APPLICATION OF THE HBV MODEL FOR THE MARITZA RIVER BASIN DISCHARGE MODELING

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Abstract: The Maritza river basin is the largest in Bulgaria. It is situated in the middle part of the country and surrounded by relatively high mountains. The climate of the region is under the influence of both Middle and East European continental climate and the Mediterranean one. The floods are mainly of snowmelt-rainfall type having peak discharge usually more than 5-10 times the average one. This situation is due to the complex natural hydrological conditions. The upper zone has regular and stable snow cover during the winter because of the higher elevation (up to 2925 m asl). The middle one, contributing most of the water during the peak discharge, has also high elevation – the average elevation of the Bulgarian part of the Maritza river basin is 600 m asl. The snow cover is not stable, the melting process is going more than once during the winter – when Mediterranean cyclones are passing the region, then snowmelt could be stimulated by rainfall resulting to abrupt floods.

For the present work one water level gauging station was selected, situated on the main river channel in the middle part of the basin. Water levels are observed by recording device and after the preparation of the annual discharge curve by the local staff, the daily mean discharges are calculated and stored in the NIMH data base in Sofia. Four meteorological stations were selected for the precipitation and air temperature data series. They are at different elevations and perform three observations per day (at 7 a.m., 2 p.m. and 9 p.m.) for the air temperature and only one observation for the precipitation (at 7 a.m.). Daily means are used for the air temperature.

The HBV model was applied for the discharge simulation. It is a conceptual precipitation-runoff model originally developed by the Swedish Meteorological and Hydrological Institute. The model describes numerically the runoff processes occurring in a natural river basin. The main input variables in the HBV model are temperature, precipitation and potential evapotranspiration. The HBV model has been modified and improved and it now exists in several versions. The used one is based mainly on the Norwegian version.

The HBV model consists of three main components: snow accumulation and melt, soil moisture accounting and generation of runoff and transformation of the hydrograph. The snow routine of the HBV model controls snow accumulation and snowmelt. The air temperature determines whether the precipitation is rainfall or snowfall. The HBV model uses a degree-day (temperature index) method for snow calculation. The soil moisture routine is a essential part of the HBV model, controlling the generation of effective precipitation from a given input of precipitation and/or snowmelt. The routine receives rainfall and/or snowmelt as input from the snow routine and computes the storage of water in soil moisture, actual evapotranspiration and net runoff generating precipitation as output. The runoff response routine transforms excess water from the soil moisture zone to runoff. The runoff response function consists of two linear reservoirs. It also includes the effect of direct precipitation and evaporation on a part which represents lakes, rivers and other wet areas in the catchement.

The dynamics of the runoff for the Maritza river basin is generally simulated quite well, with a slight tendency of underestimation of some flood peaks. The underestimation may to some extent be caused by the use of the R-square criterion as this tend to “punish” overestimation, especially in events with timing problems in the flood peak. The results indicate that the model performance is good enough for snowmelt runoff forecasting.

ANWENDUNG DES HBV-MODELLS FUR DEN ABFLUSS AUS DEM EINZUGSGEBIET DES MARITZA-FLUSSES

Zusammenfassung: Das Maritza-Flussgebiet ist das grösste in Bulgarien, befindet sich im mittleren Teil des Landes und ist von verhältnissmässig hohen Bergen umgeben. Die Überschwemmungen sind meistens von Regen und Schneeschmelze, mit maximaler Abfluss gewöhnlich 5-10 mal über den Durchschnittlichen. Die Schneedecke ist nicht stabil, die Schneeschmelze im Winter geschieht mehrmals – beim *Übergang* von Mittelmeerzyklonen kann die Schneeschmelze durch Regen stimuliert werden, welches zu plötzliche Überschwemmungen führt.

Zum Zweck dieser Erforschung wurde eine hydrometrische Station ausgewählt, um die durchschnittlichen Tages- und Nachtswassermengen(Abfluss) auszurechnen. Für die Tages- und Nachtsniederschläge und für die durchschnittlichen Tages- und Nachtstemperaturen sind vier meteorologischen Stationen, die sich auf verschiedenen Höhenzonen befinden, ausgewählt worden. Zur Analyse der Messgenauigkeit des Niederschlagfeldes wurden Angaben aus einem Meteoradar benutzt.

