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INFLUENCE OF MODEL STRUCTURE ON BASE FLOW ESTIMATION USING BILAN, FRIER AND HBV-LIGHT MODELS

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Hydrological models are widely used tools to solve a broad range of hydrological issues. Each model has its own structure defining inter-relationships of hydrological balance components, and comparative differences in the models' inner structure must be taken into account when discrepancies result from the same data. Results of base flow simulation by three different models BILAN, FRIER and HBV-light were compared based on knowledge of the models' internal structure. It was proven that the courses of modelled parameters are quite similar, but that the respective values differ. The highest base flow values were simulated by the BILAN model, due to the threshold value of the soil moisture storage incorporated within this model's structure. The lowest values were obtained by HBV-light model. Simulated base flow values were compared with groundwater heads and minimum monthly discharges. This comparison showed that the base flow values in the Nitra catchment at Nedožery profile simulated by BILAN and FRIER models are closer to the reality than those, simulated by HBV-light model.

KEY WORDS: Model Structure Differences, BILAN, FRIER and HBV-light Models, Total Runoff, Base Flow Simulation, Nitra Catchment at Nedožery Profile.

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Hydrologické modely sú nástrojmi, často využívanými pri riešení širokého spektra hydrologických problémov. Každý z modelov má svoju vlastnú štruktúru, definujúcu vzájomné vzťahy prvkov hydrologickej bilancie. Preto musí byť pri posudzovaní rozdielnych výsledkov získaných použitím tých istých vstupných dát brané do úvahy porovnanie rozdielov vo vnútornej štruktúre modelov. V príspevku boli porovnávané výsledky simulácie podzemného odtoku tromi rozličnými modelmi BILAN, FRIER a HBV-light, berúc do úvahy znalosti o vnútornej štruktúre jednotlivých modelov. Bolo dokumentované, že priebehy modelovaných parametrov sú veľmi podobné, no získané hodnoty sa líšia. Najvyššie hodnoty podzemného odtoku boli simulované modelom BILAN, v dôsledku faktu, že v modeli je zabudovaná pevná limitná hodnota pre veľkosť zásoby vody v pôde. Najnižšie hodnoty podzemného odtoku boli získané modelom HBV-light. Simulované hodnoty podzemného odtoku boli porovnané s priebehom úrovne hladiny podzemnej vody a s minimálnymi mesačnými prietokmi. Toto porovnanie ukázalo, že hodnoty podzemného odtoku v povodí Nitry po profil Nedožery simulované modelmi BILAN a FRIER sú bližšie k reálnemu stavu než hodnoty simulované modelom HBV-light.

KĽÚČOVÉ SLOVÁ: rozdiely v štruktúre modelu, modely BILAN, FRIER a HBV-light, celkový odtok, simulácia podzemného odtoku, povodie Nitry v profile Nedožery.

Introduction

Hydrological models are powerful tools in the study of hydrological extremes (*Bačová-Mitková* et al., 2010; *Vanova*, *Langhammer*, 2011; *Hanel* et al., 2012). Various models and programmes have been developed which enable simulation of the behaviour of selected water balance components, their inter-relationships and related processes. Evaluation of modelling results should be based on the knowledge of how and why these results were obtained. If these reasons are not clear, the result interpretations and conclusions may be incorrect. An example of incorrect interpretation can occur in the conclusion that one model is overestimating and another is underestimating the value of a respective variable. Explanation for differences in results is often already incorporated within the model. The same parameter in different models can incorporate several elements or be composed of different compounds, and these anomalies affect its final value.

The paper compares results of simulation of base flow using three different models – BILAN, FRIER and HBV-light. These models possess different internal structures and their concepts of solutions for water balance processes also differ. Despite these dissimilarities, the models should provide comparable results from simulation of precisely the same conditions. We had to be certain that the inputs to all three models had the same values. Our research aims to answer the following questions: (1) how the inner structure of the model influences the model's results, and (2) which model can deliver the most appropriate results. Attention was paid to the sub-surface portion of the hydrological cycle, especially to base flow, soil moisture storage and groundwater storage, and examples were selected to highlight possible problems in interpretation of these models' results. This work was performed within the FP6 Watch project.

