SMA Based Continuous Hydrologic Simulation Of The Blue Nile

K. E. Bashar\textsuperscript{1} and A. F. Zaki\textsuperscript{2}

\textsuperscript{1}UNESCO Chair in Water Resources, P.O. Box 1244, Khartoum, Sudan. 
E-mail: basharke@hotmail.com

\textsuperscript{2}UNESCO Cairo Office, P.O. Box 11541, Cairo, Egypt, E-mail: a.zaki@mail.unesco.org.eg

Abstract

Continuous hydrologic models account for the soil moisture balance in the catchment over a long-term period. Different hydrologic physical processes such as: interception, surface depression storage, infiltration, soil storage, percolation, and groundwater storage should be considered in continuous hydrologic modeling. In this paper, the Hydrologic Modeling System (HMS) model was used for continuous hydrologic simulation of the Blue Nile. The model encompasses Soil Moisture Accounting (SMA) algorithm to simulate the long-term relationship between rainfall, runoff, storage, evapotranspiration, and soil losses in the Blue Nile. The objective of this paper is to evaluate the performance and potentiality of the HMS with the SMA algorithm on the Blue Nile as a case study in the Nile basin.

Daily observed rainfall and runoff records of seven years (1990-1996) and the Digital Elevation Model (DEM) of the Blue Nile were made available for the calibration and verification stages. The obtained results were reasonable and acceptable taking into consideration the lumped time-invariant parameters used in the calibration and verification of the model.

Despite the lumping of the input, the output and the parameters accounting for the physical processes in the catchment, the model showed satisfactory performance by accounting for more than 90\% of the initial variance. More rainfall-runoff data, seasonal parametrization and modeling the Blue Nile watershed in sub-basins of smaller areas may improve the results.

Introduction

Long-term rainfall-runoff simulation requires modeling of different hydrological processes in the watershed based on water balances during a long-term period. Continuous hydrologic computer modeling may be a tool to study the hydrologic regime of a study area. However, the seasonality of the hydrological processes may be one of the main challenges facing continuous hydrologic simulation and is a main source of error in the simulation. Average\-d-value (lumped) parameters during the simulated period may be unrealistic. A seasonal parameterization approach, where separate parameters sets are established for each season, may enhance the results, yet, more data and initial conditions settings will be required.
The Hydrologic Modeling System (HMS) is a physically-based distributed-parameter model and can be applied to large river basins (Yu and Schwartz, 1998). HMS simulates the hydrologic processes, such as vertical soil moisture flow, evapotranspiration (ET), infiltration, overland flow, channel flow, and ground-water flow within a river basin. HMS includes SMA method which counts on rainfall depths and evapotranspiration rate, as inputs to define the rainfall, runoff, storage and losses relationships. There are five storage zones simulated, as shown in Fig. (1). For the simulation of water movement through the various storage zones, the maximum capacity (maximum depth) of each storage zone, initial storage condition in terms of percentage of the filled portion of each zone, and the transfer rates, such as the maximum infiltration rate, are required (Fleming and Neary, 2004). The SMA algorithm has a linear structure and may be a source of error in simulating the rainfall-runoff process which is a non-linear process. Again, seasonal or multi-parameter approach may improve model performance.

![Fig. (1). Schematic diagram of HMS/SMA algorithm (HEC 2000)](image)

It is worth to mention that, according to the SMA algorithm, evapotranspiration is only assumed to take place during dry periods and from the canopy interception storage then from surface depression storage and then from the soil profile storage. On the other hand, soil
percolation will start only when the tension zone capacity is fulfilled. According to Fig. (1), the outflow from the groundwater layer 2 storage as percolation will be considered as a loss from the system.

Study Area And Data Used

The Blue Nile and its tributaries all rise on the Ethiopian Plateau. The Blue Nile rises at a spring site upstream of Lake Tana in Ethiopia, 2,150 m above mean sea level. The Blue Nile basin can be characterized as a hilly area. The watershed receives average annual rainfall varies from 625 mm to 2,140 mm. The mean annual evaporation over the Blue Nile varies from 3.0 for lake Tana to 6.5 mm/day at Wad Medani and to 7.8 mm/day at Khartoum (Shahin, 1985).

The total area of the Blue Nile catchment including lake Tana and its basin is 324,530 Km$^2$. In this paper, only the catchment of the Blue Nile till Eddeim station on the main stream of the Blue Nile (at the border between Sudan and Ethiopia) is considered. The catchment area behind the gauging station is 254,230 km$^2$. The Blue Nile watershed was delineated using DEM-based delineation in the Watershed Modelling System (WMS) (Nelson, 2004). The DEM of the Blue Nile and the delineated watershed are shown in Fig. (2) and (3).

