SESSION 4

Surface Water Resources Management

Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2020.25510

Using satellite rainfall data to estimate direct flow

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ABSTRACT

The main objective of this paper is to develop methodology for obtaining basin hydrological data for the Blue Nile sub-basins; as well to establish different types of data bank for the Blue Nile River Basin (BNRB). Data scarcity has been regarded as a huge problem in modeling the water resources of the Blue Nile River Basin. Satellite rainfall data together with the evapotranspiration have been used to calculate the runoff data. However, in data-scarce regions such as in a transboundary basin, remote sensing data could be a valuable option for hydrological predictions when ground rainfall stations are not available; as well as the remote sensing data can be used to fill gaps in the ground rainfall stations. The satellite rainfall data for all Blue Nile sub-basins were downloaded in a monthly basis for the period 1980–2010 from the Global Weather Data for the National Centres for Environmental Prediction (NCEP) from its website (www.globalweather.tamu.edu). This data were modified with the actual measured rainfall from near gauge stations for the period 1993–1999 by using a weighting factor depending on the distance between satellite data, by using inverse equation and the distances between the middle of sub-basins and the first and second nearest measured rainfall stations, respectively, the modified satellite rainfall data have been found. The selection of the boundary coordinates is used for each sub-basin to set the nearest rainfall satellite station in the middle of each sub-basin and, this is done by using the global weather and Google earth capability. The relation between modified rainfall data and the satellite rainfall data has been found. Different types of input data are used in the WEAP model after being modified and calibrated, such as satellite rainfall data, ET_{ref}, effective precipitation, and crop coefficient K_c in the upper Blue Nile basin. The study area has been divided into 16 sub-basins. WEAP model has been applied to the whole Blue Nile basin, keeping the monthly values of K_c same among the different sub-basins for the whole simulated period of 1980–2010. The observed stream flows, using rainfall-runoff relationship, have been simulated with the measured flows by using WEAP model at the four river gauging stations (El-deim, Giwiasi, Hawata and Khartoum) in a monthly time step yielded reasonable values. By evaluating the Blue Nile River Basin at the calibration period (1980–1995) in a monthly time step, the NSE, r^2, and d results for the Blue Nile River at the gauging stations showed a very good model performance.

Keywords: Satellite; Rainfall; Blue Nile River; Flow

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1. Introduction

The Nile River, with a length of 6,825 km [1], is the longest river in the world. It comprises of three major tributaries, the Blue Nile; the White Nile, and Atbara river. The White Nile River starts its journey from the Great lakes region of Central Africa to the north. While the Blue Nile starts its journey from Lake Tana in Ethiopia. The Atbara River starts its journey from Ethiopian high lands till it joins the Main Nile river just upstream Atbara in northern Sudan. The Blue Nile River and White Nile River meet in Khartoum, capital of the Sudan, forming the Main Nile River which flows northwards through Sudan, Egypt, and drains finally into the Mediterranean Sea [1]. The 11 countries that share the Nile River Basin are Burundi, Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda.

Geographically, the BNRB is a transboundary water source shared by Ethiopia and Sudan; nonetheless Egypt is the most benefiting country from its water resources [2].

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Presented at the 13th Gulf Water Conference – Water in the GCC: Challenges and Innovative Solutions. 12–14 March 2019, Kuwait

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The importance of the BNRB can be represented in the huge percentage of its water contribution to the mean Main Nile River flow (51.61%), while it is also unique on its wide seasonal variation in its discharge and problems of erosion upstream (i.e., lost more than 250 million m^3 of topsoil) and sedimentation downstream (i.e., silt accumulation in the reservoirs) [3].

2. Satellite rainfall data

The satellite rainfall data have many applications in applied climatology and biogeochemical modeling, as well as in hydrology and agricultural meteorology. The satellite rainfall data are available through the International Water Management Institute is World Water and Climate Atlas (http://www.iwmi.org), as well as it available at the website of the Climatic Research Unit (http://www.cru.uea.ac.uk).

The satellite rainfall data for all Blue Nile sub-basins were downloaded in a monthly basis for the period 1980–2010 from the Global Weather Data of the National Centers for Environmental Prediction (NCEP) from its website (www.globalweather.tamu.edu). This data were modified with the actual measured rainfall from nearby gauge stations for the period 1993–1999 by using weighting factor depending on the distance between satellite nodes, by using inverse equation number 1. All the modified rainfall data for the 16 Blue Nile River sub-basins were found, as described in Figs. 1–16. The selection of the boundary coordinates is used for each sub-basin to set the nearest rainfall satellite node to the middle of each sub-basin and, this was done by using the global weather and Google earth capability.

$$R_m = \frac{\frac{1}{X^2}}{\left[\frac{1}{X^2+\frac{1}{Y^2}}\right]} \times R_{\text{mst1}} + \frac{\frac{1}{Y^2}}{\left[\frac{1}{X^2}+\frac{1}{Y^2}\right]} \times R_{\text{mst2}} \qquad (1)$$

where X: distance (in km) between the nearest satellite rainfall node to the middle of the sub-basin and the first nearest measured rainfall station to the middle of the sub-basin.

