DTM Impact on the Results of Dam Break Simulation in 1D Hydraulic Models

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Abstract Dam break simulation has been quite long established module in the hydraulic modeling industrial standards, which are represented in particular by the software packages USACE HEC-RAS and DHI MIKE 11 worldwide including the Czech Republic. Coincidentally, at this level, both previously mentioned hydraulic models are using identical numerical solvers DAMBRK and WSPRO. It can be expected that the use of identical schematization of the river channels and technical objects together with the parameterization of dam body and its geometric parameters will give the comparable results of hydraulic simulations. When the same approach is applied for the reservoir and dam schematization together with its operational rules, the simulations using the identical solver DAMBRK will produce almost same results. Finally, the differences of the generated floodlakes by these particular models will be most affected by the accuracy and resolution DMT/DMR and partly by the different simulation concepts of water flow in the inundation area within each individual model. Because of the extreme situations of the "dam break" are occurring rarely (in the Czech Republic with larger water works only once), the calibration data is virtually absent. It is certainly not an argument to tell, that the simulation apparatus for HPPS and POVIS in the scope of the crisis management and planning was not prepared for these situations. A sensitivity analysis is among the crucial conditions of the successful modelling. This paper focuses particularly on the impact of DTM accuracy on dam break simulations.

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1 Preface

Hydraulic modelling is already among the standard tools both for the flood risk analyses and partly for the operational hydrologic forecasting in the national context together with the worldwide trends of the rainfall-runoff and hydraulic models integration. Operational Flood Forecasting Service of Czech Republic (HPPS ČR) is provided by the Czech Hydrometeorological Institute (CHMI hereinafter) in cooperation with the River boards and possibly with the other institutions of the crisis management and planning. Another impulse for the integration of hydraulic modelling methods into routine hydrological analysis is then migration of POVIS Flood Information System within the competence of the Czech Hydrometeorological Institute, that generates the obvious demand to harmonize the outcomes of the fully established rainfall modelling (hereinafter RR) with some outcomes of hydraulic modelling (hereinafter HD). It is obvious that no group of hydrological models (RR + HD) is capable of effective and accurate simulations and predictions without quality spatial/geographical data. The urgent need of accurate geographical data and consequently the quality GIS software itself from the second half of the 90 s of the last century resulted either in the integration of the GIS modules (ESRI platform and open source libraries) into the software tools for hydrological modelling or vice versa integration of selected hydrological models within the established GIS platforms. Here we can mention the integration of the EPA SWMM or SWAT models within the ESRI ArcView GIS and ArcGIS or later the integration of TOPMODEL or SIMWE rainfall-runoff models within the GRASS GIS and SAGA GIS environment. For hydraulic models the situation is not so simple due to more complicated aspects of the model schematization and simulation together with the higher amount of the manual editing, it can be concluded that the most common type of integration or rather communication with GIS software, is the existence of preprocessor and postprocessor in GIS environment. The two most widely used 1D hydraulic models and industry standards FEMA/NFIP USACE HEC-RAS and DHI MIKE 11 have the extensions HEC-GeoRAS (ESRI ArcView GIS for 3.x, ArcGIS 9.x and 10.x or ArcINFO 7.x) and MIKE 11 GIS (ESRI ArcView GIS 3.x, ArcGIS 9.x and 10.x). These two extensions are also used in this article together with the hydraulic models mentioned above. If we restrict our goals of the hydraulic modelling issues for the particular analyses of territorial impacts of special flood due to reservoir dam failure (e.g. dam break analysis), it is obvious that the digital terrain model or digital surface model (hereinafter DMT/DMR) plays the dominant role among spatial data). Parameters of their quality, aside from the obligatory requirements for DMT/DMR (see eds. Wilson and Gallant 2000), are the position and height accuracy, raster resolution and the level of singularities capture (edges, embankments, etc.). Practical experience suggests (and analyses used in this article confirm this) that the modern generation of DMT/DMR based on the laser scanning (DMR 4G/5G ČÚZK) can be considered as an important benefit for the precision of hydraulic modelling. The aim of the article was therefore to determine whether this benefit is equally strong even for the dam break analyses and whether the older generation DMT/DMR, which are still used in the Czech Republic (e.g. digital terrain models interpolated from the datasets such is DMÚ 25 or ZABAGED) are actually suitable for this type of analyses nowadays. Finally, it is necessary to emphasize that while the floods caused by natural factors (here we can classify regional floods from the stratiform precipitation, flash floods from the convective precipitation and flooding from the spring snowmelt) has a relatively solid data base for verification and calibration outputs of RR and HD modelling. On the contrary, we fortunately haven't such calibration data for dam break flood types. Such failures are not common in European countries involving Czech republic—except the accident on the water reservoir on Bila Desna river in 1916, which represent the only catastrophe of such type occurred in our country. While this complicates the verification and calibration of HD models for this type of analysis, the authors also wishes that this situation will persist also in the future. Finally, the hydraulic modelling process itself and model outputs have to be in the accordance with applicable legislation and regulations, we could refer to another works of the authors (Jančíková 2014; Unucka 2014), where the summary of this issues can be found.

