Assessment of the runoff conditions of small ungauged catchments using GIS and fully distributed hydrologic models

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Small river basins are important not only as sources of water during the extreme runoff phases. Especially during the quite severe hydrosynoptical situations, it is necessary to determine or at least estimate the production of runoff from these areas. This is the task facing the hydrological forecast service and floods of 2009 - 2013 just accented further study of these basins. This case study deals with small basins in NP Czech Switzerland, namely Červený, Jetřichovický and Koutský brook, then the Dlouhá, Suchá and Jetřichovická Bělá. These basins are characterized by extreme relief rock formations together with basic absence of the monitoring gauges network. For the morphometric and hydrological analyses, particular GIS software products were used, such as ESRI ArcGIS, GRASS GIS and SAGA GIS. Subsequently, the development of semi-distributed and fully distributed models using HEC-HMS, SIMWE and MIKE SHE/MIKE 11 software packages and mainly industrial standards were the consequent steps. Results of the actual phases of research mentioned above are presented in this article.

Keywords: NP Czech Switzerland, distributed models, MIKE SHE, HEC-HMS, SIMWE, GRASS GIS, SAGA GIS

Introduction and goals of the case study

The problem of determining hydrological characteristics and predictions of flow during flood episodes on small, ungauged watersheds, which are also less equipped with the station network, is not only important in the context of hydrological forecasts. Although these basins are often less important from the point of view of the water board management, they become source areas of increased runoff contributing to the basins of higher order quite often. These catchments also play an important role as sources of the quick runoff peak at the context of both regional floods and floods from the convective precipitation, which are often so-called flash floods. From this perspective, it is desirable to study such types of basins and consequently analyse their character and runoff conditions as accurately as possible.

Analysis and further determination of selected hydrological parameters of each particular basin are important then. These stages of the research are carried out with the help of GIS and hydrological models that allow not only the spatial analysis of morphometric (slope orientation and length, vertical and horizontal curvatures etc.) as well as catchment hydrological parameters (e.g. spatial distribution of runoff coefficient, values of CN curves etc.). The next step, which already aims to provide hydrological forecast, is then construction, schematization and parameterization of the semi - distributed or fully distributed rainfall - runoff models. By using means of engineering geology on constructed models we can predict the consequences of various interference in the overall character of the landscape, caused by anthropogenic activities, such as development of flooding and landslide situations with increased of rainfall [25].

The phenomenon of the formation of rainfall-runoff models to the unmeasured (also called ungauged) watersheds is systematically dealt in particular [23], respectively [2, 3] or [4]. Using the fully distributed models not only in these conditions was intensively studied in [1, 21]. Because such types of watersheds are situated in the mountain areas close to the national border very often, they're frequently covered by the forests, respectively by the barren soil or rocks as in this case study. Analysis of the impacts of the forest and forest soils on the runoff conditions of watersheds is discussed in [11], [6] or [18]. Authors present the results of the previous stage solution - i.e. field researches, spatial analyses in GIS of the pilot watersheds and semi - distributed & fully distributed rainfall-runoff modelling in this article. The next phase will be especially focused on the parameterization and verification of rainfall-runoff models (e.g. retention curve, revision of Manning coefficients and bathymetry channels) using field measurements during particular rainfall-runoff events.

Pilot area

Researched Jetřichovický creek basin together with the neighbour basins is located in the central part of the National Park Czech Switzerland near the border with Germany. In terms of geomorphological structure, the explored area creates (forms) part of the province Czech Highlands and sub province Krušnohorský system, Krušnohorská hilly area and Děčínská highland. From the groundwater scope, pilot area is part of the

