land use. Area (km²)	Decrease (-) or increase (+) of land use category (km²)
Buildings	0.021	0.057	0.036
Roads	0.622	0.622	0.000
Forests	6.998	6.939	–0.059
Permanent grasslands	0.207	2.597	2.390
Arable land	2.372	0.006	–2.366



2: *Representation of each category of land use a) Current land use b) Land use of 50th years of 20th century* forests, permanent grasslands and arable land (see Tab. II, Fig. 2).

To simulate the change in land use, we have created two scenarios based upon the current land use and historical data from the fifties of the twentieth century. The first one is based on the current values of land use and the other is based on land use derived with orthophotomap, which was created in the 50th years of the 20th century. Historical orthophotomap from the 50th years of the 20th century has been created from the historical image of the Czech Republic's first nationwide surface imaging in 1958 and is accessed as a map layer provided to the public on the National Geoportal INSPIRE (Cenia, 2015).

We have calculated the runoff volume using the SCS Runoff Curve Number (CN) method. The reason was mostly its less demand on input data and calculation simplicity. Numbers of runoff curves are determined according to the methodology by Janeček (2007), with the CN values assigned based on hydrologic soil groups determined according to the BPEJ (estimated pedo-ecological unit) code and the land use.

One of the other inputs to the rainfall-runoff model is the estimate of the initial loss (Ia) in mm. Initial loss estimate is calculated based on the CN value and maximum potential retention of the watershed S (mm) (Vološ, 2015).

$$Ia = 0.2 \times S,$$

where

$$S = \frac{25400 - 254 \times CN}{CN}.$$

To determine the direct runoff, we have used the Clark Unit Hydrograph, which contains the following parameters:

Tc ..... time of concentration of the watershed (h),

R....... watershed storage coefficient (h) simulating the time of water retention in the watershed.

Several formulas are used to calculate the time of concentration; the most common formula is SCS (Soil Conservation Service) to derive T_{lag} (time lag in hours between the occurrence of peak causal rainfall and the occurrence of peak flow in the counted transverse profile of the watershed).

$$T_{LAG} = \frac{L^{0.8}(S+1)^{0.7}}{1900\sqrt{Y}},$$

L....... the longest watercourse length in the watershed [ft],

S .... potential maximum soil retention [inch],

Y ...... average watershed land slope [%].

Time of concentration is derived from the formula:

$$T_{lag} = 0,6 \times \text{Tc}.$$

To calculate the retention constants, it is possible to use the formula:

$$R_c = A \times L^B \times S_{1085}^C,$$

L....... the longest watercourse length in the watershed [miles],

S^{1085} .. average watershed land slope along the longest watercourse length if feet per mile in the section between 10 and 85% of the length.

A, B, C are coefficients, which were determined by the Czech Hydrometeorological Institute for the Czech Republic as A = 80, B = 0.342 and C = –0.79 (Vološ 2015).

RESULTS

Comparison of Elevation Models

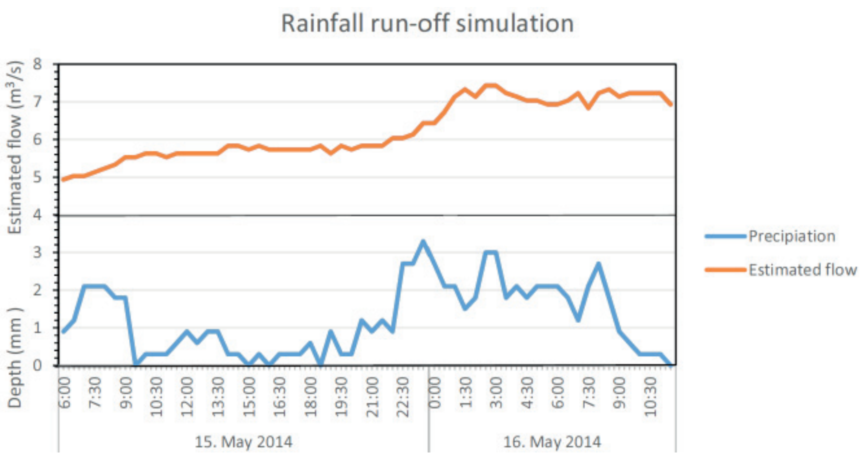
Different number of subwatersheds were automatically allocated for different input elevation models. Most (43) of them were created for the model having elevation data from ALS. It is however evident from the results that the smallest watershed established from this data has an area of only 0.02 ha, which may cause distortion of the results. Differences were also reported in the total length of watercourse as well as individual segments, and also in the average watershed land slope. The DMR 4G data and ALS data achieve similar results compared to the contour line model.