Methodology

The study area is a small sub-catchment of the upper Nitra River basin in Slovakia, with an area of 181.57 km^2 extending to gauging profile No. 6540 Nedožery. The data used covered the period 1981––2007. All three models were calibrated against observed catchment runoff using Nash-Sutcliffe (NSE) efficiency, attaining values of 0.6232 for the BILAN model (calibration period 1981–1986), 0.866 for the FRIER model (calibration period: one year 1981) and 0.7178 for the HBV model (calibration period 1981–2006). The method of Thiessen polygons was used for precipitation calculation in all three cases, and kriging was used for temperature calculations. Potential evapotranspiration was calculated by Penman-Monteith methodology, and model validations were performed for the period 1982–2006.

The base flow values obtained from different models were also compared with the minimum monthly discharges, which formed basic data for Kille calculation of the long-term groundwater runoff (*Kille*, 1970, *Fendekova*, *Fendek*, 1999).

The accuracy of base flow estimations by all three models was tested using three methods – (1) comparison of the BF values temporal course with the groundwater head in the neighbouring well No. 251, (2) the construction of cumulative curves for the base flow and groundwater heads and (3) comparison with the minimal monthly discharges. Monitoring well No. 251 Nedožery is on the left side of the Nitra River alluvial plain, approximately 600 m downstream from the Nedožery gauging profile. Groundwater head data was available only for weekly periods, and therefore it was necessary to recalculate BF data from daily to weekly values using the HydroOffice 2010 software package developed by *Gregor* (2011).

Description of models

BILAN model

The BILAN model is a lumped model which was developed to simulate components of the water balance in catchment areas (Kasparek in *Tallaksen* and *van Lanen*, 2004). This model is based on a set of relationships which describe basic principles of the water balance in both saturated and unsaturated zones. The time resolution is now one day; although it was previously one month in the older versions. The BILAN model is used by several institutions in the Czech Republic, and currently applied to model climate change impacts at hydrological regimes throughout this entire Republic (*Kašpárek*, *Peláková*, 2006). The impact of climate change on water resources and changes in water balance components in the Metuje catchment was studied by *Horáček* et al. (2008), using a combination of BILAN and ModFlow models. This latest BILAN model working on daily results was described by *Horáček* et al. (2009). The combined ALADIN-CLIMATE/CZ and BILAN models were also used at 56 catchments for climate change study in the Czech Republic (*Vizina*, *Horáček*, 2009). Experience from simulation of climate change impacts on water regimes over daily and monthly periods was described by *Vizina* et al. (2010). *Machlica* and *Fendeková* (2006) used the BILAN model for base flow values estimation in the Chvojnica catchment in Western Slovakia. In addition, temporal development of the base flow in the

Slovak Topla River catchment was also solved using the BILAN model (*Fendeková* et al. 2008), and *Machlica* et al. (2010) used this model for identification of groundwater drought in different geological conditions.

Input data used for water balance computation by the BILAN model consisted of the daily time series of basin precipitation, air temperature and relative air humidity (or potential evapotranspiration). Station measurements were distributed to the space using the kriging method. Simulated and observed daily runoff series at the outlet from the basin were used for calibration of the six parameters of the model. This was achieved by the optimisation algorithm. The model simulates time series of daily potential evapotranspiration, actual evapotranspiration, infiltration to the soil and also recharge from the soil to the aquifer. The amounts of water stored in the snow pack, in the soil and in the aquifer are simulated for each day. All these hydrological variables are applied to the catchment as a whole, and total runoff comprised the two components of direct runoff and base flow.

The calibration of parameters is executed in two steps. In the first one, the standard error of estimation (MSE) or mean absolute error (MAE) are used as the optimization criteria to calibrate the first three parameters (Spa, Dgm and Alf) which significantly affect the mean runoff. The remaining three parameters affecting the runoff distribution into its individual components (Grd, Mec and Soc) are then calibrated using the mean of the absolute values of the relative deviations. Nash-Sutcliffe (*Nash*, *Sutcliffe*, 1970) efficiency or logarithmic Nash-Sutcliffe efficiency (*Hohenrainer*, 2008) can also be used as optimization criterion.

FRIER model

The FRIER model – "*Water Distribution (**F**low, **R**outing, **I**UH) Model with Accent to **E**vapotranspiration and **R**adiation Methods"* is a rainfall-runoff model which has distributed parameters. This was developed by Horvát and it is comprehensively described in his paper *Horvát* (2008). The BILAN and FRIER model results were compared by *Machlica* and *Horvát* (2009), wherein similarities and differences in these models' structure were identified. The FRIER model was used to identify drought in the Upper Nitra River basin (*Machlica*, *Horvát*, 2010), and FRIER model results were also compared with those from the HBV and BILAN models, focusing on low flows (*Horvát* et al., 2010).

