MODELLING OF THE HYDROLOGICAL PARAMETERS IN THE EXPERIMENTAL AND REPRESENTATIVE CIUREA-TINOASA HYDROGRAPHICAL BASIN

Ioan Crăciun[1], Costel Boariu, Valentin Boboc, Petru Cercel

Abstract: The overall goal of the paper is to find the impact of the overland flow and topography on groundwater in the Experimental and Representative Ciurea-Tinoasa hydrographical basin using the MIKE 11 software developed by Danish Hydraulic Institute. The Ciurea-Tinoasa watershed consists of 4 subcatchments but, due to the small area, all of them were analyzed as a unitary one. This basin represents a relevant source of hydrological and meteorological information for Moldova area due to the fact that it is endowed with suitable equipment meant to monitor the main parameters needed to make a reliable model analysis.

Using hydrological time series consisting of daily values of rainfall, evaporation and observed discharge, the watershed was modelled by Rainfall Runoff/NAM (Nedbør-Afstrømnings-Model) module and connected to the HD network, which was modelled by the HD model of the same software, in a suitable way. The model was calibrated using the data recorded for a time period of 3 years and validated by other additional 3 years of available data.

Regarding the NAM parameters, only nine of them representing the Surface-zone, Root-zone and the Groundwater storages where used, while the snow melt and irrigation were not included. These parameters were calibrated by the automatic calibration routine which is based on a multi-objective optimization strategy in which the four different calibration objectives can be optimized simultaneously: (1) Agreement between the average simulated and the observed catchment runoff: overall volume error; (2) Overall agreement of the shape of the hydrograph: overall root mean square error (RMSE); (3) Agreement of peak flows: average RMSE of peak flow events; (4) Agreement of low flows: average RMSE of low flow events. After the parameters were calibrated twice, the results were satisfactory, with a good concordance between the observed discharged and the simulated one.

The groundwater response to overland flow and topography is obtained due to coupling these two models (HD and RR). The result includes estimated parameters such as infiltration, ground water depth, recharge, capillary flux and runoff. Taking in consideration the conceptualization of the flow system and the accuracy required in the basin which was analyzed, the choice of the methods that we used in order to estimate reliably the recharge of the groundwater is satisfactory. The methodology used allows a rapid and comprehensive determination of the recharge, which is important for estimating the available water resources and groundwater vulnerability.

Keywords: *Ciurea-Tinoasa basin, hydrological model, Mike 11, NAM model, numerical model, validation*

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1. Introduction

Rainfall inputs to the hydrological system play an important role in the generation of the discharge of a river basin. There are mathematical models that describe this uniform distribution throughout the basin (Makungo et.al. 2010; Bao et.al. 2011). The existence of the systematic records of the required parameter is very important. In the case of Ciurea-Tinoasa basin, it is equipped with appropriate equipment for collecting these data (Minea, 2012; Crăciun et al.2011).

Model calibration is an important procedure required to check the viability of the model. Automatic calibration routines for hydrological models with multiple objective capabilities are becoming increasingly popular due to the advances gained in computational power, population-based optimization techniques and the acknowledgement of the fact that a single performance measure (such as the root-mean-square error) is no longer sufficient to characterize the complex behaviour of the catchment (Madsen 2000; Khu et al., 2005; Glinska-Lewczuk, 2006; Hormwichan et al., 2009; Liu and Sun, 2010).

2. Background Information and Data

The representative Ciurea-Tinoasa basin is located at the border between the Central Moldavian Plateau and the Moldavian Plain, with an elevation of maximum 410 m and minimum 125 m. Tinoasa hydrographical basin is part of Bahlui River Basin, which is included in Prut River Basin, located in the eastern part of Romania. An analysis of the physico-geographical conditions that determine and influence the forming and regime of the water management from a hydrographical basin is necessary in order to identify the functional relation between the local and regional physico-geographical factors and the hydrological characteristics of the basin (Minea I., 2012). The descriptions of the physical features of the catchment consists of morphological indices, the percentage coverage of soil types, the percentage coverage of land use types and climatic indices.

