Hydrological Analysis and Trans-boundary Water Management of the Blue Nile River Basin

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***Abstract*-The main objective of the research is to set a transboundary water management system for the Blue Nile River Basin (within its 16 sub-basins) as well as to create calibrated satellite rainfall data for the Blue Nile River Basin (BNRB). Within the Water Evaluation and Planning (WEAP) model, the simplified rainfall-runoff option has been adopted to determine the runoff of the BNRB, using calibrated satellite rainfall data and adjusted monthly evapotranspiration factors. The WEAP model has been calibrated for the period (1980-1995) and validated for the period (1996-2010) where the simulated and observed flows have been compared at Eldeim, Giwisi, Hawata and Khartoum stations in a monthly time step yielding reasonable values. The results have effectively showed that the simulated flows are reasonable using the Nash-Sutcliffe efficiency criteria (r^2) and the Coefficient of Determination (d) of the model performance. The research has found that unmet demands for water resources projects in BNRB may reach more than 50%, especially when considering a high priority for all water resources projects in the basin for all suggested scenarios. For a better BNRB management between Sudan and Ethiopia, it is required to define the priority order for each project within the Basin and to determine allocations of supplies and demands for these projects. The above cannot be achieved without a strong cooperation reaching between riparian countries in place that eventually lead to joint operation of the large storage structures, such as GERD, Karadobi and Mendaya dams.**

Keywords- Hydrology; Mode; Transboundary Water; WEAP

I. INTRODUCTION

The Nile River; with a length of 6825 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 eleven 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]. 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].

II. METHODOLOGY

The research aims to study different scenarios over the period (2011-2041) depending on the expected and planned revolution in the BNRB, as the research has defined each water year type by specifying how much water will flow into the system in the future relative to a Normal (average) water year. This has been achieved by grouping the years from 2011 to 2041 into five categories, and then the research computes the percentage of variation from the normal year.

The research used the method that using the Climate Forecast System Reanalysis (CFSR) global meteorological dataset to obtain historical weather data. As CFSR data are available globally for each month since 1979 till the end of 2010 at a 38-km resolution.

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 [4].

WEAP have been applied in the Blue Nile River Basin (WEAP_BNRB), to examine different management scenarios, the research defined different priorities order in the systems for all water resources projects, and for filling reservoirs and generating hydropower. Such as a high priority for hydropower production in Ethiopia (= 1) and lower in Sudan (=2), whereas

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the research gave higher priorities for irrigation in Sudan (= 1) and lower in Ethiopia (= 2).

III. SATELLITE RAINFALL DATA

The satellite rainfall data have many applications in applied climatology and biogeochemical modeling, as well as in hydrology and agricultural meteorology [5]. 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 was modified with the actual measured rainfall from near bye gauge stations for the period 1993-1999 by using weighting factor depending on the distance between satellite data, by using inverse equation number 1, all the modified rainfall data for the different sub-basins can be found. The selection of the boundary coordinates are 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 capability.

$$\mathrm{Rm} = \frac{\frac{1}{X^2}}{\left[\frac{1}{X^2}+\frac{1}{Y^2}\right]} * \mathrm{R_{mst1}} + \frac{\frac{1}{Y^2}}{\left[\frac{1}{X^2}+\frac{1}{Y^2}\right]} * \mathrm{R_{mst2}} \tag{1}$$

Where:

X: distance (in km) between the nearest satellite rainfall station 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 station 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

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

Based on the average monthly evapotraspiration (ET_{ref}) data for the whole Blue Nile Basin [3], and the Average annual ET_{ref} data of all sub-basins, the monthly data for ET_{ref} in each sub-basin can be found by using manual approach, interspersed with manually implemented trials of parameter set. The monthly ET_{ref} for each sub-basin have been found by multiply the value of the average monthly of ET_{ref} of the selected sub-basin by the value of the average annual of ET_{ref} of the selected sub-basin divided by the total annual ET_{ref} for the whole Blue Nile Basin.

IV. WATER RESOURCES EQUATION

The water balance equation for the BNRB at monthly time scale can be written as [6]:

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

Where:

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

P: is precipitation (mm/month)

Q: is the total monthly runoff (mm/month) depth.

E: is the actual monthly evaporation (mm/month)

L: Are the total losses (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 [20]:

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

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

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V. 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.

$$Q = f(P, ETref) \tag{5}$$

$$Q = P * A * f_l - ET_{ref} * (A * f) * K_c * f_v - L \tag{6}$$

Where:

Q: total monthly discharge (Million m^3/month)

P: total monthly modified satellite rainfall (mm/month), which is downloaded from Global Weather Data [7].

