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A Comparative Study of Conceptual Rainfall-runoff Models using Different Number of Parameters and Time Steps: Application to Plastiras Lake River basin in Thessaly (Greece)

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Abstract

In this work, via Med basin software, two different conceptual rainfall-runoff models were used i.e. a monthly time step modified simple water balance model (Medbasin-M) comprising three calibration parameters and a daily time step (Med basin-D) comprising 14 parameters. As study area was selected the mountainous Plasters lake river basin in Thessaly of a total area of 166 km2. Rainfall and potential evapotranspiration data were used as input to both models. Additionally, measured runoff values were available for performing calibration and validation stages. As calibration period for both models was chosen from October 2012 to September 2017 and as validation period from October 2017 to September 2019. The Medbasin-M with the three parameters was proved that performs satisfactorily (e.g. NSE equals 0.57 for calibration and 0.52 for validation period). Moreover, Med basin-D gave clearly better results: 1. for the simulated daily runoff (NSE 0.73 and 0.69 for calibration and validation periods respectively) 2. for the simulated monthly runoff (NSE equals 0.9 for calibration and 0.77 for validation period). In addition, a sensitivity analysis was carried out in each case, for indicating which parameters influence the most models output.

Keywords: Rainfall-runoff Models, Calibration, Validation, Sensitivity Analysis

Introduction

Modeling the dynamic rainfall-runoff relationship is one of those fields of hydrology that has been studied most because of its key applications in water resources management. Hydrological models are described by all those mathematic transformations that use field data such as hydrological and geomorphological, as well as reasonable assumptions about the hydrological cycle and its mechanisms, so as to represent hydrological processes at an appropriate spatial and temporal scale [1].

Spatial scale, temporal discretion, stochastic or not, structure of variables and the degree of approximation of physical processes are those criteria that define the categories of the hydrological (rainfall-runoff) models. On the other hand, the structure of a model is what determines the way of runoff calculation. One of the most popular categories of rainfall- runoff models is that comprising the conceptual models, based on empirical parametric relationships describing the different runoff components. Some of them are easy to use with a few parameters, while others require a large number of interrelated ones [2, 1]. In general, the equations incorporated in the conceptual models are variants of the water balance equation and contribute to control surface water fluctuations and their storage [3].

In the present study, Med basin software has been used [4]. It incorporates two different conceptual rainfall-runoff models: (i) a monthly time step simple water balance model (Med basin-M) comprising three calibration parameters and (ii) a daily time step (Medbasin-D) comprising fourteen calibration parameters. Both models are adapted on simulating runoff in a Mediterranean environment, with precipitation and potential evapotranspiration being the main data entrance [5].

Theory

Medbasin-M

In this model, the upper soil zone is considered as a “storage reservoir" of water with total soil storage capacity Smax. According to Figure 1, the variable Si (mm) represents the soil moisture in this “reservoir” for any month i. The monthly soil moisture deficit in the river basin is defined by the Smax-Si difference, on average. To this reservoir is added the monthly precipitation Pi and the monthly potential evapotranspiration PETi is abstracted. In the event that the water quantity exceeds the total soil storage capacity Smax, it is divided into two parts with the first being the direct runoff Ri and the second the deep percolation losses Di (Fig. 1) [5].

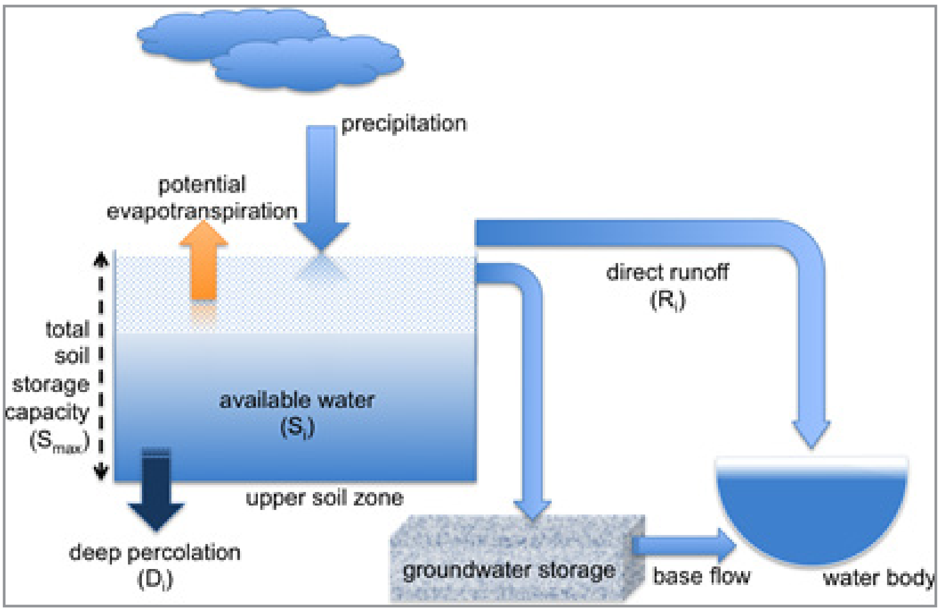


Figure 1: Schematic Representation of the Medbasin-M Model.