Fig. (2): DEM of the Blue Nile Watershed up to Eddeim

Daily rainfall and evaporation records are available for the Blue Nile watershed for the period 1/1/1990 to 31/12/1996. Furthermore, daily flow discharges record at Eddeim station were made available for the same period for comparison needs with the simulated flow discharges by HMS.
In this study, 5 years were devoted to calibration and 2 years to validation. The beginning and ending dates of the calibration and validation simulations represent inactive meteorological and hydrological conditions in order to minimize the error in setting the initial conditions. The calibration stage covered the period 1/1/1990-31/12/1994 including different levels of floods (low, moderate and high flooding cases). The verification stage focused on the period 1995-1996 which represents one low and high flood year.

Model Calibration

Rainfall Losses: SMA Parameters Definition

HMS has the capabilities to process automated calibration in order to minimize a specific objective function, such as sum of the absolute error, sum of the squared error, percent error in peak, and peak-weighted root mean square error. However, in many cases, the resulted automated parameters are not reasonable and practical. In this study, manual calibrated method was adopted to determine a practical range of the parameter values preserving the hydrograph shape, minimum error in peak discharges and volumes.

The whole 12 parameters needed for the SMA were taken into consideration in this simulation. The maximum infiltration rate and the maximum soil depth as well as the percolation rates and groundwater components had significant influence on the simulated flow discharges. The remaining parameters were adjusted to match the simulated and observed peak flows, volumes, time to peaks and hydrograph shape. The 12 parameters needed for the SMA were estimated as shown in Table (1). While adjusting parameter values during model calibration, the wet period of the year were weighted more heavily, ensuring

Fig. (3): Delineated Watershed of the Blue Nile up to Eddeim
that the model would accurately simulate, to some extent, the high flooding period in each simulated year.

Table (1) SMA parameters for Blue Nile watershed simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canopy Storage Capacity</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>Surface Storage Capacity</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>Soil Storage Capacity</td>
<td>2.0 mm</td>
</tr>
<tr>
<td>Soil Tension Storage Capacity</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Soil Maximum Infiltration Rate</td>
<td>0.6 mm/hr</td>
</tr>
<tr>
<td>Soil Maximum Percolation Rate</td>
<td>0.6 mm/hr</td>
</tr>
<tr>
<td>Groundwater 1 Storage Capacity</td>
<td>55.0 mm</td>
</tr>
<tr>
<td>Groundwater 1 Max. Percolation Rate</td>
<td>0.8 mm/hr</td>
</tr>
<tr>
<td>Groundwater 1 Storage Coefficient</td>
<td>7000 hours</td>
</tr>
<tr>
<td>Groundwater 2 Storage Capacity</td>
<td>50 mm</td>
</tr>
<tr>
<td>Groundwater 2 Max. Percolation Rate</td>
<td>0.8 mm/hour</td>
</tr>
<tr>
<td>Groundwater 2 Storage Coefficient</td>
<td>6000 hours</td>
</tr>
</tbody>
</table>

The evaporation model used in conjunction with the SMA algorithm takes into account evaporation and transpiration. To model transpiration, the rooting depth was determined to be the maximum depth of the soil profile.

*Excess Rainfall Transformation: Transform and Baseflow Parameters*

Excess rainfall was transformed to direct runoff using the Clark unit hydrograph technique. In this method, the processes of translation and attenuation of excess rainfall dominate the movement of flow through a watershed. Translation is the movement of flow down gradient through the watershed in response to gravity. Attenuation results from the frictional forces and channel-storage effects that resist the flow,(Straub et al., 2000).

The translation of flow throughout the watershed is based on time-area curve, which expresses the curve of the fraction of watershed area contributing runoff to the watershed outlet as a function of time since the start of excess rainfall. The time-area curve is bounded in time by the watershed time of concentration. On the other hand, attenuation of flow can be represented with a simple, linear reservoir for which storage is related to outflow. The two parameters HMS/Clark parameters are the time of concentration and the storage coefficient and are set for the Blue Nile as 160 and 650 hours, respectively. These parameters were derived from WMS.