Y: distance (in km) between the nearest satellite rainfall node to the middle of the sub-basin and the second nearest measured rainfall station to the middle of the sub-basin.
R_{mst1}: measured rainfall in the first nearest station
R_{mst2}: measured rainfall in the second nearest station

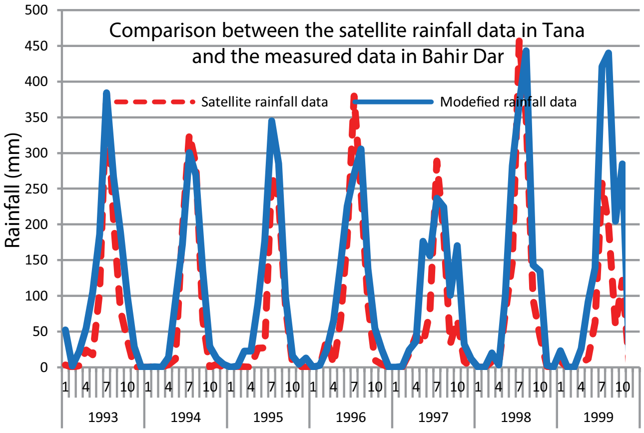

Fig. 1. Adjusted satellite rainfall data for Tana sub-basin.

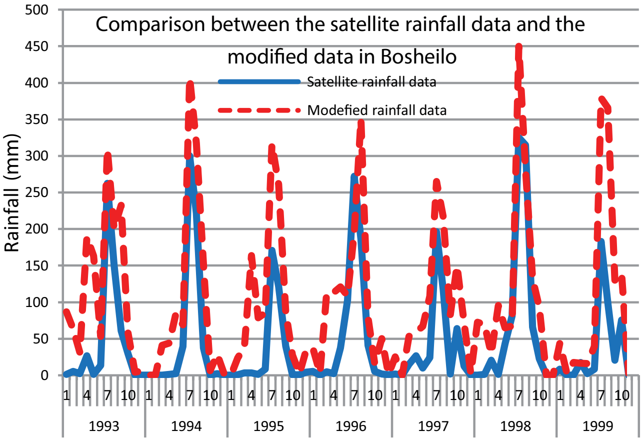

Fig. 2. Adjusted satellite rainfall data for Bosheilo sub-basin.

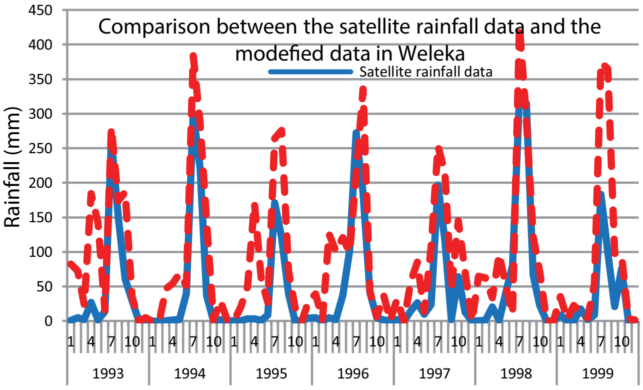

Fig. 3. Adjusted satellite rainfall data for Weleka sub-basin.

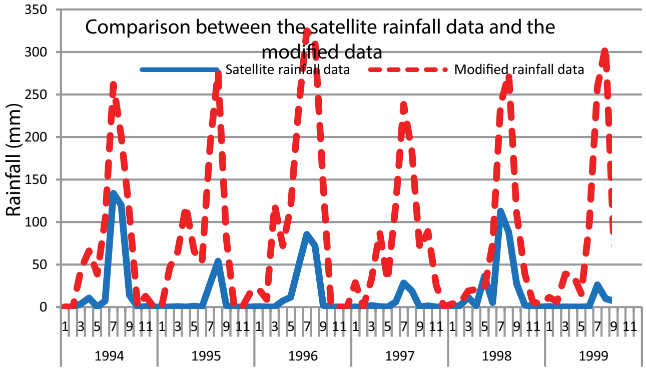

Fig. 4. Adjusted satellite rainfall data for Jemma sub-basin.

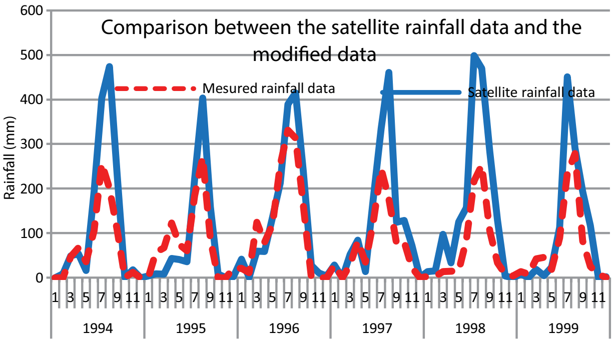

Fig. 5. Adjusted satellite rainfall data for Muger sub-basin.