2 Used Tools and Methods

As was already mentioned, this paper focuses on the analysis of the type of dam break in 1D hydraulic models and influence the accuracy of DTM/DSM on the results of these analyzes. For the actual hydraulic modeling were used industry standards USACE HEC-RAS 4.2 beta and DHI MIKE 11, 2011. Specifically, HEC-RAS 4.2 and 5.0 already integrates 1D (channel) and 2D (inundation) numerical solutions. MIKE 11 hydraulic model could be integrated with the 2D model MIKE 21c using the platform MIKE FLOOD. An important aspect for the use of 1D models (even in the context of this paper) is the fact that technical objects (e.g. dams, bridges, culverts, diverting objects, other water works) cannot be satisfactorily schematized within the 2D models and consequently there is no possibility of the proper numerical or analytical solution of their impact to the river hydraulics. Therefore, the abovementioned combination of 1D model for flow simulation in channels and the 2D model for flow simulation in inundation areas is currently (and probably in the future) the most pragmatic (Kožaná et al. 2014). Likewise, any operative communication with the RR models (e.g. HEC-HMS and MIKE SHE) is far more effective in the case of using 1D model. Both of these software products have virtually identical numeric-analytical solver for the dam body failure (NWS/FLDWAV DAMBRK) and also the solver for the influence of technical objects

(USGS WSPRO). Both models can also use a GIS preprocessor and postprocessor, specifically HEC-GeoRAS and MIKE 11 GIS ESRI ArcGIS. Part of the river Hloučela (about 12 km) and water reservoir Plumlov were schematized in these models and their preprocessors using 4th generation digital terrain model ČÚZK (hereinafter DMR 4G) and another technical objects (bridges etc.) were schematized beside the water reservoir itself. Fully automated preprocessing cannot be achieved for such situations because the schematization of the HD model including the technical objects is rather tedious task, in that respect that all required parameters cannot be obtained from the DTM. All schematization steps were therefore performed using the DMR 4G dataset and other types of DTM (interpolated by the Topo the Raster) were used only for HD model postprocessing and generation of the floodlakes. These interpolated DTMs were obtained from DMÚ 25 and ZABAGED datasets. Finally, the cell resolutions of particular digital terrain and surface models were 5 × 5 m for DMR 4G, 15 × 15 m for ZABAGED and 25 × 25 m for DMÚ 25 datasets. But it is obvious that, if there were such a variant schematization based on various abovementioned DTM datasets, the simulation of HD model and dam break analysis itself will be influenced due to the schematization errors propagation to the geometry of the longitudinal profile and cross sections. But these variations will exceed the paper extent and there is no reason using the less accurate HD model schematization nowadays. Finally, the individual DMT/DMR were compared with each other using regression analysis in ArcView GIS and IDRISI Selva (see Fig. 1). The dam break simulation results in both HD model were compared with each other, and then subjected to post-processing (analysis of the scope and depth of the flooded area) using the DMR 4G (5 × 5 m) DMT and interpolated data from the DMU 25 (25 × 25 m) and ZABAGED

