Uncertainties in Runoff Components Modelling and Frequency Analysis

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Abstract: - Study is devoted to the long term basin water balance analysis of the Bela River up to the Podbanske gauge, and to the simulation of the monthly runoff and to estimation of its individual components in the monthly time step, during the 60 years period: 1945/46–2004/05.
In the first part, water balance is set up in the monthly and yearly time step, based upon measured mean monthly discharge data from the gauging station Bela: Podbanske. Also mean monthly precipitation data over the Bela River basin were used. The second part of the study is focused on the selected runoff components modeling in the daily (HBV model), as well as monthly (model BILAN) time step, during the period 1945/46–2004/05. These models simulate hydrological processes by simplifying a catchment into series of connected storage reservoirs, where precipitation, air temperature and humidity are inputs, and the output is represented by streamflow at the catchment outlet. Both models describe observed runoff values relatively good. We achieved a sufficient agreement between observed and simulated values in regard to input data. Finally we focused on frequency analysis of daily observed and simulated discharges at gauging station Bela: Podbanske during the time period 1946–2010.

Key-Words: - hydrological balance, Bela River basin, runoff components separation, rainfall-runoff models

1 Introduction

Hydrological/water balance reflects the fundamental relationships between components of the hydrological cycle. Reliable determination of the basic components of water balance (precipitation, runoff, evaporation) depends primarily on the accuracy of direct measurement of the first two components. Evaporation will then be calculated from the first two components of the water balance.
In the '70s an extensive hydrological research, organized by the Slovak Hydrometeorological Institute (SHMI), took place in the pristine Bela River catchment in High Tatra Mountains. Detailed mapping of basic components of water balance was the aim of the research (Hlubocky et al., 1980, Pacl (1973)). Authors Hladny and Pacl (1974), Molnar and Pacl (1988), Drako et al. (1990), Molnar et al. (1991), Kostka (1992), Majercakova and Skoda (1993), Pacl (1994) or Parajka (2000) dealt with the Tatra Mountain hydrology. Hydrological balance of six catchments of the Western and High Tatra for time period 1989–1998 was elaborated by Holko et al. (2001). Their results showed that the use of all existing data does not give a satisfactory answer to the doubts which arise when determining the essential components of the hydrological balance in the different mountain watersheds. Hydrological balance of mountain river basins still remains an unexplained problem.

In the presented study:
a) in the first part we focused on the hydrological balance of the Bela River basin on the basis of the observed series of the monthly precipitation, and monthly flow;
b) then we evaluated the hydrological balance and runoff separation in the Bela River basin using two models: HBV-light and BILAN model;
c) finally, we focused on the frequency analysis of the observed and simulated daily discharges at gauge Bela: Podbanske for the time period 1946–2010.

2 Basin Description and Data

The Bela River basin up to Podbanske gauge (93.4 km^2) is located in the TANAP reserve (protected area), and is unaffected by the human activity. The Bela River starts with confluence of the Tichy and Koprovy creeks at 976.8 m a.s.l. The Bela River is a major right tributary of the Vah River (Fig. 1a,b). The whole Bela River basin has 244.3 km^2. The estuary of the Bela River is located in Liptovsky Hradok at an altitude of 629 m a.s.l. The pristine Bela River basin up to Podbanske gauge is located in the alpine part of the Tatras - in the highest degree of nature protection. In 70's, it was chosen as a representative catchment area of the High Tatra Mountains.