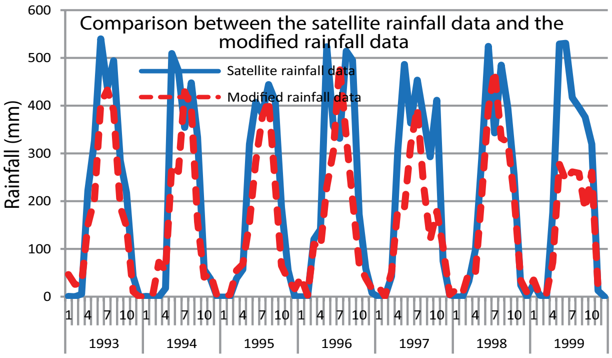

Fig. 9. Adjusted satellite rainfall data for Dabus sub-basin.

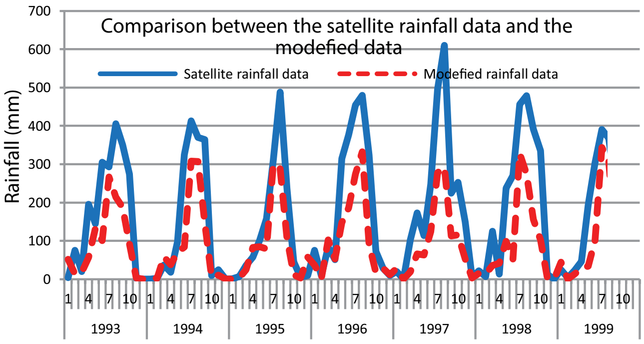

Fig. 6. Adjusted satellite rainfall data for Guder sub-basin.

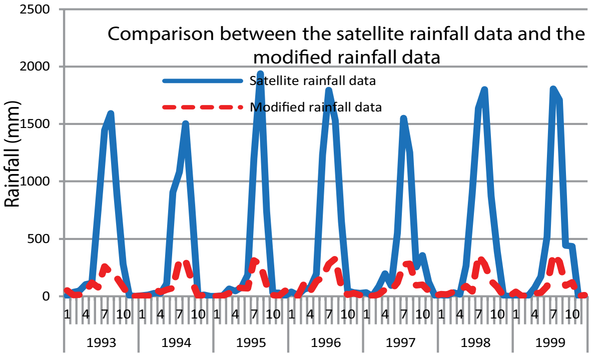

Fig. 10. Adjusted satellite rainfall data for South Gojam sub-basin.

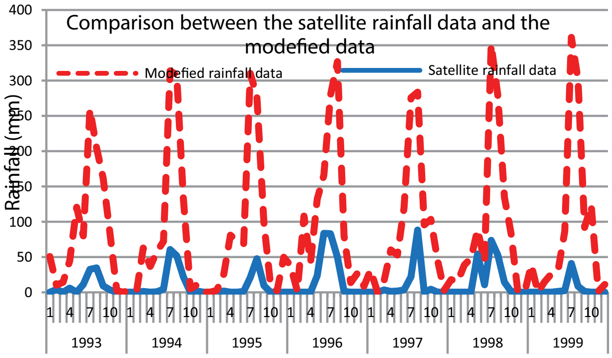

Fig. 7. Adjusted satellite rainfall data for Finchaa sub-basin.

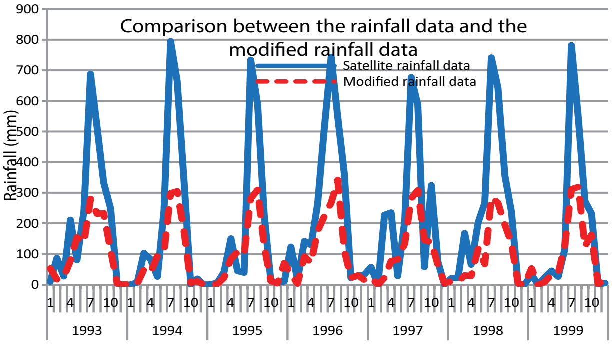

Fig. 11. Adjusted satellite rainfall data for North Gojam sub-basin.

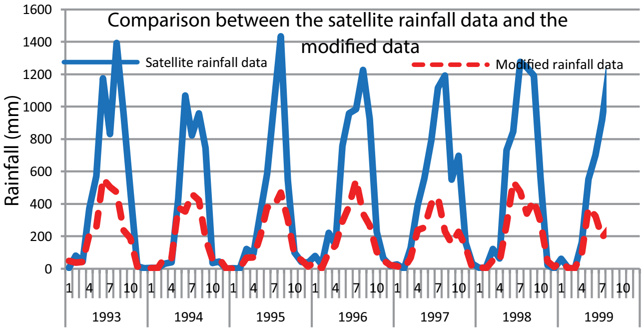

Fig. 8. Adjusted satellite rainfall data for Didessa sub-basin.

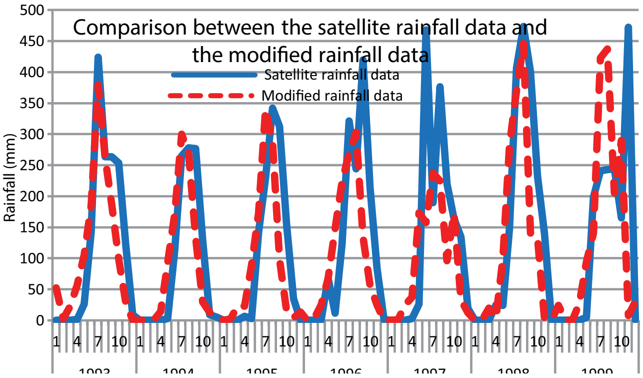

Fig. 12. Adjusted satellite rainfall data for Rahad sub-basin.