III: *Curve number – CN (Janeček 2007)*

Land-use		Curve number – CN by hydrological soil groups			
		A	B	C	D
1 Fallow area freshly aerated		77	86	91	94
2 Grassland		30	58	71	78
3 Bushes with a covering of > 75%		30	48	65	73
4 Road	40 paving, bituminous	83	89	92	93
	41 makadam, gravel	76	85	89	91
	42 unpaved, earthen	72	82	87	89
5 Forests		36	60	73	79
6 Impervious surfaces		98	98	98	98

IV: *Comparison of the model (Contour lines ZABAGED®, DMR 4G, ALS)*

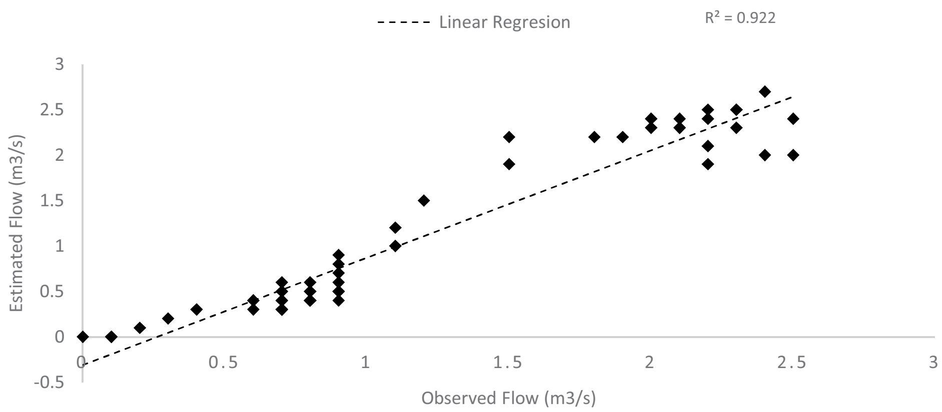
Used elevation data / *Derived watershed*	Contour lines ZABAGED®	DMR 4G	ALS
Area of watershed (km²)	7.94	7.99	7.97
Number of subwatersheds	41	42	43
Average size of subwatersheds (ha)	19.37	19.49	18.54
Maximum size of subwatersheds (ha)	61.12	82.3	62.13
Minimum size of subwatersheds (ha)	0.21	0.22	0.02
The average slope of watersheds (%)	13.54	14.92	15.3
The greatest average slope of subwatersheds (%)	18.9	24.09	21.31
Smallest average slope (%)	7.27	7.67	7.48
Derived drain lines			
The average length of the section (km)	0.37	0.41	0.41
The greatest length of the section (km)	1.73	2.13	2
The smallest length of the section (km)	0.003	0.011	0.004
The total length of the flow in the watershed (km)	15.31	16.98	17.83



3: *Rainfall run-off simulation*

V: *Comparison of the rainfall-runoff models with different elevation models*

Elevation models	Time of peak (h)	Flow (m³/s)
Contour lines ZABAGED®	9:00	6.6
ALS	8:30	6.5
DMR 4G	8:30	6.6



4: *Regression model (estimated x observed flow)*

Rainfall-runoff Model

DTM based on ALS data displayed a decrease in flow of 0.1 cubic meters per second compared to two other models (DMR 4G, contour lines). Higher detail and precision of ALS data affected also the delay in the peak of flood wave. Results of rainfall simulation in (Tab. V) are in relation to the outlet point of the watershed.

