On 2D and 3D parameter derivation for rainfall-runoff models

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Geoinformation technology, particularly GIS and digital terrain models, is commonly used at present in order to derive parameters of basins and flow paths. These parameters are subsequently used to create spatially based rainfall-runoff models. In line with the development of geoinformation technologies such models can be derived both in 2D and 3D formats. The question remains whether the 3D format is suitable for all parameters.

In order to solve the question two basic parameters that will be affected by the derivation method were selected. One of them, the Subbasin Area parameter, is essential for the calculation of the precipitation volume for a given subbasin area and subsequently for the calculation of the runoff volume. This parameter is directly dependent on the chosen derivation method since the difference in areas derived in 2D and 3D formats depends on the area gradient. The other parameter, River Length, is important for the modelling of water motion within a stream as it influences the shape of hydrograph and the size of culmination discharge. Similarly to the first parameter, it is dependent on the area gradient and thus on the used derivation method.

A semi-distributed model of the Lubina River basin in the HEC-HMS environment was chosen to represent spatially based rainfall-runoff models. The model was created on the basis of ZABAGED hypsometry data.

Suitability of the use of parameters derived in the 3D format for rainfall-runoff modelling is discussed in the concluding part of the paper.

Key words: *Rainfall-runoff modelling, model parameter, HEC-HMS*

Introduction

The progress of geoinformation technologies makes it possible to derive more and more parameters for rainfall-runoff modelling from digital terrain models and other geodata layers. One of the possibilities is easy derivation of parameters from flow paths and basins in the 3D format. However, euphoria associated with new technologies and possibilities often dominates over logical assessment of the question whether the use of 3D parameters is always suitable in task solving. In order to discuss this question two case studies – derivation of 3D flow path length and 3D basin area for the needs of rainfall-runoff modelling – are presented in this article.

Study basin

The Lubina River, which is a right tributary of the Odra River, springs under a ridge of the Moravskoslezské Beskydy Mts and, as a consequence, the basin is characterized by significant altitude differences (235 – 1256 m asl) particularly in the upper and middle basin reaches. The total basin area as far as the Petřvald outlet is 166 km^2. Average annual precipitations in the basin is 906 mm, the average annual runoff is 384 mm. Hydrologic characteristics of Lubina River see in Tab. 1 and overview map with hypsometry and localization in Fig. 1.

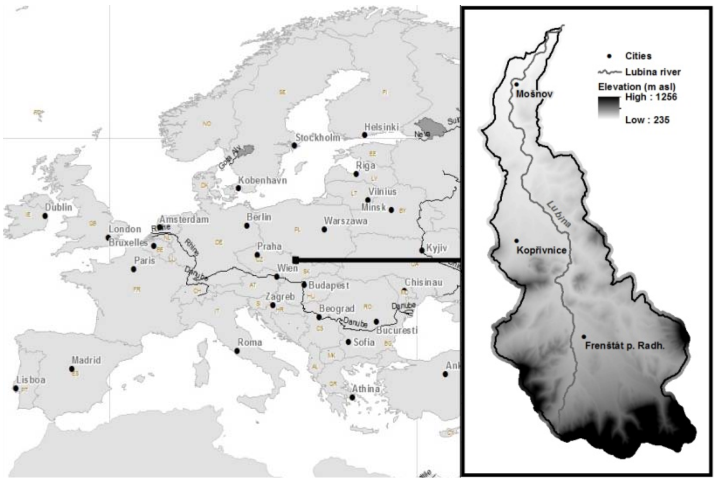

Fig. 1. Location and overview of study basin.

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Tab. 1. Hydrologic characteristics of Lubina River (flow rates in Petřvald outlet).

Average flow rate Q_a	1-yr flow Q_1	10-yr flow Q_{10}	50-yr flow Q_{50}	100-yr flow Q_{100}
		$[m^3.s^{-1}]$		
2,36	37	140	226	260

Methodology

Rainfall-runoff relations were modelled using the HEC-HMS software (Feldman, 2000) and a semi-distributed model of the Lubina River basin. Detailed character of the semi-distributed model is evident from map appendices; the area of individual basins ranged from c. 0.5 to 26 km2.The following methods were used for individual components of hydrologic and hydraulic transformation (Mishra, Singh, 2003, Schraffenberg, Flemming, 2006):

- Runoff-Volume Model / Infiltration Loss Model – SCS-CN method,
- Direct-Runoff Model – Clark Unit Hydrograph,
- Hydraulic transformation of river beds – kinematic wave approximation,
- Underground runoff – recession method.

