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Hydrological modelling using remote sensing data in Bulgaria

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Abstract: The availability of detailed well distributed in space information on precipitation is of essential importance for the hydrological modelling. Conventional measurements of precipitation are in a limited number of points represented by synoptic, climatic and precipitation stations. This information is not sufficient enough for the proper spatial distribution of precipitation. The space distribution of the ground stations is quite irregular and thus distances between stations could be quite big, sometimes more than 30 km. On the other hand, precipitation is a local event and has high variability in space. The results of the spatial distribution depend on the density of the ground measurements. Simulations with MIKE11 and Artificial Neural Networks (ANN) over two different catchments in Bulgaria using precipitation product from the H SAF are presented in this paper. Analyses are made using data from two different from hydrological point of view years (2011 and 2014) – the first being dry year and the second – wet. Conclusions on the behaviour of the precipitation estimates from the satellite product over the two catchments are made.

Keywords: Hydrological modelling, MIKE11, Artificial Neural Networks (ANN), HSAF precipitation product.

1. BACKGROUND

Remote sensing is widely used for acquisition of different meteorological parameters, needed as an input for hydrological models. Satellite Application Facilities (SAFs) are dedicated centres of excellence for processing satellite data. They form an integral part of the distributed EUMETSAT Application Ground Segment. On Figure 1 are shown the eight SAF networks.

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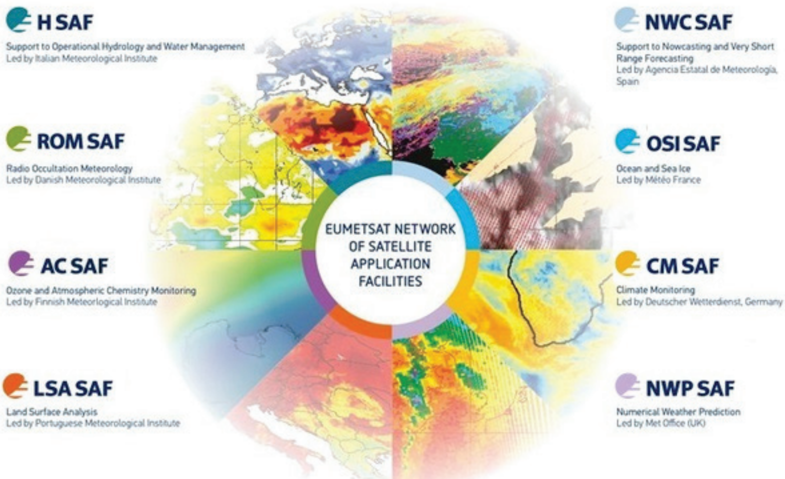

Fig. 1. SAF's network under EUMETSAT (hsaf.meteoam.it)

The HSAF "EUMETSAT Satellite Application Facility on Support to Operational Hydrology and Water Management" network started its work in 2005 with the aim to provide products, derived from satellites, needed for hydrological modelling (precipitation, soil moisture and snow products) (Panegrossi et. al., 2012; Puca et. al., 2014). The National Institute of Meteorology and Hydrology became part of the HSAF project in 2009. As a partner we validate different type of products – for precipitation, soil moisture and snow cover. We also hydrovalidate one precipitation product (H05) over two catchments using different models – statistical model (Balabanova, 2014; Dimitrov et. al., 2012) and NAM model (Dimitrov et. al., 2012; Koshinchanov et.al, 2009) and one soil moisture product (Artinyan et. al, 2008).

This article presents the results of the hydrovalidation over two pilot catchments in Bulgaria with the H05 product for two different years (dry year and wet year) for two different catchments using different type of models. Analyses and conclusions are made.

2. DESCRIPTION OF THE PILOT CATCHMENTS

2.1. Iskar river catchment (down to the town of Novi Iskar)

The study area (Figures 2 and 3 (a)) is part of Iskar river catchment up to the hydrometric station Novi Iskar and is around 3550 km^2. The study area is located in West Bulgaria at foot of Stara Planina Mountain. The climate is moderate continental.