While a part of the FRIER model runs in the GIS interface, another enables missing input data to be added while a third determines the instantaneous unit hydrograph (IUH), the water balance, runoff simulation and checks model efficiency. Runoff forecasting can also be determined and time resolution chosen: herein, daily results were selected. The input raster of the digital elevation model is instilled initially, followed by the basin area and flow direction and flow accumulation generated by the standard GIS functions. Since interception, evapotranspiration, infiltration and other important hydrologic processes are affected by the land use types, 15 of these are categorized in the FRIER model. The stream network is generated from the flow accumulation and setting the threshold for spring origins, thus generating the stream order. The total runoff is calculated as the sum of overland flow, interflow and base flow, and it is obtained by convolution of the flow response from all grid cells. The input soil texture vector map is required, and this comprises either the percentage of sand, silt and clay or USDA soil texture classification attributes. The initial soil moisture value is expressed by the global parameter SM0, and this is supported by an input map. Eleven global parameters are used to simplify hydrologic processes and to set the exact initial values to be calibrated. The FRIER model has a wide range of methods to estimate the potential evapotranspiration. Actual evapotranspiration is estimated from the relationships between the potential evapotranspiration, the rainfall, and the actual or empirical critical soil moisture. Since the rainfall excess is the sum of overland flow and changes in depression storage, the algorithm of the amount of overland flow can be assessed according to the depression storage. While interflow and percolation depend on hydraulic conductivity and root zone depth, only the interflow can depend on slope. Percolation effects changes in groundwater storage, where a part of the groundwater transpires vertically upwards while the remainder flows horizontally away as base flow. The base flow quantity is estimated from the actual available groundwater storage and the Gmax calibrating parameter.

One of the following three calibration methods can be chosen to run the FRIER model (1) manual random, (2) step-by-step methodology and (3) automatic harmonic search. The simulated discharge is compared to the measured one, with the BIAS model being used for quantitative comparison. The hydrographs are computed by the Nash-Sutcliffe coefficient, with the maximum and minimum discharge values especially monitored. The number of extreme values to be incorporated in the monitoring can be chosen, and the Nash-Sutcliffe coefficient can be calculated for selected extreme values (*Horvát*, 2008).

HBV model

HBV (Hydrologiska Byrans Vattenbalansavdelning) is a conceptual model for rainfall- runoff simulation developed by Sten *Bergström* (1992) at the Swedish Meteorological and Hydrological Institute. The HBV model has been applied for research purposes and also for water engineering and operational hydrology. The various HBV model structures, concepts and applications are described in many papers, and a comprehensive description of the model with all its equations and parameters can be found in *Seibert* (2000, 2005). *Lindström* et al. (1997) introduced HBV 96, which is a spatially-distributed version, and they compared it with a lumped HBV model for Swedish catchments. *Liden* and *Harlin* (2000) investigated HBV 96 performance for climatologically different river basins in Europe, Africa and South America. The HBV model has also been used to investigate the impact of climate change scenarios, including those in Germany (*Menzel* and *Burger*, 2002), Ireland (*Steele-Dunne* et al., 2008) and the Hindukush-Karakorum-Himalaya region (as in *Akhtar* et al., 2008). *Oosterwijk* et al. (2009) used the HBV-light version to evaluate drought occurrence in pilot basins within the FP6 Watch project. The HBV-light model consists of four components: lumped or distributed snow and soil routines, a lumped response function and a lumped routing routine. The HBV input data comprise the time series of daily precipitation, air temperature and observed stream flow. Precipitation and temperature are corrected for each elevation zone using the vertical precipitation gradient and vertical temperature gradient. HBV also requires a time series of potential evapotranspiration, based on either daily or monthly averages.

HBV can be run either as a lumped or as a semi-distributed model. The catchment can be divided into a maximum of 20 elevation zones and three vegetation zones. The Nash-Sutcliffe coefficient (*Nash*, *Sutcliffe*, 1970) or the modified-logarithmic version can be used for model calibration. In addition, the logarithmic version adds increased weight to low flow situations (*Hohenrainer*, 2008).

Base flow estimation procedures in models

In order to compare simulated base flow values, it is necessary to understand how the base flow value is calculated.