Regarding Ciurea-Tinoasa Basin, we have a catchment area ranged between 0.17 – 4.17 km^2, lengths of the main streams between 0.48 – 2.32 km, a maximum elevation of 410 metres and an average elevation ranging between 270 and 158 m. Elevation plays an essential role due its direct and indirect influences on the determination of the climatic, bio-geographical and edaphic features. The average main stream slope and average surface slope of the basin range between 10.2 and 14%, respectively 15.2 - 17%. The percentage of forestry coverage reaches a maximum of 95.4 in Humaria River Basin and a minimum of 0% in Ciurel River Basin. The representative Ciurea-Tinoasa basin has five sections on rivers Bolovani, Ciurel, Humaria and Tinoasa (closure section), where the water levels, water discharges and load were measured (**Fig.1.**). Detailed information for readers is provided by **Table 1**.

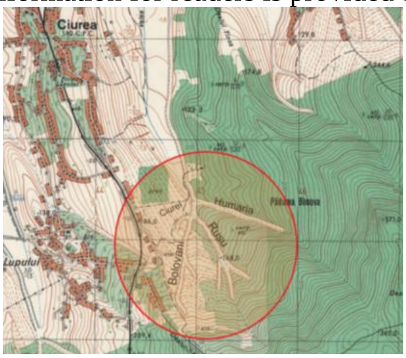

Fig. 1. *The Ciurea-Tinoasa basin*

Table. 1. Morphological data and percentage of forestry coverage of the basin

River basin	Catchment area (km^2)	Basin elevation (m)	Max elevation (m)	Avg elevation (m)	Mainstream length (km)	Mainstream slope ‰	Surface slope ‰	Forestry coverage %
Bolov ani	0.50	124.28	335	250.4	1.18	102.3	153	33.4
Ciurel	0.17	122.55	192	158	0.48	140.4	157	0.00
Humă ria	1.60	120.06	410	270	2.14	111.0	170	95.4
Tinoas a	4.17	118.80	410	272	2.32	103.9	159	77/6

Our case study analyses all the parameters measured at the weather-station during the years 2009, 2010 and 2011: time series between 2009 January 1st and 2011December 31 for temperature (Fig. 2), rainfall (Fig. 3) and evaporation (Fig. 4).