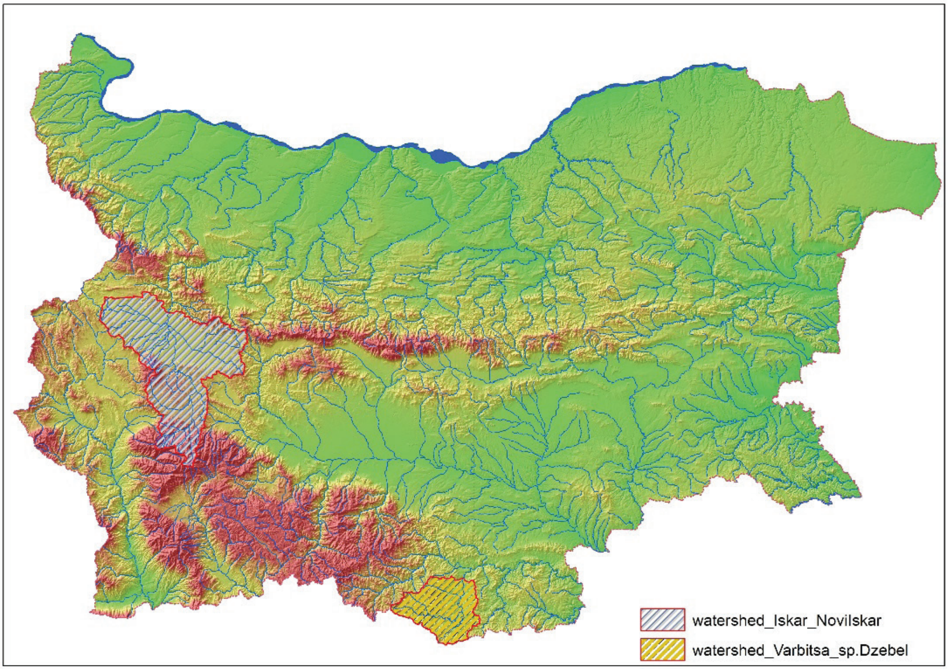

Fig. 2. Location of the pilot catchments for hydrovalidation

Annual accumulated precipitation is approximately 600 mm. The highest rainfalls occur in May and in June and are about 85 mm. The lowest rainfalls occur in February and March and are about 30 mm. Winter accumulated precipitation is approximately 110 mm. Average snow cover is about 10 cm and days with snow are about 50–80 days per year. Accumulated precipitation during spring season is about 160 mm; during summer – about 180 mm and during autumn – about 140 mm. Mean annual temperature is +8°C – +9°C. Mean temperature during winter is about –2°C, during spring – about +9°C, during summer – about +20°C and during autumn – about +10°C. The wet period is during spring and the beginning of summer. The dry period is during summer and autumn.

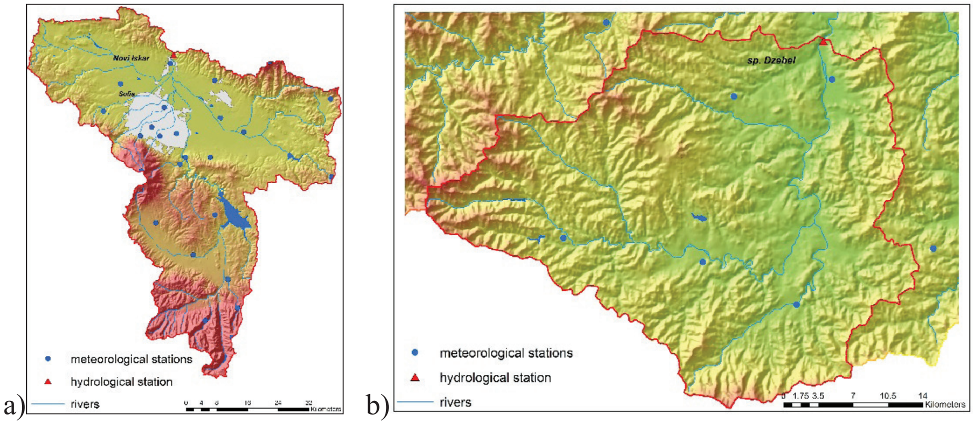

Fig. 3. Iskar (a) and Varbitsa (b) river catchments and locations of meteorological stations

2.2. Varbitsa river catchment (down to sp. Dzhebel)

The Varbitsa river is situated in the South Bulgaria and is part of the Arda's catchment – its right tributary. Its springs are situated just below the peak Martazyan in the South–East Rodopi Mountain. The length is 98 km, the catchment area is around 1200 km^2 and flows in Studen Kladenets Dam. The highest point of the catchment is around 1390 m and the lowest – around 200 m; the average height of the catchment is about 550 m a.s.l. (Figures 2 and 3 (b)).

