Updating and Assessment of the Eastern Nile Model in RiverWare for Reservoir Management

Asmaa M. Kamel¹, Doaa Amin¹ and Mohamed M. Nour Eldin²

¹Water Resources Research Institute (WRRI), National Water Research Center (NWRC), Ministry of Water Resources and Irrigation (MWRI), Post Code:13621, Cairo, Egypt.
²Irrigation and Hydraulic Department, Faculty of Engineering, Ain Shams University, Post address:11517, Cairo, Egypt.

Abstract

Understanding and modelling the complex nature of river systems are essential for efficient use of the water resources. The Nile River, a transboundary river shared between 11 countries with high potential conflicts, was modelled to play an important role in solving conflicts by means of understanding problems and cooperation options. Many water allocation and operation models are used to study and produce some scenarios to support the cooperation among the basin countries. RiverWare software is one of the most recently used models for studying the reservoirs operation management. Where the developed water allocation model called Eastern Nile Model (ENM) using RiverWare software, has proved its worth application on the ENM. The effective use of Riverware tools in ENM requires the updating of hydrological conditions, but the hydrological data in ENM ceased in 2002, casting doubt on the possibility of using it for recent periods. In this study, the hydrological conditions in the model were updated from 2003 to 2014 with a simulated flow data, which were taken from the output of rainfall-runoff distributed model (Nile Forecast System (NFS)), the calibrated NFS simulation period. The methodology of the updating data could be applied again, when the simulated NFS data will be available. The ENM evaluation was performed by comparing the simulated with the observed outflows at the locations of Diem, Khartoum and Dongola stations using statistical criteria. All metrics were considered very good or good. As a result, the ENM is ready for developing reservoirs operational policies with several alternatives and priorities for filling and the operation stages of any planned reservoir. Moreover, the ENM is able to quantify and evaluate the impacts of future development in upstream countries in the Nile basin.

Keywords: River system modelling; Evaluation; Eastern Nile; Transboundary Rivers; Riverware; Reservoir simulation

1. INTRODUCTION

Modelling river system is the most important unit for planning, developing, and managing water resources. In addition, reservoir system and its operation policy is a primary element in these models. Seeking optimal operation of reservoir systems was the target of many researchers. The Eastern Nile Basin is politically significant, being a transboundary basin shared by four countries, and covers more than one half of the Nile Basin [1]. Thus, there are many models that have been developed in order to investigate the best management for the Nile system.

River Basin Simulation Model (RIBASIM) river basin simulation model is one of the most used models in the Nile river management. RIBASIM was used to quantify the trade-off between hydropower generation from Tekeze dam, downstream environmental flow, and new irrigation development in the western part of Ethiopia [2]. It was used also to simulate the existing system and management conditions of the Eastern Nile Basin [1],[3]. Then, Sief ElDin [4] used RIBASIM to study four scenarios of the Ethiopian development projects and estimate their impacts on Egypt. RIBASIM has advanced flexible features in operating goals for several different types of demand (hydro-power, irrigation, etc.) and the option to manage the system with priority to different demands.

Hec-ResSim (Hydrologic Engineering Center - Reservoir System Simulation) Model is one of such models used to simulate the water system in the Eastern Nile Basin. Wondimagegnehu and Tadele [5] used the Hec-ResSim, to simulate current and future inflows and hydropower generation on the operation of the Blue Nile cascade of dams, Beko Abo, Mandaya and Border. The model is used for the entire Eastern Nile Basin for Abbay–Blue Nile, Tekeze-Setit-Atbara, Baro-Akobo-Sobat and Main Nile Sub basins [6].

The Nile Basin Initiative (NBI) developed a new decision support system that improved the regional modeling system. The Nile Basin Decision Support System (NB-DSS) encompasses three components: information system, analytical part containing simulation and optimization tools, and multi criteria analysis tool [7]. Firstly, Gharib [8] used NB-DSS to simulate the impacts of alternative development scenarios and to assess the benefits and trade-offs. Secondly, Hamid [7] used NB-DSS to assess the impacts of planned Ethiopian dams on the Sudanese reservoir system up to Khartoum. In addition, Sileet et al. [9] used NB-DSS to assess the positive and negative impacts of the planned water projects in the Blue Nile sub-basin on both national and regional levels, on the Blue Nile Sub-basin and downstream countries.