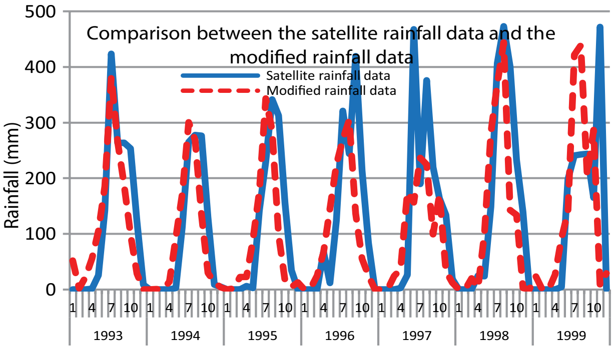

Fig. 13. Adjusted satellite rainfall data for Dinder sub-basin.

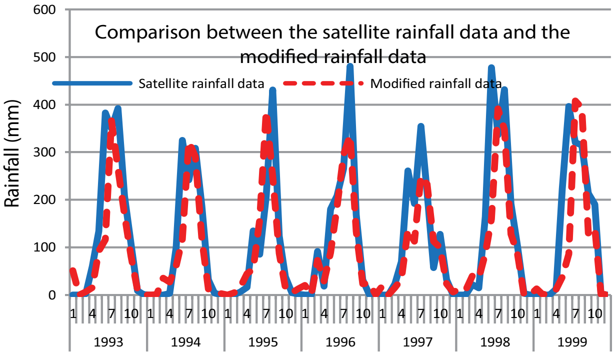

Fig. 14. Adjusted satellite rainfall data for Beles sub-basin.

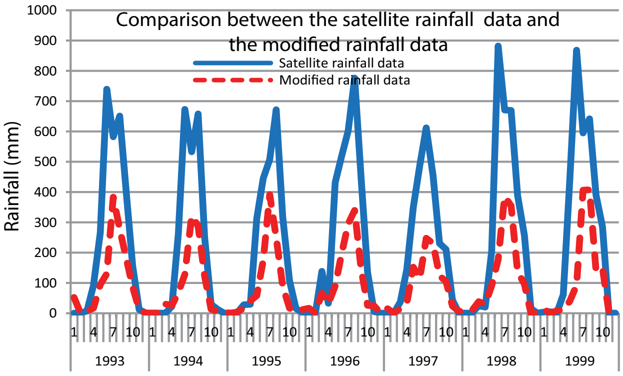

Fig. 15. Adjusted satellite rainfall data for Wonbera sub-basin.

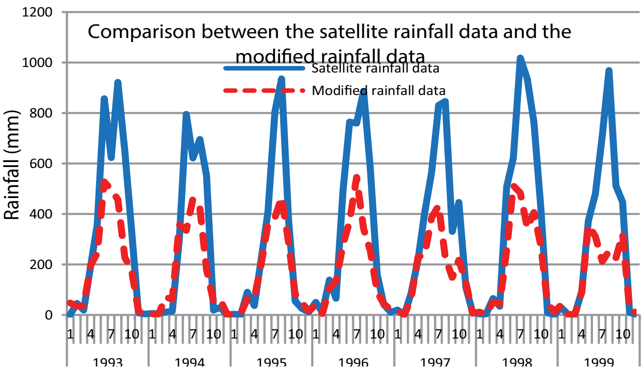

Fig. 16. Adjusted satellite rainfall data for Anger sub-basin.

R_m: modified rainfall for the nearest satellite rainfall station, which represents the rainfall for the middle of sub-basin.

Based on the average monthly $\mathrm{ET}_{\mathrm{ref}}$ data for the whole Blue Nile Basin [3] and the average annual $\mathrm{ET}_{\mathrm{ref}}$ data for each sub-basin, the monthly data $\mathrm{ET}_{\mathrm{ref}}$ for each sub-basin can be found. The monthly $\mathrm{ET}_{\mathrm{ref}}$ for each sub-basin have been found by multiplying the value of the average monthly of $\mathrm{ET}_{\mathrm{ref}}$ of the selected sub-basin by the value of the average annual of $\mathrm{ET}_{\mathrm{ref}}$ of the selected sub-basin divided by the total annual $\mathrm{ET}_{\mathrm{ref}}$ for the whole Blue Nile Basin.

3. Water balance equation

The water balance equation for the BNRB on monthly basis can be written as (Tekleab, 2010):

$$\frac{ds}{dx} = P - Q - E - L \tag{2}$$

where:

$\frac{ds}{dx}$ is storage change per time step (mm/month).

P is the precipitation (mm/month).
Q is the total monthly runoff (mm/month) depth.
E is the actual monthly evaporation (mm/month).
L is the total loss (such as deep percolation and interception losses).