The catchment is influenced by Mediterranean type of climate with comparatively mild, wet winters and hot, dry summers. The mean annual precipitation is around 850 mm, and more than 60% of it falls in the winter period – November–March. In the upper part, the catchment is covered by forest lands and in the lower part the river bed becomes wide and covered by sands. There are two periods of high waves – in February–March and October–November. The peaks in February–March are often formed from intensive rainfalls (from Mediterranean cyclones) combined with snowmelt, which sometimes leads to floods in the valley especially in the lower part of the river. The dry period in the months July–September.

3. MODELS' DESCRIPTION

3.1. ANN (Artificial Neural Networks)

Recently Artificial Neural Networks are widely used as a potentially useful way for modeling nonlinear systems. The ANN provide a quick and flexible approach for data integration and model development. ANN are a powerful and flexible mathematical model that is designed to model the human brain and its ability to learn tasks (Govindaraju et.al, 2013). The ANN are trained to recognize and generalize the relationship between a set of inputs and outputs.

In 1932 L. K. Sherman used ANN for the first time in hydrology. He set up an engineering model for the transformation of the precipitation in runoff at the outlet of a given catchment. Then in the early 1990s ANN have been widely used in hydrology. ANN treat the hydrological system as a black box and try to find a relationship between historical inputs (rainfall, temperature, etc.) and output (runoff) – Figure 4. The used software for this study is NeuroSolutions.

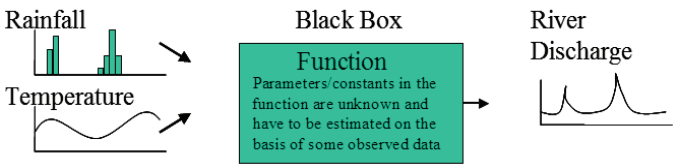

Fig. 4. Black box model

3.1.1. Approach and methodology

The approach to build the model is very simple and is as follows:

The catchment is divided in 6 sub catchments (Figure 5).

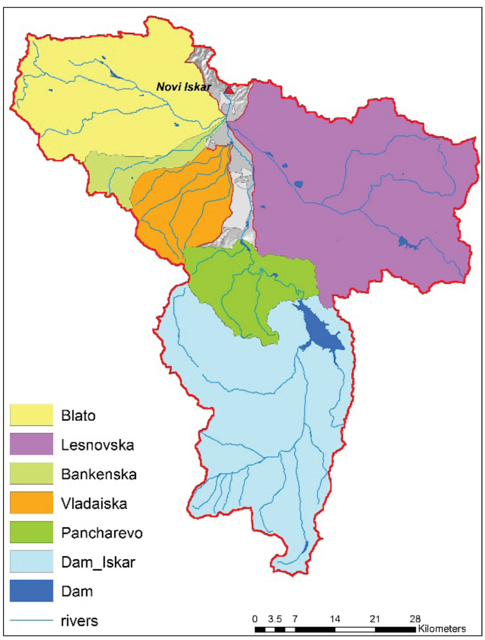

Fig. 5. Tested catchment and sub-catchments

3.1.2. Data requirements

For each sub catchment average 24-hour precipitation total is calculated. Two methods are used:

- **Thiessen method** – applied for historical meteorological data series of 19 rain gauges (Figure 6).

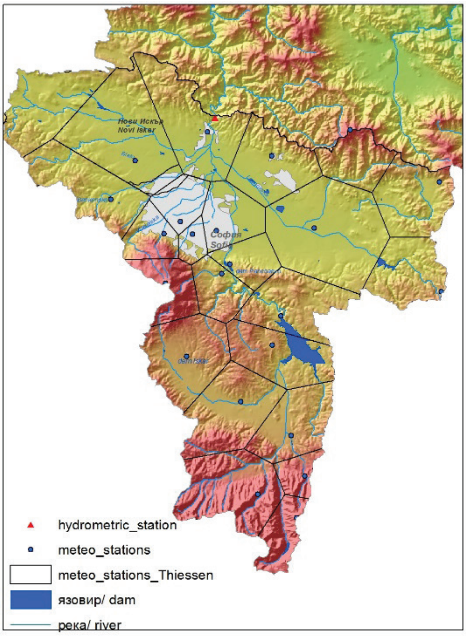

Fig. 6. Thiessen polygons

- **Method of average value** – applied to calculate average spatial precipitation from HSAF product for each sub-catchment. This approach is suitable because HSAF product grid is uniformly distributed with a cell size of around 4 km (Figure 7).

