DEVELOPMENT OF A SEMI-DISTRIBUTED HYDROLOGICAL MODEL TOOLBOX TO PREDICT RUNOFF RESPONSE IN THE UNGAUGED CATCHMENT OF MORNOS, GREECE

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ABSTRACT

Prediction of runoff response in ungauged catchments has been one of the key issues in water science. Despite the considerable effort the hydrologic community has devoted over the past decade, there is still need to develop robust frameworks capable of representing the dynamic behaviours of catchment processes (e.g. streamflow). Runoff prediction has been particularly challenging in the poorly- or usually un-gauged Greek catchments, whereas predictions are subject to significant uncertainty due to erroneous and/or limited available data. The Athens Water Supply and Sewerage Company (EYDAP SA) has funded a project to measure, and simulate the hydrological fluxes (e.g. rainfall, snowfall, streamflow, evaporation) of the 560 km² Mornos catchment, Greece, that supplies the metropolitan area of Athens with fresh water. In this study, we present the Mornos Water Balance Model Toolbox (MWBMT) recently developed to simulate the hydrological processes in the catchment. Moreover, we improve the model performance by assimilating information provided by EYDAP SA (i.e. monthly runoff contribution and water level at the reservoir). The rainfall–runoff model structures are based on the Soil Conservation Service Curve Number (SCS-CN) method, whereas topographical, geological and land use information is used to complement parameter identification. In addition, a simple water balance equation is used to estimate the change in the reservoir’s storage. The analysis is based on daily data from the available 15-month period to drive the original SCS-CN model aiming to support the reservoir’s water management. Finally, we present the sources of error/uncertainty causing poor model performance over different time periods and point towards ways for improvement.

Keywords: Rainfall-runoff models, ungauged catchments, semi-distributed modelling, SCS-CN, Mornos reservoir, MWBMT

1. INTRODUCTION

In the previous and current decade, the hydrological community has devoted substantial attention on ungauged and poorly gauged catchments, since streamflow prediction at these systems is highly uncertain yet it represents the majority of practical applications (Pechlivanidis et al., 2011). Several initiatives (i.e. the Prediction in Ungauged Basins; Sivapalan, 2003) focused on, among others, imprecisely observed data, inaccuracies in catchment characteristics, imperfect model structures and parameter values, and uncertainty in model predictions. As a result, several methods have been developed to characterise the effects of heterogeneity, improve process understanding and provide access to new data resources, with the goal to describe the water processes everywhere.

Current methods to predict runoff generation in ungauged catchments are based on statistical regionalisation approaches that relate flow properties or model parameters to
physical and hydro-climatic descriptors of a catchment (Wagener and Wheater, 2006; Pechlivanidis et al., 2010). Other methods aim to constrain the parameter space by estimating the dependence of response indices (statistical properties of discharge) using physical characteristics (Bulygina et al., 2011). These methods have been successfully tested in well gauged catchment areas around the world, characterised by the availability of long periods of data; however their potential has drawn little attention when limited physical and data information is available. Empirical models based on the unit hydrograph theory have also been used to predict the catchment response (Melendi et al., 2011). The simplicity of such models has allowed them to be applied relatively easily to ungauged catchments.

One of the methods that have been widely used for the estimation of direct runoff from storm rainfall is the Soil Conservation Service Curve Number (SCS-CN) method (US SCS, 1972). SCS-CN requires no or limited calibration since model parameters are related to topographic, soil and land use properties (Jain et al., 2006, Soulis and Valiantzas, 2012). Due to the low input data requirements, the method has been incorporated in many widely used hydrological models (e.g. SWAT and HEC-HMS). Baltas et al. (2007) states the advantages of the SCS-CN method: i) simplicity, ii) stability, iii) predictability, iv) reliance on only few parameters, and v) responsiveness to major runoff-producing catchment properties (soil type, land use, surface condition, and antecedent conditions). These SCS-CN rainfall-runoff models have therefore a great potential in Greek catchments since discharge records are not always available and/or the period of record is often short for precise estimation of highly parameterised models. On the other hand, Soulis et al. (2009) states the weak points of the method: i) the impact of rainfall intensity and its temporal distribution is not considered, ii) the effects of spatial scale are not addressed, iii) high sensitivity to changes in values of its sole parameter, CN, and iv) the effect of antecedent moisture conditions is not clearly addressed.