By assuming storage, fluctuations are negligible over monthly time scale, the water balance equation can be reduced to [4]:

$$P - Q - E - L = 0 \tag{3}$$

$$Q = P - E - L \tag{4}$$

4. Runoff estimation

A comprehensive effort has been made to download the rainfall satellite data from 1980 to 2010 in monthly basis at all of the Blue Nile sub-basins. The simplified rainfall runoff method has been used to determine the contribution of each tributary to the BNRB. The runoff from each BNRB sub-basins are estimated by using the rainfall-runoff simplified method, which considers that each sub-basin within a catchment have different climate data.

$$Q = f\left(P, \mathrm{ET}_{\mathrm{ref}}\right) \tag{5}$$

$$Q = P \times A \times f_1 - \mathrm{ET}_{\mathrm{ref}} \times \left(A \times f\right) \times K_c \times f_v - L \tag{6}$$

where:

Q is the total monthly discharge (Million m^3/month).
P is the total monthly modified satellite rainfall (mm/month).

A is the sub-basin area.

f_1 is the percentage of each sub-basin area that will be wetted by rainfall.

ET_{ref} is the monthly average evapotranspiration for a reference land class.

K_c is the crop coefficient.

f is the represents the adjusted factor for real and average of ET_{ref}.

f_v is the percentage of the vegetation cover.

L is the loss (=0).

5. Simulation MODEL (WEAP)

In order to test WEAP model's ability and to simulate runoff in the basin, the record was split into two parts. The data for the first 16 years (1980–1995) were used to calibrate the runoff, where the second 15 years (1996–2010) are used for validation process. To determine the adjusted factor for real evapotranspiration for each sub-basin on monthly basis during calibration step, a trial and error procedure with a range of logical values and actual existing was used (average value for the whole Blue Nile Basin), thus the evapotranspiration can be generated.

The WEAP model data have been simulated with the measured stream flows in the four main stations (Eldeim, Giwasi, Hawata, and Khartoum) and it shows a very good performance for the 16 sub-basins of the Blue Nile Basin. The Nash and Sutcliffe efficiency ENS was applied for monthly flow for the period (1980–1995) was found 89% in the Eldeim station, while for the verification period (1996–2010) it was found to be 80%. The model performance was tested also by percentage bias (PBIAS) at Eldeim station at the calibration period which gives (–18.72) a negative value which indicates overestimation simulated data at Eldeim station. As well as other efficient criteria, such as coefficient of determination (r^2) and the index of agreement (d) are also considered to test the model performance, where it was summarized in Table 1. Thus the model shows high accuracy in all its tested stations. As well, the model was tested for its efficiencies at the validation period (1996–2010; Table 2).

6. WEAP setup for Blue Nile river basin and simulations

Stockholm Environment Institute (SEI) developed the WEAP model, which was used to evaluate and manage water resources projects. The WEAP model essentially performs different demand calculation methods, such as rainfall-runoff method.

The WEAP model has been selected to be applied as one of the research methodology for its huge advantages, such as easy to use; free 2-year license for research work; its ability for simulation of a wide range of data, rainfall, runoff, and other hydrological data.

A WEAP model was set up for BNRB between Sudan and Ethiopia. The model used different sources for input data and information to establish a transboundary water resources management for the BNRB countries. In particular, the models were required to address different questions to secure sustainability of water resources management in the BNRB.

Long-term monthly total values (January to December) for the research period (1980–2010) as well as total annual values for both water availability and demand were used in the modeling.

The WEAP model first configured to simulate the current situation '1980–2010'. As well as, the research used five different scenarios to assess the situation in the future.

Due to the limitation (availability) of the input data in the WEAP model, that is, 'rainfall' from satellite website for the period 1979 till 2010 from website (www.globalweather.tamu.edu), and easy to calibrate these data with the measured data, the research used the period 1980 to 2010 as a research period.

Table 1
Model efficiencies at selected stations at the calibration period (1980–1995)

Station	River	Nash–Sutcliffe efficiency (NSE) %	Coefficient of determination (r^2) %	Index of agreement (d) %
Eldeim	Blue Nile	89	95	97
Giwasi	Dinder	96	98	99
Hawata	Rahad	88	95	97
Khartoum	Blue Nile	67	88	92

Table 2
Model efficiencies at selected stations at the validation period (1996–2010)

Station	River	Nash-Sutcliffe Efficiency (NSE) %	Coefficient of Determination (r^2) %	Index of agreement (d) %
Eldeim	Blue Nile	80	90	95
Giwasi	Dinder	62	84	85
Hawata	Rahad	86	93	96
Khartoum	Blue Nile	72	88	93

7. Analysis and results

The research used the satellite website to download the monthly rainfall data for all Blue Nile sub-basins for the period 1980–2010. Then the satellite rainfall data were modified with the actual measured rainfall stations for the period 1993–1999. Figs. 17–19 show the comparisons between the satellite rainfall data at the middle of Tana sub-basin and the nearest measured rainfall data before (that are Gonder and Bahir Dar stations) and after modification, by using weighting distance factor.

Before the modification, the Nash efficiency was 76%, where after modification the efficiency has been found as 94%, which gives more reliable rainfall data.