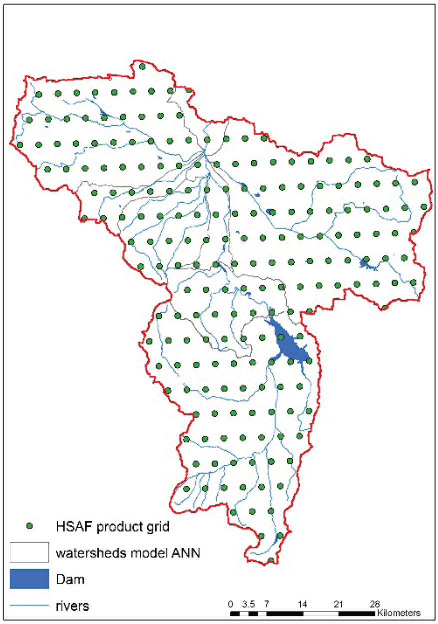

Fig. 7. H05 product grid

The flow data with lag -1 day at the hydrometric station is also used as an input variable in the ANN. The reason for this is that as the rainfall data contain a number of zero values the conditions of rainfall and no-rainfall is difficult to be identified by the ANN with only rainfall time series as inputs. In such case the previous river flow provides an indication as to whether rain has occurred or not. Also such flow adds further information on that: the longer the rainfall is zero, the more the response flow decreases.

For each sub-catchment the accumulated precipitation for previous three days is included as a variable. In such way the soil moisture could be taken into account. Seasons are also included to describe the impact of baseflow and snowmelt.

The Multilayer Perceptron with one hidden layer is used. It is the most common neural network model. ANN is trained for the period 1991–2004. ANN is validated (cross validation) for 2005–2006. Cross validation data set is used to determine when the network has been trained as well as possible without overtraining. ANN is tested for 2008. The set is used to test the performance of the ANN.

3.2. NAM (Nedbor Afstromnings Model) model of MIKE 11

This model is developed by the Department of Hydrodynamics and Water Resources at the Technical University of Denmark and describes the behaviour of the land phase of the hydrological cycle. NAM represents various components of the rainfall-runoff process by continuously accounting for the water content in up to four different and mutually interrelated storages. Each storage represents different physical elements of the catchment. The NAM model can be characterized as a deterministic, lumped, conceptual model with moderate input data requirements. It simulates the rainfall-runoff processes occurring at the catchment scale (DHI-MIKE BY 2009).

By default, in the NAM model are included 9 parameters representing the surface zone, root zone and ground water storages, which can be automatically calibrated.

A scheme of the NAM model is given on Figure 8

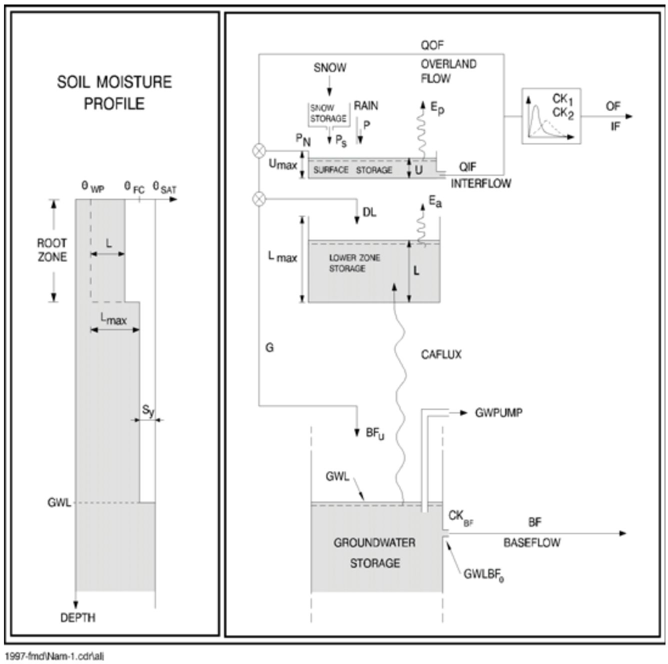

Fig. 8. Principal scheme of the NAM module (DHI-MIKE BY 2009)

3.2.1. Data requirements

The input data for the NAM model are 24 hours precipitation totals from the rain-gauge stations. Here again two methods for estimation of the precipitation are used:

- **Thiessen method** is used in order to obtain mean 24 h precipitation from the rain-gauges over the catchment (Figure 9).
- **Method of average value** – applied to calculate average spatial precipitation from HSAF product.