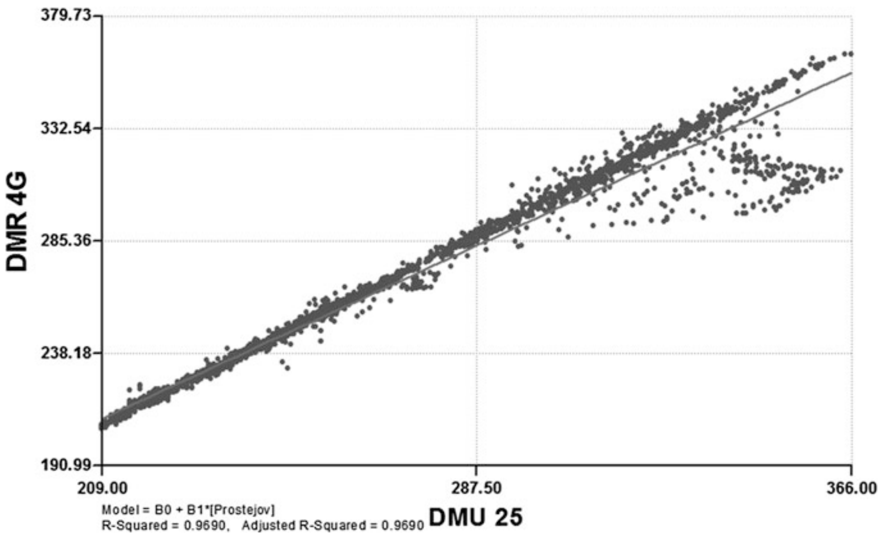

Fig. 1 Regression analysis of DTM values between DMÚ 25 a DMR 4G datasets in pilot area

(15 × 15 m). It is obvious that the grid resolution of DTM/DSM influences the extent of floodplains especially at the borders of inundation. The authors are aware of this fact and focus on the overall extent of the flooded area and floodlakes depths.

3 Brief Pilot Area Description

Hloučela River Basin is the watershed of 4th order since the number of hydrological sequence are from 4-12-01-045 to 4-12-01-057. Catchment area is 129 km^2 according to data of the Czech Hydrometeorological Institute and DIBAVOD. River Hloučela has its source in the woods of Drahanská vrchovina highlands north from the Buková village and has two sources that are spaced about 830 m as the crow flies. Hloučela is at its closing profile (total length 39 km) the right tributary of Romže (3rd order river), which then flows rightward as the Valová river onto Morava river (2nd order) near the village Uhřičice. The geological bedrock of the basin consists mainly of the Paleozoic metamorphic rocks of the Bohemian Massif, but the area of interest spans to the border of the Outer Western Carpathians, where fluvial, glacifluvial and partly eolic and lacustrine sediments of Cenozoic and Quaternary are dominant. Cambisols, gleysols and fluvisols are the most common soil types in the pilot catchment. Fluvisols are most frequented especially in the inundation areas of Hloučela and Romže rivers. Hloučela river basin belongs to moderately warm area (MT), only a small portion of the NW part of the basin lays in the cold area (CH7) and similarly the lowest parts of the catchment to the SE then belong to the warm area (T2) according to Quitt classification of climatic regions. Agricultural areas and forests are the main land use types in the catchment area (Safar 2003). Hydraulic model schematizations started above the Plumlov dam and ended on the confluence with the Romže river (0 m river stationing). Plumlov dam itself has the 9860 m stationing position in whole river schematization. Definitely, the schematization were extended above Plumlov reservoir to ensure adequate simulation of dam break due to the inflow above the Q_{100}/Q_{1000} in combination with improper manipulation on the dam outlets. Observing profile with gauge is in the category “A” of HPPS ČR with the serial number 333. Value of the average discharge Q_A is 0.580 $m^3\ s^{-1}$, Q_1 value is 7.40 $m^3\ s^{-1}$, Q_{50} value is 34.5 $m^3\ s^{-1}$ (above the Plumlov reservoir is then over 38.5 $m^3\ s^{-1}$ due to the influence of reservoir transformation effect) and Q_{100} value is 41 $m^3\ s^{-1}$ (over 47 $m^3\ s^{-1}$ above the Plumlov reservoir). For other values of N-year and m-daily Q we can refer to the pages of HPPS ČR (http://hydro.chmi.cz). Lesy ČR, s.p. is administrator of the upper part of basin and Povodí Moravy, s.p. of the lower parts of basin. Brno branch of the Czech Hydrometeorological Institute guarantees the HPPS ČR for the Hloučela river basins and its profiles, while the operational hydrological forecasting calculations are performed using the HYDROG RR model including the ensemble forecasts including ESP-ALADIN LAEF. Nowcasting forecasts are based on COTREC method in Brno and Ostrava branches of Czech Hydrometeorological Institute. Hydraulic transformation of flood waves on Morava river is provided at