A: sub-basin area, which are calculated by determine the delineation of each sub-basin by using Watershed Modelling System (WMS).

f_l: percentage of each sub-basins area that will be wetted by rainfall

ETref: Monthly average Evapotranspiration for a reference land class

K_c: crop coefficient

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

f_v: percentage of the vegetation cover related to the total sub-basin area, which is varying from month to month and from basin to basin, (represents the vegetation cover percentage related to total catchment area, =1.0)

L: Losses, such as seepage, percolation and other losses, which are negligible here for research purposes (= 0).

VI. SIMULATION PROCEDURE

The WEAP model data has been simulated with the measured stream flows in the four main stations (El-deim, 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, Nash and Sutcliffe (1970), 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 80%. The model performance was tested also by percent 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.

TABLE 1 MODEL EFFICIENCIES AT SELECTED STATIONS AT THE CALIBRATION PERIOD (1980-1995)

Station	River	Nash-Stucliffe 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.

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TABLE 2 MODEL EFFICIENCIES AT SELECTED STATIONS AT THE VALIDATION PERIOD (1996-2010)

Station	River	Nash-Stucliffe Efficiency (NSE) %	Coefficient of Determination (r^2) %	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.
Krt	Blue Nile	72	88	93	O.E.

O.E.: OVERESTIMATION VALUES. U.E.: UNDER ESTIMATION VALUES.

VII. WEAP SETUP FOR BLUE

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 [8]. The WEAP model have been selected to be applied as one of the research methodology for its huge advantages, such as easy to use; free two year license for research work; it is ability for simulation a wide range of data, rainfall, runoff, and others 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 modelling. The WEAP model firstly 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, i.e. '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 simulation period.

VIII. 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 was modified with the actual measured rainfall stations for the period 1993-1999. Fig. 1, Fig. 2 and Fig. 3 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.

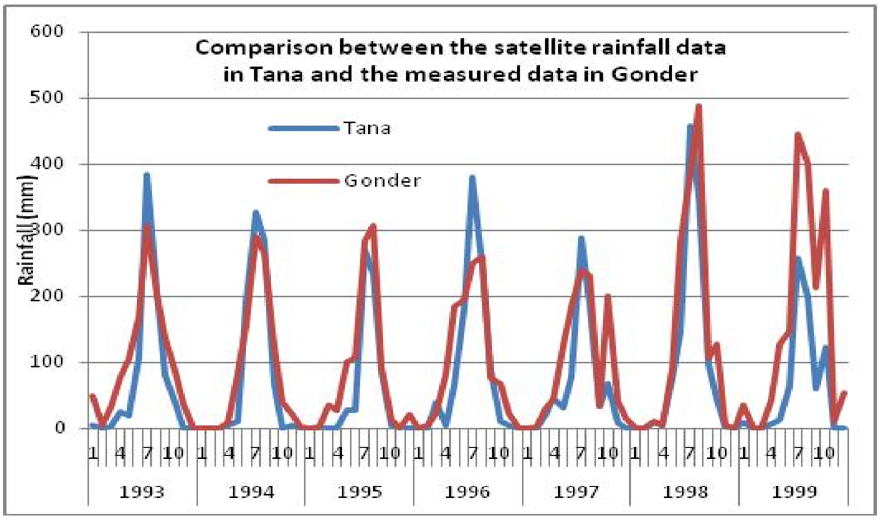

Fig. 1 Comparison between the satellite rainfall data at middle of Tana sub-basin and Gonder rainfall station (before modification)

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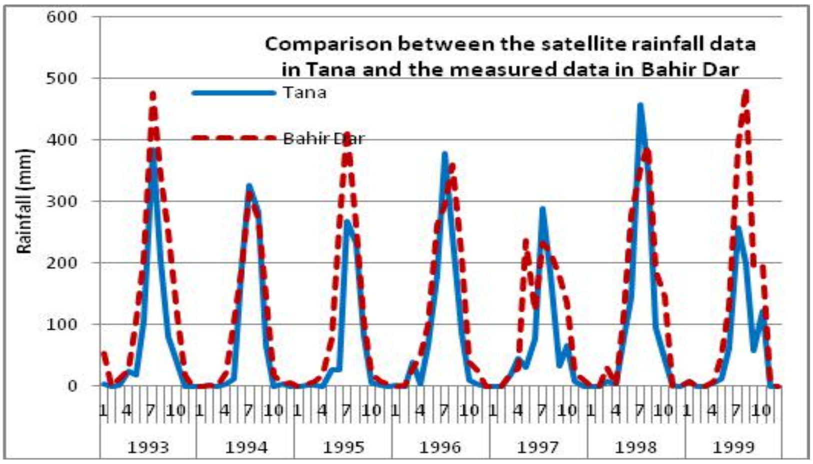

Fig. 2 Comparison before modification, satellite rainfall data at middle of Tana sub-basin and Bahir Dar rainfall station