The base flow (BF) in the BILAN model is calculated as the outflow from a linear reservoir representing groundwater storage (*GS*). The outflow from the groundwater reservoir is controlled by a *Grd* parameter:

$$BF = Grd.GS\,. \tag{1}$$

The original source for groundwater storage is the soil moisture storage (*SW*) and Percolation (*PERC*), described as water exceeding the soil moisture capacity (*Spa* parameter):

$$PERC = SW - Spa\,. \tag{2}$$

Percolation is divided into the recharge to direct runoff storage and recharge to groundwater storage. Therefore, the change in groundwater storage is given as:

$$\Delta GS = \max(PERC - c.PERC^2) - BF\,, \tag{3}$$

where *c* is one of the following two coefficients; (1) the *Mec* parameter for snow melting conditions, or (2) the *Soc* parameter for summer conditions.

The base flow in the FRIER model is calculated similar to that in the BILAN model, where groundwater storage is multiplied by a coefficient, which bears similarity to the *Grd* parameter in Eq. (1), and which is also calibrated during the model calibration process. Groundwater storage is defined as the quantity of water in the zone of saturation, and this includes amounts during stages when water is entering and leaving the storage. Groundwater storage capacity refers to the volume of saturated groundwater able to be extracted or replaced in the aquifer under natural conditions, and the groundwater discharge normally forms a base flow to the hydrograph at the basin outlet. While groundwater storage capacity is governed by the thickness and extent of the aquifer and its porosity, groundwater movement is governed by the hydraulic gradient and the hydraulic conductivity of the aquifer (*Liu & de Smedt*, 2003). Evapotranspiration from groundwater storage may be produced by a deep root system or by capillary rise in areas with a shallow groundwater table. This happens only when the soil moisture is lower than field water capacity, and has a greater impact during summer than in winter, thus producing the effect of a steeper recession during dry periods. The base flow is not calculated in each cell but only as a single value for the whole basin, as in all lumped models. The instantaneous unit hydrograph of base flow serves as flow retardation following the interflow. This retardation is calibrated by the UH calibrating parameter. The base flow dependency from the average slope of the basin is used in the linear method, and dependency from flow travel time is used in the non-linear method of the instantaneous unit hydrograph determination. The base flow quantity is estimated from actual available groundwater storage and the Gmax calibrating parameter.

The base flow in the HBV model is expressed as Q_2 – runoff component from the lower groundwater zone. The input for the uppermost groundwater reservoir emanates from the output from the soil routine. This recharge consists of the fraction of rain and snowmelt that bypasses the soil reservoir, depending on the wetness of the soil moisture reservoir. Thus the recharge is generated by rainfall or snowmelt, and not by depletion in the soil moisture reservoir. Water leaves the upper groundwater reservoir by percolation to the lower reservoir (PERC) or by generation of a $Q1$ or $Q0$ discharge, as follows; the upper reservoir is divided into (1) a relatively slow component ($Q1$: intermediate flow) generating runoff proportional to the amount of storage in the upper reservoir (SUZ), and (2) generation of runoff during large recharge events ($Q0$: peak flow), where incoming water volume exceeds the fixed percolation value (PERC) and the water volume in the upper groundwater reservoir exceeds the threshold (UZL). The recession coefficient of the upper zone above the threshold (K0) is larger than the recession coefficient of the upper zone below the threshold (K1). Water can leave the lower reservoir by generating a runoff ($Q2$: base flow) proportional to the amount of storage in the lower reservoir (SLZ). The lower groundwater reservoir has the smallest recession coefficient (K2). Additionally, when lakes are present in the modelled catchment, precipitation (P) on the lake area, calculated as a percentage of the total catchment area, is added directly to the lower groundwater reservoir, and the evaporation on the lake area (E) is subtracted directly from the lower groundwater reservoir. The reason for this result is the constant water availability in this lower reservoir.

Results

Before the differences in the sub-surface part of the hydrological balance were studied, the observed runoff was compared with the total runoff simulated by all three models. The results for the average long-term monthly values are shown in Fig. 1.