Beside the precipitation, mean daily temperatures over the catchment and calculated monthly PET, using Thornthwaite's formula (Thornthwaite, 1948) are used. Snow module is included in the model set–up and the catchment is divided into 2 elevation zones for better simulation of the snow accumulation and snow melt process in the mountainous part of the catchment. Mean daily discharge at the outlet is used for the calibration process.

For the calibration process the above set of data for the period 2011–2014 is used.

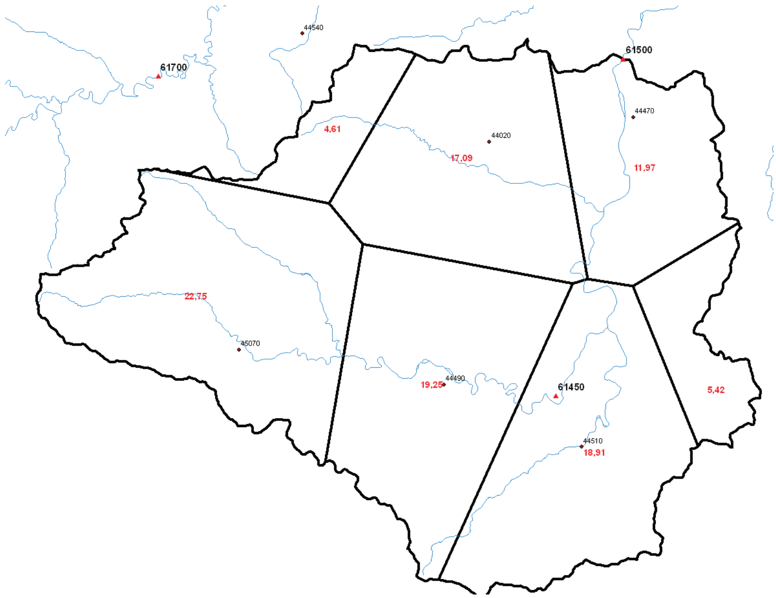

Fig. 9. Thiessen polygons over Varbitsa river catchment

4. MODELS' QUALITY

4.1. Iskar river model

On Figure 10 are presented the hydrographs with simulated and measured discharges and statistical scores for the tested period with ANN using ground data. The model accuracy is evaluated by the RMSE and Nash criteria (E) RMSE = 14.4, E = 0.797.

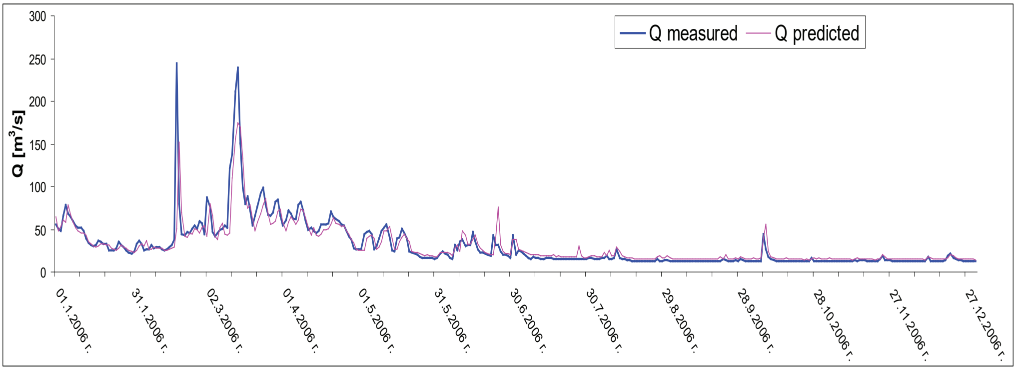

Fig. 10. Testing the ANN for 2006

4.2. Varbitsa river model

Since 2011 was a dry year, and the other 3 years (2012–2014) were quite similar in hydrometeorological conditions (wet years), for the calibration of the model were used 2 years (2012–2013) (Figure 11) and for validation – 2014. For the calibration period the statistical scores are RMSE = 23.7, E = 0.860.