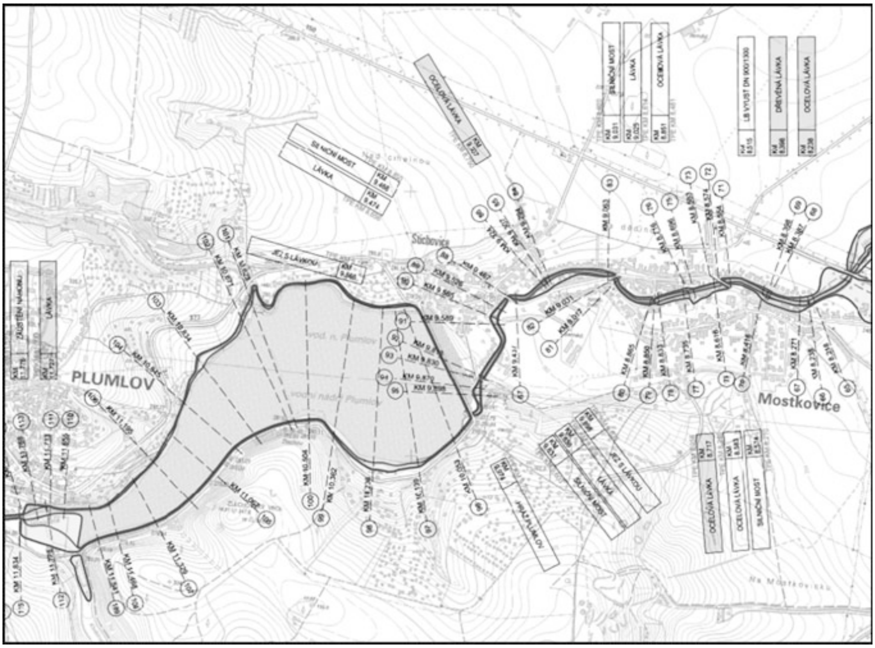

Fig. 2 Cross sections placement in HD model construction around the Plumlov reservoir

the Brno branch using MIKE 11 HD model with RR module MIKE NAM. Basic technical parameters of the Plumlov reserovoir and dam can be obtained on the website of Povodí Moravy, s.p. (http://www.pmo.cz/cz/uzitecne/vodni-dila/plumlov/) or in more detail, including the history of construction and reconstruction of the waterworks in author's work Jančíková (2014). Location of the cross sections for the schematization of HD models HEC-RAS and MIKE 11 near VD Plumlov is illustrated in Fig. 2. Calibration of models were performed for the Q_{50} and Q_{100} discharges and water levels. Fortunately, there is no observations and inundation areas evidence for the dam break situation, as was mentioned in the preface.

4 Selected Results

For detailed results of the entire cascade of the GIS preprocessing, HD modelling itself and final GIS postprocessing see the work of Jančíková (2014). For a more detailed description of the characteristics of hydraulic model HEC-RAS and MIKE 11 You can then refer to the websites of the model manufacturers, or to the work of Unucka (2014) respectively. After schematization of Hloučela river in models HEC-RAS and MIKE 11 using their particular GIS extensions the flow simulations of Q50 and Q100 were performed followed by the calibrations of hydrographs and rating curves in the channel of Hloučela river and locally the extents of floodlakes. Results correlation values between the HD models was very good (over 98.6 %), which corresponded to the entrance hypothesis of the authors that using the same input data, virtually identical schematization, simulation methods such is Bernoulli equation (HEC-RAS and MIKE 11) or the dynamic wave approximation (MIKE 11 for verification), USGS and NWS WSPRO/FLDWAV DAMBRK (HEC-RAS and MIKE 11) together with very similar mechanisms of the GIS postprocessing (for differences can again refer to the manufacturer's manuals or the SW) we can expect a high degree of results correlation of both 1D HD models. After this the dam break simulations phase were performed itself beginning in the dam crest (278.63 m above sea level) with downwards progression which stopped at the value of 271.5 m above sea level with total failure width 55 m on its upper part. The results of HD models simulations (floodlakes extents) and correlation values depths in channels and inundation are shown in Figs. 3, 4, 5 and 6.