During the comparison between simulated and observed flow of the rainfall-runoff model on the stream gage, regression correlation was achieved with the coefficient of determination R^2 0.922 (see Fig. 4).

VI: *Flood areas when using different models. (Contour lines ZABAGED®, DMR 4G, ALS)*

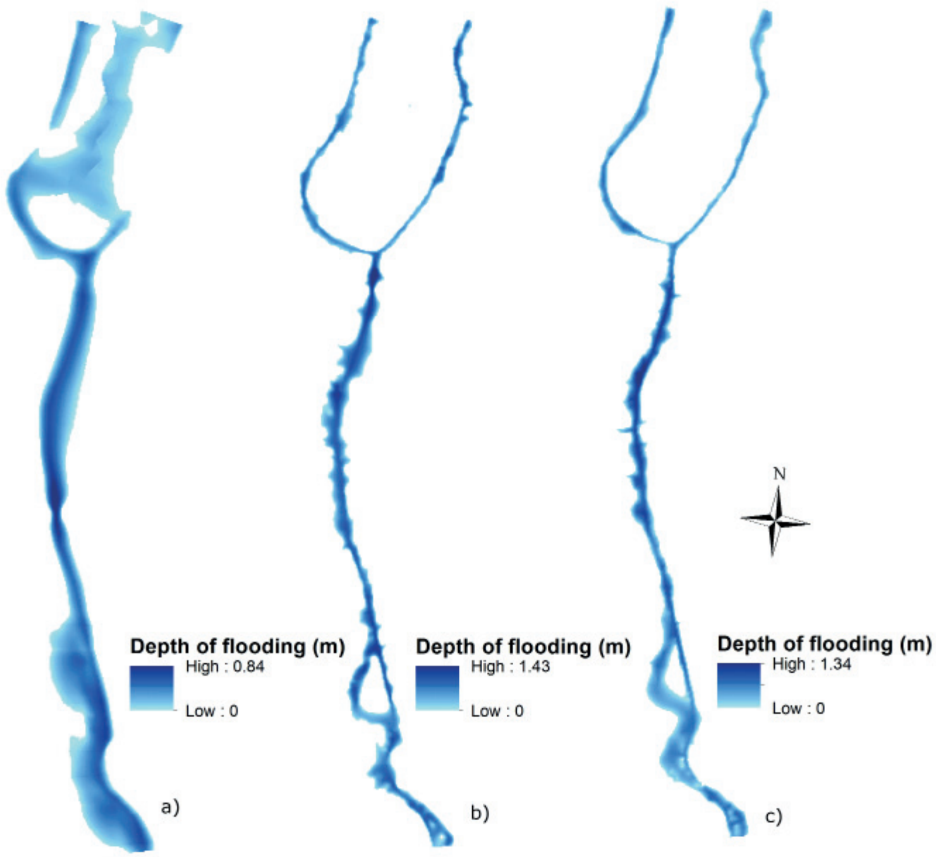
Elevation models	Maximum depth of flooding (m)	Flooding area (ha)
DMR 4G	1.29	0.789
ALS	1.43	0.788
Contour lines ZABAGED®	0.84	1.851

VII: *Comparison of flow (Current land use, Land use of 50th years of 20th century)*

	Time of peak discharge (h)	Peak discharge (m^3/s)
Current Land use	8:30	6.6
Land use 50th years of 20th century	8:30	7.4

VIII: *Comparison of flooding area (Current land use, Land use of 50th years of 20th century)*

	Maximum depth of flooding (m)	Flooding area (ha)
Current Land use	1.29	0.789
Land use 50th years of 20th century	1.34	0.810



5: *Effect of different elevation data on the final simulation. DTM produced from: a) Contour lines ZABAGED® b) ALS c) DMR 4G*

Hydrodynamic Modelling

Accuracy of input elevation data affects the depth of flooding and the area of floodplains. The biggest outflow occurred when using DTM created from contour lines. Total overflow was more than double compared to a simulation conducted on data from ALS and DMR 4G. By contrast, models created from DMR 4G and ALS differ only slightly from each other by about 10 square metres in the total area (Tab. VI, Fig. 5).