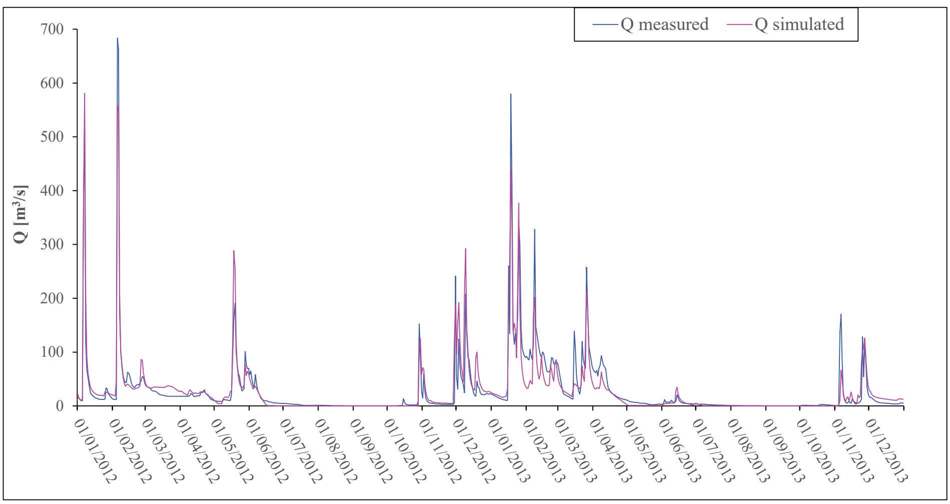

Fig. 11. Calibration of the NAM model

5. RESULTS AND DISCUSSIONS

After the process of calibration is finished, ground data for precipitation are replaced by the H05 product data and simulations are performed. Below are presented results from the simulations for both catchments and discussions on them are made.

5.1. Iskar river catchment

On Figure 12 are shown the hydrographs for the 2011.

- ***Statistical scores:***

Qsim SAT vs. *Qobs* Correlation Coefficient = 0.82; E = 0.56;
Qsim GD vs. *Qobs* Correlation Coefficient = 0.86; E = 0.61.

where
Qobs – observed discharges (m^3/s)
Qsim GD – simulated discharges using ground data (m^3/s)
Qsim SAT – simulated discharges using satellite data (m^3/s)

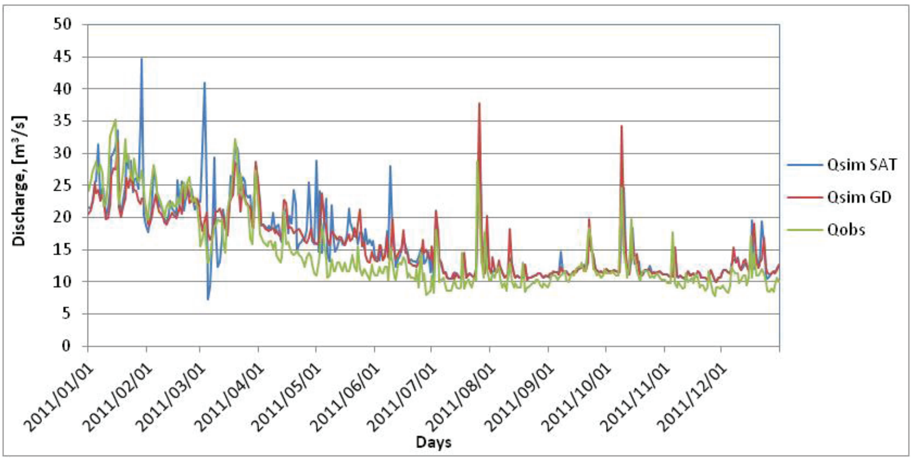

Fig. 12. Hydrograph for the period 01.01–31.12.2011 (Iskar river)

- ***Description and discussion about results:***

The precipitation amounts during the high flows in 2011 from satellites and ground data are quite similar. The periods with precipitation events are 07.07–16.07, 13.08–15.09, 24.09–07.10, 19.10–04.12.2011. The accumulated snow cover at mountainous areas is up to 20–30 cm after 05.12.2011. The discharge is mostly uniform for the period and is below long term average discharge. Simulated discharges both with satellite data and with ground data are overestimated (Figure 12).

Below on Figure 13 are shown simulations for 2014.