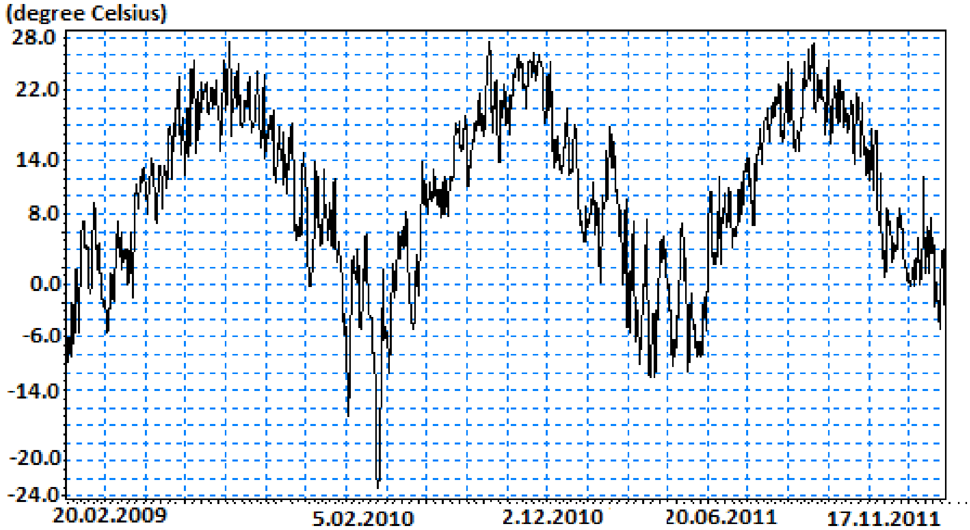

Fig.2. *Temperature time series*

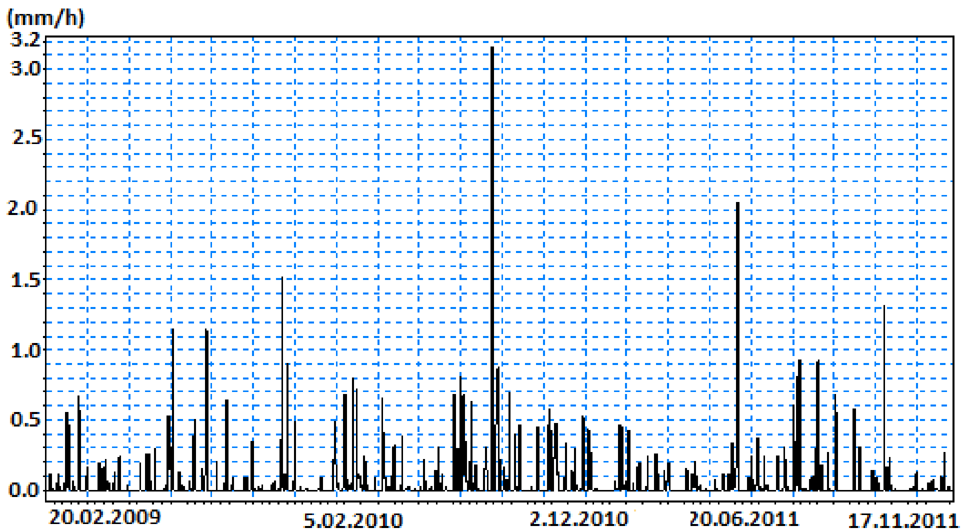

Fig.3. *Rainfall time series*

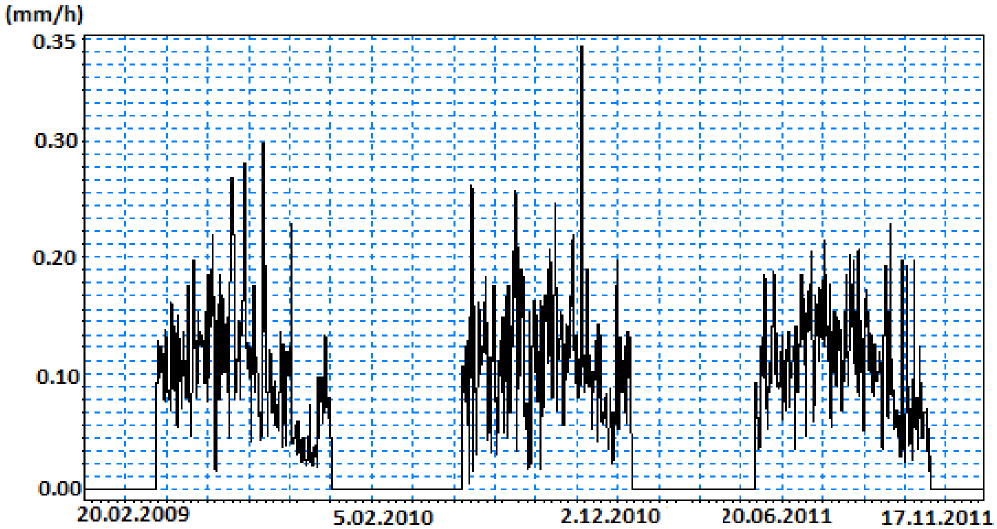

Fig.4. *Evaporation time series*

3. Model Description

Within the developed expert system, the software module for simulating flows and water levels in estuaries, rivers and channels is based on the use of Mike 11, a professional engineering software package developed by the Danish Hydraulic Institute. The software modules used are: HD hydrodynamic module for computing water movement along rivers and RR /NAM rainfall-runoff for estimating surface runoff from watersheds (DHI, 2008).

The hydrodynamic module solves the vertically integrated equations for the conservation of the continuity and momentum, i.e. the Saint Venant equations. A network configuration describes rivers and floodplains as a system of interconnected branches. Flood levels and discharges are calculated at alternating points along the river branches as a function of time. It operates on the basic information from the river and floodplain topography, including man-made features and boundary conditions.

Rainfall-Runoff/NAM module is based on physical structures and equations used together with semi-empirical ones. Being a lumped model, NAM treats each catchment as a single unit. The parameters and variables represent, therefore, average values for the entire catchment. As a result, some of the model parameters can be evaluated from the physical catchment data, but the final parameter estimation must be performed by calibration against the time series of the hydrological observations (DHI, 2008).