Change in Land Use

According to Bičík, Jeleček and Štěpánek (2001), there is a long-term trend of decline in arable land due to the expansion of forests and grasslands, as well as built-up areas. Within the area of interest, however, the housing development has only a negligible influence on the final simulation because of its small area. The main change in the land use observed between the 1950s and now is the conversion of arable land to permanent grasslands (meadows and pastures). This change had a positive effect on the reduction of the total flow rate by 0.8 cubic metres per second (about 12 per cent). Along with a decrease in the flow amount, also a decrease in the total flooded area by 3 per cent was observed compared to the past. These factors may cause flood damage reduction.

DISCUSSION

Elevation model as one of the main inputs to the rainfall-runoff and hydrodynamic simulation has an impact on the final simulation. In the case of rainfall-runoff simulations the differences in the results from the various data sources are almost negligible. The same cannot be claimed for hydrodynamic simulations, where the use of different elevation models may have a major impact on the area of the flooding. The least suitable for simulation is DTM created from contour lines. Šilhavý and Čada (2013) showed that when comparing elevation models created from ALS data and contour lines there is a mean altitude error 0.86 m. The smaller accuracy of the model is the cause of obliterating the surface terrain and neglecting part of the streambed itself. Therefore, if no refinement of this model is used, e.g. by own geodetic measurements, such model is unsatisfactory for hydrological simulation. In simulation, there occurs overflow beyond the real streambed of the given watercourse and this overflow increases by twice against simulation based on elevation data acquired by modern methods. There is a little difference in outflow among models created from ALS or DMR 4G data, because both models were created by the same method, only certain generalization and distortion of the real terrain occur in the DMR 4G model. This change also affects the final rainfall-runoff and hydrodynamic simulation. The area of the resulting flood slightly increases due to generalization by mere 10 square metres in DMR 4G compared to the ALS method. So the results indicate that the DMR 4G model has only minor differences due to generalization and offers a reasonable level of detail for hydrological modelling. One of the other important input factors, which enter the rainfall-runoff and hydrodynamic models, is the land use. In the case of this study, it was the SCS CN method, which is included even in the HEC-HMS program and is well applicable in the Czech Republic. The results confirm the values obtained in similar studies, e.g. by Jeníček (2007). The resulting rapid reduction in the peak flow rate by 12 per cent is due to higher rate of land use changes in the examined periods, mainly the conversion from arable land to the category of permanent grasslands. This trend of decreasing arable land is also evident from the study by Bičík, Jeleček and Štěpánek (2001). Increase in the maximum flow rate also has impact on the final hydrodynamic simulation. We have observed an overall 3 per cent decline in the extent of flooded area compared to the past. Small changes in the simulation are caused by small size of the catchment area and also by small changes in land use among studied periods. The results displayed that even very small change in land use in the catchment area can result in expansion of the flooding area and this expansion could be the cause of damages to human health or property. It should be noted that the model was built from data of one precipitation event only and not be calibrated. Therefore results might be slightly distorted due to this fact.

CONCLUSION

The flow in watercourses is a complex process that may be affected by a number of input parameters. One of the most important input parameters to hydrological models are DTMs and the land use. The study showed that when using different input elevation data (ALS, DMR 4G, contour lines), there occur different outflow and different flow velocities. We have particularly demonstrated the inappropriateness of existing contour line data of ZABAGED® and vice versa showed adequate accuracy of the DMR 4G model.

Also changes in the land use may affect the resulting water runoff from the landscape. The effects of land use changes to higher watershed retention has long been known, this study however directly confirms the specific impact these changes have on reducing the runoff and therefore the flow, their peak values and total extent of flooding.

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Contact information

Josef Divín: divin.josef@seznam.cz
Tomáš Mikita: tomas.mikita@mendelu.cz