DOI: 10.2478/sspjce-2025-0005

sciendo

Water Allocation in The Lower Niger River Basin, Nigeria Using WEAP Model

O.T. Amoo[1*], O.A. Taiwo[2], A.W. Salami[2]

[1]Centre for Global Change, Walter Sisulu University, Private Bag X1 UNITRA 5117, Mthatha, South Africa
[2]Department of Water Resources and Environmental Engineering, Faculty of Engineering and Technology, University of Ilorin, Nigeria
[*]e-mail: ejire36@gmail.com

Abstract

The study explores the use of the Water Evaluation and Planning (WEAP) model to determine the water resources available and allocate them among competitive users, comprising domestic, agricultural, industrial, and hydropower users. The resultant optimization result shows the initial total water demand for the base year (2010) to be 3.74 Mm^3, which increases to 8.32 Mm^3 for the projected year 2035. The study has provided valuable insights into optimizing available water resources, with total unmet demand estimated at 0.92 Mm^3 for 2010 and 2.04 Mm^3 for the foreseeable year 2035. The correlation coefficient between simulated ungauged (Shonga) rainfall and convoluted runoff (0.72) to a similar nearby basin (Jebba) with known rainfall and runoff data shows a good NSE validation result (0.63). Beyond water allocation modelling, the study suggests strategies such as water conservation policies, infrastructure improvements and community engagement for efficient regulation of the basin's water use.

Keywords: unmet demand, water allocation, WEAP model, water conservation, Nigeria

1 Introduction

The need to simulate how water resources will be affected, in the face of a changing climate, variability and increasing demand by the growing population, calls for review. The reallocation of resources and management has challenged decision-makers towards the development of tools for a better understanding of the hydrologic processes that govern the generation and movement of water [1]. Moreover, formidable freshwater management and strategies for conservation are confronted in many parts of the globe [2]. This developmental change has dared to make water managers reasonably allocate available water resources to meet the competing demands. Hence, the evolution of an integrated approach that places ecosystem and water quality preservation, water demand side with water supply side in the context of sustainable watershed management, which represents evolving tools in solving this challenge [3,4].

Moreover, most problems associated with water resource allocation are closely related to maintenance and investment, insufficient water infrastructure, inequities in access to their services delivery, deteriorating raw water quality, recurrent droughts and floods driven by

climatic variation and man-induced anthropogenic activities [5]. The outcome of climate variability has resulted in excessive heat waves, wildfires, and flooding in some areas. Hence, both water behavioural change and water technology innovation are required to manage the available freshwater sustainably. Hence, the study explores the use of the Water Evaluation and Planning (WEAP) model for water allocation in the Lower Niger River Basin (LNRB), Nigeria.

The Niger River flows, and its tributaries have been the major water supply in the North Central hydrological area I in Nigeria. There have been several dams along its path exerting considerable pressure on ecosystem resources, coupled with climate variability effect which have had severe consequences on the status of the Niger River and have affected all facets of our lives. The LNRB has witnessed that conflicts often arise between the upstream and downstream users over resource allocation. The effect of Jebba hydropower release, incessant water drawn for the town's users, and the supply to meet the Shonga irrigation scheme have caused many complaints by farmers about water shortages and increasing floods when the authorities open the dam without prior informing people, thereby resulting in untold hardship [6,7]. Thus, the study provides modelers with a valuable tool for effective decision support that helps optimize water distribution systems among competitive users: domestic, agricultural, industrial, and hydropower uses.

Recent computer science developments have allowed complex river basin modelling to be simplified and optimization problems to be resolved quickly without going through the rigour of simulation in resolving users' conflicting limitations and objectives in arriving at possible solutions to the problems. Simulation and optimization techniques have been embedded in many computer programs, thereby assisting the limited human thinking in resolving many of the catchment water allocation problems. Optimization models are intended to achieve system improvement in arriving at the best solution among a series of available solutions, in contrast to simulation models, which are best suited for enhancing and assessing system performance[8]. The most common river basin modelling tools that are particularly related to water allocation planning and sustainable watershed management are not limited to: VENSIM-DSS [9], MODSIM-DSS [10,11], CALSIM [12], Waterware [13], Riverware [14], HEC-family of models (HEC-3, HEC-5, and HEC-ResSim) [15], RIBASIM [16], and Mike Basin [17,18]. Others are WEAP [19,20]; REALM [21], and OASIS [22].