*Model Results*

The simulated flow discharges as an output of the HMS based on the above-mentioned parameters are compared to the observed ones for the calibration period is shown in Fig. (4). Fig. (5) illustrates the scatter of the observed and estimated discharges testing the accuracy of the simulated flow discharges.
It can be pointed out that the model produced relatively reasonable results taking into consideration averaged (time invariant) parameters were used for the whole calibrated period (4 years) and lumped parameters values for the whole area of the Blue Nile watershed. From Fig. (4), it can be noticed out that the model succeeded to produce a relatively similar hydrograph shape. However, the Nash-Sutcliffe (1970) coefficient of efficiency ($D^2$) was used to judge the model performance. The estimated $D^2$ value for the calibration period is 0.78 which may be satisfactory to judge on the similarity and consistency between the observed and estimated hydrograph shape.

$$D^2 = \frac{\sum (y - \bar{y})^2 - \sum (y - \hat{y})^2}{\sum (y - \bar{y})^2}$$

where:  
\[\hat{y}\]: Estimated flow discharges by the model  
\[y\]: Observed flow discharges,  
\[\bar{y}\]: Mean of \(y\) in the calibration period

As depicted from Fig. (5) it is clear that the model produced relatively over estimated results due to the fact that the periods of high flows were given much consideration and weight during the calibration phase. It should be mentioned that, in the calibration stage, one set of parameters were applied to the whole period which comprised different levels of flooding years cases. Accordingly, the model performance differed from one year to another. For example, the model produced extremely overestimated flows for year 1990 which represents the low flooding level case. However, the model performance was fairly better for the moderate (years 1991 and 1992) and high (years 1993 and 1994) flooding level cases.
Validation

Model validation demonstrates the capability of the model to produce accurate predictions for periods outside the calibration period, (Refsgaard and Knudsen, 1996). Model validation for this study was used to determine the effectiveness of the calibrated parameters in predicting the flow discharges at Eddeim for the period 1/1/1995 - 31/12/1996. The validation period covers low and high flooding year cases. Fig. (6) shows the simulated and observed flow discharges for the validation period. Fig. (7) shows demonstrates the scatter of the observed and estimated discharges for the validation stage. It can be noticed that the simulated discharges values are higher than the observed ones. The estimated $D^2$ value for the validation period is 0.69 which is relatively small value. Similar to the calibration stage, the model produced rather over estimated flows in the case of low flooding year.
Fig. 6: Computed and observed hydrographs after calibration in HMS

Fig. 7: Scatter diagram of Observed versus estimated discharge for verification

Although, the model produced acceptable results for the high flow period of year 1996, unfortunately, it did not respond well to the considerable high rainfall occurred in the
beginning of this year which occurred after dry period, i.e. high rainfall on dry condition. This may be ascribed to the effect of the linear structure of the SMA algorithm in simulating the rainfall-runoff process which is a non-linear process. Finally, it may be noted out that seasonality (wet and dry seasons), spatial distribution of rainfall and the expected soil and land cover heterogeneity may be source of errors in the hydrological modeling in a large scale watershed such as the Blue Nile (254,230 km$^2$). This may lead to the importance of developing a seasonal parameterization approach where each simulated year is divided into two simulation periods (wet and dry seasons) and accordingly one parameter set is obtained for each period. A Geographic Information System (GIS) based data can also improve the model performance.

**Conclusions and Recommendations**

An HMS continuous hydrologic simulation model was developed for the Blue Nile based on Soil Moisture Accounting (SMA) algorithm. The HMS application produced satisfactory performance taking into consideration lumped parameters and uniform spatial rainfall were used. The model showed satisfactory performance by accounting for more than 90% of the initial variance. However, the development of model parameterization methodology using geographic information systems is highly recommended. More hydrological data and satellite images are highly needed to take into account the climatic, hydrological and soil characteristics spatial variability in such large basin for better and accurate modeling of the hydrological processes in the catchment.

**Acknowledgments**

This paper was prepared based on the research activities of the FRIEND/Nile Project which is funded by the Flemish Government of Belgium through the Flanders-UNESCO Science Trust Fund cooperation and executed by UNESCO Cairo Office. The authors would like to express their great appreciation to the Flemish Government of Belgium, the Flemish experts and universities for their financial and technical support to the project. The authors are indebted to UNESCO Cairo Office, the FRIEND/Nile Project management team, overall coordinator, thematic coordinators, themes researchers and the implementing institutes in the Nile countries for the successful execution and smooth implementation of the project. Thanks are also due to UNESCO Offices in Nairobi, Dar Es Salaam and Addis Ababa for their efforts to facilitate the implementation of the FRIEND/Nile activities.
Reference