We can characterize the actual parameters of the special flood situation due to dam break by the following parameters:

- Peak flow Qmax = 204 $m^3\ s^{-1}$,
- flood wave volume W = 4.8 million m^3,
- dam break wave celerity during the culmination raises up to 12.6 $m\ s^{-1}$ just below the dam and in the first 300 m from the Plumlov water reservoir, in next kilometer downstream value drops to 1.3 $m\ s^{-1}$ in the channel Hloučela (outside the channel the further decline occurs),

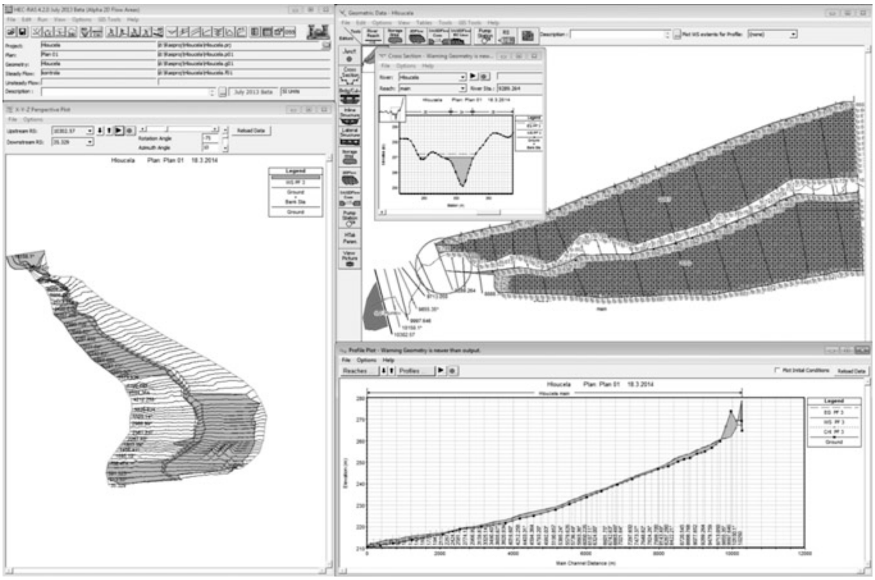

Fig. 3 Schematization of Hloučela river in HEC-RAS model for 1D and 2D flow solution