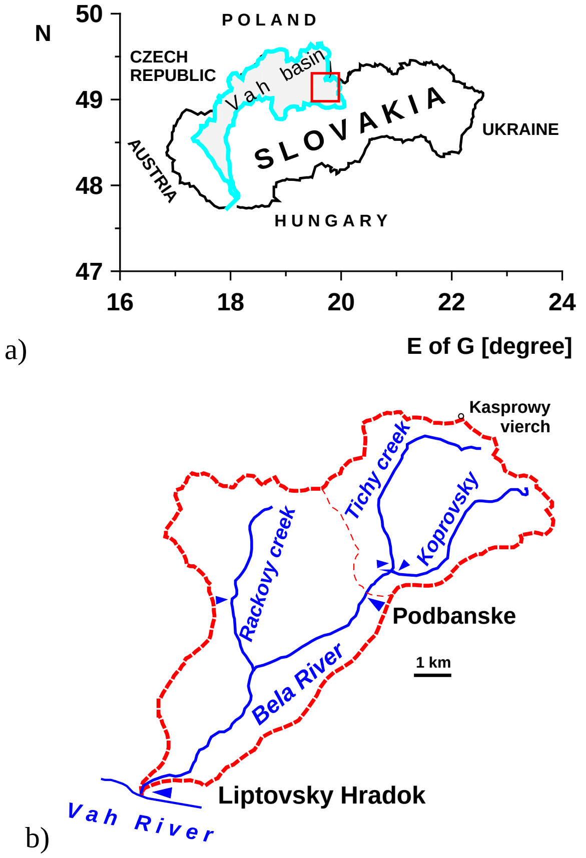


Fig. 1 a) Location of the Bela River basin in the upper Vah River basin; b) Scheme of the Bela River basin.

Water level observations of the Bela River at Podbanske water gauge started in the year 1924. Average daily discharges are computed since 1928 (Halmova and Pekarova, 2013). The percentiles of the average daily discharges (period 1928–2010) are shown on the Fig. 2. The highest average monthly runoff occurs during snowmelt: in May monthly average surface runoff depth is 249 mm and 194 mm in June. This represents almost 38% of the total annual runoff. In March runoff is the most balanced and highest runoff fluctuations are recorded in August. To calculate the mean monthly areal precipitation totals, we used the monthly precipitation from Podbanske meteorological station, and from the Polish observatory Kasprowy Wierch. Precipitation (temperature) gradient we calculated from annual precipitation (temperature) from stations in different altitudes in the vicinity of the Bela River basin (Fig. 3) (Zelenakova et al., 2014; Markovic et al., 2014). In terms of monthly precipitation totals, in the long-term average (period 1945/46–2004/05) most precipitation falls in the month of July (238 mm) and a minimum in February (96 mm)).

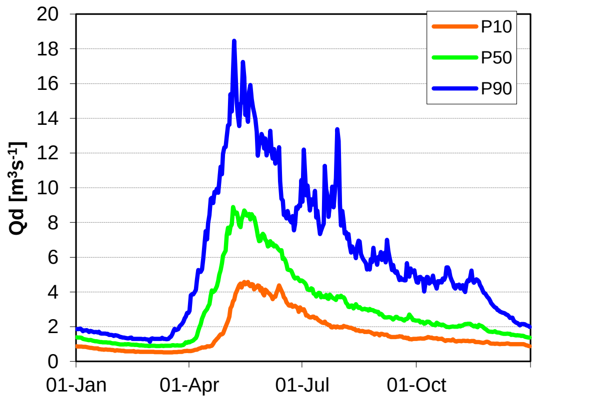


Fig. 2 Long-term percentiles of the average daily discharge, Bela River at Podbanske, 1928–2010. P10 – lower decile, P90 – upper decile.