Meanwhile, Bahaa [10] used the GERD-HAD Simulation (GERD-HAD SIM) model, which is a recently developed...
Modelling tool to investigate the downstream impacts of the GERD on HAD and determine the best long-term operating policy for the GERD that cause minimum impact on HAD.

Apart from the previous river basin models, the Center for Advanced Decision Support for Water and Environmental Systems (CADCWS) at the University of Colorado in Boulder developed a river basin/system modelling tool called RiverWare, which is an ideal platform for operational decision-making, responsive forecasting, operational policy evaluation, system optimization, water accounting, water rights administration, and long-term resource planning. The flexible representation of RiverWare allows changing policy objectives and facilitates clear understanding and communication of policies to decision makers and stakeholders [11].

RiverWare allows many agencies to improve the water resources management. For example, The Tennessee Valley Authority (TVA) replaced site-specific simulation models by RiverWare models for daily scheduling of reservoir releases. Then, TVA began using RiverWare’s optimization solution for scheduling daily turbine releases. In the meantime, the U.S. Bureau of Reclamation (USBR) used RiverWare models instead of a suite of models for management of the Colorado River. The USBR's Riverware models manage 348 reservoirs and 58 hydroelectric plants in the Western U.S., with total storage of 245 million acre-feet and 14,300 MW of hydro generation capacity [12]. An interagency team including the U.S. Army Corps of Engineers (USACE), USBR, and the U.S. Geological Survey (USGS) has applied a rule based simulation and water accounting in RiverWare to a daily time step Upper Rio Grande Water Operation Model (URGWOM). For the San Juan River Basin, located in Arizona, Colorado, and New Mexico, an operation model was developed with efforts from the USBR and the USGS. The model was used by operating policies to meet water supply demands, flood control, target storages, and the filling criteria in its reservoirs. In 2017, Basheer and Elagib [13] demonstrated the concept of Water-Energy Productivity (WEP), defined as the amount of energy produced per unit of water lost in the process, by developing a water allocation model of the White Nile in Sudan, including Jebel Aulia Dam (JAD), using RiverWare. This study was done to illustrate the relationship between energy generation and water losses by examining the sensitivity of the Water-Energy Nexus (WEN) to changing dam operation policy. Afterwards, the impacts of cooperation in the Blue Nile basin, as a transboundary river basin, on the Water-Energy-Food nexus (WEF nexus) were quantified and evaluated using a daily RiverWare model [14]. Recently, Abudu et al. [15] applied RiverWare modeling approach to evaluate the management decisions on surface water and groundwater diversions in the agricultural watershed of the Urumqi River Basin of Xinjiang in Northwestern China. Awaad et al. [16] investigated the optimum operation policy for the GERD by minimizing the differences between the generated energy and the firm energy and projecting of this operation policy on the flow at El Diem Gage. This study was done using RiverWare model with around one thousand hydro-climatological traces. The variety of physical and policy situations in these applications demonstrates RiverWare’s ability to represent site-specific conditions with a variety of modelling needs [11].

Although several applications were done using ENM on RiverWare software, (e.g. [13], [14], [17], and [18]), there is a lake of the hydrological data, which describe the recent period, where the available data in ENM is until 2002. This shortage of the available data may question the ability of the model to simulate the recent period. Therefore, to get benefit of the Riverware tools with the ENM, Wheeler’s version of the ENM need to be updated. Consequently, this paper aims to update the historical hydrological conditions in the ENM until 2014, and then evaluate the model using statistical criteria.

2. STUDY AREA AND DATA USED

2.1. The Nile River

The Nile River is the longest river in the world stretching nearly 6,700 km, covering more than 35° of latitude [18]. The Nile River basin is covering an area of approximately 3,762,000 km² [20]. The climate is mainly tropical in the upstream parts of the basin and arid and semi-arid in the downstream parts. The elevation varies from less than 20 to 2,150 m a.m.s.l (meters above the mean sea level). Even though the Nile is the longest river, the flow volume is not large compared to major rivers. The total Nile basin water resources comprise only 84 BCM/year of runoff as measured at Aswan High Dam [21], [22]. The mean annual rainfall varies from 1,200 mm in the upstream parts to less than 10 mm in the downstream parts [20].