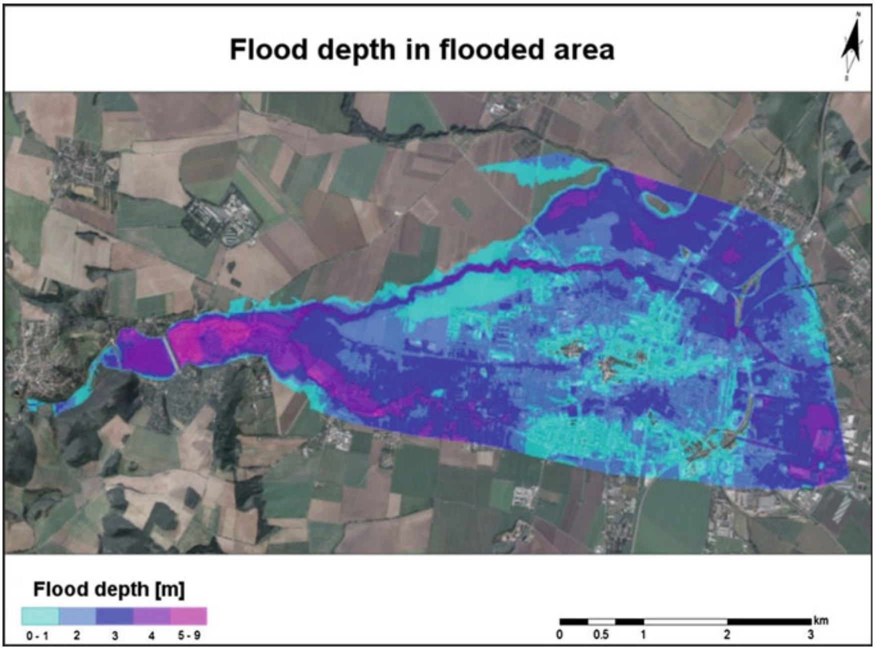

Fig. 4 Water depths and inundation are extent generated by MIKE 11/MIKE 11 GIS

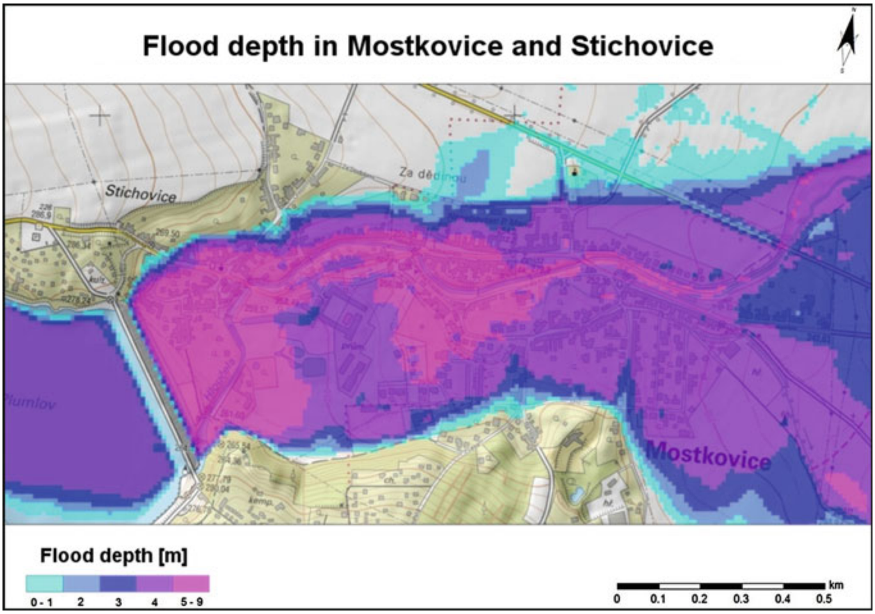

Fig. 5 Water depths and inundation are extent generated by MIKE 11/MIKE 11 GIS around the Plumlov reservoir dam

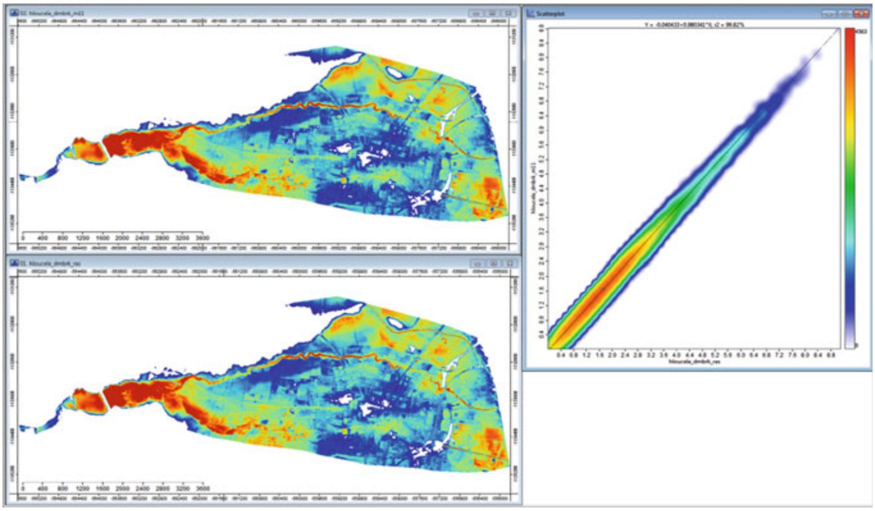

Fig. 6 Floodlakes generated by HEC-GeoRAS (*top left*), MIKE 11 GIS (*bottom left*) and regression analysis of both floodlakes in SAGA GIS (*right*)

- the speed of the break wave in the inundation area below the dam is 8 m s^{-1}, on the edges of inundation and downstream below then decreases to 0.5 m s^{-1},
- the depth below the Plumlov reservoir in the riverbed Hloučela increases up to 9 m during the culmination, in the Prostějov downtown decreases (<1 m),
- the culmination Q occurs approx. 1 h from the beginning of the dam body break,
- the maximum extent of floodplain is computed about 17.0 km^2 in HEC-GeoRAS and 17.2 km^2 in MIKE 11 GIS (these differences are due to different postprocessing when the HEC-GeoRAS are considered cross sections to the edge of considered floodplain, while such approach isn't required in the MIKE 11 GIS).

Computed floodlakes extents consequently calculated using DTMs interpolated the from DMU 25 and ZABAGED datasets indicated more significant result differences, especially in part 1.3–4.4 km from the Plumlov reservoir (cadastral evidence of Mostkovice and Prostějov) when the abovementioned parameters of the dam break wave floodplains significantly reduced and similar values depths and ranges overflowing is achieved again until cadastral area Prostějov from the station by about 6 km. According to the analysis carried out so far, there is noticeable effect complete secondary errors height grid cells DMÚ 25 (most obviously here) and ZABAGED (already small differences due to higher grid resolution and discretion terrain edges and point field dimensions during interpolation Topo to Raster). This approach has impact on the artificial "carving" of the cross sections and the height values of the banks opposite to DMR 4G dataset. The situation is summarized in the following Table 1.