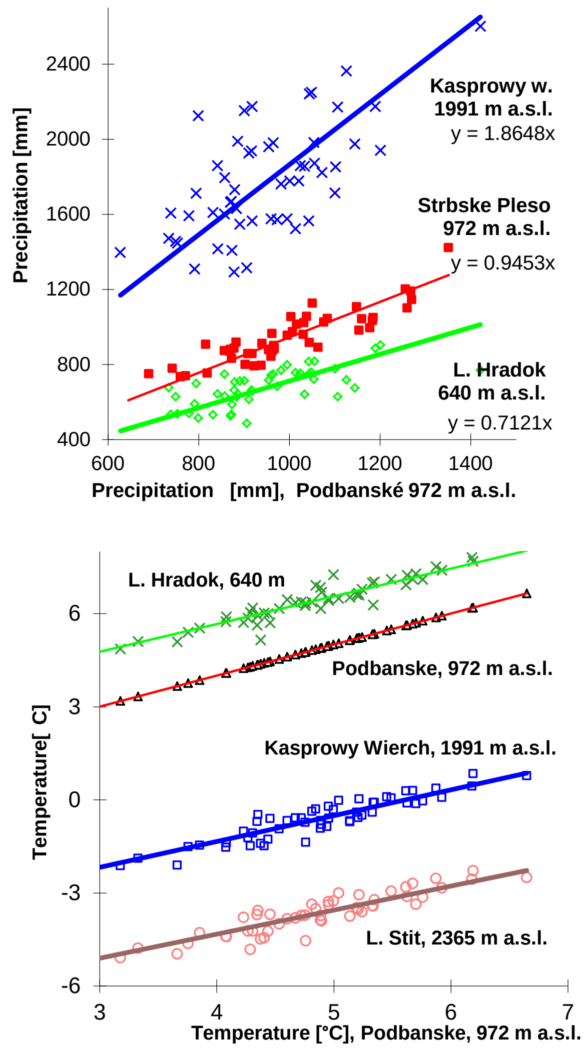


Fig. 3 Relationship between annual precipitation (upper) and average annual temperature (lower) at Podbanske meteorological station and stations in different altitude.

3 Water Balance Models

Over the last decades, hydrological rainfall-runoff models in a basin scale have become an important tool in the water management. The user has been able to choose the right model depending on the topic of study. The biggest problem remains the problem of getting high-quality, sufficiently long series of input data. After proper model selection and calibration, its subsequent use has irreplaceable contribution either in the water management or ex post evaluation of specific situations in river basins.

Among the conceptual models with lumped parameters there belong e.g. monthly water models BILAN, WBMOD, WatBal, or rainfall runoff models in daily time step HBV, SAC SMA Sacramento soil moisture model, HEC-HSM model or GLOBAL model (Cisty et al., 2013). On the other side, Takanashi et al. (2011) used model constructed with many element models as rainfall model, stream model, evaporation model, and river flow model. Authors simulated the flows through the underground soil after the rainfall and values are compared with actual survey of the recorded data to check its accuracy. As a consequence, a connected rainfall model and river model was constructed as good result.

3.1 HBV-light model

We used the rainfall-runoff HBV-light model to simulate the daily discharges of the Bela River at Podbanske station. HBV or HBV-light model, developed by the SMHI (Swedish Meteorological and Hydrological Institute), has become widely used for runoff simulations in Sweden and other countries around the world during the last 20 years, (Bergström, 1992), (Seibert, 2005). After twenty years the model has become a standard tool for runoff simulations and forecasting. Many of the applications abroad can be considered as scientific tests of the model feasibility under specific conditions.

The HBV-light model can be classified as a conceptual model for runoff simulation, it has a simple structure, and it is semi-distributed model. It uses subbasins as primary hydrological units and within these an area-elevation distribution and rough classification of land use are made. The option of subbasins is usually used in geographically and climatologically heterogeneous basins. There are 12 free parameters to be found by calibration (Valent et al., 2011). The HBV-light model consists of three main components:

• Subroutine for snow accumulation and melt,
• Subroutine for soil moisture accounting,
• Response and river routing subroutine.

The model simulates daily discharge using daily rainfall, average daily temperature, and potential evaporation as input. The catchment may be divided in up to 20 elevation- and 3 vegetation zones.

After the calibration the HBV model can be used to extend runoff data series (or filling gaps), for data quality control, for runoff separation and water balance studies, for runoff forecasting (flood warning and reservoir operation), to compute design floods for dam safety, to investigate the effects of changes within the catchment.

3.2 The water balance model BILAN

As a second model, we used the hydrological model BILAN with the monthly time step to assess the individual components of the water balance of the Bela River basin up to station Podbanske. Model belongs to a group of conceptual models with lumped parameters (Kasparek and Novicky, 2004a, b). The model schematizes catchment areas into three water reservoirs. The structure of the model consists of a system of relations describing the basic principles of water balance of the unsaturated and saturated zones, including the impact of vegetation cover and groundwater. Observed time series of monthly precipitation, air temperature and potential evapotranspiration (or relative humidity) are the inputs into the model BILAN.