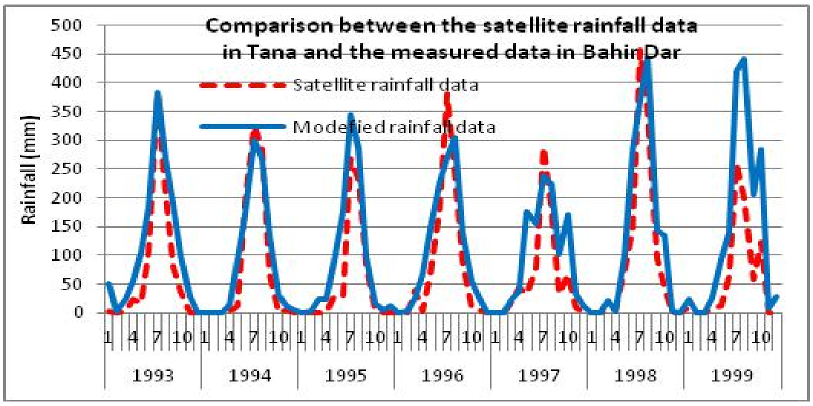

Fig. 3 comparison after modification between satellite rainfall data at middle of Tana sub-basin and at the Gonder and Bahir Dar rainfall stations

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

IX. WATER RESOURCES PROJECTS AT CURRENT SITUATION (2010)

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 are some information are obtained from direct contact with responsible and research engineers. The gathering data includes different information regarding water flow through the turbines and water required for irrigation in monthly values.

The research make different assumptions, regarding irrigation return flows, consumption, maximum monthly flow percent of demand (withdrawal), loss from system (return flow). The research used equation No. 1 to calculate monthly time series runoff from all Blue Nile sub-basins. 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 evapotraspiration in monthly basis, for all the 16 sub-basins, have been used to evaluate the efficiency of the WEAP model (at El-deim station), at Giwasi (Dinder), Hawata (Rahad) and finally the WEAP model performance has been evaluated for the entire Blue Nile basin (at Khartoum station), Fig. 4.

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 rainfall and runoff purposes, where the second 15 years (1996 - 2010) are used for validation. The WEAP model data has been calibrated and validated against the historical stream flow data, by using different types of efficiencies, in the four main stations (El-deim, Giwasi, Hawata and Khartoum), as it can be seen in Table 1 and Table 2.

During the calibration period (1980-1995), the WEAP model efficiency was calculated using Nash and Sutcliffe method (ENS) for monthly flow prediction in El-deim station and was found to be 89% (as shown in Table 1), while for the verification period (1996-2010) it was found as 80% (Table 2). The model performance was tested also by using percent bias (PBIAS) method at El-deim station for the calibration period which gives (-18.72), where the negative value indicates there was an overestimation simulated data at El-deim station. As well as other efficient criteria such as coefficient of determination

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(r^2) and the index of agreement (d) are consider to test the model performance, as it was summarized in Table 1 and Table 2. 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 El-deim station and other gauged (Giwasi, Hawata, and Khartoum) as well as can be used at any ungauged stations.

There is a broad scientific consensus that global Climate Change is a real problem, which will alter the hydrological cycle in different important steps. There is still little certainty about how to form these changes, or when they will be detected. By given these uncertainties, the research used the assumption to repeat the historical input data (1980-2010) as to be occur again (2011-2041) and to form and constructs the future scenarios, based on the future plan by BNRB countries, Table 3.