The comparison involved models whose geometric structure and parameters were derived from a digital terrain model based on ZABAGED hypsometry data (vector representation of contour lines in Czech State Maps at a scale of 1:10 000). Individual models only differ in the subbasin area and the length of flow paths that were derived either in 2D (the same as the length and area of the vector ground plan of an object in ArcGIS 10) or in 3D (computation of the inclined length of flow path or subbasin area on the basis of the combination of vector ground plan of an object and the above mentioned digital terrain model using the functions of Spatial Analyst ArcGIS 10).

Parameters derived in such a manner gave rise to 4 semi-distributed rainfall-runoff models in HEC-HMS environment that were marked as shown in Tab. 2:

Tab. 2. Model designation and rainfall-runoff parameters (derived in GIS using both 2D and 3D methods) used for the calculation of subbasin runoff and hydrograph at the outlet.

Model Denomination	Flow Path Length	Subbasin Area
2D	2D	2D
3D line	3D	2D
3D basin	2D	3D
3D	3D	3D

Comparison of derived parameters

The parameters of flow path (length) and subbasin (area), which have been derived both in 2D and 3D formats, differ in relation to the gradient of area they lie on. Comparing the flow path lengths brought a difference of as little as 10 ‰ within a model basin, whereas the comparison of subbasin areas showed a difference of as much as 10 %. Values obtained in the comparison of 2D and 3D derivation methods have been displayed by means of cartographic methods of expressions in Fig. 2:

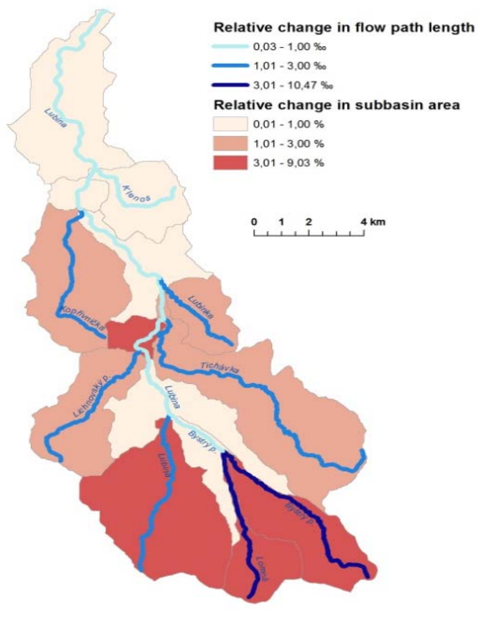


Fig. 2. Relative change in flow path length and subbasin area in the application of 2D and 3D derivation methods in a model basin.

Modelling results

The modelling itself made use of a precipitation event of 15 to 28 June 2009 (Czech Hydrometeorological Institute, 2010) which had characteristics of an extreme heavy precipitation. Antecedent basin saturation was relatively small; the average antecedent precipitation index (API) was 8 mm. In accordance with the SCS method, the CN values were adjusted to values expressing low antecedent basin saturation. A "2D" model was then calibrated to the value of measured culmination discharge and subsequently parameters were taken over for other models involved in the comparison. Nash-Sutcliffe Equation (NSE) was used as model evaluation criterion (Nash et al., 1970, Song et al., 2012). Culmination discharge values, NSE values and modelled hydrographs are given in Tab. 3 and Chart. 1:

Tab. 3. Culmination discharge values for models with parameters given in Tab. 2 (measured culmination discharge value is 139 m^3s^{-1}).

Model denomination	Culmination discharge $[m^3.s^{-1}]$	Difference from "2D" model $[m^3.s^{-1}]$	Difference from "2D" model [%]	NSE
2D	139.1	0	0	0.68
3D line	139.1	0	0	0.68
3D basin	143.3	4.2	3.02	0.66
3D	143.3	4.2	3.02	0.66