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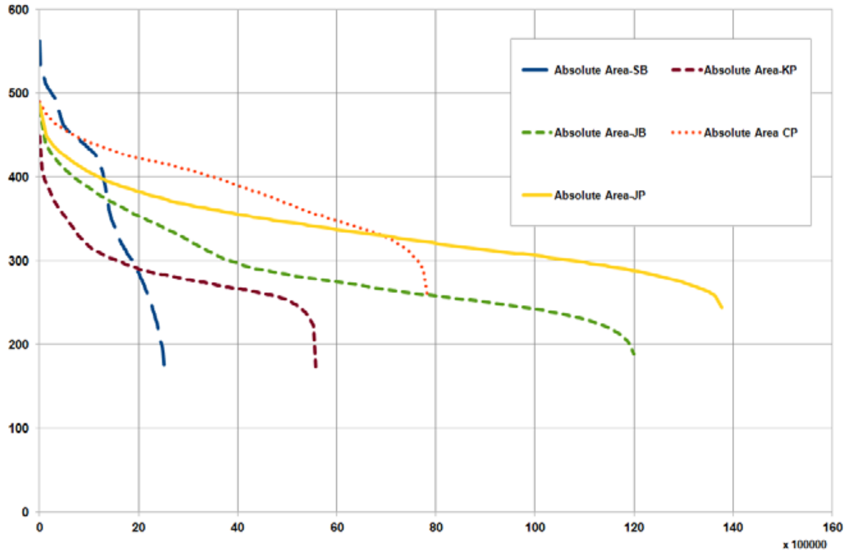
hydrogeological zone 4660 - Cretaceous structures of Lower Kamenice and Křinice rivers. Number of hydrological sequence of this subbasin is 1-15-01-0120. The highest elevation value of this basin (derived from LiDAR DEM) is 487 m above sea level, mean basin elevation is 335 m above sea level, the lowest elevation of basin (outlet and contribution into Křinice in the area of Zadní Jetřichovice) is 243.7 m above sea level. Basin area derived from DEM using r.watershed is 13.75 km^2. The height ratios of the pilot basin in relation to other basins of the National Park Czech Switzerland are shown in Graph 1 (hypsographic curve of the main basins of the broader pilot area is shown in Graph 1). Watershed is composed of Cretaceous sandstone sediments, established on the old crystalline basement situated on the eastern edge of the Krušnohorská unit. The relief is then formed by Turonian sandstone structure, to whose formation has contributed volcanic activity during the Tertiary. In addition the gradually denuded, initially underground volcanic infill is formed by volcanic relief elevations, contributing particularly to its vertical zonation. For large structures dominate the structure of the platforms and canyons (especially Labe, Kamenice, Křinice).

The area is characterized by the occurrence of vertical rock walls, abris, rock towers and top plateaus. Gorges and ravines are usually wet, with reduced insolation and with the significant occurrence of frost hollows. The investigated basin is essentially completely covered predominantly by coniferous forests with reduced herb layer, but targeted interventions by forestry are gradually converting them to mixed forests. Given the small slope of the ravines thalwegs and large permeability bedrock, surface flows are often ephemeral, flowing nature. According to the Czech national basin typology, examined segments can be grouped 1.1 "Source area of the forest", 1.6 "Source area of the wetland, fen and bog", 2.1 "Natural foothill torrent - forest track" and 2.4 " Natural foothill torrent - rock track, gorge" [19]. Besides the shape and morphology of the thalweg, channels play an essential role in the runoff hydrograph properties and then consequently the morphological parameters of inundation areas. These aspects were taken into account by the team of authors using the combination of fully distributed rainfall model MIKE SHE and hydraulic model MIKE 11 beside the conventional approaches based on the semi - distributed models which are typically represented by HEC - HMS (optionally, together with fully distributed representation of several methods such as gridded SCS - CN). Overview of the pilot area and the analysed watersheds are shown in Figure. 1.



Graph 1. Hypsographic curves of the pilot catchments.

Tab. 1. Overview of the basic parameters of pilot catchments.

Catchment name	Hydrologic order	Hypsometric integral	Melton index	Area [ha]	Mean elevation [m n.m.]	Forest cover [%]
Červený potok	1-15-01-0100-0-00	0.566	0.084	783.4	388.3	99.5
Suchá Bělá	1-14-05-0260-0-00	0.535	0.249	252.5	378.7	99.2
Jetřichovická Bělá	1-14-05-0200-0-00	0.349	0.085	12	291	99
Jetřichovický potok	1-15-01-0120-0-00	0.377	0.066	1377	335.5	99.5
Koutský potok	1-14-05-0220-0-00	0.435	0.12	558	289.7	97
Dlouhá Bělá	1-14-05-0260-0-00	0.432	0.156	797.5	313.2	98.1
Grosser Zschandbach	-	0.423	0.118	978.4	350.4	95.2
Bílý potok	1-14-05-0080-0-00	0.578	0.109	435.7	419.5	79
Kachní potok	1-14-05-0240-0-00	0.343	0.209	484.4	316.7	92.3