The model structure is shown in **Fig. 5**. It is an imitation of the land phase of the hydrological cycle. NAM simulates the rainfall-runoff process by continuously accounting for the water content in four different and mutually interrelated storages that represent different physical elements of the catchment. These storages are: snow storage, surface storage, lower or root zone storage and groundwater storage.

The RR module takes nine parameters and six initial condition values. The nine parameters were calculated according to the equations and guidance provided by DHI but later they were also subject to auto-calibration for further fine tuning (DHI, 2008).

Surface storage moisture intercepted on the vegetation as well as water trapped in depressions and in the uppermost, cultivated part of the ground is represented as surface storage. Umax denotes the upper limit of the amount of water in the surface storage. The amount of water, U, in the surface storage is continuously diminished by evaporative consumption as well as by horizontal leakage (interflow). When there is a maximum surface storage, some of the excess water, P_N, will enter the streams as overland flow, whereas the remainder is diverted as infiltration into the lower zone and groundwater storage.

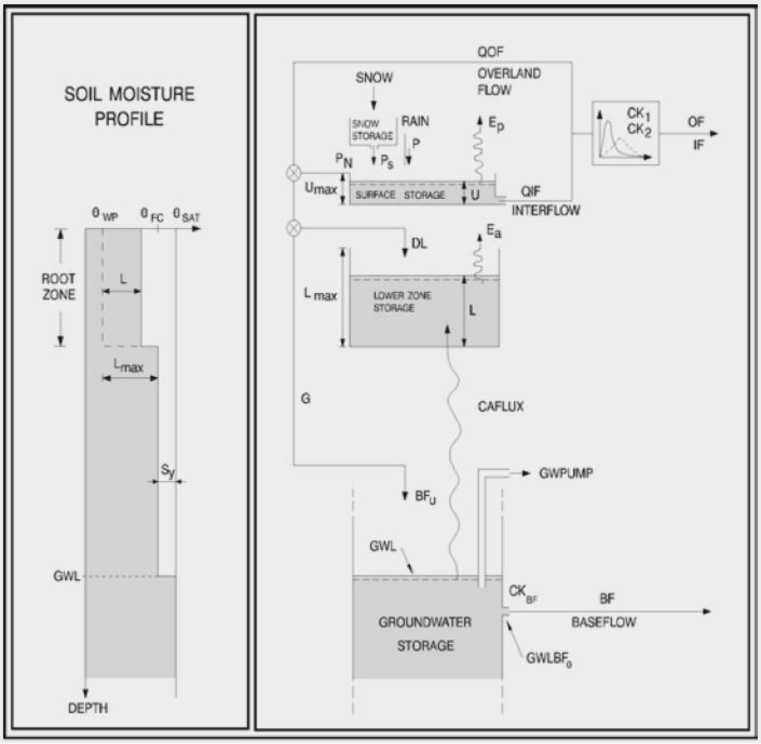

Fig. 5. *NAM Model scheme (DHI, 2008)*

The soil moisture in the root zone, L_{max}, a soil layer below the surface from which the vegetation can draw water for transpiration, is represented as lower zone storage. L_{max} denotes the upper limit of the amount of water in this storage. Moisture in the lower zone storage is subject to consumptive loss from transpiration. The moisture content controls the amount of water that enters the groundwater storage as recharge and the interflow and overland flow components.

Evapotranspiration demands, Ep, are first met at the potential rate from the surface storage. If the moisture content U in the surface storage is less than these requirements ($U < Ep$), the remaining fraction is assumed to be withdrawn by root activity from the lower zone storage at an actual rate Ea. Ea is proportional to the potential evapotranspiration and varies linearly with the relative soil moisture content, L/L_{max}, of the lower zone storage.

Overland flow, Q_{OF}, when the surface storage spills, i.e. when $U > U_{max}$, the excess water P_N gives rise to overland flow as well as to infiltration. Q_{OF} denotes the part of P_N that contributes to overland flow. It is assumed to be proportional to P_N and to vary linearly with the relative soil moisture content, L/L_{max}, of the lower zone storage. The proportion of the excess water PN that does not run off as overland flow infiltrates into the lower zone storage. A portion, ΔL, of the water available for infiltration, (P_N -Q_{OF}), is assumed to increase the moisture content L in the lower zone storage. The remaining amount of infiltrating moisture, G, is assumed to percolate deeper and recharge the groundwater storage.