As a first step, a trial depth of the soil moisture Si' is computed by [1]:

$$S_i' = S_{i-1} + P_i - E_i \text{ (mm)} \quad (1)$$

where:
S_{i-1}: soil moisture for the month i-1 (mm)
P_i: precipitation for the month i (mm)
E_i: potential evapotranspiration for the month i (mm)

Monthly direct runoff Ri (excess water) depends on the value of S_i' (Eq.1). Thus: If $S_i' > S_{max}$

$$R_i = (S_i' - S_{max}) \cdot K' \quad (2)$$

$$D_i = (Si' - S_{max}) \cdot K \quad (3)$$

$$S_i = S_{max} \quad (4)$$

where:
$K' = 1 – K$
D_i: deep percolation losses for the month i (mm)
K: separation parameter ($0 \leq K \leq 1$) If $0 \leq S_i' \leq S_{max}$

$$R_i = 0 \quad (5)$$

$$S_i = Si' \quad (6)$$

$$D_i = 0 \quad (7)$$

If $S_i' < 0$

$$R_i = 0 \quad (8)$$

$$S_i = 0 \quad (9)$$

$$D_i = 0 \quad (10)$$

Runoff calculated from the above described model is mainly concentrated in the winter months, because the model does not consider the groundwater storage. In order to overcome this disadvantage, the following equation is proposed:

$$Q_i = a \cdot R_i + (1-a) \cdot Q_{i-1} \quad (11)$$

where *Qi* is a second, more accurate, approximation of the runoff Ri and 'a' is the lag parameter ($0 < a \leq 1$). This parameter expresses the delay of rainfall's conversion to runoff. Values close to 0 correspond to a long delay and as a result, runoff is transposed to spring and summer months, whereas values close to 1, correspond to an instant response of the river basin and thus, instant runoff formation.

Medbasin-D

Medbain-D is based on the MERO model developed in the late 1960s with application in river basins of the island of Cyprus [6]. Also, regarding the Medbasin-D model, a modified version was used which was applied by Giakoumakis et al. in river basins of Aegean islands [7]. Subsequently, the model was reinforced with additional tools, such as those of shaping climate change, drought and water resources scenarios, and incorporated calibration capabilities with alternative optimization algorithms [5].

The data entered in the model are the daily precipitation and the daily potential evapotranspiration. The structure of the model is based on the separation of the surface and subsurface soil system into storage zones in which all those processes that determine the path of the runoff take place. Figure 2 shows a simplified schematic representation of the processes performed in the Medbasin-D model.

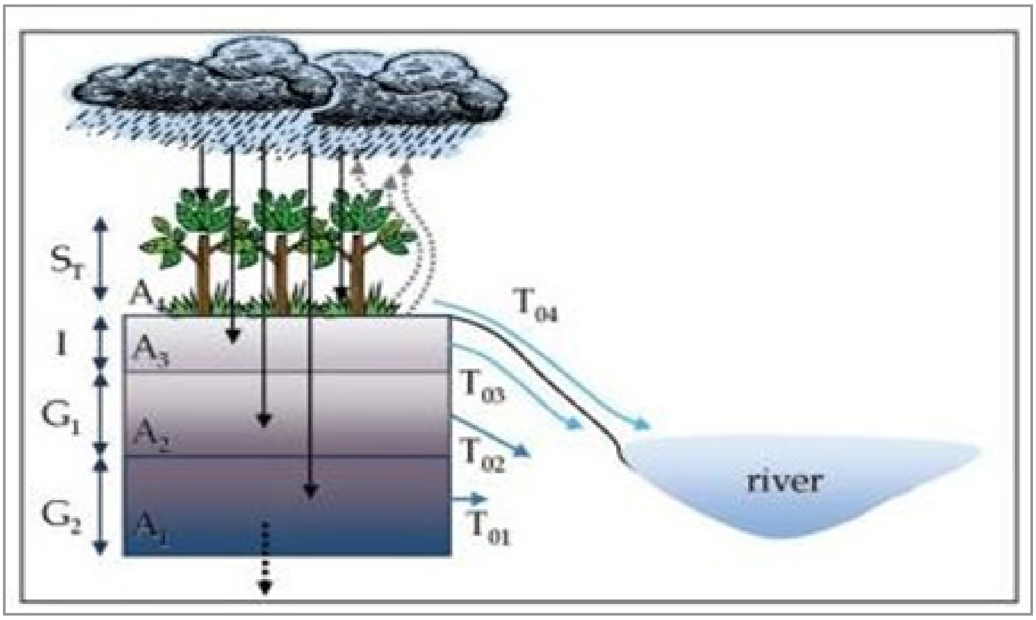


Figure 2: Simplified schematic representation of the processes performed in the Medbasin-D model

In this Figure is illustrated that the daily river runoff is the sum of the runoff from four different "reservoirs", i.e. it is composed of overland flow ST, interflow I, G1 the flow from the temporary storage reservoir and G2 the flow from the underlying permanent storage resercoir (temporary and permanent spring reservoirs) respectively, which in some way correspond to the so-called base river flow. Parameters A1, A2, A3, A4 represent the surfaces in the water intake basin for each "reservoir", while T01, T02, T03 and T04 are delay coefficients that determine the outflow from the "reservoirs". Usually their values range up to 24 hours for the overland flow (T04), 2 to 8 days for the interflow (T03), from 8 to 50 days for the temporary spring reservoir (T02) and 50 to 250 days for the permanent spring reservoir (T01) [7]. Parameters A_1, A_2, A_3, A_4 and T01, T02, T03, T04 are determined via the model calibration process.