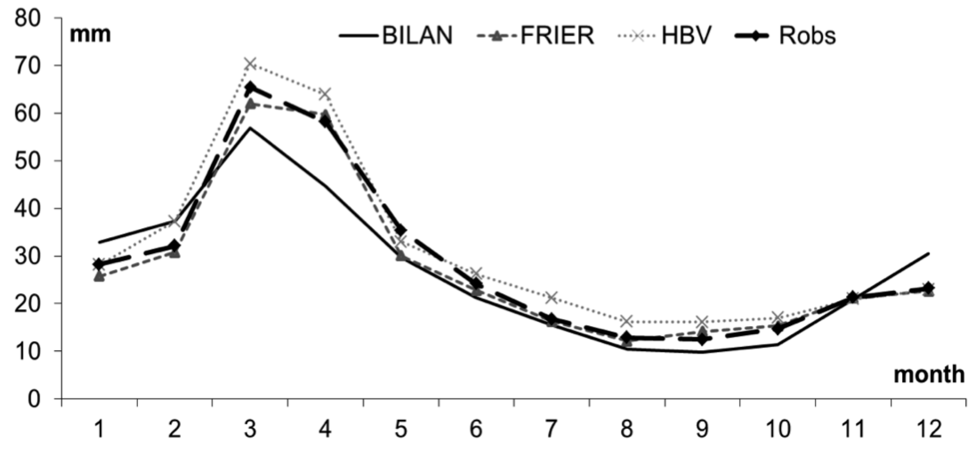

Fig. 1. Comparison of observed average long-term monthly runoff during the period 1981–2006 and and total runoff simulated by BILAN, FRIER and HBV-light models.

When comparing the simulated values of total monthly runoff calculated by all three models (Fig. 1), significant differences were noted between the simulated and observed runoff only in the BILAN and HBV-light models. These differences occurred in two seasons – in spring (March, April) and from mid-summer to early autumn (July, August, September and October). Both of these are peak seasons, with maximum runoff in April and minima during July – October.

The most significant difference of 23 % between the measured and simulated values in the BILAN model occurred in April by underestimating peak flows during the snow melting period, and also 31 % in December by overestimating the observed runoff (Tab. 1 shows the number in bold-type for under-/overestimations of more than 20 %). The second period with the highest differences occurred in the summer-autumn period when stream flow is mostly recharged by the base flow. Results indicated that underestimation by BILAN reached 19–23 % and overestimation by the HBV-light model approached 26–30 %. Simulated total runoff in the FRIER model was very similar to the average long-term observed values, with the largest differences of 14–15 % between the measured and simulated values estimated for May and September.

Differences in the modelled base flow values are quite apparent in the daily time series. These differences are caused by the models' different concepts and internal structure, and here the 1991–1993 period has been selected to highlight the differences (Fig. 2).

T a b l e 1. Mean monthly values of observed total runoff [mm] and simulated total runoff (% ratio from the observed total runoff) using the BILAN, FRIER and HBV-light models.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Observed runoff	28	32	65	58	35	24	17	13	12	15	21	23
BILAN	116	116	87	*77*	84	88	92	81	*78*	*78*	98	*131*
FRIER	91	96	95	103	85	94	97	95	114	104	99	98
HBV	100	116	107	110	93	108	*126*	*126*	*130*	116	98	99

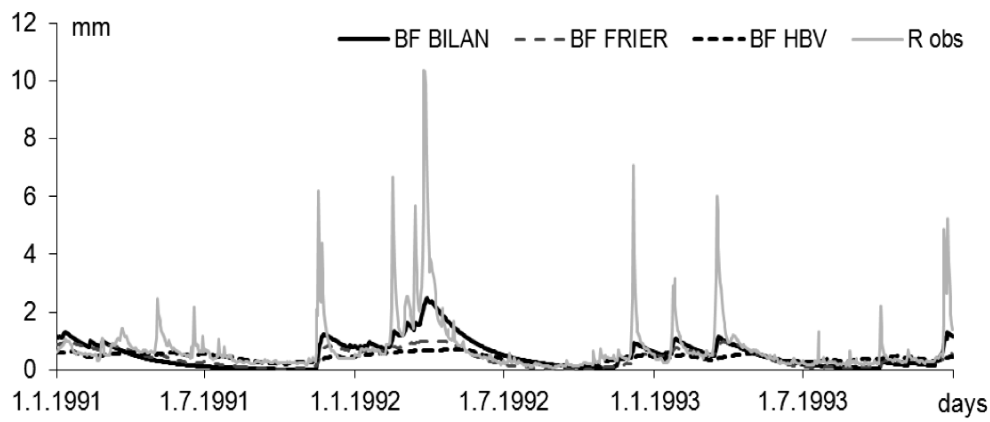

Fig. 2. Daily observed runoff (R obs) and base flow values (BF) from BILAN, FRIER and HBV-light models.

The BF values obtained by the BILAN model are the highest of all modeled results. However, the soil moisture storage (SM) course in Fig. 3 shows that a limit–fixed threshold value of SM is incorporated in the model, and this must not be exceeded. This limit allows water percolating through the unsaturated zone to contribute only a certain extent to the soil moisture storage, and then the water continues to percolate through to the groundwater. This process causes the recharge of water for base flow storage, which can reach relatively higher values in the BILAN model than in the other two. Base flow in the FRIER model is a little slower because of its gridded structure, and it also has a higher evapotranspiration value due to water consumption by deeper level tree-root systems.