Interflow contribution, Q_{IF}, is assumed to be proportional to U and to vary linearly with the relative moisture content of the lower zone storage.

Interflow and overland flow routing is routed through two linear reservoirs in series with the same time constant CK_{12}. The overland flow routing is also based on the linear reservoir concept but with a variable time constant.

Groundwater recharge – the amount of infiltrating water, G, recharging the groundwater storage depends on the soil moisture content in the root zone.

Soil moisture content, L – the lower zone storage represents the water content within the root zone. After apportioning the net rainfall between overland flow and infiltration to groundwater, the remainder of the net rainfall increases the moisture content L within the lower zone storage by the amount ΔL.

The baseflow, BF, from the groundwater storage is calculated as the outflow from a linear reservoir with a time constant CKBF.

In Mike11, RR-NAM, the auto-calibration can be run to optimize four ‘‘objective functions” (Madsen, 2000; Liu and Sun, 2010). Details of their theoretical justification and computational procedure are given by Madsen (Khu and Madsen, 2005).

The objective functions are as follows: agreement between the average simulated and observed catchment runoffs: overall volume error (%WBL), overall agreement of the shape of the hydrograph: overall root mean square error (RMSE), agreement of peak flows: average RMSE of peak flow events and agreement of low flows: average RMSE of low flow events.

In order to interpret model results and to evaluate the performance of the calibration and validation, in addition to the simple plot of simulated and observed flows (Qsim and Qobs, **Fig.6.**) and to the observed runoff over the simulated one, the following statistical indicators were considered: Mean Absolute Error (MAE), Percentage Bias (%BIAS) or water balance error (%WBL), Root Mean Square Error (RMSE), Relative Root Mean Square Error (RRMSE), Coefficient of determination (R^2) and Pearson Correlation Coefficient (PCC).

A calibration usually commences by adjusting the water balance in the system. The total evapotranspiration over a certain period should correspond to the difference between the accumulated net precipitations and the runoff. The evapotranspiration will increase together with the rise in the maximum water contents in the surface storage U_{max} and the root zone storage L_{max}, and vice versa. The peak runoff events are caused by large quantities of overland flow. The peak volume can be adjusted by changing the overland flow runoff coefficient (CQ_{OF}), whereas the shape of the peak depends on the time constant used in the runoff routing (CK_{12}).

Table 2. Final values of RR-NAM parameters

Parameter	**Value**
Catchment area km^2	6.44
Simulation periods – validation	2009-2011
Umax (mm)	30.5
Lmax (mm)	186
CQOF (–)	0.215
CKIF (h)	751
CK1,2 (h)	30.7
TOF (–)	0.511
TIF (–)	0.591
TG (–)	0.415
CKBF (h)	245

The amount of base flow is affected by the other runoff components: a decrease in overland flow or interflow will result in a higher baseflow and vice versa. The shape of the baseflow recession is a function of the base-flow time constant (CKBF). If the baseflow recession changes to a slower recession after a certain time, a lower groundwater reservoir should be added, including calibration of CQlow and CKlow. Initially, the root zone threshold values T_{OF}, T_{IF} and TG can be set to zero. After a first round of calibration of the parameters U_{max}, L_{max}, CQ_{OF}, CK_{12} and CK_{BF}, the threshold parameters can be adjusted for further refinement of the simulation results.