8. Water resources projects before Roseires heightening

The current water resources projects demand data were collected from data provided by Sudan Ministry of Water Resources, Irrigation and Electricity, Ministry of Water and Energy (Ethiopia) and agencies or from previous studies, where there is some information obtained from direct contact with responsible and research engineers. The gathering data include different information regarding water flow through the turbines and water required for irrigation in monthly values.

The research makes different assumptions, regarding irrigation return flows, consumption, maximum monthly flow percentage of demand (withdrawal), loss from system (return flow).

The research used Eq. (1) to calculate monthly time series runoff from all Blue Nile sub-basin. As well as, the research used a joint calibration to calibrate the rainfall runoff model for flow time series. The research considered each sub-basin, within the model domain to find realistic parameters. The adjusted factors of evapotranspiration in monthly basis, for all the 16 sub-basins, have been used to evaluate the efficiency of the WEAP model (at Eldeim station), at Giwasi (Dinder), Hawata (Rahad) and finally the WEAP model performance has been evaluated for all the Blue Nile basin (at Khartoum station; Fig. 20).

In order to test WEAP model's ability and to simulate runoff in the basin, the record was split into two parts.

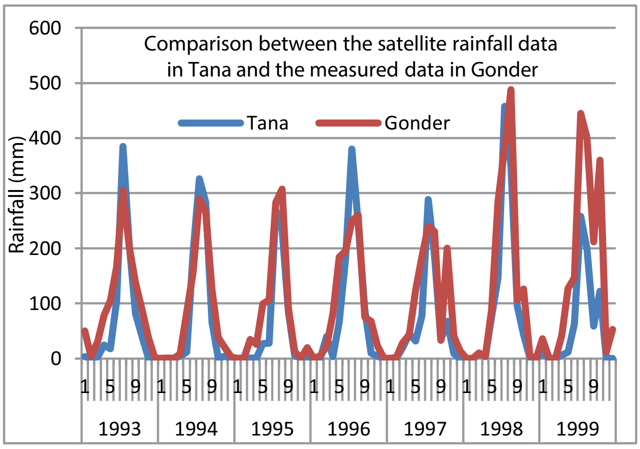

Fig. 17. Comparison between the satellite rainfall data at middle of Tana sub-basin and Gonder rainfall station (before modification).

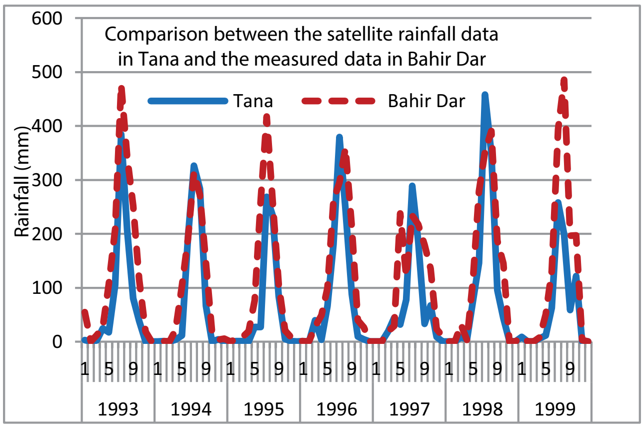

Fig. 18. Comparison before modification, satellite rainfall data at middle of Tana sub-basin and Bahir Dar rainfall station.

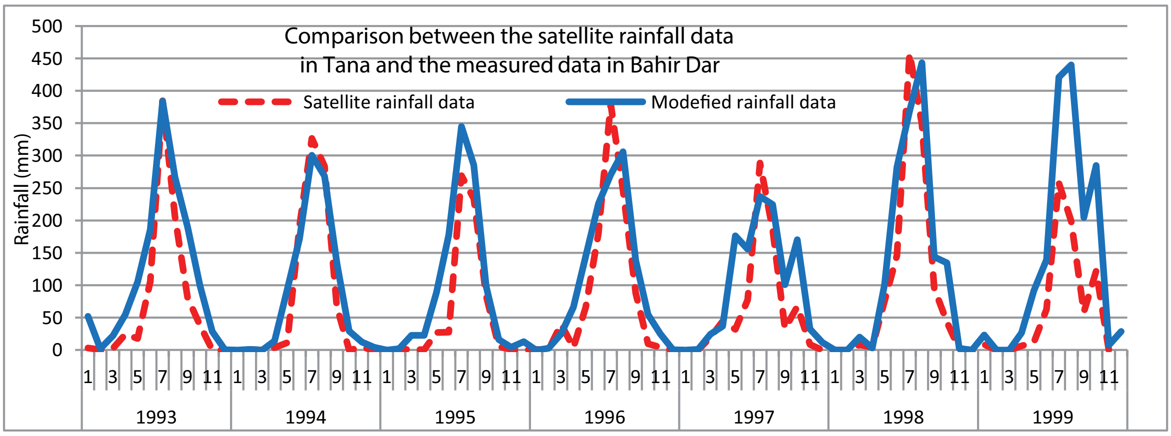

Fig. 19. Comparison after modification between satellite rainfall data at middle of Tana sub-basin and at the Gonder and Bahir Dar rainfall stations.

The data for the first 16 years (1980–1995) were used to calibrate rainfall and runoff purposes, where the second 15 years (1996–2010) are used for validation.