The two basic water storage zones defined in the Medbasin-D model are interconnected and are distinguished in the interception system (U) due to vegetation etc., above the ground surface, and the ground water storage system (L). The upper soil zone is considered to cover the area of the root zone where the stored soil moisture L1 can reach a maximum value known as soil field capacity (Field Capacity-LFC). The underlying lower zone with stored soil moisture L2 receives the excess moisture of the upper soil zone, when its value exceeds that of LFC. The maximum value of the interception storage (Umax), the maximum soil moisture Lmax (maximum sum of L1 and L2), as well as the soil field capacity LFC are not derived from field measurements, but their values are determined during the calibration process of the model, in order to achieve the best possible adjustment to the observed values of the daily runoff.

The outflow functions from the respective "reservoirs", which give the sum of the individual components of the daily runoff, were based on data from Cyprus and are as follows [6, 4]:

Overland flow ST (mm)

$$ST = (-0.32 + 0.071 * P_N + 0.05 * (PRST - 0.5) - Q_0) * CT \quad (12)$$

if $P_N \leq 10\ mm$

$$ST = (-0.45 + 0.06 * P_N + 0.0025 * P_N^2 - 0.00001 * P_N^3 + 0.25 * (P_N - 8) * (PRST - 0.5) - Q_0) * CT \quad (13)$$

if $P_N > 10\ mm$

$$ST = (1.43 - 0.039 * P_N + 0.0032 * P_N^2 - 0.000003 * P_N^3 + 0.25 * (P_N - 8) * (PRST - 0.5) - Q_0) * CT \quad (14)$$

if $P_N > 40\ mm$

where PN net precipitation, PRST = (L1+L2) / Lmax is the ratio of the sum of the soil moisture of both zones to the maximum soil moisture Lmax, while Q0 and CT are calibration parameters. Initially, they were taken constants with values of 0.05 and 0.4, respectively [6].

Inter flow I (mm)

$$I = (P_N - ST)(0.01 + 0.05\ PRST) \quad (15)$$

For the base (underground) flow (temporary and permanent spring reservoirs) the following applies:

$$G = CL_2 * \ L_2^2/(L_{max} - L_{FC}) \quad (16)$$

where CL2 is the groundwater flow control parameter (derived from the model calibration) with a value range from 0.001 to 0.1 and L2 is the stored soil moisture in the lower soil zone.

The four "reservoirs" release water that is added to the daily runoff using the multiplication coefficients of delay: F = 1-exp (-1 / T0i), i = 1,2,3,4. For eqns (12), (13) and (14) i = 4, for eqn

(15) i = 3 and for eqn (16) i = 2 and 1 for the quantities G1 and G2, respectively (Fig. 2).

The difference of daily precipitation (P) from the corresponding potential evapotranspiration (Ep) is the initial input to the model, primarly reduced by the U-storage. The amount of precipitation remaining is the net precipitation PN. If the value of the latter is negative, it is deducted as actual evapotranspiration (Ea). Otherwise the overland flow ST is calculated from either eqn 12 or 13 or 14. If PN remains positive after abstraction of ST, the interflow I is also calculated (eqn 15). If PN remains positive after abstraction of I, it is added as soil moisture L1, first to the upper soil zone and then as soil moisture L2 to the underlying soil zone. Otherwise it is removed first from L1 and then from L2 as actual evapotranspiration (Ea) based on the ratio: Ea / Ep = PRST. If L1 + L2-Lmax positive (PRST> 1) the temporary and permanent underground "reservoirs" (temporary and permanent spring reservoirs, respectively) are fed directly, otherwise if PRST <1, through the outflow eqn (16).

Evaluation Criteria

The efficiency of each simulation performed, was checked by the well-known NSE coefficient, given from the following equation [8]:

$$NSE = \{\sum(y_{oi}-\tilde{y}_o)^2 - \sum(y_{oi}-y_{ci})^2\} / \sum(y_{oi}-\tilde{y}_o)^2 \qquad (17)$$

where:
y_{oi}: observed runoff for the month or day i (mm)
$\tilde{y}_o$: mean value of observed runoff (mm)
y_{ci}: calculated runoff for the month or day i (mm)

Study Area

The Plastiras lake in central Greece (Thessaly district) was formed after the construction of an arched concrete dam in 1959. The upstream of the dam site river basin (Tavropos river) is the north east part of the Acheloos river basin and has an area of 166.2 km2(Fig. 3). Its west border is defined by the mountains of Agrafa, from where the main streams feeding the lake originate, i.e. Megalo Potami, Kerasiotis and Karytsiotis. The mean altitude of the river basin was estimated as equal as 1382 m. The mean annual precipitation reaches 1386.3 mm (Plastiras dam rain gauge station with reference to the mean altitude of the river basin- precipitation gradient 30 mm/100 m), [9].