Apart from historically dominated tools that emphasize building blocks of either the engineering component e,g, Riverware, or natural e.g, SWAT [23,24] systems, the WEAP model presents a robust decision support system (DSS) for catchment hydrology and socio-economic factors to be analyzed in an interactive computer-based environment. The model provides a comprehensive, flexible, and user-friendly framework for policy analysis and other metaphysical aspects of water development projects to be analysed [25]. Aside from its wide popularity, the model's ability to perform scenario analyses offers a unique tool for IWRM. Only a few models could compare with WEAP in flexibility, either in GIS incorporation or with hydrological and climatic model integration, while analysing different scenarios. MODSIM rigidity in its static rules and expertise requirements limits its usage in water systems dynamics [26]. OASIS suffers from its inability to integrate GIS and perform groundwater modelling [27]. Tools such as WaterWare, HEC-family, and RIBASIM do not address operational 24-hour short-term optimal water allocation and water control in open channels, while some models have evolved to meet changing water utility needs but are not built to support GIS technology. Comparing the reliability index in MIKE BASIN shows better matches in simulation, even in the distribution of deficits among nodes, while WEAP showed better results for optimization

[28]. WEAP is only limited by its reliance on static assumptions to evolve scenarios without cognizance of dynamic changes in socio-economic and climate variability [29, 30].

The WEAP model was specifically selected for LRNB, based on the optimization problem at hand, the basin characteristics, the limited available data, flexibility, and the time constraint for the study. The model (WEAP) is useful for quick and efficient coordination of decision-making to balance human activities in a given catchment [31]. Unlike other models, it can simulate and optimize benefits, enhancing equity. The WEAP model presents an integrated approach to water management in contrast to other piecemeal tools that artificially separate soil, land, and climate change from human intervention. Aside from the fact that the model could assess hydrological cycles across various scales. It could predict future scenarios using both the spatial-temporal changes information witnessed in the river basin [32-34]. The model allowed the simulation and analysis of various water allocation scenarios and scenarios of users' behaviour to be modelled [35]. Lang et al. [36] assessed the benefits and limitations of applying the WEAP model for assessing and testing the water demand management scenarios in the Steelport sub-basin of the Olifants River, South Africa. The model's main disadvantage lies in its over-reliance on the changes in scenario creation without specifying how these scenarios should be developed. Also, it is the deliberate placing of human interference outside the system's architecture [37-38].

To approach the management of water resources in each geographical context, IWRM has been advocated for systematic management of land, water, and the river basin in a coordinated manner that considers upstream and downstream interests for sustainable allocation, monitoring, and development of these unique resources, which promotes mutual benefit for all [39-41]. The most widely accepted definition is: "IWRM is defined as a process that promotes the coordinated development and management of water, land and related resources, to maximize the resultant economic and social welfare equitably without compromising the sustainability of vital ecosystems" [42]. Furthermore, IWRM has evolved as: "Equitable access to sustainable use of water resources by all stakeholders at catchment, regional and international levels, while promoting equity, addressing poverty, generating economic growth and creating jobs in order to sustain life" [41,43]. The river basin had been considered as a unit, providing essential information for policymakers in an integrated manner, and offering a modeling framework for a comprehensive social, economic, and environmental analysis to be performed within agreed-upon limits. The coordination of human activities and other water demand users, therefore, calls for an integrated approach to management of both the supply and demand sides of water use, with land use. Hence, this study evaluates the use of WEAP software for IWRM at Shonga irrigated agricultural areas to improve crop yields and optimize the available water resources.