The aim of the model is to simulate monthly time series of hydrological variables and apply it to the entire river basin. From the hydrological variables model simulates potential evapotranspiration, actual evaporating, and infiltration into the zone of aeration, percolation into groundwater aquifers, water reserves in snow cover, soil and aquifer (Horacek et al., 2009).

Total runoff in the month consists of three components: base flow, interflow (hypodermic) and direct flow. Direct flow is considered as fast runoff component of total runoff, which does not affect the evaporation, and soil water balance. Hypodermic flow is considered as the water excess in the aeration zone. In winter, during snowmelt, this runoff component also includes direct runoff. The base flow is the slow component of the total runoff, the delay in the basin may be longer than one month. The model in the vertical direction distinguishes three levels, namely the surface, soil zone and groundwater zone. The size of the flows between the reservoirs is determined by the model algorithms, which are controlled by eight free parameters.

Time series of measured monthly discharges (runoff) in the closing profile Bela: Podbanske were used for model calibration. The model parameters include: soil water storage, direct flow, snow melt factor, factor to calculate the amount of water in liquid form in the winter, the parameter managing percolation distribution, hypodermic flow and groundwater recharge in terms of the melting snow in the winter and summer, parameter managing drainage from groundwater aquifer.
The values of model parameters obtained from the optimization algorithm can be influenced by the maximum number of iterations performed by the algorithm.

4 Results

4.1 Hydrological (water) balance

Hydrological balance quantifies the water circulation in a closed system with catchment runoff concentrated in the final profile of the watercourse. The atmospheric precipitation in the basin is the only input to the basin. The difference in soil water at the beginning and end of time period for a sufficiently long period can be neglected. In that case, we can identify total annual evapotranspiration with a difference of precipitation and runoff. For the monthly balance - if we determine the monthly total evapotranspiration in an independent manner - we are able to determine the change in water supplies in the basin according to the water balance equation.
The water balance equation in the following form was used:

$$P = R + ET + \Delta S, \tag{1}$$

where:
P – annual average precipitation total [mm]; *R* – annual average runoff [mm]; *ET*–evapotranspiration [mm] and ΔS – average total losses that have a higher significance in shorter time intervals Δt. For the long-term water balance this element might be neglected and replaced by $\Delta S = 0$.

Long-term mean annual Bela River basin precipitation depth (up to Podbanske) is 1718 mm, mean yearly runoff depth is 1175 mm and the balance evaporation equals to 543 mm. The highest and lowest runoff at profile Bela: Podbanske, for the period of measurements, was 1701 mm (1947/48) and 665 mm (1960/61).
The runoff coefficient varies from 43 to 87% with

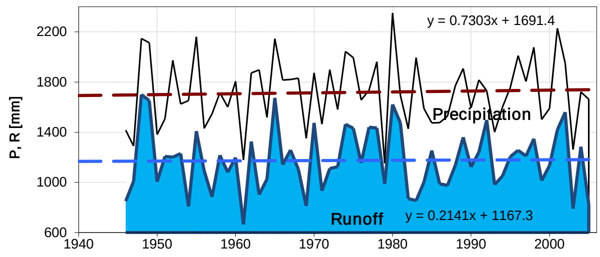


Fig. 4 Annual precipitation and annual runoff; long term linear trends of the precipitation totals and runoff (Bela River Basin, water years 1945/46–2004/05).

the average 67.1% (Fig. 4). From the long term point of view, there are no trends in precipitation and runoff in pristine Bela River basin.

4.1.1 Monthly evapotranspiration

For the long term monthly water balance calculation it is necessary to know the actual course of the annual evapotranspiration in the study basin. Availability of data on evapotranspiration or vapour is low. Average monthly and annual potential evapotranspiration values for different stations in Slovakia can be found in tabular and map form, for example, in Tomlain (1991). Of course the number of such processed stations is limited. In such areas lying near the station, but at a significantly different altitude, the applicability of such data is limited.
Modelling of the average monthly values of potential evapotranspiration was dealt by Miklanek (1995). Based on an extensive set of potential evapotranspiration data from several stations at different altitudes he proposed a simple method that allows modelling of the average monthly values of potential evapotranspiration at any altitude, if an estimate of the annual total is known. For the annual potential evapotranspiration approximation Miklanek used the equation of normal distribution in the form:

$$ETPR(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left(-\frac{(x-x_m)^2}{2\sigma^2}\right)} \tag{2}$$

where:
ETPR - relative potential evapotranspiration [%],
x - number of month (x = 1, 2, ... 12),
x_m - time of maximal ETPR expressed in months as a decimal number,
σ - the parameter that influence the shape of the curve.