Zur Simulierung des Abflusses wurde das “Conceptual model” HBV in seiner norwegischen Version benutzt. Das Modell beschreibt zahlenmässig den Abflussbildungsvorgang im natürlichen Flussbecken. Das Modell besteht aus drei Grundteilen: Schneeanhäufung und Schneeschmelze; Bodenfeuchtigkeitsbilanz; Abflussgenerierung und Transformation des Hydrographs. Die Grundeingangsvariablen sind Lufttemperatur, Niederschlag und Evapotranspiration.

Die Dynamik des Abflusses aus dem Maritza-Flussbeckens ist im allgemeinen gut, mit leichter Tendenz zur Unterschätzung mancher von den Höhenwassermengen(Abfluss). Diese Unterschätzung ist wahrscheinlich durch die Anwendung des R-Quadrat-Kriteriums hervorgerufen, welches sehr sensibel zu den Überschätzungen und besonders zu den Fällen mit Verschiebung der Höhenwassermengen in der Zeit, ist. Die Ergebnisse zeigen, dass das Modell gut genug für das Vorhersagen des Schneeschmelzeabflusses ist.

1. Summary

The Maritza river basin is the largest in Bulgaria, situated in the middle part of the country and surrounded by relatively high mountains. The floods are mainly of snowmelt-rainfall type having peak discharge usually more than 5-10 times the average one. The snow cover is not stable, the melting process is going more than once during the winter – when Mediterranean cyclones are passing the region, then snowmelt could be stimulated by rainfall resulting to abrupt floods.

For the present work one water level gauging station was selected to calculate the daily mean discharges. Four meteorological stations located at different elevation zones were selected for the daily precipitation totals and air temperature daily means. Weather radar data were also used to analyze the accuracy of precipitation fileds measurements.

The HBV conceptual model was applied for the discharge simulation. The Norwegian version of the model is used for the present study. The model describes numerically the runoff processes occurring in a natural river basin. The model consists of three main components: snow accumulation and melt, soil moisture accounting and generation of runoff and transformation of the hydrograph, while main input variables are air temperature, precipitation and potential evapotranspiration.

The dynamics of the runoff for the Maritza river basin is generally simulated quite well, with a slight tendency of underestimation of some flood peaks. The underestimation may to some extent be caused by the use of the R-square criterion as this tend to “punish” overestimation, especially in events with timing problems in the flood peak. The results indicate that the model performance is good enough for snowmelt runoff forecasting.

2. Introduction

During the last few decades mathematical runoff models have become one of the most wide-spread tools in hydrology. They can applied to solve a large number of problems in hydrology and water resources. The most common are simulations of the natural river discharge and operational forecasting. Simulation of the natural discharge means that the models are used to simulate runoff from meteorological data input available in the catchment or in its neighbourhood. The models are first calibrated and tested in order to verify their ability of runoff simulation from the meteorological data.

The HBV model is widely used for operational runoff forecasting in many countries (Sweden, Norway, etc.). This paper presents a study for the application of the HBV model using data for the Maritza river basin in Bulgaria and the obtained results.

3. Model description

The HBV model originally developed at the Swedish Meteorological and Hydrological Institute in the first half of the seventies (Bergström 1976) has gained widespread use for a large range of applications. It can be classified as a semi-distributed conceptual model. It uses sub-basins as primary hydrological units, and within these an area-elevation distribution and a crude classification of land use (forest, open, lakes) is implemented. The model consists of three main components:

- subroutines for snow accumulation and melt;
- subroutines for soil moisture accounting;
- response and river routing subroutines.

The main structure of the HBV model (Saelthun, 1996) is a sequence of sub-models as it is shown on fig. 1: snow, soil moisture, dynamic and routine. The model is further structured in altitude intervals. This subdivision can be applied only to the snow sub-model, or to the whole model. Even when the model distributed on altitude intervals, the parameters are generally the same for all sub-models. Interception, snow melt parameters and soil moisture capacity can however be varied according to vegetation type. The main input variables in the HBV model are temperature precipitation and potential evapotranspiration.