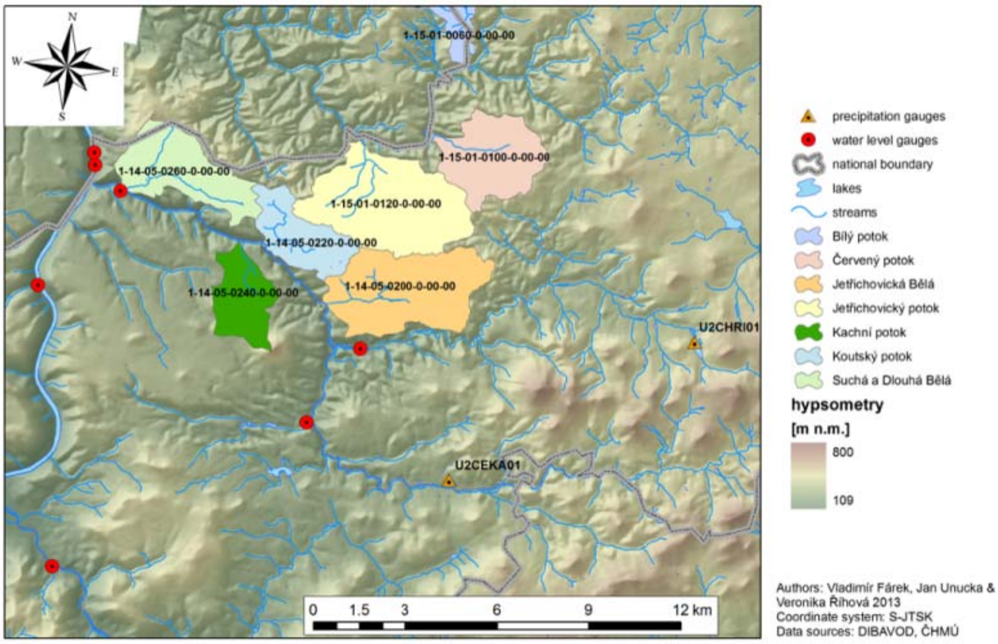


Fig. 1. Map of the pilot catchments together with the gauges network in their surroundings..

Methods

Progress of the work and used methods can be divided into three basic groups:

1. *Collecting and preprocessing of the spatial data.*
2. *Morphometric and hydrological terrain analysis.*
3. *Rainfall-runoff modelling.*

Authors emphasized the fact that verified and validated tools and methods were used in phases 2 and 3. To achieve this, standard GIS platforms and also the use of the industrial standards at the level of hydrological modelling were taken into account. The following chapters then describe the different techniques and methods in greater detail in the context of analyses and simulations. The basic requirement was to test the hypothesis of surface runoff depending on morphometric parameters of pilot river basins and, at the same time, usability of selected tools and methods in the extremely shaped relief sandstone landscapes.

At the level of GIS analysis tools, DEM ESRI ArcGIS, GRASS GIS and SAGA GIS were used. At the level of actual rainfall-runoff modelling, mainly industrial standards FEMA/NFIP were used, such as HEC - HMS (semi-distributed model with the possibility of fully distributed approach for particular methods), MIKE SHE/MIKE 11 (fully distributed model) and a fully distributed model SIMWE in GRASS GIS platform. Results of the GIS analyses and hydrological modelling were then correlated using the geostatistical approaches, such as regression of grids in GRASS GIS and ESRI ArcGIS etc. For the comparison of the rainfall - runoff models results, the sampling points (profiles on the water courses) were established for some representative parts of the pilot basin (e.g. closing profiles, outlets of particular thalwegs etc.).

Surface runoff and overland flow modelling approaches

Surface runoff occurs basically by exceeding of the infiltration capacity of the soil (infiltration excess - Horton runoff) or by exceeding of the water retention capacity of the soil (saturation excess - Dunne runoff) and by the exfiltration of water in the lower part of the slope in predisposed watershed and hillslope segments (return flow) [3]. Using different algorithms from the digital elevation model (DEM below), we acquire the parameters of flow direction (FD) - the direction of runoff and subsequently flow accumulation (FA) - the accumulation of runoff. FD refers to the way in which direction is outflow generated from each cell of DEM to the other low-lying cells and globally estimates the tendencies of water and material flow above particular DEM. Thus, we can talk about the drainage track or flowtrack - most frequent term for such phenomenon is the flow path. FA then determines how many cells are drained through a particular cell. Because the cells of hydrological correct DEM are connected to one another, we can determine the cumulative amount of material that passes through each cell. In principle, FD determines using two general groups of methods:

- SFD - Single flow direction - each cell has only one drain neighbouring cell located below.
- MFD - Multiple flow direction - outflow of cells is allowed in several low-lying cells disperse runoff.

FD is designed in a grid of 3x3 cells, and the two principles (MFD and SFD) are solved by a variety of algorithms in this case study. The simplest algorithm is SFD D8, when the drainage is implemented in one of the 8 neighbouring cells with a maximum height difference (∂Z). Diagonal cells are multiplied by √2 to compensate for their lower ∂Z. The variant RhoD8 applies, that diagonal cells are assigned a pseudo-random value (with an average of $\sqrt{2}$), the variant D∞ is then allowed to drain into a single cell, but in (relatively) any angle (0-360˚). For MFD algorithms, drainage is estimated using various algorithms implemented in multiple cells, typically by the weight based on their degree ∂Z relative to the central cell. These basic principles are derived from a number of algorithms and theoretical work, implemented in different GIS and hydrologic modelling software packages (e.g. HEC- GeoHMS, GRASS GIS, SAGA GIS, uDig, ESRI ArcGIS, DHI MIKE SHE). The moment is satisfactorily implemented into the grid lines and the accumulation of runoff eventually named as local drain direction map. It is possible to obtain a real drainage by multiplying the cells accumulating by the relevant operators and values. Each particular software package used in this case study varies by using procedures and a series of equations (e.g. SCS - CN, Green - Ampt, Saint Venant approximations, Muskingum - Cunge, Manning equation etc.) to quantify the remaining data inputs for consequent numerical and analytical modelling of rainfall-runoff processes.