When comparing the BILAN and FRIER results of soil moisture storage, their course is similar, with approximately 15–20 mm discrepancy between their lines shown in Fig. 3. Larger differences can be seen in shorter periods, especially during heavier rain events. The highest SM values were obtained with the HBV-light model, and this may account for the fact that the modelled BF values are the lowest of all three models (Fig. 2).

The differences in BF values are also reflected in the groundwater storage values (GS) in Fig. 4.

The groundwater storage values during 1991–1993 are very similar in the periods of recession limb of the hydrographs, as recorded in the late summer to early winter months. As with the base flow values, the highest values were established by the FRIER model and their lowest by the HBV-light model.

The accuracy of base flow value estimation by all three models was tested using three methods: (1) comparison of the BF values temporal course with the groundwater head in the neighbouring well N. 251, (2) by the construction of the cumulative curves for base flow and groundwater heads and (3) by comparison with minimal monthly discharges. The 1982–1986 courses of groundwater head and BF values for all three models are depicted in Fig. 5.

The cumulative frequency curves in Fig. 6 were used for assessment of base flow and groundwater head course resemblance. Here, the similarity between the base flow curve obtained by the BILAN model and groundwater level cumulative curve is quite apparent. The cumulative base flow curves obtained by the FRIER and HBV-light models differ distinctly – and here, underestimation of the base flow could be the cause of this difference.

Base flow values obtained from each model were also compared with the minimum monthly discharges, which form the basic data in the Kille method for calculation of the long-term groundwater runoff (*Kille*, 1970; *Fendekova*, *Fendek*, 1999). The results of the regression analysis from linear, exponential and multiplicative models are shown in Fig. 7 a), b) and c). Resulting correlation coefficients are labelled; R(lin) for the linear regression model, R(exp) for the exponential model and R(mult) for the multiplicative model.

The closest dependence was established for BF values from the FRIER model (Fig. 7b) with a correlation coefficient (R) ranging from 0.78 to 0.86 (R(exp): exponential regression). The R values for BF simulated by the BILAN model were only a little lower, varying from 0.73 to 0.82 (Fig. 7a). Meanwhile, the weakest correlation for the BF values resulted from the HBV-light model (Fig. 7c). Here the R value ranged from 0.61 to 0.71, depending on the regression model type.

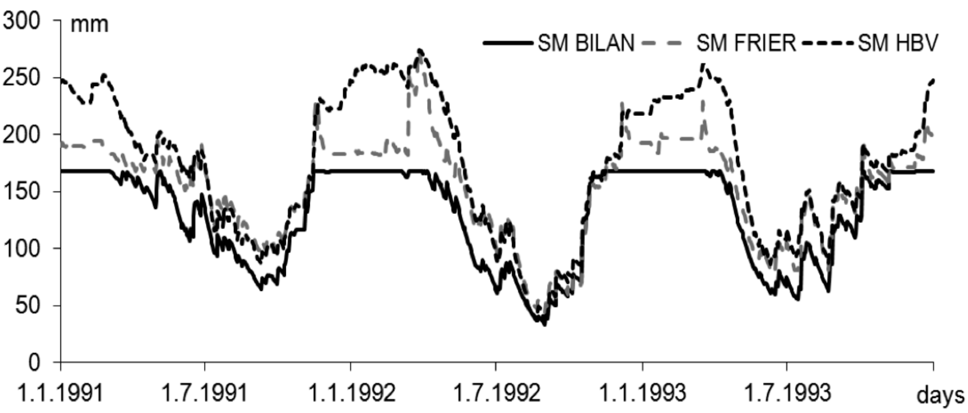

Fig. 3. Daily soil moisture values (SM) from BILAN, FRIER and HBV-light models.