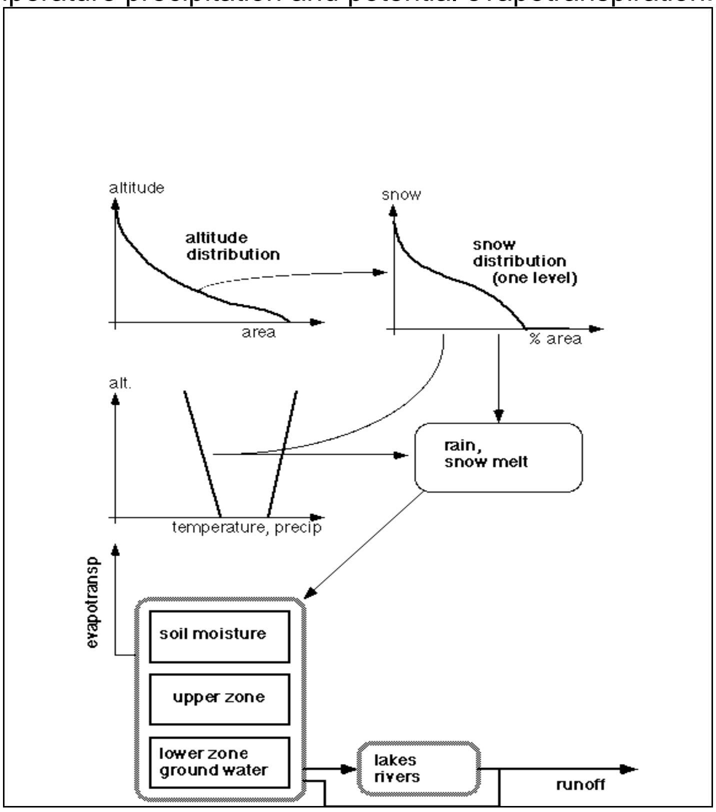

Fig. 1 Structure of the HBV model (Saelthun, 1996)

In the HBV model the air temperature is accepted as a determining factor whether precipitation accumulates in form of snow or enters the soil moisture zone. Snow accumulation in an altitude level starts when precipitation falls at temperature lower than certain threshold value.

It was found that a distributed description of the snow cover within an altitude interval performs better (Aam & Killingtveit, 1978). The actual form of the snow distribution is specified by its coefficient of variation.

Basically the HBV model uses a temperature index (degree-day) method for snow melt calculation. The temperature index melt equation is

$$M = CX \cdot (T - TS) \cdot \Delta t \quad \text{for} \quad T > TS$$
$$M = 0 \quad\quad T < TS \quad\quad (1)$$

where M is the melt (in mm), T is the altitude level temperature during the time step Δt, TS the threshold temperature, and CX the temperature index.

Melt water is retained in the snow until the amount of liquid water reaches a fraction LV, parameter. Over this threshold melt water leaves the snow pack. All nine subdivisions of the snow distribution in an altitude zone are treated individually.

When the temperature is below the melt threshold temperature, liquid water in the snow pack will refreeze, but at a lower efficiency than the melt. The refreeze equation is

$$F = CFR \cdot CX \cdot (TS - T)\,) \cdot \Delta t \quad \text{for} \quad T < TS$$
$$F = 0 \quad\quad " \quad T > TS \quad\quad (2)$$

CFR is a dimensionless constant less than 1.

Potential evapotranspiration can either be given as parameters to the model, or calculated by a temperature index method. In the first case, average potential evapotranspiration in mm/day is given for each month by parameters. These are used as fixed values, and there is no differentiation between altitude levels, nor vegetation zones.
By the temperature index method, the potential evapotranspiration is calculated for each time step using a simple temperature index method (Lindström et al, 1994):

A central part of the HBV model is the soil moisture zone. This zone receives melt water from snow, rain on snow and free areas and computes the storage of water in soil moisture, actual evapotranspiration and the net runoff generating as output. In addition water can be drawn up from the ground water zone to the soil moisture zone. Actual evapotranspiration is calculated based on the water content in this zone, and the percolation to the dynamical parts of the model as a function of the water content.

The runoff response routine is the part of the HBV model which transforms excess water from the soil moisture zone to runoff. The runoff response function consist of two linear reservoirs. It also includes the effect of direct precipitation and evaporation on a part which represents lakes, rivers and other wet areas in the catchment. The two linear reservoirs distributes the runoff in time and by choosing suitable values for the parameters the model can obtain both a quick response for high flows and a slow response for low flows, as usually seen in observedhydrographs.

4. Hydrological conditions in Maritza river basin

The HBV model was applied to the basin of Maritza River for the cross section "Plovdiv". The main purpose was to test the capability of the model to simulate a given hydrograph of Maritza River after calibration.