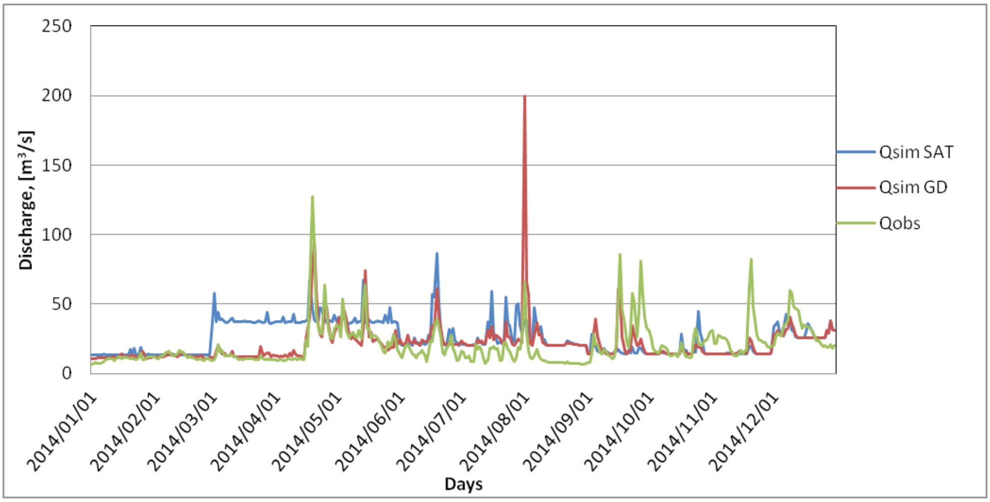

Fig. 13. Hydrograph for the period 01.01–31.12.2014 (Iskar river)

- ***Statistical scores:***

Qsim Sat vs. *Qobs* Correlation Coefficient = 0.24; E = -0.39;
Qsim GD vs. *Qobs* Correlation Coefficient = 0.61; E = 0.24.

- ***Description and discussion about results:***

For the whole period the precipitation total is equal to the long term average. Only in 02.2014 the monthly total is about 20%–40% below monthly average.

The low flow period is till 15.04.2014. After that several high waves occurred in the region – from 17.04 to 17.05.2014, from 31.07 to 01.08, from 16.09 to 18.09, from 27.09 to 28.09 and from 18.11 to 29.11.

The peaks of the runoff are quite well simulated with satellite data as a shape but as a magnitude are underestimated by the model (Figure 13). It could be summarised that for the whole period the precipitation product total is equal to the ground precipitation product total. For January 2014 product data significantly overestimate ground measured data. For February and April 2014 product data underestimate ground measured data. For March, May and June 2014 product data overestimate ground measured data. There is some problem during extreme events, when satellite data are below ground data. The simulated discharge with satellite data overestimate the observed data for the low flow period January-August 2014.

5.2. Varbitsa river catchment

Below on Figure 14 are presented the hydrographs for 2011.

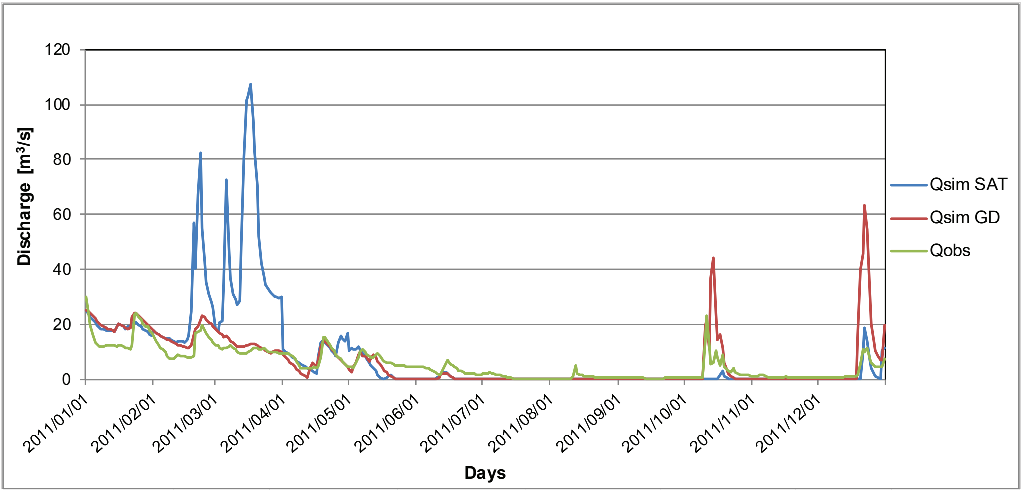

Fig. 14. Hydrograph for the period 01.01–31.12.2011 (Varbitsa river)

- ***Statistics scores:***

Qsim SAT vs. *Qobs* Correlation Coefficient = 0.61; E = -5.90;
Qsim GD vs. *Qobs* Correlation Coefficient = 0.78; E = -0.21.