The Nile basin includes two main regions; the Eastern Nile and the Equatorial Lakes (Figure 1). The Eastern Nile region stems from the Ethiopian plateau and contributes with more than 85% of the total runoff; it includes the sub-basins of the Sobat River, the Blue Nile, and Atbara River. The Equatorial Lakes region starts from the Great Lakes of central Africa (Victoria, Albert, Kyoga, Edward); it is the main source of the White Nile that expands till the beginning of the huge swamp area (Sudd region).

2.2. The Blue Nile Basin

The Blue Nile originates from Lake Tana in Ethiopia at an elevation of 1,780 m a.m.s.l and flows to Sudan through a steep slope. It has a total catchment area of about 314,000 km². The river continues running northward until it joins the White Nile in the Sudanese capital, Khartoum (Figure 1). The Blue Nile Basin constitutes only around 10% of the entire Nile Basin area, however, contributes about 60% of its total mean annual flow measured at the High Aswan Dam [23], [24] and [25]. Thus, runoff variability in upstream countries is of great importance to the sustainable development of downstream countries such as Sudan and Egypt.
2.3. Data Used

The historical flow data was collected from the Nile Basin Volumes for about five hydrological stations in the Nile Basin. Table 1 shows the period of the collected data and the percentage of the filling data. The collected data are monthly data. These data will be used to evaluate the performance of the ENM after updating the model by the recent available simulated data (2003-2014).

<table>
<thead>
<tr>
<th>Station</th>
<th>Start day</th>
<th>End day</th>
<th>Percentage of available records</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diem</td>
<td>1/1/2003</td>
<td>31/12/2014</td>
<td>≈ 100%</td>
</tr>
<tr>
<td>Khartoum</td>
<td>1/1/2003</td>
<td>31/12/2014</td>
<td>100%</td>
</tr>
<tr>
<td>Atbara</td>
<td>1/1/2003</td>
<td>31/12/2014</td>
<td>100%</td>
</tr>
<tr>
<td>Malakal</td>
<td>1/1/2003</td>
<td>30/11/2013</td>
<td>100%</td>
</tr>
<tr>
<td>Dongala</td>
<td>1/1/2003</td>
<td>31/12/2014</td>
<td>100%</td>
</tr>
</tbody>
</table>

3. METHODOLOGY

3.1. Nile Basin Model Schematic

One of the most important RiverWare applications is the ENM. This model was developed to contain all the major features in the Nile Basin that significantly affect water management and distribution [17]. Then, the recently raised Rosaries Dam, the newly developed Upper Atbara and Setit Dam complex, and the GERD were included in simulations of future conditions. Figure 2 represents the ENM schematic as developed in the RiverWare software. A full description of the model Schematic was illustrated by Wheeler and Setzer [18]. The ENM was calibrated during the period (1951-1970) and validated during the period (1971-1990) [17].

3.2. Updating the developed Eastern Nile Model in RiverWare Software

The ENM schematic contains 162 control points; each control point represents the flow from small tributary catchment. The control point flow is the main input for the model, and it can be fed by observed, simulated or forecasted information. The available flow data in the model database is made of monthly time series from 1900 till the end of 2002. In order to update the ENM, the control flow points in the model will be updated from 2003 to 2014 by simulated flow data produced from Nile Forecast System (NFS).

The NFS is a hydro-meteorological distributed model, which simulate the Nile flow till the Dongala station (the end point before flow entering Lake Nasser). The main inputs of NFS are: the rainfall which estimated from the satellite images and merged with observed rain gauge data, and the observed mean monthly evapotranspiration. The main hydrological models in NFS are: water balance, hill-slope and river routing models, more details about NFS described in [27] and [28]. The NFS hydrological models is calibrated and validated several times, the last calibration was done in 2012 [29]. The calibrated...
simulated flow was very close to observed one, especially in the eastern Nile, where the values of comparison criteria; the Nash Sutcliffe efficiency (NSE), Root mean square error (RMSE) and the Mean Absolute Error (MAE) were 0.92, 1.38 BCM and 0.77 BCM respectively [29].

The shortage of the observations in the Nile catchment leads to use a simulated data in order to update the ENM. The simulated data were taken from the NFS output. The main control points on the Nile stream are located in the NFS schematic that run the hydrological models and introduce simulation flows at each feeding control point.