Table 1 Comparison of the selected results of hydraulic modelling based on the various types of DMT for GIS postprocessing

Type of DTM	Cell size (m)	Floodlake extent (km^2)	Maximum depth (cm)
DMR 4G	5 × 5	17.2	9.2
DMÚ 25	25 × 25	14.7	10.7
ZABAGED	15 × 15	15.8	9.6

5 Discussion

It's evident from previous chapters that the HD models and the industrial standards in particular in this group of hydrologic models provide an effective analytical tool, particularly in cooperation with the GIS. Selected aspects of these mathematical models, including connectivity to GIS are well summarized in publications such are Bedient et al. (2007, 2013), Dyhouse (2007) and Di Baldassarre (2012). The data input and model structure uncertainties and consequent pitfalls of the improper use of mathematical models are discussed in Beven (2009). Technical reports and case studies are downloadable on the website USACE/HEC (including the aforementioned modules NWS/FLDWAV DAMBRK a WSPRO USGS). In this regard, it should be noted however, that in the present article presented only the simulation of scenarios during the special type of flood due the dam break event (albeit with calibrated 1D and 2D hydraulic models). As has been stated several times before, not only by the authors in previous sections of the text, hydrological and hydraulic models provide accurate results when there is an availability of the high-quality input data and vice versa, which Starý called the "data crisis" (in Jandora et al. 2002). A virtually identical conclusions in the next case study is also presented by the team of authors Kourgialas and Karatzas (2013) in the catchment areas of the island of Crete or in the Elbe basin case studies (Chaterjee et al. 2008). In both cases, the platform DHI MIKE was obviously proven in different physical-geographical and hydrological conditions. Similarly, the potential of HD model HEC-RAS tested for similar analyses in the work of Johnson et al. (1999). For detailed verification and validation of models it would be necessary to perform hydrometric measurements during the special flood event occurrence. However measurement during extreme discharge conditions brings significant error and data inaccuracy using both classical methods (hydrometric propeller) or new technologies based on ADCP. Finally, it is in fact hardly technically feasible not only on the level of measurement itself, but also on the level of rating curve construction, which represents further complication of the HD model calibration. Generally, the situation can be summarized by saying that, if the hydraulic models give satisfactory results during the floods caused by natural factors, we can expect that equal simulation apparatus can generate similarly good results for the special flood events simulations assuming the use of high-quality input data and verified tools (industrial standards). An interesting contribution to the debate is the article of USACE/HEC developers Ackermann and Brunner (2005) or Xiong (2011).

6 Conclusion

We can conclude that the phenomenon of the dam break events and simulation of this type of special flood represents a challenge both for geoinformatics and for hydroinformatics and hydrological modeling. Input hypothesis of the direct impact of DTM quality and resolution was confirmed with the utilization of GIS analyses and mathematical modelling. The greatest spatial accuracy of hydraulic model schematization can be achieved by using the LIDAR based DTM/DSM (DMR 4G ČÚZK) in combination with geodetic measurements of thalwegs and cross-sections. An interesting aspect will be the comparison with the next generation of digital terrain/surface model DMR 5G. It is interesting not just in the case of special flood events simulation, but also for the spatial and temporal reconstruction already occurred flood events caused by the natural factors. Finally, it is clear that the implementation of the so-called Flood Directive (2007/60/EC) was prepared responsibly and passed without significant problems in the Czech Republic at the level of methods, tools and input data. So we can expect that there will be further development of methods HPPS CR for which Czech Hydrometeorological Institute is responsible in cooperation with the River Boards and other institutions involved in crisis management and planning. Data of State Administration of Land Surveying and Cadastre (ČÚZK) then form an integral part of the critical data base. At the level of mathematical models we can already hardly expect fundamental changes, industrial standards such are USACE HEC-RAS and DHI MIKE 11 show their quality at the level of a separate HD modeling and even by the integration possibilities with other tools for RR modeling (HEC-HMS, MIKE SHE etc.), urban hydrology simulations (MIKE URBAN, EPA SWMM) or hydrogeological modeling packages (MODFLOW, FEFLOW).

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