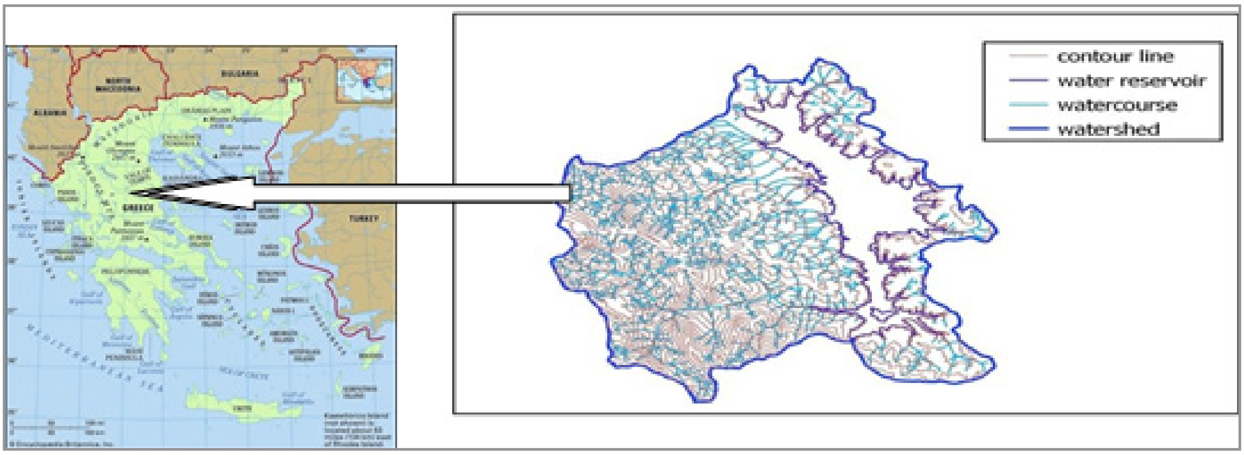


Figure 3: Plastiras lake River Basin

The direct annual runoff of the Tavropos river upstream the Plastiras dam site amounts to 147 hm3, demonstrating the rich surface water potential of the river basin. Mean annual evaporation losses from the reservoir were estimated via Penman's method, as equal as 1068 mm [9].

Theoretically, the lowest level for water withdrawal of Plastiras reservoir is at the altitude of 776 m (dead volume). The total capacity of the reservoir at 792 m (upper storage level) reaches 361.8 hm3, whereas its dead volume equals 75.5 hm3 [10]. As a result, the total active capacity of the reservoir equals 286.3 hm3. Withdrawal of water is mainly performed for irrigation purposes after a hydroelectric power station (HPS) is fed from the reservoir through a tunnel of 3.5 m diameter (altitude difference between reservoir's surface and HPS or total height of fall being 577 m, the greatest in Greece).

After leaving the hydroelectric power station (HPS), (three units Pelton of a total installed power of 130 MW), the water from the turbines is stored in a regulatory reservoir near Mitropolis village with a capacity of 600,000 m3(Fig. 4).

Figure 4: HPS and Regulatory Reservoir in the Area

Then a quantity is directed to the water refineries of the neighbouring city of Karditsa and the rest to the main irrigation canal of the collective surface irrigation network of the area. It is estimated that the mean annual outflow from the Plastiras reservoir averages 160 hm3, of which 145 hm3 are used for irrigation of 21,500 hectares of agricultural land in the plain of Thessaly (13,000 ha belongs to Karditsa district and 8,500 ha to Larissa district), while 15 hm3are used to meet the water supply needs of the city of Karditsa [9].

Results and Discussion

Runoff Simulation and Evaluation

Monthly and daily data of a 7 hydrologic year time period, i.e. from 2012-13 to 2018-19 (precipitation, potential evapotranspiration and measured runoff values) were available. Precipitation and temperature data were taken from the Plastiras dam rain gauge station (altitude 801 m a.s.l.) Potential evapotranspiration was calculated via Thornthwaite's method (mean annual value 635 mm for the time period considered) [9]. For the calibration of Medbasin-M and Medbasin-D models, data of the first 5 hydrologic years were used, whereas the validation was performed using data from the subsequent 2 hydrologic years. The calibration procedure was carried out by applying a trial and error approach [4, 1].

In Tables 1 and 2 are presented the optimum sets of values of the parameters of the Medbasin-M and Medabsin-D models respectively, determined during calibration.

Table 1: Optimum Set of Values of Parameters (Medbasin-M)

Parameter	Value
a	0,90
K	0,56
S_{max} (mm)	100

Table 2: Optimum Set of Values of Parameters (Medbasin-D)

Parameter	Plastiras
Umax (mm)	5
Lmax (mm)	160
LFC (mm)	115
T01 (days)	40
T02 (days)	24
T03 (days)	1.5
T04 (days)	0.2
A1 (km2)	55
A2 (km2)	85
A3 (km2)	130
A4 (km2)	141.2
CT	1
Qo	0
CL2	0.01

NSE values, for both calibration and validation periods, for the Medbasin-M and Medbasin-D models, are summarized in Table 3.