The statistical relations between the control points and the main points or the confluence at the stream, which feed by NFS output, are used to obtain the control points contributed to the flow at confluences in the model. This process was done by computing the contribution percentage for each control point upstream the confluence as averages from the historical flows (1900 - 2002). For example, the four control points (1219, 1234, 222 and 228) contributed to the flow at confluence 9 in the Blue Nile in addition to the flow from upstream. Figure 3 presents an example of the control points contributed to the flow at confluence 9 and Table 2 shows the contributions of each control point to the flow at confluence 9.

![Figure 3. Example of the control points contributed to the flow at confluence 9](image)

**Table 2. The control points contribution to the flow at confluence 9**

<table>
<thead>
<tr>
<th>Confluence</th>
<th>Control point</th>
<th>Contribution percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue Nile Confluence 9</td>
<td>1219</td>
<td>0.965</td>
</tr>
<tr>
<td></td>
<td>1234</td>
<td>1.278</td>
</tr>
<tr>
<td></td>
<td>222</td>
<td>4.481</td>
</tr>
<tr>
<td></td>
<td>228</td>
<td>1.092</td>
</tr>
</tbody>
</table>

Then, the control points data in the ENM in RiverWare were updated for the period (2003-2014). Figure 4 shows example of some updated control points slots.
3.3. Evaluation of the Eastern Nile Model Schematic

The model control points data was updated with the simulated flow data for the period (2003-2014), and then the model was evaluated. The observed flow data for the key locations (Diem, Khartoum, and Dongala) were used to evaluate the model performance during the period (2003-2014). The evaluation was performed by simulating the historical conditions in the calibrated model including, channel diversions, dam operations and same pattern of the water user diversion request, as well as simulating the hydrologic flows. Actual reservoir pool elevations and historical dam operation policies, built in the calibrated model, were used to drive the simulation. Three statistical criteria; Root mean square error (RMSE), Standard Deviation Ratio of observations (RSR), the Nash Sutcliffe efficiency (NSE), and the percentage of the BIAS are used for the comparison.

\[
RSR = \frac{RMSE}{STDFV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}(Z_s - Z_o)^2}}{\sqrt{\sum_{i=1}^{n}(Z_o - \overline{Z_o})^2}} \tag{1}
\]

\[
NSE = 1 - \left[ \frac{\sum_{i=1}^{n}(Z_o - Z_s)^2}{\sum_{i=1}^{n}(Z_o - \overline{Z_o})^2} \right] \tag{2}
\]

\[
PBIAS = \frac{\sum_{i=1}^{n}(Z_s - Z_o)}{\sum_{i=1}^{n}(Z_o)} \times 100 \tag{3}
\]

Where \(Z_s\) is the simulated value for the constituent being evaluated, \(Z_o\) is the observation for the constituent being evaluated, \(Z_o\) is the mean of observed data for the constituent being, and \(n\) is the total number of observations.

For RSR, it ranges between 0, which is the optimal value, to a large positive value. It means that the lower value of RSR means lower value of RMSE, and the better the model simulation. NSE varies from 0 to 1 and value of 1 corresponds to a perfect match of the model simulation outputs to the observation. The optimal value of PBIAS is 0.0, positive values indicating overestimation bias, and negative values indicating underestimation bias. In general, the model simulation can be judged as “satisfactory” if NSE > 0.50, RSR < 0.70, and PBIAS < ±25% for the Streamflow [29].

4. RESULTS AND DISCUSSION

The evaluation was performed by comparing the simulated outflows with the observed outflows at the effective locations of Diem, Khartoum and Dongala stations respectively, shown in Figure 5.

Figure 5 (a, b, and c) show the match between the Riverware simulated flow and the observed data; as it possible to notice, it does not catch the peak for some flood seasons. The mismatching in the peaks may be return to the flash floods which occurs in most of this period in the west of Khartoum station and affect the main stream directly. These amounts of water affect the scale of Khartoum station on the Blue Nile and then the scale of Dongala station. There is a small deviation.
between the simulated flow and the observed at Khartoum station in the recession period, where the observed data could have some error in the recession period due to the rating curve equation. The worst result in Dongala station simulation is the flood season 2009, the beginning of the Merowe dam operation. This could be due to the different operation rules in the first two years of the Merowe dam operation. In general, the model updating depends on a simulated data (from NFS simulated flow), which is not error free. However, the error could be accepted in the absence of observed data. In addition, the main objective from these kind of models is producing scenarios to support the decision makers with scientific information for planning and management, which encouraged to accept this error.