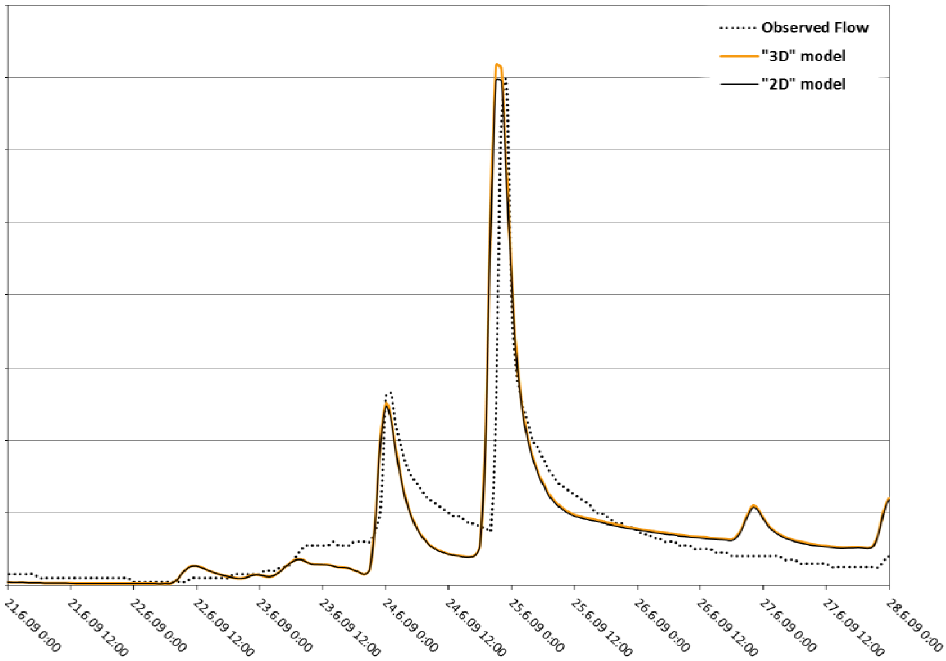


Chart. 1. Modelled hydrographs (hydrographs of "3D line" and "3D basin" models are not displayed due to identical values with "2D" and "3D" models) (see Tab. 2).

The results of modelling at the outlet show that the 3D derivation of flow path length does not show itself in the modelled hydrograph. However, the 3D derivation of subbasin area already has some effect on the culmination discharge in an order of units of percent.

A detailed view of the culmination discharge at outlets of individual subbasins points to rather significant influence of 3D derivation of areas in the upper articulate part of the basin (Fig. 3):

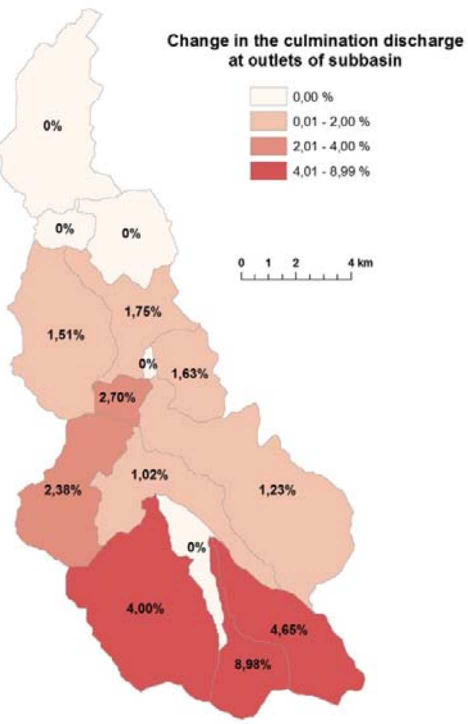


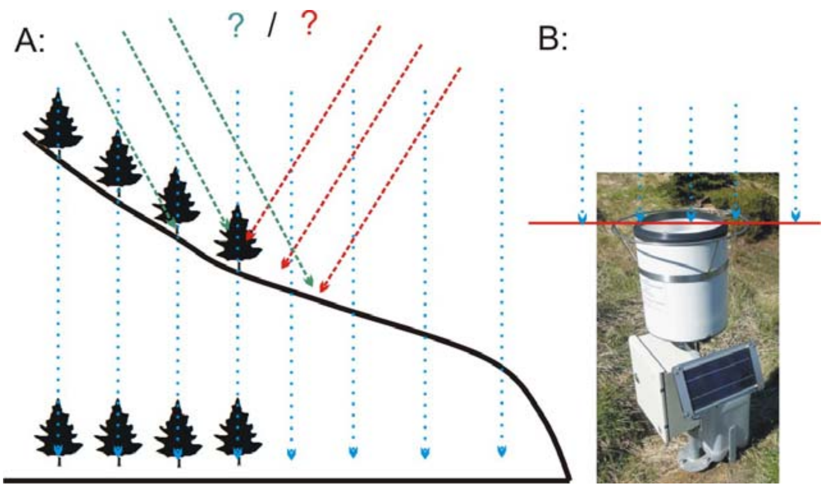
Fig. 3. Change in the culmination discharge at outlets of individual subbasin in 2D and 3D basin area derivation.

Discussion

The above mentioned results of basin modelling show the influence of 3D parameter derivation particularly in the case of the subbasin area parameter. Nevertheless, in case of small, strongly articulate mountain basins, the flow path length derivation may play an important role too. These two factors together may influence the modelling results by up to tens of per cent. However, can this derivation method be considered correct from the methodological point of view?

In compliance with the results, the 3D derivation can be recommended in order to derive the flow path length parameter. This parameter is one of the main parameters in the application of the method of kinematic wave approximation and it directly affects the time period of the river flow as far as the outlet. The flow path length, which approximates the real water trajectory in the river bed thanks to the 3D derivation, can specify the modelled culmination discharge time. As for this parameter, the difference between the 2D and 3D derivations is insignificant and can therefore display itself only in the modelling of short and extremely steep basin reaches.