This study is inspired by a recent project funded by the Athens Water Supply and Sewerage Company (EYDAP SA) to measure and simulate hydrological fluxes (e.g. rainfall, snowfall, streamflow, evaporation) in the 560 km² Mornos catchment, Greece, which supplies the metropolitan area of Athens with fresh water. In this paper, we present and apply our recently developed rainfall-runoff toolbox (Mornos Water Balance Model Toolbox - MWBMT) which is based on the SCS-CN method to simulate the hydrological response of the poorly gauged Mornos catchment and further estimate the water budget in the natural reservoir. Section 2 introduces the study area and data used. The development of the rainfall-runoff model is introduced in Section 3. Section 4 presents the results, and finally Section 5 states the conclusions.

2. STUDY AREA AND DATA

The 560 km² catchment of Mornos is located in the Western part of Central Greece and belongs to the county of Fokida (Fig. 1). The catchment (most downstream point is the dam location) has an average altitude of 1082 m (altitude varies between 443 and 2489 m). The average annual rainfall and streamflow are 950 mm (snow occurs at higher elevation which is unknown) and 235 million m³ respectively. The reservoir can store water up to about 780 million m³. Areas at high elevation receive snow during winter (snow accumulation) and dispose this amount of water in early spring (snow melting). The two main tributaries of the area are: the 267 km² upper Mornos and the 95 km² Kokkinos subcatchments.

In December 2011, the National Observatory of Athens (NOA) installed 4 weather stations, 2 snowgauges and 2 water level gauges (at Kokkinos and Lefkaditis) over the catchment. Data from a third water level gauge at an upstream point of Mornos river operated by the Athens Water Supply and Sewerage Company (Upper Mornos) have
also been collected and integrated in the dataset (Fig. 1). The water level gauges measure the water depth at the Kokkinos and Mornos subcatchments, whereas the Upper Mornos water level gauge measures water depth at an upstream location to the one NOA installed (Fig. 2). The weather stations measure several meteorological variables (rainfall, humidity, pressure, temperature etc.) at a 10 minute temporal resolution; however for our objectives, we have aggregated the data at daily time steps. The arithmetic average was used to estimate the mean areal precipitation. As expected, several challenges have to be dealt with prior to any hydrologic analysis (i.e. erroneous series, gauge malfunctioning, noise, uncertain rating curves; see Fig. 2). Although some poor quality data had to be corrected (i.e. correction of water level based on temperature), it is important that every sources of error/uncertainty is taken into consideration when analysis results.

**Figure 1.** The catchment of Mornos, Greece.

A 30x30 m² Digital Elevation Model (DEM; source was ASTER GDEM) was used to identify the areas that contribute to the locations of our flowgauges. Land use data were downloaded from the CORINE Land Cover 2000 database. The land use categories include permanent crops, forest, shrubs and the water bodies (reservoir and rivers). A hydrogeological map of a 1:50000 scale was also used to define hydrological soil groups, depending on soil texture and permeability.

**Figure 2.** (a) Mean areal rainfall and water levels (10 min) at Kokkinos, Upper Mornos and Lefkaditis stations during 15/12/2011 - 28/02/2013, and (b) generated rating curves.
3. MATERIAL AND METHODS

3.1. The semi-distributed Mornos Water Balance Model Toolbox

The MWBMT has been primarily developed to estimate continuous streamflow at (ungauged or poorly gauged) points along the river system in the Mornos catchment. However, it is important to note that the toolbox was not developed to replace existing hydrological models, but rather to complement, since MWBMT is parsimonious and allows quick setups and evaluations of semi-distributed SCS-CN models. Currently, three SCS-CN based models of various sophistication and complexity are available: the original SCS-CN method (US SCS, 1972), the simplified SAHU model (Sahu et al., 2010), and the Mishra-Singh model (Mishra and Singh, 2004). The catchment is delineated into a network of subunits (61 subunits in this study) and the model is applied (as a lumped structure) to each subunit. Routing of surface runoff to the catchment outlet is also calculated. Topologically, MWBMT simulates streamflow for the uppermost stream subunits first and accumulates the flow down the channel network. Each subunit is considered as lumped, with the hydrological processes and meteorologically forcing data homogeneous within each one of them. Then the degree of spatial distribution is represented mainly through the number of subunits. Fig. 3 shows the architecture of the toolbox. Generally, the scripts can be used to prepare the input data files (i.e. estimate snow accumulation/ melting and potential evapotranspiration), identify model parameters and evaluate model performance. In addition, the toolbox offers scripts for data analysis and visualisation, and parameter sensitivity analysis.