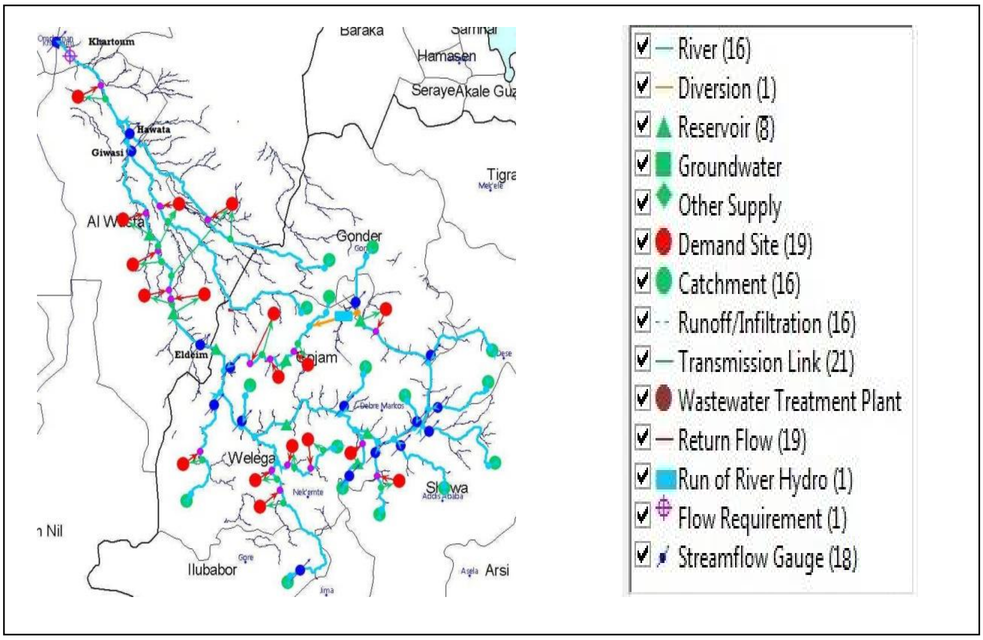

Fig. 4 Schematic Figure of the BNRB in the WEAP model

TABLE 3 BLUE NILE RIVER BASIN 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

X. DISCUSSION

In 2011 the Blue Nile Basin countries consumed about 7803 Million m^3/year (196.9 Million m^3 for Ethiopia, and 7606.2 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 9493 MW in 2031 (9148 MW utilized by Ethiopia, and 345 MW utilized by Sudan). The 1959 Nile water agreement between Sudan and Egypt, gave Egypt 55.5 Billion m^3/year, where it gave Sudan 18.5 Billion m^3/year. After consuming all the future water demanded for Sudan and Ethiopia irrigation projects, the research found that Egypt share will not be affected by any reduce in their quota from the Blue Nile share.

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

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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. It has been noticed that all the hydropower requirement in Roseries dam have been met, where there is 16.4% regarded as an unmet hydropower demands in Sennar dam. This is due to less hydropower priority that is given in Sennar dam rather than in Roseries dam. Besides, there is about 40% regarded as unmet hydropower demands in Chara Chara dam and Tana-Beles. This is due to the equal priority that has been given to both of them.

Regarding Scenario (S-2), there are unmet demands to satisfy the irrigation requirement, especially in 2017, due to the first filling of the reservoir [9]. 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 to the other demands. The research has found that there are unmet demands for irrigation requirements for Gezira scheme as 71.9% from the total requirement in 2017, where this value decreases to 6.7% from the total requirement in 2018. This is due to the assumption of high hydropower priority (=1.0) rather than for irrigation. It has been noticed that all the hydropower requirements in Roseries dam have been met, where there is 10.5% regarded as an unmet hydropower demands in Sennar dam. This is due to less hydropower priority that given in Sennar dam rather than in Roseries dam. Besides, there is about 41.5% regarded as unmet hydropower demands in Chara Chara dam and Tana-Beles in 2017. This is due to the equal priority that has been given to both of them. In addition to that there is 12.8% unmet hydropower demand in 2017 for GERD. This is due to the proposed filling program in the first year.

Regarding (S-3), it has been noticed that there will be 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 will be 83% unmet demand for Lower and Upper Beles irrigation water projects. As it has been noticed that all the hydropower requirement in Roseries and Sennar dams have been met, where there will be 60.7% and 66% is regarded as an unmet hydropower demands in Karadobi and Beles Dangur dams respectively in 2024, this will be due to the filling program in the first year.

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. It has been noticed that all the hydropower requirement in Roseries and Sennar dams have been met, where there is 51.1% and 79.7% is regarded as an unmet hydropower demands in Mendaya and Beles Dangur dams respectively in 2024, this was due to the proposed filling program in the first year.

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 is 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. 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. As it has been noticed that all the hydropower requirements in Roseries and Sennar dams have been met, where also all hydropower requirement by GERD, Karadobi and Mendaya have been met. There is only an unmet hydropower demands by Chara Chara dam and Tana-Beles. As another result for hydropower demands, when the research has also examined the situation of the BNRB by setting the GERD reservoir-filling priority for supply to be something which has less priority (=3). It has been noticed that all the hydropower requirements in Roseries and Sennar dams have been met, where also all hydropower requirement by GERD and Mendaya have been met. There is only an unmet hydropower demands by Karadobi, Chara Chara dams and Tana-Beles.

To sustain the availability of water in BNRB under different scenarios, water management should be adjusted to satisfy the different needs for water resources projects by setting an agreed operation rules for the upstream reservoirs to maintain the increased downstream requirements. This can be achieved by reaching a joint cooperation between the shared countries.

XI. CONCLUSIONS

As there is a broad scientific consensus that global climate change is a real problem, which will alter the hydrological cycle in different important steps. There is still little certainty about how to form these changes, or when they will be detected. By given these uncertainties, the research used the assumption to repeat the historical input data (1980-2010) and to form and construct the future scenarios, these data contain dry, very dry, wet, and very wet years. The availability of water in the BNRB has been examined for each scenario and for each country (Ethiopia and Sudan).

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

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monthly flows. Different water management models exist, but WEAP model have 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 to 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 was 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 was 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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