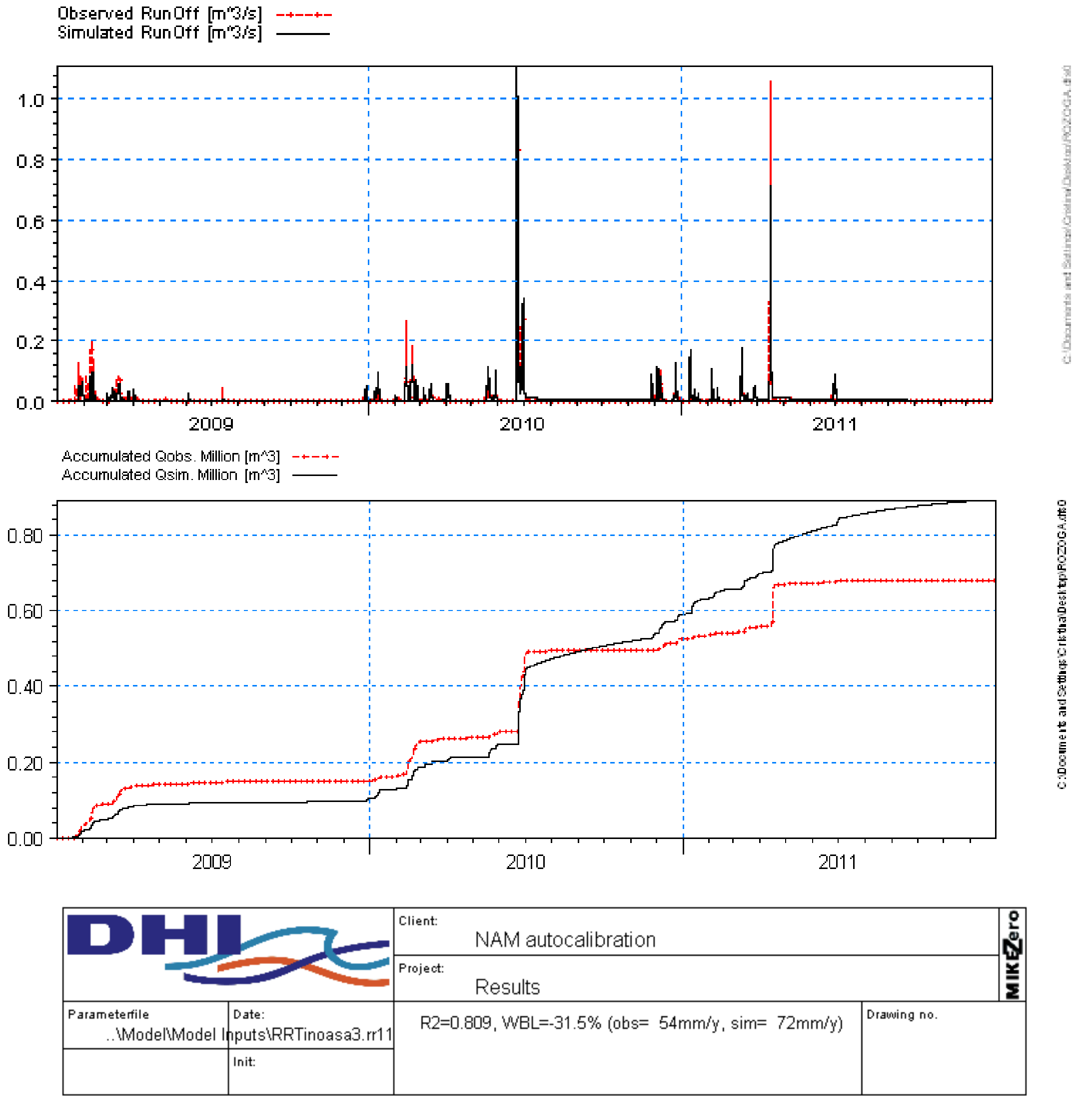

Fig.6. Auto-calibration results for Ciurea-Tinoasa basin

For individual calibration of the groundwater parameters GWLBF0 and SY, the simulated groundwater level is compared to the observed groundwater levels. The snow module parameters are calibrated against periods with snow-melt runoff.

The seasonal pattern is expected to change with significantly higher runoff during winter. The modelled change in the seasonal hydrological pattern is most pronounced in first or second-order streams draining loamy catchments, which currently have a low baseflow during the summer period. Reductions of 40-70% in summer runoff are predicted for this stream type (Andersen at al. 2006).

Mean absolute error (**MAE)** is a measure of average deviation, therefore the lower its value, the better is the prediction. In our case of study MAE.

Percentage bias **(%BIAS**) is frequently used in hydrology and represents the average of residuals as a fraction of the average flow. In general, lower values of %BIAS indicate a better model performance.

RMSE is a measure of the scatter of the residuals; in our case study RMSE is 0.020, a value of RMSE close to zero indicating a good model performance. **RRMSE** is equal to

RMSE value normalized by the mean value of Q_{obs} thereby giving sense to the scatter relative to the mean flow.