![Figure 3. General structure of the MWBMT.](image)

3.2. Determining curve number (CN)

Prior to simulation, the SCS-CN method requires estimation of the curve number (CN) parameter that characterises the soil permeability and land use. The curve number is used to determine how much rainfall infiltrates into soil or aquifer and how rainfall becomes surface runoff. Curve numbers depend on land-use, soil characteristics and antecedent moisture conditions. CN values vary from 0 to 100; a high CN means high runoff and low infiltration (usually observed in urban areas), whereas a low CN means low runoff and high infiltration (dry soil). Information from land use, hydrologic soil group, and antecedent soil moisture conditions are needed to estimate CNs (Soulis et al., 2009).
A methodology has been developed for application in continuous time hydrological modelling allowing the temporal variation of $CN$. A CN value for ‘normal’ soil moisture conditions ($CN_2$) can be a priori calculated from land use and soil information and further adjusted in the calibration process. Since runoff and infiltration characteristics on a soil plot depend on antecedent moisture conditions, $CN$ is adjusted to a lower value $CN_1$ under dry conditions and a higher value $CN_3$ under wet conditions given by (Soulis and Valiantzas, 2012):

$$CN_1 = \frac{CN_2}{(2.334 - 0.01334 \cdot CN_2)}$$

$$CN_3 = \frac{CN_2}{(0.4036 + 0.0059 \cdot CN_2)}$$

The curve number is then interpolated between $CN_1$ and $CN_3$ using:

$$CN_t = (CN_3 - CN_1) \cdot \frac{SS_{t-1}}{S_{\text{max}}} + CN_1$$

where SS is a state variable representing unsaturated zone soil storage (cm) at time $t$ and $S_{\text{max}}$ is the maximum allowable unsaturated soil storage which is computed from the catchment storage capacity equation using $S_{\text{max}} = (1000/CN_t - 10) \times 25.4$. The term $SS/S_{\text{max}}$ is the unsaturated zone soil moisture content at time $t$.

### 3.3. The SCS-CN model

The original SCS-CN method was used in this study. Daily runoff time series for each subunit is computed by the formula:

$$ER_t = \frac{(P_t - I_a)^2}{(P_t + S - I_a)}$$

for $P_t > \lambda \cdot S$

$$ER_t = 0$$

for $P_t \leq \lambda \cdot S$

where $S$ is the potential maximum retention (function of $CN$), $I_a$ is the initial abstraction representing losses due to interception, infiltration and surface storage, all of which occur before runoff begins and taken as a function of $S$ ($I_a = \lambda \cdot S$, commonly $\lambda$ is set equal to 0.2; however, in this study $\lambda$ was calibrated), $ER$ is the depth of runoff or excess rainfall in mm at time step $t$ and $P$ is the rainfall height in mm at time step $t$. In the mountainous parts of the catchment where snow accumulation and snowmelt are important processes, we replace $P$ with effective precipitation described as the sum of rainfall and snowmelt.

**Snow accumulation / melting component:** Snow accumulation and melt is based entirely on average daily temperature. When average daily temperature $T_t$ is below 0°C, any precipitation falling on that day is added to the snow pack, rather than routed through the rainfall-runoff portion of the model.

$$Snow_t = \begin{cases} 
  Snow_{t-1} + P_t & \text{if } T_t \leq 0^\circ C \\
  Snow_{t-1} - P_{St} & \text{otherwise}
\end{cases}$$

and $P_{St} = M_{\text{snow}} \cdot T_t$, with the condition that Snow is non-negative and where $Ps$ represents water melted from the snow pack (cm), $T$ is mean daily temperature ($^\circ$C), and $M_{\text{snow}}$ is a calibrated model parameter (mm $^\circ$C$^{-1}$ day$^{-1}$).