On the other hand, the 3D derivation can be debatable in case of the subbasin area parameter. In this respect, the discussion is desirable as the parameter exerts much greater influence on the modelled discharge value than the flow path length. This effect can be observed as a consequence of the use of the parameter in the computation of precipitation volume within basin (measured or predicated precipitation height at the adjacent gauge station) as well as the basin area itself. The problematics – 2D or 3D (sub)basin area derivation – is shown in Fig. 4.



***A**: influence of slope gradient on impinging precipitation with the problematics of the impinging precipitation inclination.* ***B**: precipitation measurement using a precipitation gauge).*

Fig. 4. 2D or 3D basin area derivation: logical and methodological problem.

If precipitation impinges the surface vertically, the same amount of water drops lands on horizontal ground plan as on arbitrarily inclined area (Fig. 4, A:). In such a case, the influence of vegetation is negligible since the same principle holds true also for vertically growing higher vegetation. Similarly, this hypothesis can be applied in case of horizontal and solid precipitation. This being supposed, 3D area derivation causes an error in the model due to the computation of precipitation volume which is bigger that the precipitation volume that lands on the basin area.

In case of non-vertical precipitation impingement the problem becomes complicated. Selecting suitable derivation method other factors need to be taken into consideration, namely the slope orientation and wind direction and force. The computation of impinging precipitation volume must then be solved focusing on individual elementary areas of the relief and the task is no longer single 3D area computation. Such a computation method is inconvenient for semi-distributed models (subbasin area includes a number of variable inclined areas). However, it can be used in case of distributed models provided that there are sufficient data on wind direction and force.

Another factor that needs to be considered is the methodology of precipitation measurement (Fig. 4, B:). If a rain gauge is used, the rain gauge inlet port is located horizontally so that the gauge station data are related to horizontal area. Converting the rain gauge station data into 3D subbasin area brings an error into the rainfall-runoff model.

Conclusion

The aim of the article is to point at the problematics of the derivation of flow path length and subbasin area parameters in 2D or 3D formats for the needs of semi-distributed rainfall-runoff models as well as to trigger discussion especially on the derivation method of the subbasin area parameter in the 3D format and its relation to the computation of a rainfall event in a basin.

In the Lubina River basin used as a model basin a difference was found between the flow path length derived in 2D or 3D in an order of tens of per mil

Bigger differences were observed in connection with 2D and 3D derivation method of the subbasin area parameter: direct comparison of the area brought differences in an order of tens of per cent, whereas the comparison of culmination discharges at the basin outlet showed a difference of c. 3 %.

With regard to the fact that the model basin is characterized by significant altitude differences especially in its upper part (upland) and partially also in its central part (hilly land), even greater impact of the methodology of parameter derivation can be expected in case of smaller mountain basins.

The results obtained from the model basin cannot be generalized as they are strongly related to the basin relief, however, two general recommendations may be made based on the above presented study:

a) It is suitable to derive flow path length in 3D format. Although the influence of this parameter on modelled discharges at the outlet is indistinctive, this derivation method leads to model improvement. Moreover, the effort made in order to obtain 3D flow path length is relatively small considering the derivation of the parameter in GIS.
b) 3D derivation of the subbasin area parameter cannot explicitly be recommended. On one hand, the parameter exerts relatively big influence on modelled discharges, however, en error might appear in the model with the 3D subbasin area derivation in relation to the calculation of the subbasin precipitation volume. This problematics should further be discussed (see chapter Discussion).

References

Czech Hydro meteorological Institute : Precipitation amount per hour - database listing. *15.6. – 28.6. 2010, ČHMÚ.*

Feldman, A.D., ed.: Hydrologic Modeling System HEC-HMS. *Technical Reference Manual. Hydrologic Engineering Center, 2000.*

http://www.hec.usace.army.mil/software

Mishra, K., M., Singh, V., P.: Soil Conservation Service Curve Number (SCS-CN) Methodology. *Kluwer Academic Publishers. 2003, ISBN 1-4020-1132-6.*

Nash, J. E., Sutcliffe J. V.: River flow forecasting through conceptual models part I. A discussion of principles. *Journal of Hydrology, 1970, 10 (3): 282–290.*

Schraffenberg, W.A., Flemming, M.J.: Hydrologic modeling system HEC-HMS user's manual, version 2. *U.S. Army Corps of Engineers, Davis, 2006, Calif. USA*.

http://www.hec.usace.army.mil/software/hec-geohms/download.html

Song, X., Zhan, Ch., Xia, J., Kong, F.: An efficient global sensitivity analysis approach for distributed hydrological model. *Journal of Geographical Sciences. 2012, 22(2): 209-222. ISSN 1009-637X*