The Maritza River basin is the largest in Bulgaria. It is situated in the middle part of the country and surrounded by relatively high mountains (fig. 2). The climate of the region is under the influence of both Middle and East European continental climate and the Mediterranean one. The floods are mainly of snowmelt-rainfall type having peak discharge usually more than 5-10 times the average one. This situation is due to the complex natural hydrological conditions. The upper part has regular and stable snow cover during the winter because of the higher elevation (up to 2925 m a.s.l.). The middle one, contributing most of the water during the peak discharge, has also high elevation – the average elevation of the Bulgarian part of the Maritza river basin is 600 m a.s.l. The snow cover is not stable - the melting process is going more than once during the winter – when Mediterranean cyclones are passing the region, then snowmelt could be stimulated by rainfall resulting to abrupt floods. Another problem making river flow modeling in the region more difficult and complex is related to the soil moisture conditions and evapotranspiration. This part of the country is semi-arid and during the summer significant precipitation volumes could not produce flood wave going most of all for infiltration and evapotranspiration. In the region, except for the three winter months the evaporated amounts are limited not by the energy but by the availability of water and the soil conditions. The latest is especially true for the lower part (river terraces) where the snow cover is occasional and the groundwater storage could be significant.

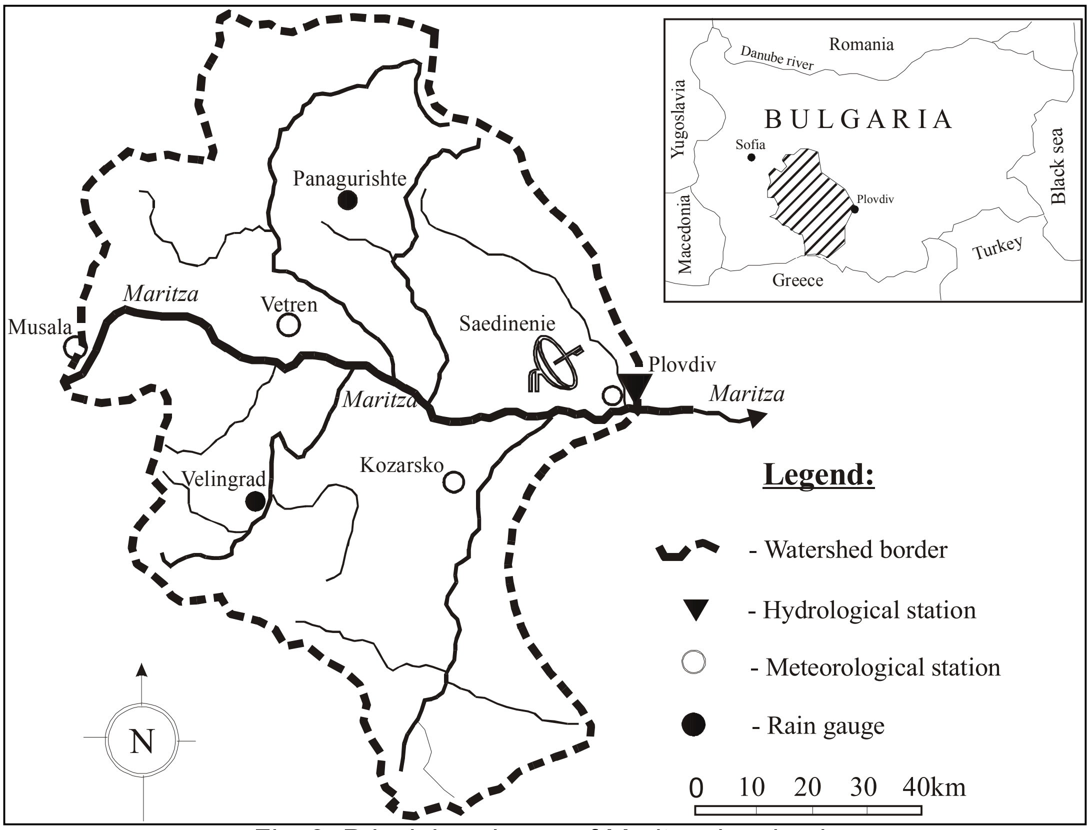

Fig. 2. Principle scheme of Maritza river basin

5. Description of the data set used

For the purpose of the present work one water level gauging station was selected ("Plovdiv", fig. 2), situated on the main river channel in the middle part of the basin. Water levels are observed by recording level gauges and after the preparation of the annual discharge curve by the local staff, the daily mean discharges are calculated and stored in the NIMH data base in Sofia. Four meteorological stations with different weight (more of them belong to the "climatological stations type in Bulgaria) were selected for the air temperature data series and six for the precipitation. They are at different elevations and perform three observations per day (at 7 a.m., 2 p.m. and 9 p.m.) for the air temperature and only one observation for the precipitation (at 7 a.m.). Daily means are used for the air temperature. Based on the information on data availability, the period of October 01, 1981 –December 31, 1987 was selected for the model calibration.