1.1 Study area

The study was conducted in the Edu Local Government Area of Kwara State, Nigeria, using the Shonga District as a case study. This area is geographically located within the coordinates 9° 1' 0" North and 5° 9' 0" East of the equator. The area is inhabited predominantly by the Nupe ethnic group, mainly smallholder farmers. The study area has two distinct seasons - wet season (April and October) and dry season (November – March), with an average rainfall range of 50.8 mm to 2413.3 mm. The minimum and maximum average temperature ranges from 21.1°C -

25.0 °C, and 30 °C to 35 °C. Agricultural activities are the predominant occupation of the inhabitants [44,45].

2 Materials and methods

The literature review was carried out on the present water resource uses in the area and how they were allocated to different users. A brief site survey and interviews with farmers and other users were conducted on how efficient and realistic the present employed method was, and suggestions for improvement in meeting their needs were gathered. Thereafter, ArcGIS Software was used for the spatial basin area delineation before being imported into the WEAP Model for Water Demand and Supply simulation analysis. The different users' water allocation was developed based on a priority-driven rule [35]. The generated information and data about water quantity were fed into the WEAP model, considering the study area to be an ungauged basin. The model was run, and many scenarios were carried out using 2010 as the base year and for a 25-year forecast period in the WEAP software.

2.1 WEAP setup

The ArcMap software was used to map out the Shonga Catchment area using the Digital Elevation Model (DEM) satellite images of the Edu Local Government. Figure 1 depicts an ArcMap Interface of the study area and its drainage network.

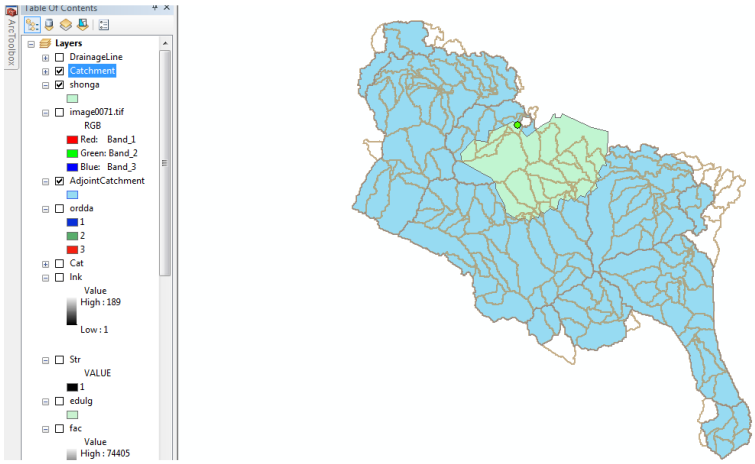

Figure 1: An ArcMap interface showing the study area and its drainage network

2.2 Creating and modelling the study area

Study area modelling starts with physical element definition. All users and water infrastructure elements were spatially represented to denote the demand and supply side of the system. This was followed by defining the study period, units and hydrologic trend representation, which were used as model inputs for setting up the study area. The model representation is as shown in Figure 2.