The values of x_m and σ depend on altitude. Linear relationships were derived for this dependence. Monthly values of potential evapotranspiration, in relative terms, can be calculated on the basis of this linear relationship if we know the locality altitude. The absolute values of potential evapotranspiration in each month can be determined, if known an annual precipitation total or at least its assessment. In this case, the following equation may be used:

$$ETP(x) = ETPR(x)EP \quad (3)$$

where:
ETP - modelled monthly potential evapotranspiration [mm.month^{-1}];
EP - annual potential evapotranspiration [mm.year^{-1}].

Relative monthly values *ETPR(x)* were primarily calculated for potential evapotranspiration distribution during the year. But it can be used also for other similar phenomena, such as evaporation from the water surface. In the months with maximum evaporation there occurs in our case also maximum precipitation and water availability should not be a factor modifying the distribution of actual evapotranspiration compared with potential. This allows to assume that the potential and actual evapotranspiration will be very similar in the study basins and the relationship can be used also for the distribution of actual evapotranspiration as well as evaporation balance.

4.1.2 Monthly evaporation

Monthly evaporation values at Podbanske station were calculated from the annual balance of evaporation on the basis of the percentage distribution according to Miklanek.

Table 1 shows the monthly values of water storage in the Bela River basin for a period of hydrological years 1940/1941–2004/2005. Water storage (S) in the Bela River basin rise from September to March and from April to August the accumulated reserves of water in the basin are depleted. Fluctuations of water resources changes in the basin were in the long 65-year average of 337 mm. The courses of water balance components for the long-term monthly averages of the station Podbanske are shown in Fig. 5. Such water balance allows us to allocate the average monthly change in water storage in the basin, or in the soil and groundwater.

Table 1: Long–term monthly components of water balance in the Bela River basin for time period 1945/1946–2004/2005. (P – precipitation, R – runoff, ET – evapotranspiration, S – water storage)

	P [mm]	R [mm]	ET [mm]	S=P-R-ET	cum S
XI	122.8	60.9	9.0	52.9	53.0
XII	115.4	43.1	2.2	70.1	123.0
I	103.8	36	0.7	67.2	190
II	95.8	30.2	3.5	62.0	252.0
III	103.0	35.6	13.1	54.4	307.0
IV	112.6	111.0	35.9	-34.3	272.0
V	175.2	249.4	72.8	-147.1	125.0
VI	216.8	193.9	109.3	-86.4	39.0
VII	237.6	151.2	121.3	-34.9	4.0
VIII	177.3	108.6	99.6	-30.9	-27.0
IX	142.1	80.7	60.4	1.0	-26.0
X	124.6	71.5	27.1	26.0	0.0
Year	1727	1172	555	0.0	

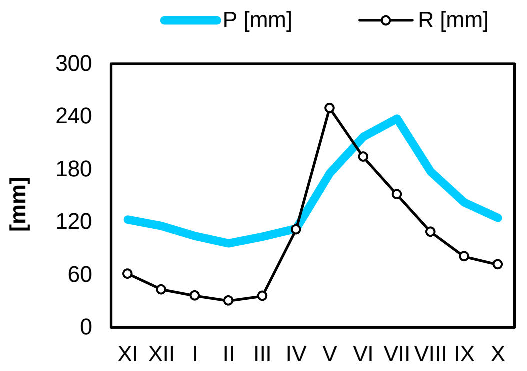


Fig. 5 Long-term monthly runoff R and precipitation P, the Bela River basin, 1945/46–2004/05.