6. Application of whether radar data

The weather radar used is Russian machine type MRL-5, operating at 10cm. wave length, situated at the central part of the "Mariza" river basin - fig. 2, at the village "Saedinenie". Pre-processed radar data with 4 km. resolution were used in this study. The "volume data" frequency was 15 min, but for our purposes the rain intensities were averaged on hourly intervals. This way we received more than 70 rainfall events within the period studied - June, 1994. The preliminary analysis shows that the rainfall events in this period are caused by two type of processes: local convective storms and frontal storms. as far as the soil conditions are of primary importance for the generation of floods in suumer time, the second type of frontal storm events should be more interesting for our purposes. A picture of this kind is given on fig. 3, where several successive areal distributions of hourly precipitation amounts over the "Mariza" river basin are shown. Thise amounts vary within the range of 0 to 5 mm. per hour while the storm front obviously progresses from North-West to South-East.

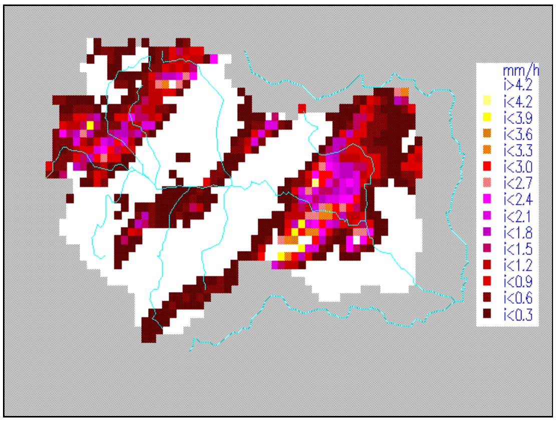

Fig. 3. Radar patterns 17h, 14.07.94

Using the radar data a correlation analysis of the spatial distribution of the intensities was done. The main question was how big are the spatial variations at the lowland and at the mountain part of the river basin. For that purpose at each point of the Horton network or sub-basin network is selected one central point, which is correlated with the neighboring ones. After the calculations, a relationship between the distances of the points, where the radar patterns are positioned and the correlation coefficients between the intensities at those points. The results of the Linear Regression Models fit to those two data sets are shown on figure 4. One cane sees that the highest distance in the first variant is about 25 km. as far as the sub-basin is relatively small. In the second case this figure is 12 km., which means that the Horton figures are comparable in size with the smallest pattern, which can be measured by the radar - 4 x 4 km. square. The significance level of the correlation coefficient at the tolerance probability level of 0.95 is about 0.5.

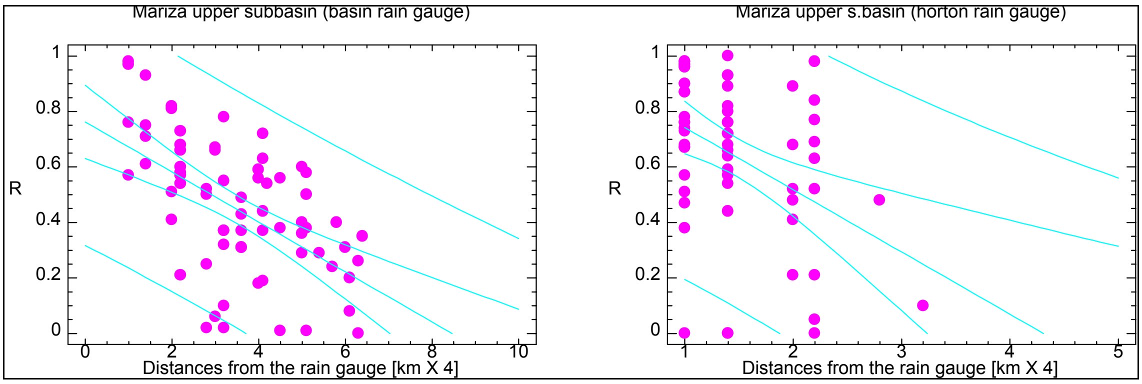

Fig. 4. Regression of the correlation function vs. the distance between the:

- *left - sub-basin representative rain gauge and the radar data pixels within the sub-basin*
- *right - current Horton figure representative rain gauge and radar data within that figure*

The regression lines fitted for the upper elevation zones reach the insignificance level at distances about 12 - 14 km. For the lower elevation zones the correlation functions become insignificant at distances 20 - 30 km. The picture at the different sub-basins/zones could be accepted to be similar except for the upper zone of the Stryama river, the lowest right graph of fig. 2.8. This is a hilly terrain at the lowest part of the basin, where the observation conditions are not very good. The relations in the second variant - "Horton figure rain gauge" are more chaotic, possibly because of the smaller distances included in those data sets. The regression lines fitted have wider tolerance intervals and slighter slopes with respect to the X-axis.

7. Results

A calibration period of seven years (1981 – 1987) was used for parameter evaluation of the HBV model, as it was mentioned above. The simulation was started on the October 01, 1981 in order to avoid carry over effects due to snow storage.

Two data sets with different temperature and precipitation stations were used for model calibration. The aim was to investigate results using different combinations of the stations. The combinations are given in table 1.

Table 1 Different combinations of stations

Combination	Temperature station	Precipitation station
First	Musala – 2925 m asl Kozarsko – 250 m asl	Musala – 2925 m asl Panagurishte – 556 m asl Kozarsko – 250 m asl
Second	Vetren – 875 m asl Plovdiv – 160 m asl	Vetren – 875 m asl Velingrad – 745 m asl Plovdiv – 160 m asl

In table 2 are shown the values of accumulated discharge volumes for the observed runoff and for different combinations of the stations for the model calibration. They are also divided for the different years of the calibration period as well as for the whole period.

Table 2 Accumulated volumes from the different periods

Periods	Observed runoff (mm)	Simulated runoff – first comb. (mm)	Simulated runoff – second comb. (mm)
01.10.1981 – 31.12.1982	189,1	174,8	175,6
01.01.1983 – 31.12.1983	182,2	131,8	116,3
01.01.1984 – 31.12.1984	192,8	152,6	126,7
01.01.1985 – 31.12.1985	101,9	92,2	97,5
01.01.1986 – 31.12.1986	132,3	118,2	115,8
01.01.1987 – 31.12.1987	105,8	159,8	114,2
01.10.1981 – 31.12.1987	890,1	829,4	796,1

The agreement between the observed and computed hydrographs expressed as R^2 – values (see below) for different modifications and periods is given in table 3. R^2 is the Nash efficiency criterion:

$$R^2 = 1 - \frac{\sum (Q_{sim} - Q_{obs})^2}{\sum (Q_{sim} - \overline{Q})^2} \quad (3),$$

where:

Q_{obs} is observed discharge;

$\overline{Q}$ - average discharge;

Q_{sim} - simulated discharge,

Table 3 R^2 values for the hydrographs agreement

Periods	R^2 – first combination	R^2 – second combination
01.10.1981 – 31.12.1982	0,08	0,10
01.01.1983 – 31.12.198	-0,23	-0,57
01.01.1984 – 31.12.1984	0,32	0,20
01.01.1985 – 31.12.1985	0,00	-0,27
01.01.1986 – 31.12.1986	0,38	0,23

01.01.1987 – 31.12.1987	-0,37	0,54
01.10.1981 – 31.12.1987	0,10	0,09

Plots of simulated hydrograph for different stations combinations together with recorded discharge for chosen years of the calibration period are shown fig. 5 and fig. 6. In the same plots are also presented the snow storage (mm), snow melt (mm), snow covered area (%), accumulated difference between observed and simulated runoff, daily temperature (^{o}C), and daily totals of precipitation (mm/d). Snow storage, snow melt and precipitation are catchments averages, while temperature is represented to the medium catchment altitude.