Used software packages of GIS and hydrological modelling

Among the software products were dominantly used packages such as ESRI ArcGIS, GRASS GIS, SAGA GIS within the stage of GIS analysis of DEM and other data inputs (e.g. geology, soil types, hydrologic soil groups, land use and land cover). Consequently, SIMWE, HEC-HMS, MIKE SHE and hydraulic model MIKE 11 were used at the level of hydrological modelling in both semi-distributed and fully distributed approaches. Detailed descriptions of individual software packages can be found on the websites of certain software producers or developer communities in the case of open source software such as GRASS GIS and SAGA GIS. Partial descriptions of these tools in relation to these types of analyses and simulations are also discussed by the team of authors, e.g. [7] and [20]. An important factor in the use of fully distributed rainfall - runoff models is the possibility of distribution of the basin hydrological parameters for individual grid cells, so - called grid in GIS and computational grid (grid or mesh) within the tangible schematization of the rainfall - runoff model. It is obvious that the spatial accuracy is then primarily determined by the size of these cells. One of the key factors (with regard to the issue of so - called extreme relief of rocky sandstones), is the existence of high - quality digital elevation model (DEM). In the area of interest, DEM obtained by laser scanning pilot area (the so - called LiDAR) with a resolution of 1x1 m was used. Such input DEM is a prerequisite for a small degree of uncertainty in the input data. In fact it is the best DEM technology involved in this type of studies and similar case studies confirmed this, see e.g. [9]. For the morphometric and basic hydrologic analyses of the pilot basin the following models were chosen: ESRI tools ArcHydro and Spatial Analyst, other morphometric analyses were performed using GRASS GIS modules r.terraflow, r.watershed, r.topidx and r.slope.aspect. Further morphometric analyses were accomplished in SAGA GIS, e.g. the depth and width of the valley, terrain moisture index and topographic convergence index. More detailed documentation of the above analyses and specific modules can be found on the websites of GIS platforms and also in [10], [13], [14], [15] and [22]. The data preparation and schematization of distributed models SIMWE and MIKE SHE were performed on all interest basins (see Table. 1). Further comprehensive and more detail-focused schematization of rainfall-runoff models HEC- HMS and MIKE SHE and the schematization of the hydraulic model MIKE 11 (interconnected with MIKE SHE) were then performed on Jetřichovický creek basin at this stage of research (Fig. 2).

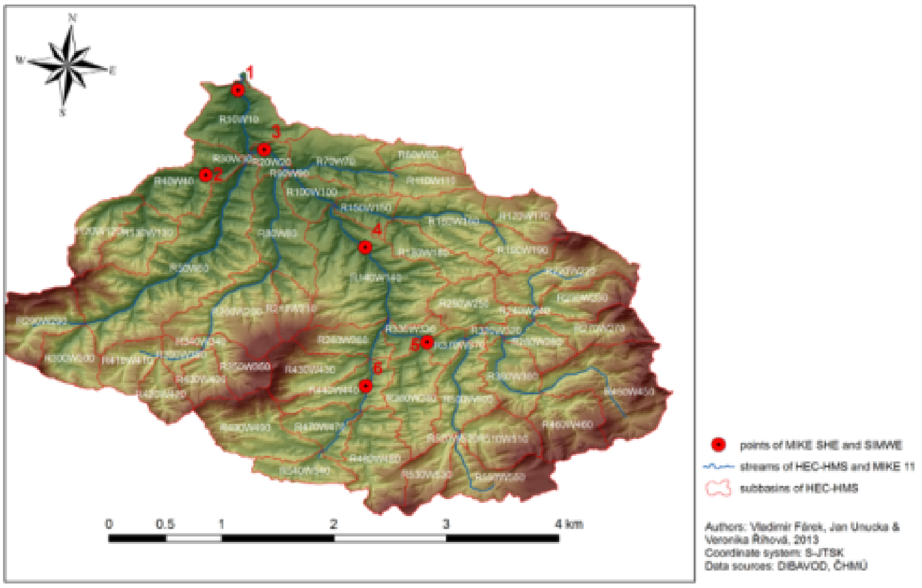


Fig. 2 Comparison points of MIKE SHE/11, HEC-HMS and SIMWE results

Rainfall-runoff models HEC-HMS and MIKE SHE as well as the hydraulic model MIKE 11 are broadly validated as hydrologic modelling and forecasting tools and also the industrial standards of FEMA/NFIP. Model SIMWE has interesting potential as a fairly robust tool for fully distributed simulation of surface runoff from the causal precipitation. Methods used for the hydrologic transformation of rainfall were Richards´ equation, SCS-CN, Green-Ampt and linear reservoir together with MODFLOW finite differences method for the groundwater flow simulation. For the hydraulic transformation phase of the rainfall-runoff process were used kinematic wave and dynamic wave approximation of St. Venant equations in MIKE 11 and HEC-HMS models.