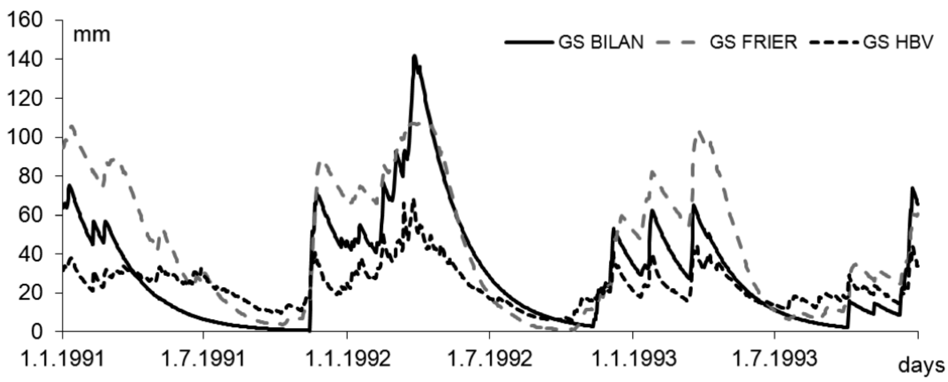

Fig. 4. Daily groundwater storage (GS) values from BILAN, FRIER and HBV models.

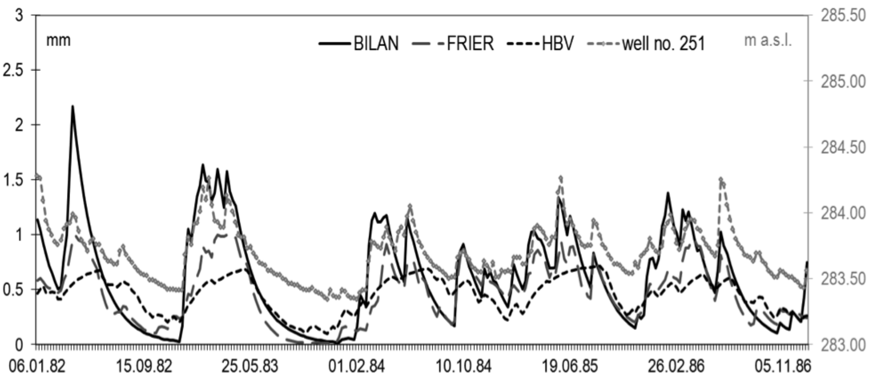

Fig. 5. Time series of groundwater head (well 251 Nedožery, m a.s.l.) and base flow (BILAN, FRIER and HBV models in mm) in weekly time resolution.

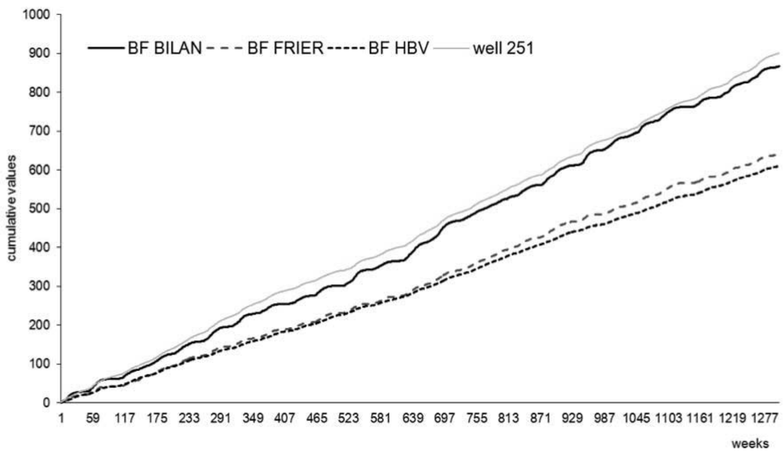

Fig. 6. Cumulative curves of groundwater heads and base flow from all models.

Discussion

The following basic limiting factors must be mentioned before final conclusions can be drawn. Although the base flow theory has developed in hydrology and hydrogeology over many decades, no unified definition of this phenomenon is universally accepted. The problem that groundwater runoff and base flow cannot be measured directly still remains unresolved. One alternative is to measure spring yields of water drained from enclosed hydrogeological structures lacking surface streams. Many methods have been developed to estimate the base flow value, but quite different results have emanated from the same input data. Since it is currently impossible to measure actual base flow values, each author has made an individual determination concerning which methodology delivers the most realistic results.

Base flow values for the Nedožery closing profile were estimated using three different hydrological balance models, and all three were calibrated on the total runoff measured in the closing profile of the sub-catchment. It is generally agreed that similar simulations of the total runoff can be reached by variable combinations of model parameters. Since our inputs into all three models were the same, our results can now be compared.

Each model has its strong and weak points. Despite overestimation of the base flow values in periods of high flow, such as melting snow and heavy rain, and the BILAN model's limitations in estimating soil moisture values, the results of base flow estimation using BILAN model are considered by the authors for the most realistic at the Nedožery profile. This was confirmed by the comparison of the base flow values resemblance with the groundwater head cumulative frequency line courses, as well as by quit high values of correlation coefficient of the relation with the minimum monthly discharges.