**Routing:** After computing surface runoff using the SCS-CN method, which represents the rainfall excess amount corresponding to effective precipitation, routing takes place to transform surface runoff to direct runoff that is produced at the outlet of the subunit. This is carried out using a single linear reservoir method, given by:

$$q_t = C_0ER_t + C_1ER_{t-1} + C_2q_{t-1}$$

$$C_0 = C_1 = \frac{1}{(2 + 1/K)}$$

$$C_2 = \frac{2 - 1/K}{(2 + 1/K)}$$

where $K$ represents the single linear reservoir storage coefficient (day$^{-1}$) and assumed a function of time of concentration. It is worth noting that in this model formulation, the mass remains conserved during the routing process.

**Baseflow:** The baseflow ($q_b$) is assumed to be a fraction ($b$) of $F$ as below:
\[ q_{b t-\text{NLAG}} = b_f \cdot F_t \]

where \( F \) is the cumulative infiltration (\( F = P - I_a - \text{ER} \)), and \( \text{NLAG} \) is the baseflow lag time (days). The total daily discharge is the sum of \( q_t \) and \( q_b \).

**Evapotranspiration:** The Romanenko’s empirical equation, a temperature-based method, is used to estimate potential evapotranspiration, \( \text{PET} \) (Oudin et al., 2005). Actual evapotranspiration, \( \text{ET} \) (mm) is further estimated using \( \text{PET} \) and is calculated by:

\[ \text{ET}_t = \frac{\text{SS}_{t-1}}{\text{Smax}} \cdot \text{PET}_t \]

where \( \text{SS}/\text{Smax} \) is a soil moisture term which reduces \( \text{ET} \) based on soil dryness and mitigates the tendency for the subsurface to dry during long periods without precipitation.

### 3.4. Water budget model

In our application, a simple water budget model related to the degree of physical representation of fluxes is set. The model conceptualised for the reservoir of Mornos takes the following form:

\[ P_{L,t} + Q_{in,t} + Q_{evinos,t} - G_{W,t} - E_t - Q_{out,t} - Q_{overflow,t} = \Delta \text{Storage} \]

where \( P_{L,t} \) is the rainfall that falls directly into the lake, \( Q_{in} \) is the streamflow that contributes to the reservoir, \( Q_{evinos} \) is the water volume imported from Evinos’ connecting tunnel, \( G_{W} \) is the groundwater loss, \( E \) is the evaporation from the reservoir, \( Q_{out} \) is the discharge distributed to the city of Athens, \( Q_{overflow} \) is the discharge due to overflowing water, and \( \Delta \text{Storage} \) is the change in the water storage of the reservoir. Most of these components can be estimated using measured and simulated data. \( Q_{in} \) is estimated in a daily step according to the SCS-CN rainfall-runoff model. Discharge from the Evinos River (\( Q_{evinos} \)) and water level data have been provided by EYDAP SA. A relationship between water level and storage volume allows calculation of \( \Delta \text{Storage} \). \( E \) is estimated from the evaporation pan installed next to the dam. The amount of water distributed to the city of Athens is measured; hence \( Q_{out} \) data are available. Groundwater losses are practically difficult to be measured, and thus they are estimated given that the other terms of the equation are known.

### 3.5. Model identification

The lack of adequate and informative discharge data (see Fig. 2) limits our potential to parameterise the model using traditional calibration methods based, for instance, on daily flow observations. However, EYDAP SA has been empirically estimating monthly runoff volumes, which are used to assess model adequacy (Dec 2011 for model warm up and Jan 2012 - Feb 2013 for evaluation; although their empiric estimation is also uncertain, these values were used as reference). In total, 20,000 Monte Carlo simulations are generated to investigate the parameter space; 6 parameters (\( CN, K, b_f, \text{NLAG}, \lambda, \text{Msnow} \); see Table 1) are calibrated and homogeneously distributed over the model domain. The initial soil moisture conditions were not calibrated, since the simulations start in December, hence the soil is assumed saturated. The absolute bias in the monthly runoff volume (MonVol) was used to evaluate the model given by:
Table 1. Model parameters and their range and model performance measure.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>CN</td>
<td></td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>K</td>
<td>day⁻¹</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>bf</td>
<td></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>NLAG</td>
<td>day</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>λ</td>
<td></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Msnow</td>
<td>mm °C⁻¹ day⁻¹</td>
<td>0.7</td>
<td>9</td>
</tr>
</tbody>
</table>

where \( Q_{sim} \) is the simulated monthly runoff volume, \( Q_{obs} \) is the monthly runoff volume provided by EYDAP SA, \( n \) is the length of the time series (Jan 2012 - Feb 2013; 14 values). Higher the MonVol, poorer is the model performance and vice versa. MonVol has the advantages of having the same units as the variable.