Table 3: NSE for Calibration and Validation Periods for Medbasin-M and Medbasin-D

Model	NSE	
	C	V
Medbasin-M	0.57	0.52
Medbasin-D (daily runnoff values)	0.72	0.69
Medbasin-D (monthly runoff values)	0.90	0.77

The monthly runoff simulation results using Medbasin-M and Medbasin-D are presented in Figure 5. Moreover, the daily runoff simulation results using Medbasin-D are illustrated in Figure 6.

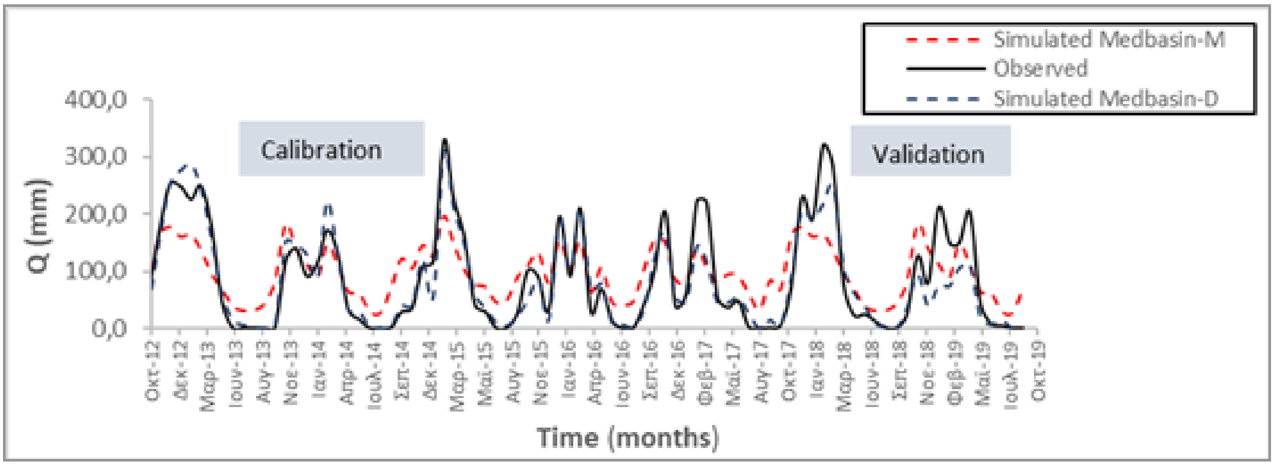


Figure 5: Monthly Measured and Simulated runoff for Calibration and Validation Periods (Medbasin-M and Medbasin-D).

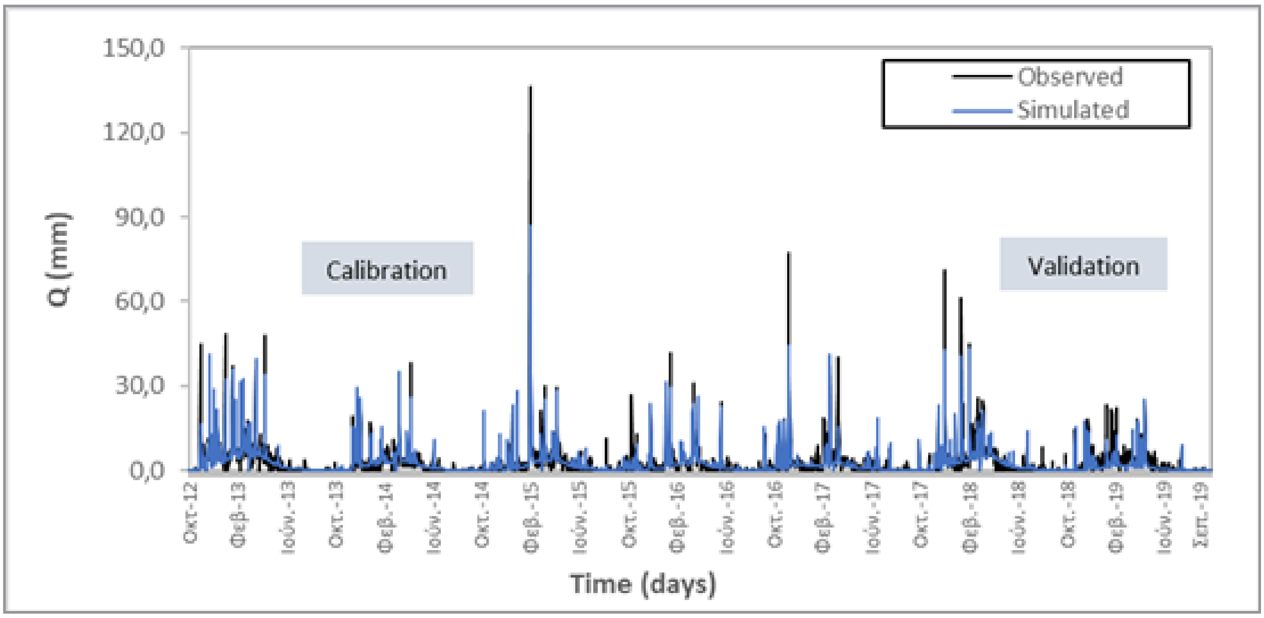


Figure 6: Daily Measured and Simulated Runoff for Calibration and Validation Periods (Medbasin-D).