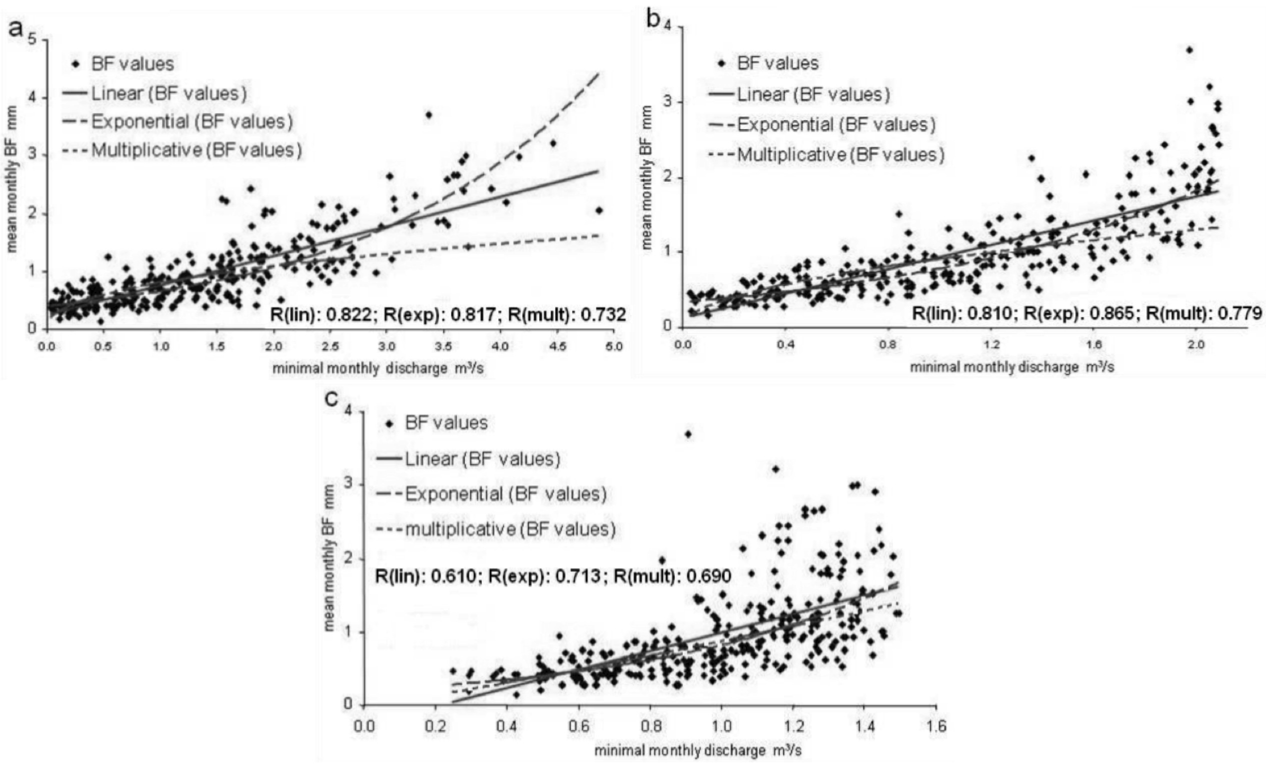

Fig. 7. Dependency between base flow and minimal monthly discharges: a) BILAN, b) FRIER, c) HBV-light.

Conclusion

The main aim of this paper is to illustrate differences in the structure of the BILAN, FRIER and HBV-light hydrological models, and apply this knowledge to base flow analysis.

It is difficult to define which model solution is the best or closest to actual conditions without understanding how the results are produced. It has therefore been highlighted herein that differences in the models' internal structure influenced the base flow simulation results. Although the models simulate the course of variables in a similar manner, they all produced different values. Despite the adequate simulated total runoff by all three models, the different structure of the total runoff resulted in different values for the base flow, soil moisture and groundwater storage. Results of this study suggest that the BILAN model is the closest to the actual conditions. This was demonstrably confirmed by comparison of the resemblance to the groundwater head cumulative frequency line courses, and by quite high correlation coefficient values for the relationship with minimum monthly discharges. While the FRIER model also performed satisfactorily, results obtained by the HBV-light model were the least acceptable for the Nitra catchment at Nedožery profile and the hydrological variables to approach base flow. These conclusions were subsequently confirmed in the second step of our research, where the three models were applied to drought analysis (paper prepared to be submitted).

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