\[ \text{Figure 5. The comparison of the RiverWare simulation flow and observed flow data at (a) Diem station; (b) Khartoum station; (c) Dongola station} \]
The evaluation criteria were performed over the period (2003-2014). Table 3 shows the evaluation results respectively of the NSE, BIAS % and RSR at three locations; Diem, Khartoum and Dongala. All metrics were accepted according to published criteria [29]. The NSE for all stations is > 0.75, where they are categorized as very good. The RSR values for all stations < 0.5, where confirmed the category of the accepted values. The Bias (%) is very small, however the maximum values (-12.02 %) still within the acceptance range.

Table 3. Evaluation criteria for the simulated flow compared to the observed

<table>
<thead>
<tr>
<th>Location</th>
<th>Evaluation period (2003-2014)</th>
<th>NSE</th>
<th>BIAS (%)</th>
<th>RSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue Nile at Diem</td>
<td></td>
<td>0.89</td>
<td>-8.94</td>
<td>0.33</td>
</tr>
<tr>
<td>Blue Nile at Khartoum</td>
<td></td>
<td>0.86</td>
<td>-12.02</td>
<td>0.37</td>
</tr>
<tr>
<td>Main Nile at Dongola</td>
<td></td>
<td>0.83</td>
<td>-1.51</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Note. NSE = Nash-Sutcliffe efficiency; BIAS (%) = Percent bias; RSR = RMSE/observations standard deviation ratio.

The evaluation criteria were formed also for the HAD reservoir to check the calibration for the reservoir routing by comparing the HAD observed level with simulated level at first day of each month during the period (1985 – 2014), see Table 4, which represents the values of the evaluation criteria for the HAD reservoir. The results of NSE and the RSR is accepted and categorized as good results and the Bias (%) is very small.

Table 4. Evaluation criteria for the simulated HAD upstream level compared to the observed

<table>
<thead>
<tr>
<th>HAD Upstream Level</th>
<th>NSE</th>
<th>BIAS (%)</th>
<th>RSR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.69</td>
<td>-1.34</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Figure 6 (a, b, and c) show the simulated mean monthly flow compared with the observed mean monthly flow at the locations of Diem, Khartoum and Dongala respectively during the evaluated period (2003-2014). The simulated flow for the three locations is close to the observed flow. There is a slightly overestimation in the flood limb from May till June in Khartoum, where it is underestimation in Dongola. For the three locations, the simulated flow doesn't catch the flood peak values accurately, but the error according to the statistical criteria could be accepted. It is obvious from the results of the statistical criteria that the BIAS (%) at Dongola gauge is lower than its value at Diem gauge, but NSE at Dongola gauge is lower than NSE at Diem gauge and this is due to the instability of the operation policies of Merowe dam.

Figure 6. Mean monthly simulated and observed flows at (a) Diem station; (b) Khartoum station; (c) Dongola station
Figure 7, shows the simulated of the monthly first day compared with observed monthly first day during the period (1985-2014). The simulation is overestimated during the periods (1985-1998) and (2010-2014), and slight underestimated from 2005 till 2010, however they are too close in the period from 1998 till 2005.

5. CONCLUSIONS

This paper succeeded to update the Nile Schematic on RiverWare software until 2014 after Wheeler et al. [17] fed the model with data until 2002, while the updating methodology could be applying at any time the data will be available.

The model evaluation was performed by simulating the historical conditions including, channel diversions, dam operations and same pattern of the water user diversion request, as well as simulating the hydrologic flows for the updated data (2003-2014).

The NSE, BIAS % and RSR at the effective locations of Diem, Khartoum and Dongola stations were considered as the statistical criteria for the evaluation process. All metrics were considered very good or good.

Finally, this study is able to define a well-designed operation-policy modelling framework that provide accuracy, transparency, and flexibility to develop and test innovative solutions and explore several alternatives and solution scenarios for the negotiations.

More significant researches are coming up using the output from this paper to investigate innovative solutions considering the GERD and other future development projects namely “Mendaia, Beko Abo and KaraDodi dams”.

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Conflicts of Interest: The author declares no conflicts of interest.

REFERENCES