The coefficient of determination expresses the strength of association between two variables. $\mathbf{R^2} = 1$ indicates a perfectly positive relationship between two variables but it is not an automatic guarantor of a good simulation as it is insensitive to the additive and proportional differences between the observed and the predicted time series (Vazquez, 2009). In our case R^2=0.809, not including snow melt, the result being satisfactory.

As a result of the simulation, fig. 7 shows the evolution of the relative moisture content, Fig. 8 the evolution of the groundwater depth, Fig. 9. the interflow and Fig. 10 the surface storage overflow.

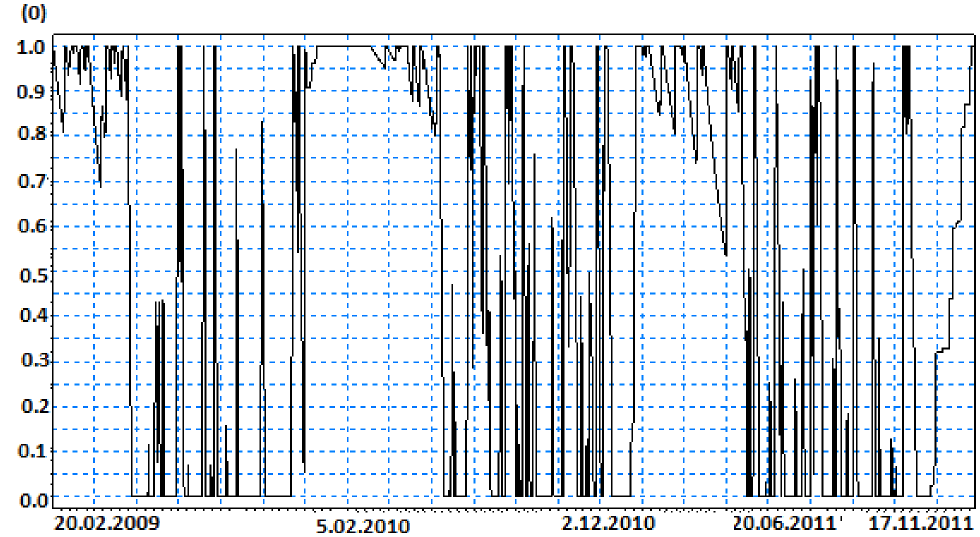

Fig.7. *Simulated time series of relative moisture content*

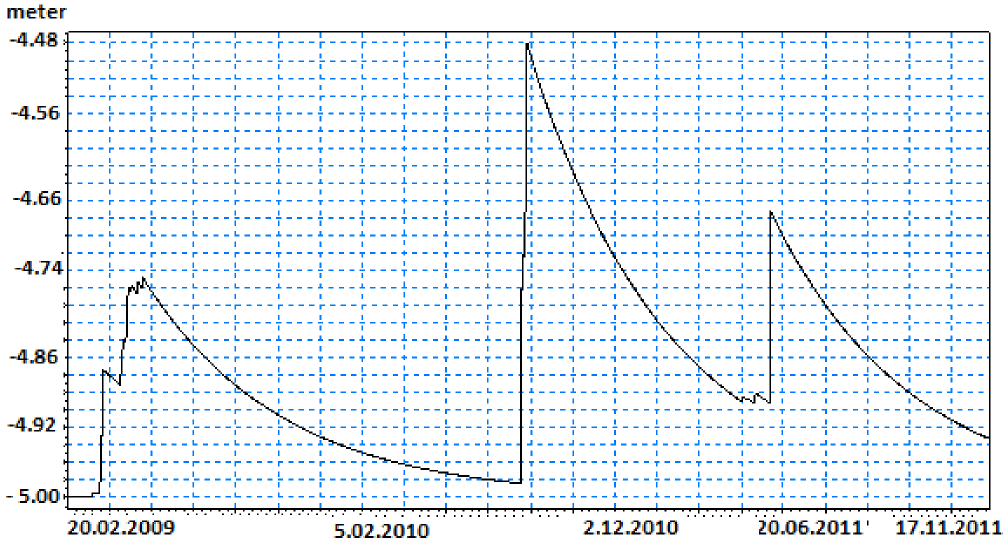

Fig.8. *Simulated time series of groundwater depth between 2009-2011*

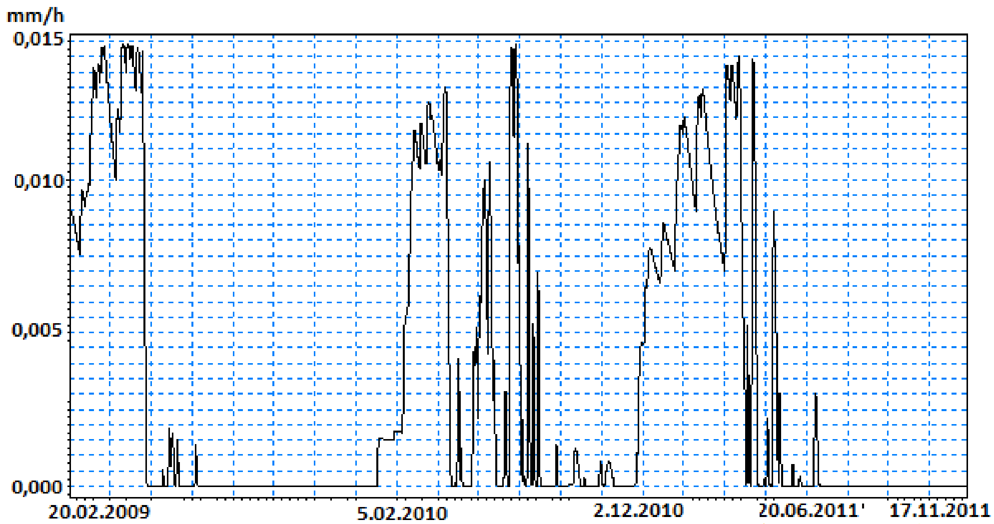

Fig.9. Simulated time series of the interflow

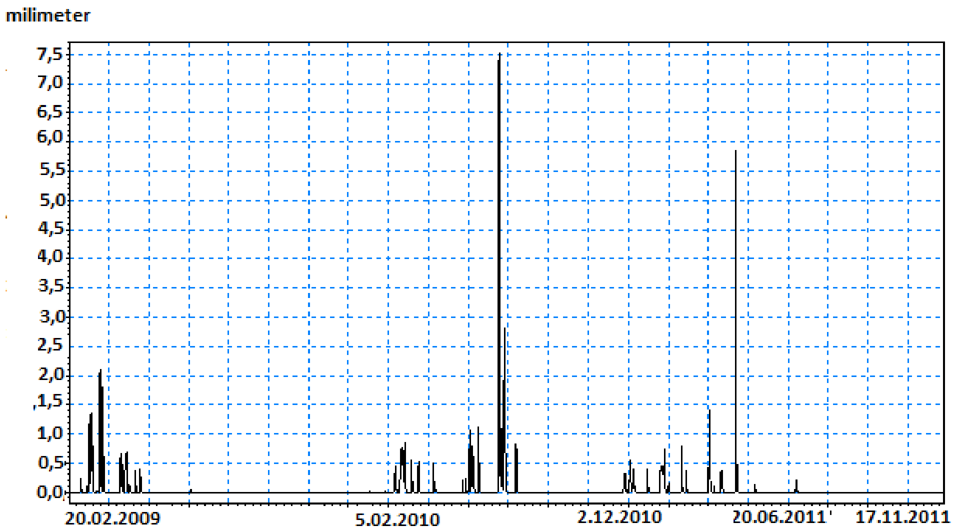

Fig.10. Simulated time series of the surface storage overflow

4. Conclusions

By coupling two models (Mike 11-HD and Mike11-RR) we obtained the groundwater response to overland flow and topography. The result includes estimated parameters such as infiltration, ground water depth, recharge, capillary flux and runoff. Taking in consideration the conceptualization of the flow system and the accuracy required in the basin which was analyzed, the choice of the methods that we used in order to reliably estimate the recharge of the groundwater is satisfactory. The methodology used allows a rapid and comprehensive determination of recharge, which is important to estimate both the available water resources and the groundwater vulnerability.

The indicators and parameters resulted from the model calibration are ranged between admissible errors, a fact that is confirmed by the model validation. Due to this confirmation, the rate of confidence and performance of the model regarding its utility in other hydrographical basins is increasing.

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