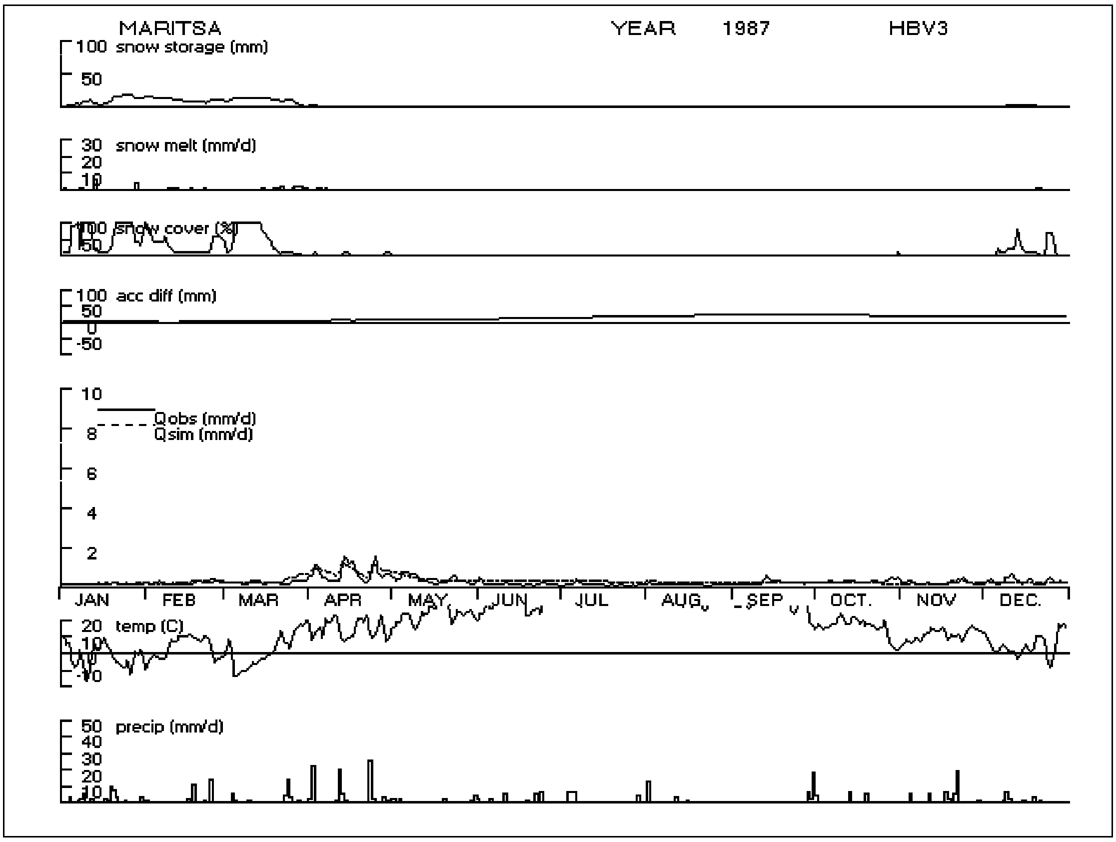

Fig. 5. Graphic results from the HBV model simulations – first combination of stations