Results of the case study within the main pilot basin

Figure 3 shows the results of analyses of depths valley using SAGA GIS algorithms in the basin of Jetřichovický stream. This is the result of a very effective and useful morphometric analysis in SAGA GIS in cases, when the terrain conditions of the pilot area tend to be more complicated. The entry prerequisites for this analysis were the depth, width and slope of the valley, which affects the size and shape of the runoff hydrograph. The depth of the valley as parameter refers to the magnitude of erosion processes within the particular geological conditions of the catchment. They are also a reflection of lithological and morphostructural aspects of the basin with the fact that in the lithologically almost homogeneous pilot area, the depth of the valley is mainly a reflection of the geomorphological and erosive action of the surface runoff and fluvial erosion. Along with other analyses such as the definition of flow accumulation grid, SAGA wetness index, topographic index [3], we can then derive the „*significance*" of individual parts of the pilot basin in terms of surface-runoff and shallow hypodermic runoff production. These results were compared with simulation results of HEC-HMS, SIMWE and MIKE SHE / MIKE 11 models, as shown in Figure 4 to 6.

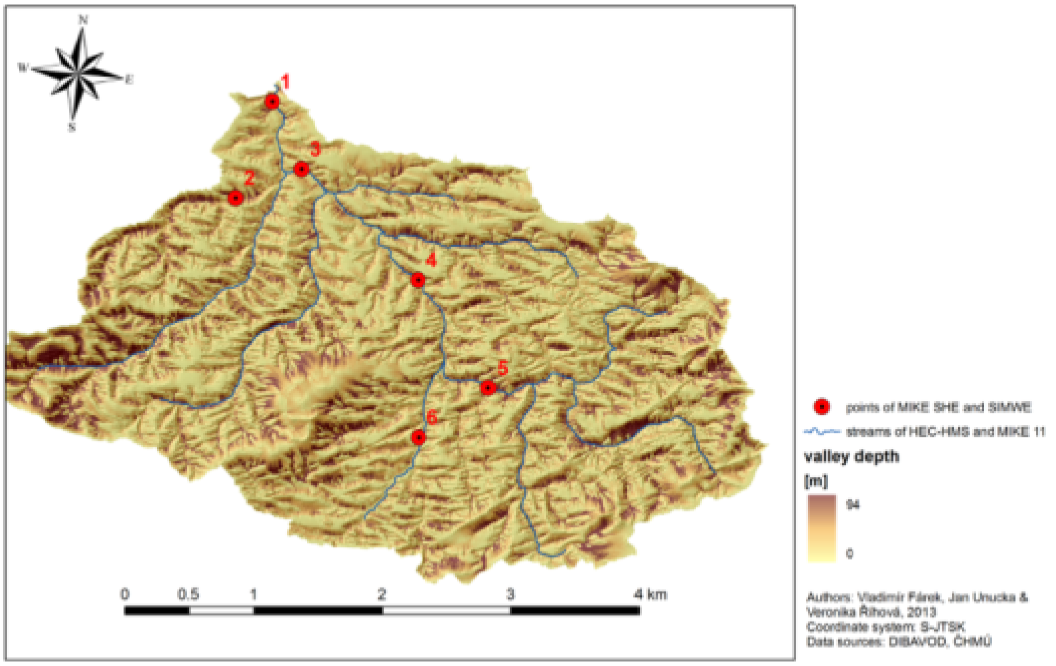


Fig. 3 Valley depth of Jetřichovický potok pilot catchment. Result of SAGA GIS analysis

Lower values of culmination discharges simulated by MIKE SHE (2.32 $m^3.s^{-1}$) compared with the SIMWE model (2.66 $m^3.s^{-1}$) are probably caused by the higher complexity of the MIKE SHE model, which unlike SIMWE also considers and simulates hypodermic runoff and baseflow. Simulated rainfall episode was episode 6/2013 in all cases. Figure. 7 then shows the relationship between the depth of the valley generated by the analysis in SAGA GIS and time of concentration values generated in the framework of preprocessing HEC-HMS in ArcGIS / HEC-GeoHMS. The coefficient of determination reached 0.23 when all grid cells were selected, not just sample points of particular grids. If there had been selected sampling points located in the thalweg or its close surroundings using the buffer method, the value of regression would be significantly increased to the value 0.71.

In Table. 2, comparison of the simulation results of the rainfall-runoff models HEC-HMS, MIKE SHE and SIMWE in selected comparative points can be found (see Figure 2). It is apparent that despite the use of different software products, such as HEC- HMS, MIKE SHE/MIKE 11 and SIMWE and different methods and approaches during the schematization and simulation phases, the results are comparable and statistically correlated quite well [24].