- ***Description and discussion about results:***

In the beginning of 2011 the simulation with ground data gives comparatively good results due to the high moisture content in the catchment. After June, till the end of the year, there is prolonged period of significantly less precipitation than the usual for this period of the year. This leads to decreasing of the soil moisture in the catchment, and even the precipitation events in October and December doesn't generate surface runoff. Due to the fact that the model is calibrated for wetter conditions, the simulated runoff is bigger than the observed during the rainfall periods in the end of the year.

Due to the higher values of estimated precipitation from the H05 product in March and in the days towards the end of April 2011, the model simulates unrealistically high values of surface runoff (Figure 14). In the period of no rainfall both simulations (with ground data and with H05 product) are similar due to the lack of surface runoff. For the periods with rainfall events (in October and December) the H05 product tends to underestimate the real events (Koshinchanov, 2016). This is the reason why in October there is no simulated runoff and in December, the runoff is well simulated in time and magnitude (Figure 14).

Below on Figure 15 are shown hydrographs for 2014.

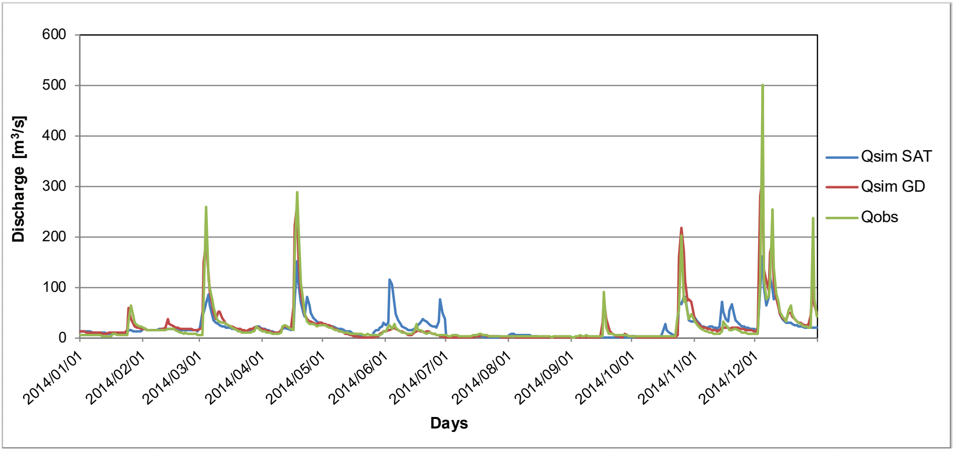

Fig. 15. Hydrograph for the period 01.01–31.12.2014 (Varbitsa river)

- ***Statistical scores:***

Qsim Sat vs. *Qobs* Correlation Coefficient = 0.73; E = 0.49;
Qsim GD vs. *Qobs* Correlation Coefficient = 0.89; E = 0.79.

- ***Description and discussion about results:***

The model performance with ground data is quite good – the values of the Correlation Coefficient (R) and the Nash–Suitcliffe Coefficient (E) on yearly base are quite high: 0.89 and 0.79 respectively. Mainly during the summer months the *R* values are not very high. What is interesting that this year even in the winter months (February) the simulation with ground data is not very good and the *R* and *E* are not very high. A possible explanation for the low values of the *R* and *E* coefficients could be in the process of accumulation of snow cover and the subsequent process of snow melting, not very well described by the model due to the limited number of elevation areas.

During the year 2014 five high waves are observed, all of them in the period October–April, caused by heavy precipitation events from Mediterranean cyclones. Because of the fact that the H05 product tends to significantly underestimate those heavy events (Koshinchanov, 2016), all of the high waves' peaks simulated with satellite product are well captured in time but quite underestimated as a magnitude. In the summer period could be observed just the opposite – light precipitation events are quite overestimated by the H05 product and as a consequence there are peaks in the simulated discharges with H05 product, which don't actually exist (Figure 15).

6. CONCLUSIONS AND REMARKS

As a summary it could be mentioned that for dry years there is overestimation of the product for precipitation both over Iskar and Varbitsa river catchments. In wet years the product shows quite underestimation of the precipitation for Varbitsa river catchment, but similar values over Iskar river catchment.

For Iskar river catchment - in 2011 generally overestimation of discharge both by the ground and product data. In 2014 the peaks are quite good simulated in time and shape but as a magnitude they are underestimated (with one exception). During the low flow period the simulated discharge with product data is above the observed discharge.

For Varbitsa river catchment – which is under the influence of Mediterranean cyclones – the satellite product quite underestimates the events with heavy precipitation (during the "wet" period) and overestimates light events (during the "dry" period), consequently the simulated discharges are higher than observed during low flow period and lower during the wet period.

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