The results obtained showed a satisfactory simulation of the monthly runoff from Medbasin- M model, with the quality control criterion of the simulation NSE being equal to 0.57 for the calibration and 0.52 for the validation periods (Table 3 and Figure 5).

The corresponding values of the NSE for the estimated monthly runoff from the daily Medbasin-D model were as equal as 0.9 and 0.77, respectively, which means that this model is clearly performing better than the monthly one for the monthly runoff values (Table 3 and Figure 5). The simulation of the daily runoff values by the Medbasin-D model was quite satisfactory too, with the NSE being estimated at 0.73 and 0.69 for the calibration and validation periods respectively (Table 3 and Figure 6). The better simulation quality for the monthly runoff values from the Medbasin-D model is explained by the fact that the extreme (maximum) values due to storms of the daily measured runoff are not approached as satisfactorily as the monthly values (i.e. the sum of the daily simulated values for each month, with the differences between measured and simulated runoff being so significantly reduced).

Sensitivity Analysis

A number of trial simulations was carried out using Medbasin-M and Medbasin- D models. For each trial, one among the three parameters of the Medbasin-M and one among the fourteen parameters of the Medbasin-D was changed, whereas the others were kept constant, according to the optimal values referred in Tables 1 and 2, respectively.

For the Medbasin-M, sensitivity analysis results indicate that model's performance is almost insensitive to the variation of the parameter Smax. On the contrary, the parameter K seems to affect the most simulation results, while the parameter a has also a considerable effect on the performance of the model (Fig. 7). For the Medbasin-D, it appears that the parameters LFC - soil field capacity, Lmax - maximum soil moisture and CL2 - groundwater flow control parameter, out of a total of fourteen calibration parameters, influence the most model's output (Fig. 8).