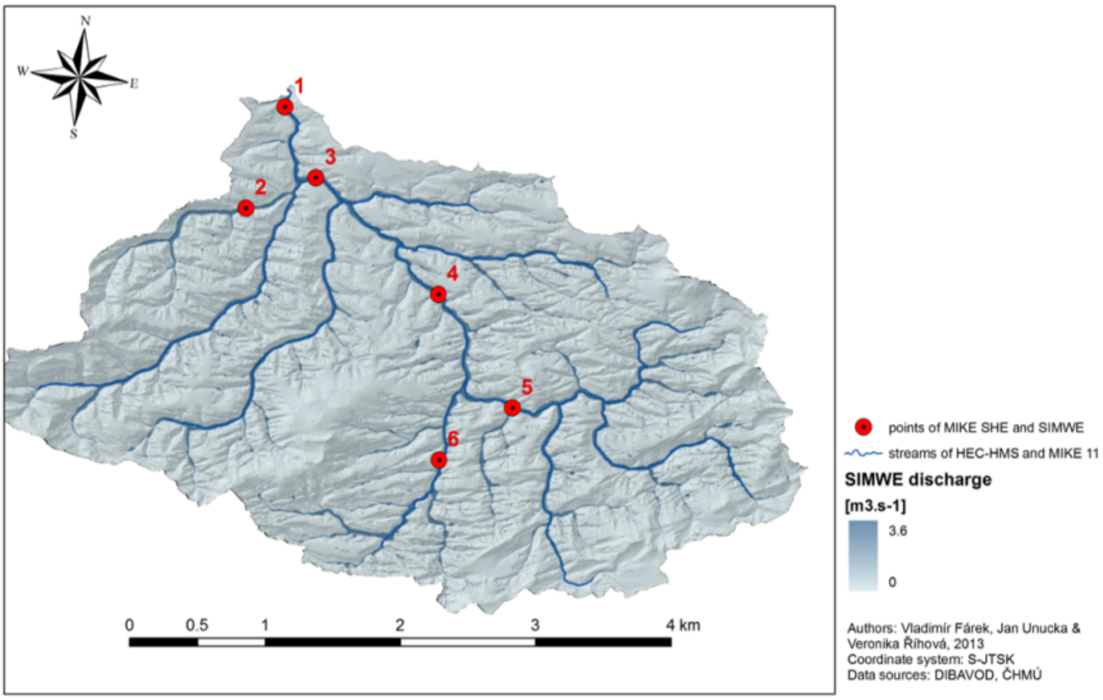


Fig. 4 Overland flow discharge value, result of SIMWE/GRASS GIS simulation

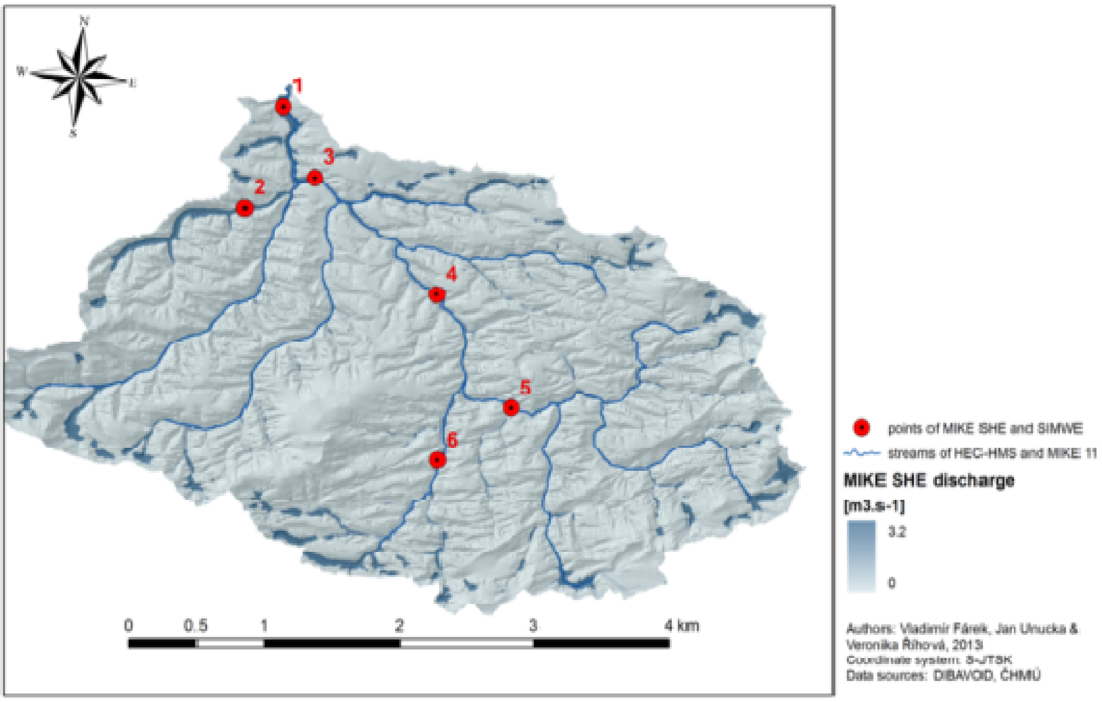


Fig. 5 Overland flow discharge value, result of MIKE SHE/MIKE 11 simulation

Tab. 2 Comparison of the simulated peak discharge in comparison points. Episode 6/2013