4. RESULTS

4.1. Model ability to simulate streamflow characteristics

To investigate the adequacy of the model structure, daily streamflow is simulated based on the best model parameter set selected using the MonVol measure, and compared to the observed flow records calculated using the rating curves in Fig. 2b. Fig. 4 presents an example of parameter identifiability and model’s potential to describe the streamflow signal in the Upper Mornos station. Out of the 6 model parameters only two (\( \lambda \) and CN) were identifiable using the MonVol objective function. Fig. 4a presents the dotty plots for \( \lambda \) which is highly identified in the 0.15-0.5 range, probably because the existence of pervious areas leads to high initial abstraction ratio. This is an interesting result indicating that the commonly pre-determined assumption of 0.2 is not always correct. In addition, it is noted that although some parameters were not sensitive to MonVol, these parameters show sensitivity to other performance measures (i.e. the Nash-Sutcliffe efficiency); however this analysis is beyond this paper’s objectives.

As expected, the model is not fully able to represent all characteristics of the hydrological signal, i.e. medium flows (Fig. 4b). Despite the existence of erroneous data, the model cannot adequately represent the recession in the first winter period (Dec 2011 – Feb 2012). This could be due to wrong parameterisation and assumption of the antecedent conditions or even because the simple SCS-CN model hypothesis is not adequate enough to represent such flow signatures. However, it is important to note that the model response shows sensitivity to the rainfall signal; a number of runoff events occur when rainfall events take place, whereas the rising limb can be matched well by the model. This

![Figure 4. Parameter identification and simulated daily flow in the Upper Mornos station.](image-url)
is a positive sign given the limited calibration of the model and the highly uncertain observed data; note that the MonVol value achieved is <100 hm$^3$ for the 14 month period.

4.2. Model ability to simulate monthly patterns

We next investigate the potential of the model to simulate the monthly pattern of runoff volume. Fig. 5 presents the monthly distribution of simulated runoff and empirically calculated runoff from EYDAP SA. Both runoff distributions follow the distribution of monthly rainfall, whereas a very good agreement is achieved between the estimated and observed runoff for the winter and summer seasons. However during the spring (Mar – May) season, the model significantly underestimates the runoff contribution. Data from EYDAP SA show that runoff is generated without significant rainfall events; hence the contribution could be from snow melting. This result points towards the need for a more accurate representation of temperature’s spatial distribution; and hence a more accurate estimation of the snow melting contribution.

![Figure 5. Total monthly runoff and rainfall distribution for the period Jan 2012 - Feb 2013.](image)

Finally, we assess the rainfall-runoff model results from an end-users viewpoint analysing the change of water storage in the reservoir in the year 2012 using the water balance model component of the toolbox (Fig. 6). Once again a very good agreement is observed between the EYDAP SA and SCS-CN data during the winter and summer seasons (average relative difference is less than 7%). The difference in change of storage between SCS-CN and EYDAP data during spring is again due to the model’s inability to adequately represent the snow melting processes.

![Figure 6. Estimated change of reservoir’s water storage using the water budget equation.](image)
5. CONCLUSIONS

The MWBMT toolbox presented here allows application of semi-distributed rainfall-runoff models based on the SCS-CN method. In this study we investigated the potential of the SCS-CN method when no (or limited) data information is available and when several sources of error/uncertainty reduce the precision of observed records. Application of the model in the poorly gauged catchment of Mornos showed adequate representation of the monthly flow patterns with the exclusion of snow melting periods. In addition, in this study we illustrate the uncertainty in the generation of rating curves which is further propagated in the discharge data; a source of uncertainty which must be highly considered when evaluating hydrological models. Specifically for the Mornos catchment, an interesting approach would have been to condition the model identification using both water level records from the reservoir and observed monthly runoff volumes. This is left for future work. Finally, we note that model improvements could be achieved by spatially distributing precipitation and temperature; hence allowing a better understanding and representation of the snow accumulation/melting processes.

REFERENCES