4.2 Calibration and verification of the models

Model HBV-light was calibrated on daily data from the Bela River basin over the period 1945/1946–2000/2001 and verified over the period 2001/2002–2010/2011. According to Bergström (1992), different criteria can be used to assess the fit of simulated runoff to observed runoff:

- visual inspection of plots with Q_{Sim} and Q_{Obs},
- accumulated differences,
- statistical criteria.

$$R_{eff} = 1 - \left[\frac{\sum_{t=1}^{n} \left(Q_{sim}(t) - Q_{Obs}(t) \right)^2}{\sum_{t=1}^{n} \left(Q_{Obs}(t) - \overline{Q}_{Obs} \right)^2} \right] \quad (4)$$

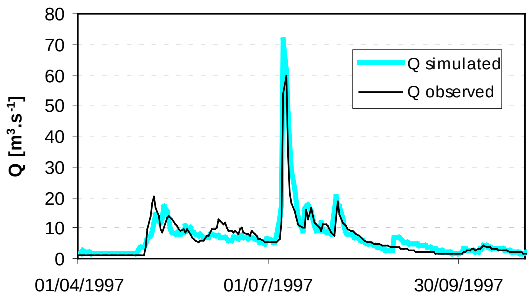


Fig. 6 Observed and simulated discharge, HBV-light model, daily time step, from 1.4.1997 to 31.10.1997.

R_{eff} compares the prediction by the model to the simplest possible prediction, a constant value of the observed mean value over the entire period.

R_{eff} = 1: Perfect fit, $Q_{Sim}(t)= Q_{Obs}(t)$.

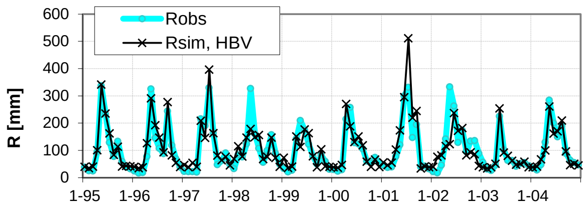
R_{eff} = 0: Simulation as good (or poor) as the constant-value prediction.

R_{eff} < 0: Very poor fit.

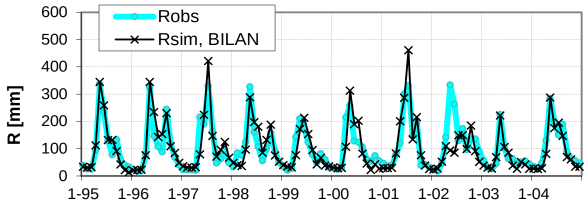
Comparison of the observed and simulated discharge from 1.4.1997 to 31.10.1997 can be seen in Fig. 6. The coefficient of efficiency was 0.72.

Observed (R_{obs}) and simulated (R_{sim}) monthly runoff, using HBV-light model, for the 10-year period from 1995 to 2004 is plotted in Fig. 7a. In view of the fact that we used only one station as input to the model, the result is good. Correlation coefficient is 0.83 (R2=0.66).

Model BILAN was calibrated on monthly data from the river basin Bela over the period 1946/1947–2000/2001. Observed runoff (R_{obs}) and simulated (R_{sim}) monthly runoff for the 10-year period from 1995 to 2004 is plotted in Fig. 7b. Correlation coefficient is 0.81 (R2=0.66).



a)



b)

Fig. 7 Comparison of the monthly observed R_{obs} and simulated R_{sim} runoff values, a) HBV-light model; b) BILAN model; period 1995–2004.

4.3 Simulation of runoff separation

Using the models HBV-light and BILAN we simulated the course of the average monthly values of the individual runoff components in the Bela River basin for the entire period 1940/1941–2004/2005. According to the HBV-light model, the long-term base flow was 40%, soil flow 46.5% and direct flow 14% of total runoff. According to model BILAN, the base flow constitutes 59.32%, interflow 17.95% and direct flow 22.70% of total runoff, respectively. In Fig. 8 there is shown the runoff separation by HBV-light model (simulated values from 1.4.1997 to 31.10.1997).