Comparison point	S-JTSK X	S-JTSK Y	MIKE SHE/11	HEC-HMS	SIMWE
1	-734992	-953184	3.35	3.1	**3.6**
2	-735281	-953934	0.14	0.12	**0.16**
3	-734761	-953709	3.11	3.0	**3.3**
4	-733858	-954571	2.45	**2.68**	2.6
5	-733309	-955410	1.17	1.1	**1.35**
6	-733852	-955794	0.95	0.92	**1.02**

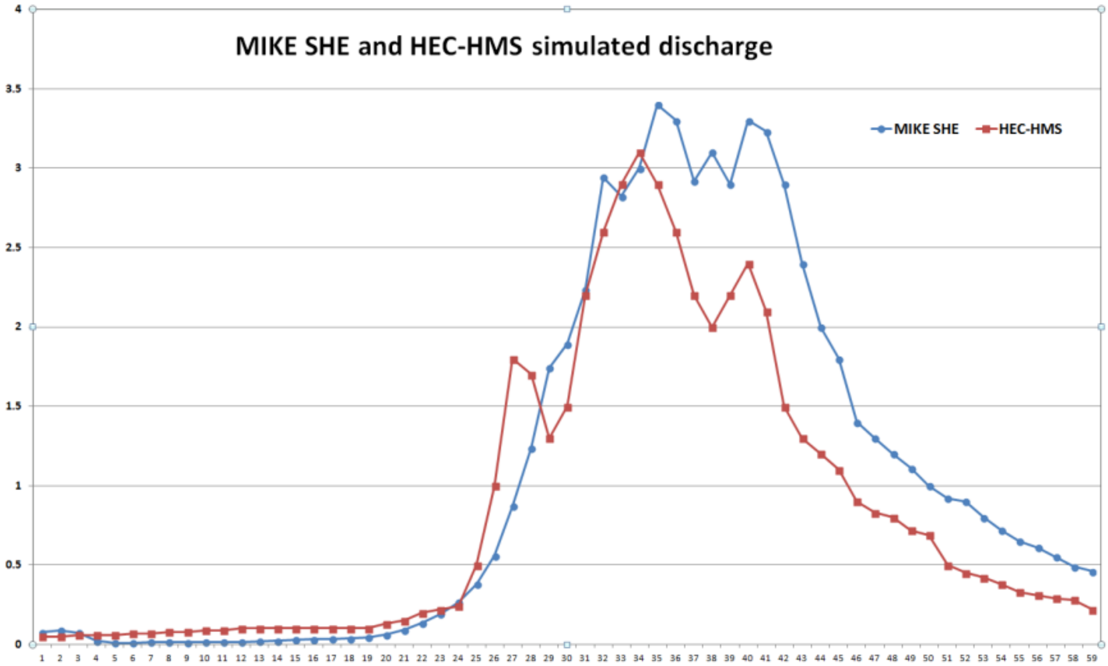


Fig. 6 Comparison of simulated hydrographs in catchment outlet by MIKE SHE and HEC-HMS models