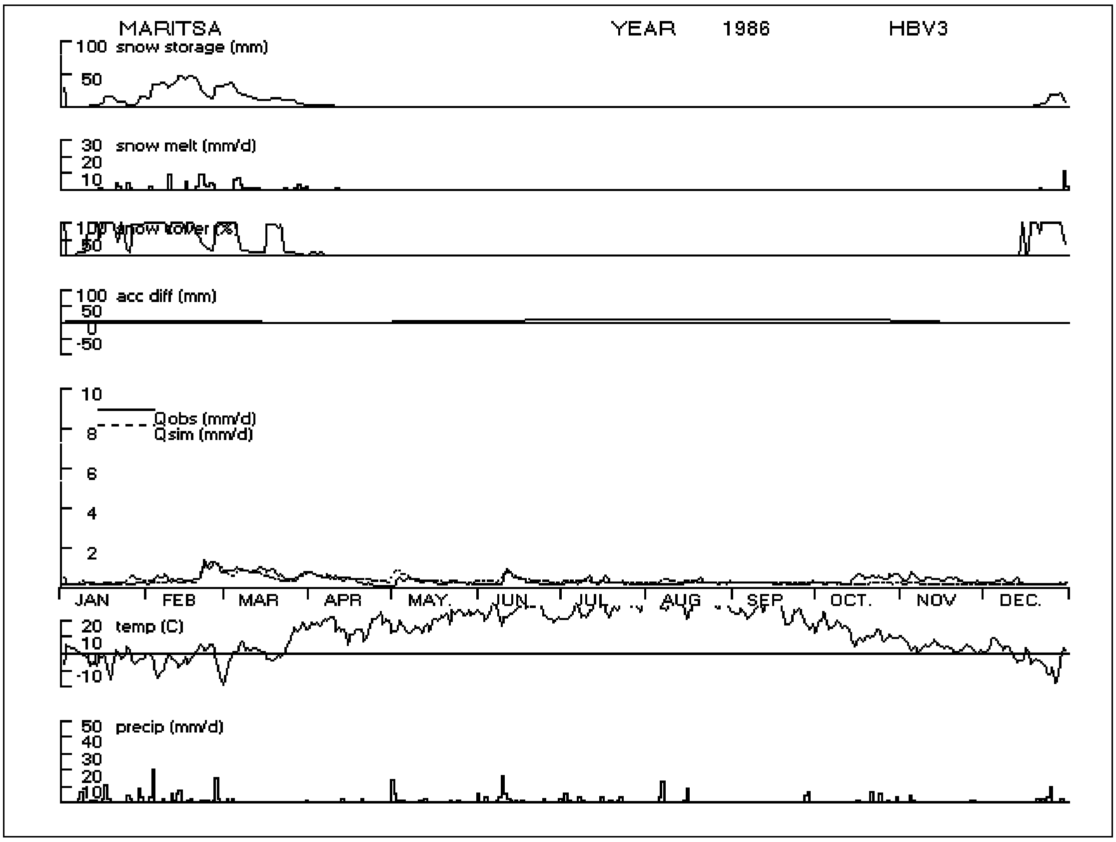

Fig. 6. Graphic results from the HBV model simulations – second combination of stations

8. Comments on the simulations

The total volume of runoff during the calibration period is approximately well reproduced, which is of course natural, as this is one of the calibration criteria. The volumes of the individual years are also well simulated for most years, with the exception of 1983 (50,4 mm underestimation), 1987 (54,0 mm overestimation) for the first modification and 1983 (65,9 mm underestimation), 1984 (66,1 mm underestimation) for the second. The volume is underestimated for the whole period by approximately 7% for the first combination of stations and 11% for the second. The standard error of the estimate of yearly volumes is 15%. The estimation of yearly volumes could be improved by using more precipitation stations.

The dynamics of the runoff is generally simulated well, with a slight tendency of underestimation of some flood peaks. The underestimation may to some extent to be caused by the use of the R^2 criterion, as this tend to "punish" overestimation, especially in events with timing problems in the flood peak. The weakness of R^2 as a criterion of fit is evident for some of the simulations. During 1987 of the first combination calculations, for example, the negative value indicates a very poor model, while it can be seen from the plot that this is an effect of the dry season with very low initial variance. Conversely the high spring flood in 1986 (first combination) gives a high initial variance and high value of R^2. The poor response of simulated discharge during the floods in November 1985 (first) and September 1987 (second) indicates that the HBV model has problems in correctly simulating of small floods in dry periods. Simulating autumn and winter floods with mixed rain and snow precipitation is always difficult and in some cases the model fails on such floods, for instance in November 1986.

The simulations using the first combination of meteorological stations performed better then the second. It may be caused of bigger altitude difference between the measurement stations. The station representatives are also important and the analyses in this direction should continue. The simulations could be additionally improved in future after analyzing the real weight for runoff generation of each measurement station. It should be kept in mind that the winter precipitation data involving snow fall are strongly influenced by wind.

9. Conclusions

As first, the results from the calibration of the HBV model are promising for the Maritza river basin (cross section “Plovdiv”). Of course, some additional efforts in future should be done using the following main directions:

- Analyzing the importance (weight coefficient) of each temperature station for the runoff factors formation (snow cover, snow melt, evaporation etc.);
- Necessity to involve more precipitation stations in the input data for the HBV model;
- Analyzing the importance (weight coefficient) of each precipitation station for the formation of the runoff;
- Necessity to involve more precise information for the vegetation types and there distributions of different altitude zones and areas;
- Analysis of the model accuracy with respect to the variations and errors in the different type of input information;
- Analysis the robustness of the HBV model related to the parameters under calibration, assuming that the input information is exact one.

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