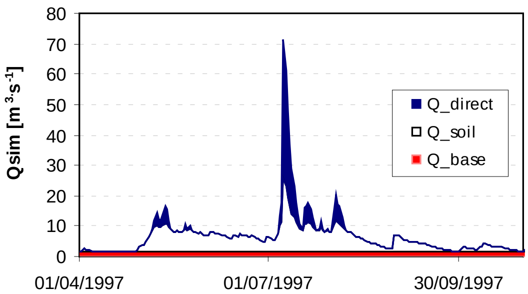


Fig. 8 Runoff separation by HBV-light model (simulated values from 1.4.1997 to 31.10.1997).

4.4 Frequency analysis of daily observed and simulated discharges

First we computed basic statistical characteristics of observed as well as simulated daily discharges by HBV-light model (Table 2) for the time period 1946–2010. Then we tested the null hypothesis that the samples have the same mean. We compare the means of these two samples with T-test. We construct confidence intervals for each mean and for the difference between the means. The confidence interval for the difference between the means extends from -0.063095 to 0.0652789. Since the interval contains the value 0.0, there is not a statistically significant difference between the means of the observed and simulated discharges at the 95.0% confidence level.

Table 2 Summary statistics of the observed and simulated daily discharges; time period 1946–2010.

	Qd obs	Qd sim
Count	23376	23376
Average	3.3	3.3
Variance	13.2	11.9
Standard deviation	3.6	3.4
Minimum	0.5	1.2
Maximum	72.6	52.0
Stnd. Skewness	248.5	254.5
Stnd. kurtosis	952.5	824.1

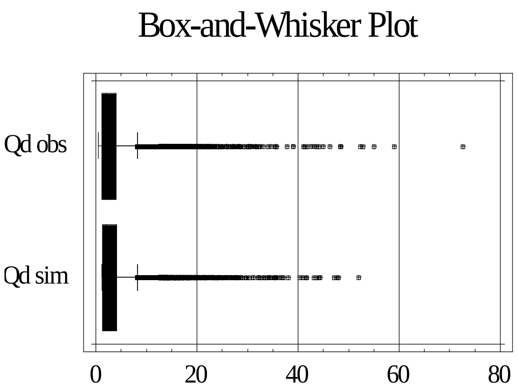


Fig. 9 Comparison of the differences between the means of the observed and simulated discharges, at the 95.0% confidence level.

Visually we can compare differences on the Box and Whisker plot (Fig. 9).
The results of the analysis of the daily input data show that the HBV model generally underestimates the peaks - culmination flows. For the analysis of monthly data input the model gives good results.

5 Conclusion and discussion

In the first part, water balance is set up in the monthly and yearly time step, based upon mean monthly discharge data from the gauging station Bela-Podbanske. Also mean monthly precipitation data over the Bela River basin were used. From water balance of the whole observation period it follows, that the long-term average annual Bela River basin precipitation total (up to Podbanske) is 1718 mm, annual runoff depth is 1175 mm, and the balance evaporation equals to 543 mm for 1945/46–2004/05 period.
The second part of the study is focused on the selected runoff components simulation from the Bela River basin in the monthly, as well as daily time step, during the period 1940/41–2004/05. To assess this aim, we used BILAN and HBV-light models, which set individual components of total runoff. Total runoff was divided into three components: baseflow, interflow (soil flow), and direct runoff. According to the HBV-light model, the long-term base flow was 40%, by the BILAN model it was 59.32%, respectively. Fendekova et al. (2014) identify soil flow for Bela-Podbanske to 55% of the total runoff.
The models describe observed runoff values relatively good. We achieved a sufficient agreement between observed and simulated values in regard to input data. Main non-agreement of simulation is in the area of maxima. In evaluating the results, we have realized that not only comparing two different models, but also the input data to the models are slightly different. HBV-light model works with daily precipitation and air temperature, and these data for the period 1945/46 to 2004/05 we obtained only from the station Kasprowy Wierch. Therefore, it may appear that the HBV model gives worse results.
In the third part the frequency analysis of the observed and simulated discharge were done.
Rainfall-runoff models found a wide application in all sections of water management giving water managers a simple tool to solve various problems such as management of water systems, flood risk management, impact of climate change on water regime of a country and many others. However, the use of rainfall-runoff models is very often linked with various problems such as vast simplification of complex system of runoff creation, or quality and quantity of input data (Holko, 1998; Pekarova et al., 2009, 2010).

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