The WEAP model data have been calibrated and validated against the historical stream flow data, by using different types of efficiencies, in the four main stations (Eldeim, Giwasi, Hawata and Khartoum), as it can be seen in Tables 3 and 4.

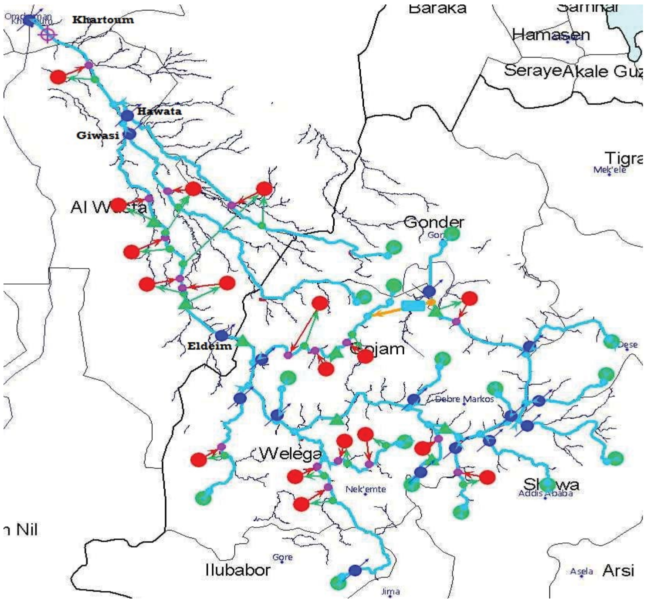

Fig. 20. Schematic of the BNRB in the WEAP model.

During the calibration period (1980–1995), the WEAP model efficiency was calculated using Nash and Sutcliffe method (ENS) for monthly flow prediction in Eldeim station and was found to be 89% (as in Table 3), while for the verification period (1996–2010) it was found as 80% (Table 4). The model performance was tested also by using percentage bias (PBIAS) method at Eldeim station for the calibration period which gives (–18.72), where the negative value indicates there was an overestimation simulated data at Eldeim station; as well as other efficient criteria such as coefficient of determination (r^2) and the index of agreement (*d*) are considered to test the model performance, as it was summarized in Tables 3 and 4. Thus the model shows high accuracy in all the tested stations, where it was suggested that the WEAP model has high degree of efficiencies during the calibration and validation periods, thus it can be used for future analysis for flows in Eldeim station and other gauged (Giwasi, Hawata, and Khartoum); as well as the model can be used at any ungauged stations. Table 5 and Fig. 21 show the proposed future structural scenarios and expected result obtained by WEAP model, respectively.

9. Discussion

In 2011, the Blue Nile Basin countries consumed about 7,803 Million m^3/year (196.9 Million m^3 for Ethiopia, and 7,606.2 Million m^3 for Sudan) to satisfy irrigation requirements. At the same time, the production of the hydropower from the Blue Nile Basin reaches at the current status 513 MW (218 MW benefits by Ethiopia, and 295 MW benefits by Sudan), where it reaches up to 9,493 MW in 2031

Table 3
Model efficiencies at selected stations at the calibration period (1980–1995)

Station	River	Nash–Sutcliffe efficiency (NSE) %	Coefficient of determination (r^2) %	Index of agreement (*d*) %	PBIAS
Eldeim	Blue Nile	89	95	97	O.E.
Giwasi	Dinder	96	98	99	O.E.
Hawata	Rahad	88	95	97	O.E.
Khartoum	Blue Nile	67	88	92	O.E.

O.E.: overestimation values.

Source: Prepared by the researcher.

Table 4
Model efficiencies at selected stations at the validation period (1996–2010)

Station	River	Nash-Sutcliffe Efficiency (NSE) %	Coefficient of Determination (r2) %	Index of agreement (d) %	PBIAS
Eldeim	Blue Nile	80	90	95	O.E.
Giwasi	Dinder	62	84	85	U.E.
Hawata	Rahad	86	93	96	U.E.
Khartoum	Blue Nile	72	88	93	O.E.

O.E.: overestimation values.

U.E: underestimation values.

Table 5
Proposed future scenarios

Scenario number	Scenario code	Description
Scenario 1	S – 1	This scenario considered construction of Tana-Beles and Roseries Dam Heightening (TBRDH), considering all projects in Current situation, for the period 2011–2016
Scenario 2	S – 2	This scenario considered construction of Grand Ethiopian Resilience Dam (GERD), considering all projects in S-1, for the period 2017–2023
Scenario 3	S – 3	This scenario considered construction of Karadobi Dam with others future irrigation projects, considering all projects in S-2, for the period 2024–2030
Scenario 4	S – 4	This scenario considered construction of Mendaya dam, considering all projects in S-2, for the period 2024–2030, as parallel scenario to S-3
Scenario 5	S – 5	This scenario considered construction of all projects in S-3 and S-4, for the period 2031–2040

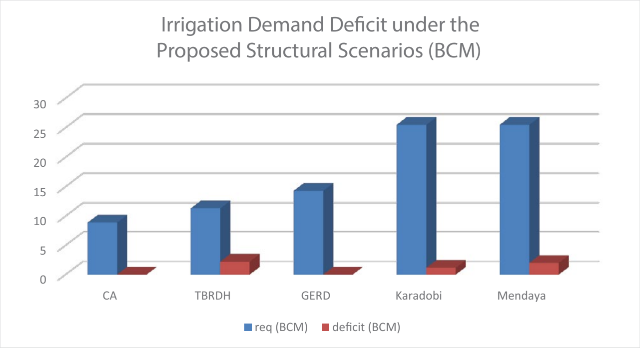

Fig. 21. WEAP results for selected structural scenarios for irrigation water requirements.