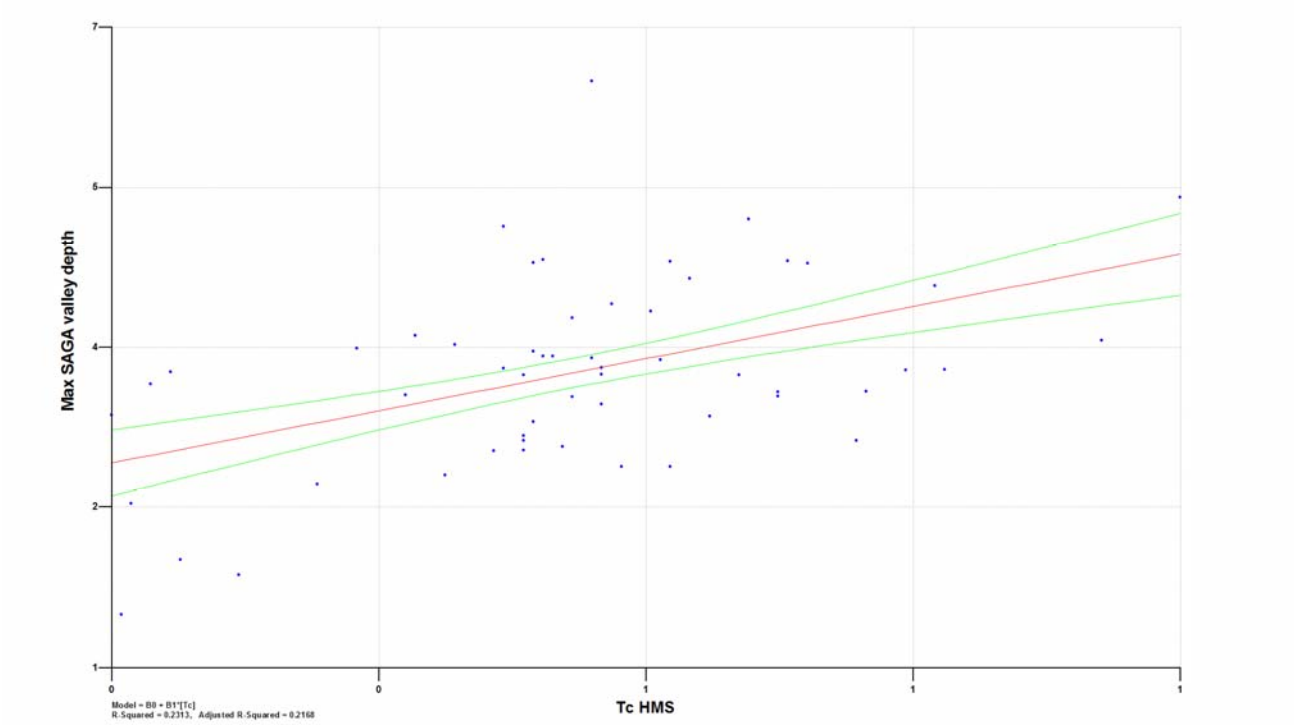


Fig. 7 Regression between SAGA valley depth a HEC-HMS time of concentration grids

Discussion

The results show that the initial hypothesis of the surface runoff and morphometric parameters dependency was predominantly confirmed in selected pilot basins. The appropriateness of using fully distributed rainfall-runoff models and methods of continuous simulation (e.g. MIKE SHE) within the unmeasured basins is discussed, among others, by the authors in [5, 8, 12] and [17]. In [17], inter alia, the importance of such studies in terms of simulation and prediction of the impact of flash floods is emphasized, at which point the experience from the years 2009 to 2013 in pilot river basins confirms. Works [2, 3, 4] and [23] remain major monographs in this regard. One of the most important factors in this scope is the availability and quality of the input data (except in the case of operational hydrometeorological data of the ungauged basins) together with the used software and methods especially at the level of the rainfall-runoff modelling. MIKE SHE represents without any doubt one of the most complex and effective tools. Its performance and potential for such studies increase with the possibility of combination with the hydraulic model MIKE 11 (and thus alternative to simulate channel routing using the real geometry and not the subsidiary and simplified geometric shape) and connectivity to the groundwater flow models MODFLOW / FEFLOW. Another advantage is the use of continuous methods instead of the event methods in the hydrologic transformation of precipitation, as discussed in [8]. Importance of the MIKE SHE model for the comprehensive and fully distributed analysis, simulation and prediction are discussed in [3, 16]. The general aspects of using fully distributed models are particularly concerned in [21]. The disadvantage of using MIKE SHE compared to SIMWE is much higher demand on hardware performance and the parameterization of the model, which cannot be described as trivial, particularly in the combination with MIKE 11 hydraulic model and groundwater flow model MODFLOW setup. Beven [3] in addition, points to the fact that a simple robust model can in some cases and in some combination of physical-geographical conditions and hydrosynoptic situations before calibration tend to produce more satisfying results. This is also discussed in [16].

Conclusion

The above preliminary results of GIS analyses and rainfall-runoff modelling point to several interesting facts. First, we can state that the initial hypothesis of the importance of verification results of GIS analysis using a fully distributed rainfall-runoff models was proved. This verification was accomplished using industrial standards FEMA/NFIP as is HEC-HMS, MIKE SHE and MIKE 11 together with the fully distributed open source model SIMWE, which is the part of GRASS GIS platform. Especially in the case of the use of HEC-HMS and MIKE SHE/MIKE 11 models, numerous case studies already exist. So it can be said that both models are broadly verified and validated (even within the FEMA/NFIP particular evaluation phases). The model SIMWE for GRASS GIS can still be desirable to increase the number of case studies using it, to which also this article tried to contribute. At the same time, it can be stated that the open source GRASS GIS and SAGA GIS is becoming more robust platform for morphometric and hydrological analysis of DEM. If the assumption is satisfied quality and accurate data about the altimetry (LiDAR), the results are, in the opinion of the team of authors, fully satisfactory, good practices and realistic surround by a field survey verification and simulation in a fully distributed rainfall-runoff model. Whether we consider the relatively simple determination of FD and FA (here a severely complicated extreme sandstone relief of pilot river basins) or a more sophisticated analysis such as the depth of the valley, valley width, curvature and relief thalweg, time of concentration index or topographic wetness index, such analyses bring several important information about the type of basin. The logical next step in the research of pilot river basins will be selected measurements and other hydrological characteristics to accomplish the parameterization of model MIKE SHE. Finally, this is an important aspect of the contribution to knowledge, qualification and quantification of parameters of the hydrographical network in less accessible areas of the national border and rocky relief.

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