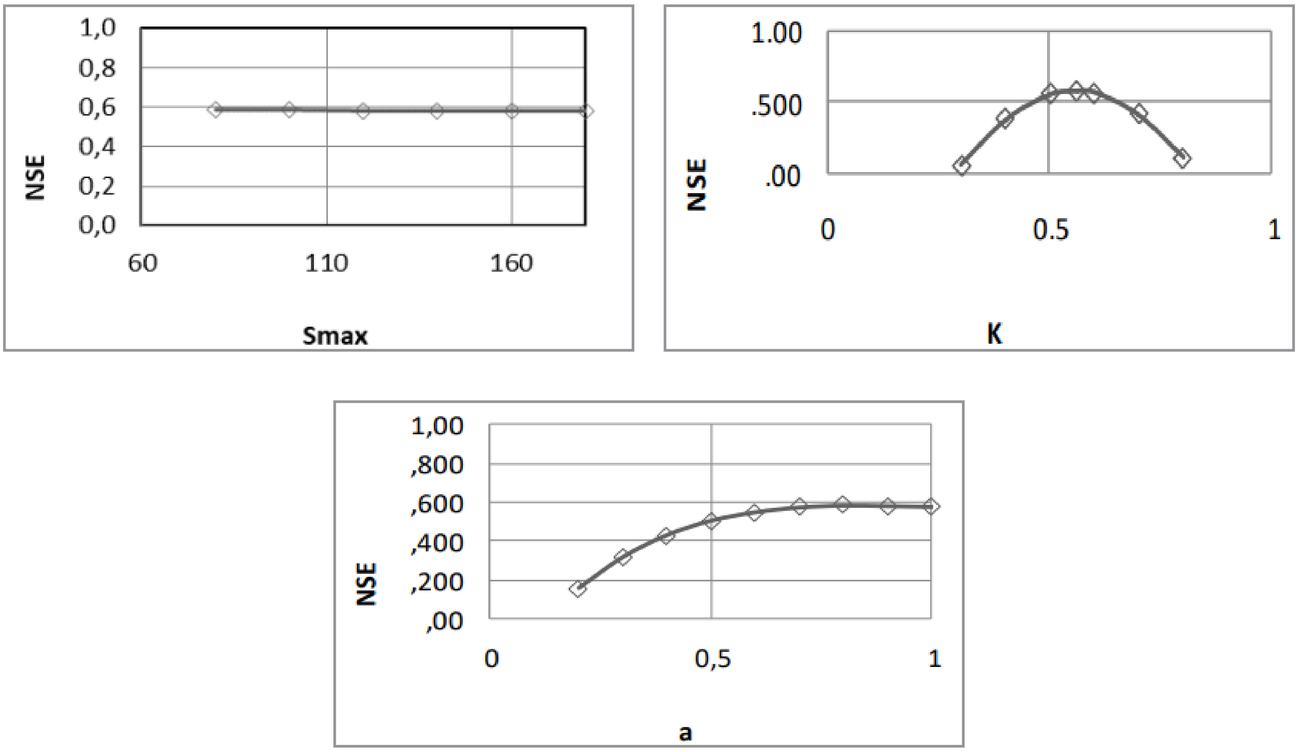
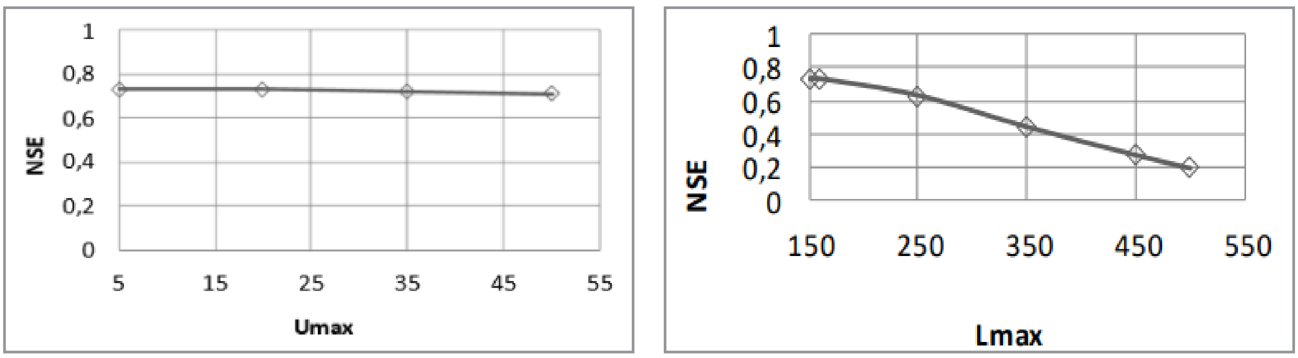
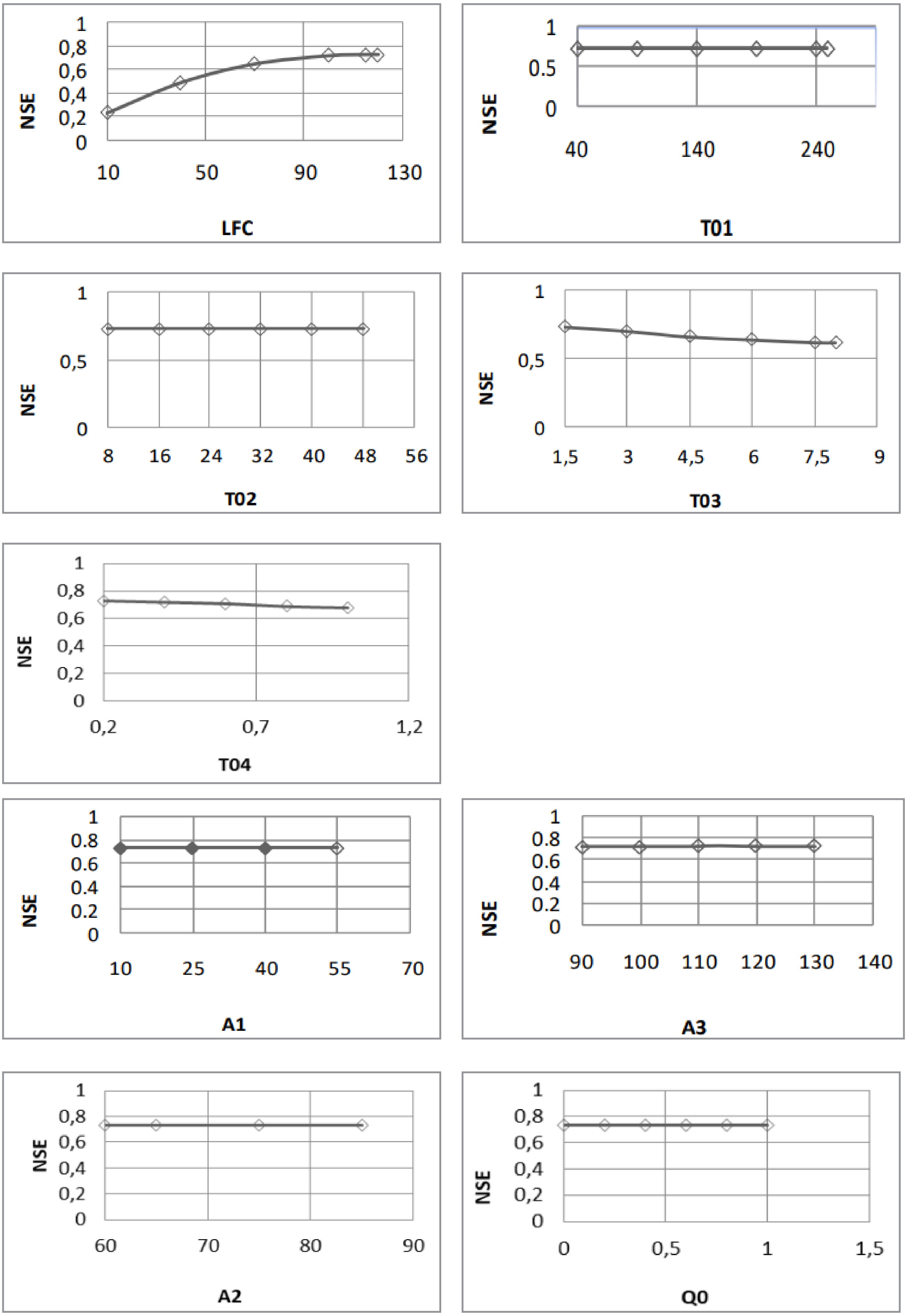


Figure 7: Variation of NSE as a Function of the Parameters of the Medbasin-M.