(9,148 MW utilized by Ethiopia, and 345 MW utilized by Sudan).

In setting WEAP for Blue Nile River Basin (WEAP_BNRB), it is required to define the priority order in the systems for all water resources projects, and for filling reservoirs and generating hydropower. The research gave a high priority for hydropower production in Ethiopia (=1) and lower in Sudan (2), whereas the research gave higher priorities for irrigation in Sudan (=1) and lower in Ethiopia (=2).

Regarding Scenario (S-1), there are irrigation demands deficit for Gezira and Sennar-Khartoum and for other irrigation projects, which can be due to the increased amount of the Roseries storage after heightening, especially due to the increase in the top of inactive (volume in reservoir not available for allocation), which was increased from 30.1 Million m^3 (in the current situation 2010) to 172.4 Million m^3.

One of the main research contributions is the establishment of different types of data bank for the BNRB, independent of the intervention of the human being, especially for the transboundary river basin and hence not waiting for data sharing protocol which may take a long time to be realized.

Regarding Scenario (S-2), there are unmet demands to satisfy the irrigation requirement, especially in 2017, due to the first filling of the reservoir [5]. There are only 9% irrigation demand deficit for Gezira scheme, and 7.8% for Sennar-Khartoum schemes. Also, there is 18.7% unmet demand for irrigation project in Finchaa which is due to the proposed extension of the project. This simulation has been made by giving a less priority to reservoir filling (priority = 3). At the same time, the research assumes high hydropower priority (=1), when comparing with the other demands.

Regarding (S-3), it has been noticed that there are no unmet irrigation demands for Gazira and all other Sudanese irrigation projects except for the whole future irrigation projects (i.e., Kenana-1, Kenana-II, Kenana-III, Kenana-IV) with about 9%. For Ethiopian irrigation projects, it has been noticed that there is 83% unmet demand for Lower and Upper Beles irrigation water projects.

Regarding Scenario (S-4), it has been noticed that there are no unmet irrigation demands for Gazira and all other Sudanese irrigation projects except for the whole Future irrigation projects (i.e., Kenana-1, Kenana-II, Kenana-III, Kenana-IV) with about 15.6%. For Ethiopian irrigation projects, it has been noticed that the whole water requirement for Lower and Upper Beles irrigation water projects is unmet.

Regarding Scenario (S-5), it has been noticed that there are no unmet irrigation demands for Gazira and all other Sudanese irrigation projects except for the whole Future irrigation projects (i.e., Kenana-1, Kenana-II, Kenana-III, Kenana-IV, Dinder, Roseries, Rahad-II and Rahad-III) with 40%, where the total water requirements are 9.43 BCM. For Ethiopian irrigation projects, it has been noticed that there is about 24% unmet demand for Lower and Upper Beles irrigation water projects.

Regarding Scenario (S-5), the research also examined the Blue Nile River Basin by changing the GERD reservoir-filling priority to be something of less priority (=3). It has been noticed that in this case there are no unmet irrigation demands for all the Sudanese irrigation water projects.

10. Conclusion

Rainfall-runoff relationship is a tool to predict the river discharge. Based on the mathematical relationship and assumptions in the rainfall-runoff relationship for the BNRB, a simplified rainfall-runoff relationship was used to predict the monthly flows.

Different water management models exist, but WEAP model has been selected to adapt current and future analysis regarding water resources projects.

The Blue Nile River has 16 major sub-basins, with a total basin area of 203,665 km^2, and average annual flow of about 51.61% when comparing with the annual flow of the Nile River for the simulation period (1980–2010). This large percentage reaches up to 72% of the Nile River flow in the flood period (July, August and September).

The satellite rainfall data for all Blue Nile sub-basins were downloaded in a monthly basis for the period 1980–2010 from the Global Weather Data website for the National Centers of the Environmental Prediction (NCEP; www.globalweather.tamu.edu).

The satellite rainfall data were modified with the actual measured rainfall from nearby gauge stations for the period 1993–1999 by using a weighting factor depending on the distance between satellite data.

The selection of the boundary coordinates was used for each sub-basin to set the nearest rainfall satellite station in the middle of each sub-basin and, this was done by using the global weather and Google earth websites.

The research used the satellite rainfall data for all Blue Nile sub-basins which was downloaded on a monthly basis for the period 1980–2010 from the Global Weather Data. The downloaded satellite rainfall data were modified with the actual measured rainfall from the nearest available gauge station. Using the below simplified rainfall-runoff relationship, the research obtained the runoff in monthly time steps for each Blue Nile sub-basins at its outlet utilizing the capability of WEAP.

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