NSE
1
0,8
0,6
0,4
0,2
0
10
50
90
130
LFC
NSE
1
0.5
0
40
140
240
T01
NSE
1
0,5
0
8
16
24
32
40
48
56
T02
NSE
1
0,5
0
1,5
3
4,5
6
7,5
9
T03
NSE
1
0,8
0,6
0,4
0,2
0
0,2
0,7
1,2
T04
NSE
1
0.8
0.6
0.4
0.2
0
10
25
40
55
70
A1
NSE
1
0.8
0.6
0.4
0.2
0
90
100
110
120
130
140
A3
NSE
1
0,8
0,6
0,4
0,2
0
60
70
80
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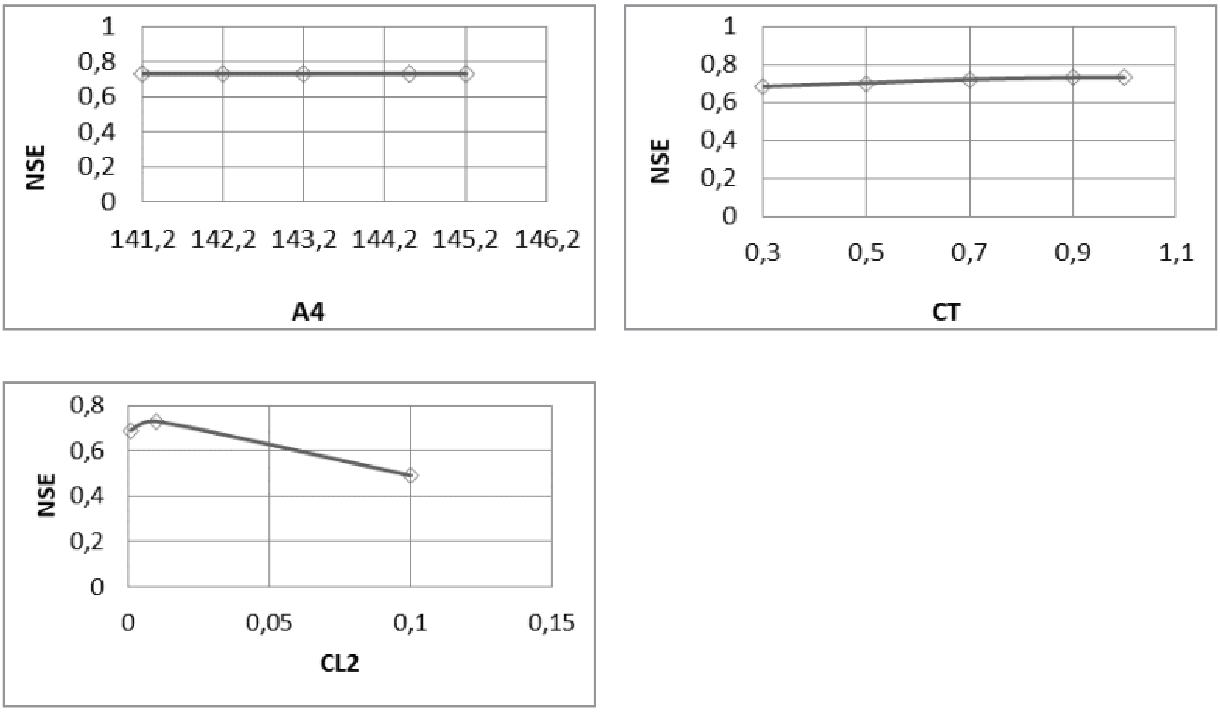

Figure 8: Variation of NSE as a function of the parameters of the Medbasin-D.

Concluding Remarks

From the present study the following can be concluded:

- Via Medbasin software two different rainfall-runoff models were used, performing simulations with data from Plastiras lake river basin in Thessaly (Greece). For both models five hydrologic years calibration and two years validation periods were considered. The monthly time step model (Medbasin-M) comprises three calibration parameters whereas the daily time step model (Medbasin-D) fourteen.
- The Medbasin-M was proved that performs satisfactorily (e.g NSE equals 0.57 for calibration and 0.52 for validation periods), while Medbasin-D gave clearly better results for the simulated monthly runoff values (e.g NSE equals 0.9 for calibration and 0.77 for validation periods). For the simulated daily runoff its performance was quite satisfactory too (e.g. NSE 0.73 and 0.69 for calibration and validation periods, respectively).
- From the sensitivity analysis on both models, the following were concluded: 1. The separation parameter K for Medbasin-M and 2. The Lmax, LFC and CL2, maximum soil moisture, soil field capacity and parameter controlling flow to the spring reservoirs, respectively for Medbasin-D, turned out to influence the most models output.

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