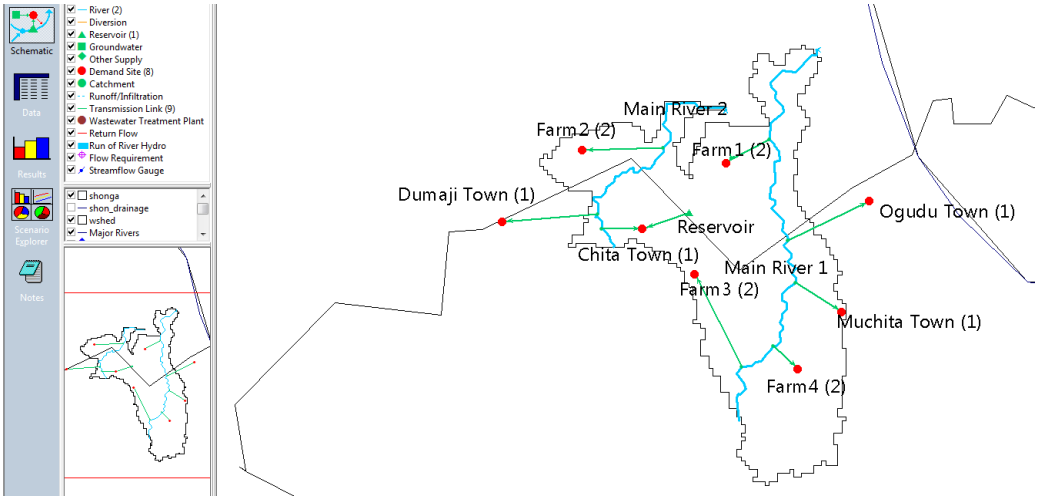

Figure 2: Construction of the model

2.3 The WEAP model data requirement

The WEAP model data requirement comprises adequate representation in quantity of the available water used for the different users [domestic, irrigation, hydropower and livestock], the cultivated area, and evapotranspiration data input. This data includes firstly the water resources and secondly, the main water users. Two rivers (Main Rivers 1 and 2) and a reservoir were considered as the water resources available in the modeled area. The demand sites include four towns and four farms in the catchment area. In the model, nodes were used to represent the demand sites and the reservoir, while transmission links were used to link the various demand sites to their supply.

2.4 Sites demand

The objective of simulation with the WEAP model is to maximize water delivered to various demand elements and in-stream flow requirements according to their ranked priority. The demands of the same priority are referred to as equity groups. These equity groups are indicated in the interface with a number in parentheses (from 1, having the highest priority, and 99, the lowest). Data Demand sites in the WEAP model were selected and edited concerning Annual Activity Level, annual Water use, monthly variation, and water consumption rate definition for each activity. These Data concerns.

The annual activity level determines the water demand for various users: domestic, irrigation, or industrial purposes, to determine the level of water consumption per unit of activity, while the monthly variation states the monthly share of the annual demand

Priority demand: Priority is given to domestic demand, which is given priority 1, and the agricultural demand is assigned priority 2.

The monthly variation is expressed as a percentage of the yearly value. The values for all the months must amount to 100% over the full year. Table 1 depicts the input data for domestic demand sites for the base year 2010.

Table 1: Input data for domestic demand sites for base year 2010

Demand site	Annual activity level	Annual water use rate	Monthly variation	Rate of consumption	Priority
Chita Town	1310 persons	36.5 m^3/person/year	days in a month	100%	1
Muchita Town	1577 persons	36.5 m^3/person/year	days in a month	100%	1
Dumaji Town	1532 persons	36.5 m^3/person/year	days in a month	100%	1
Ogudu Town	1350 persons	36.5 m^3/person/year	The number of days in a month	100%	1

Table 2: Input data for domestic demand sites for base year 2010

Demand site	Annual activity level	Annual water use rate	Monthly variation	Rate of consumption	Priority
Farm 1 Dairy Cattle Crops	190 Prod. Units 150 ha	46 m^3/Prod.Unit/year 3500 m^3/ha	Jan 3%, Feb 2.8%, Mar 3.7%, Apr 5.8%, May 6.6%, Jun 8.6%, Jul 13%, Aug 16%, Sept 14%, Oct 10.5%, Nov 9.2%, Dec 7.0%	90%	2
Farm 2 Crops	300 ha	3500 m^3/ha	Jan 3%, Feb 2.8%, Mar 3.7%, Apr 5.8%, May 6.6%, Jun 8.6%, Jul 13%, Aug 16%, Sept 14%, Oct 10.5%, Nov 9.2%, Dec 7.0%	85%	2
Farm 3 Crops	380 ha	3500 m^3/ha	Jan 3%, Feb 2.8%, Mar 3.7%, Apr 5.8%, May 6.6%, Jun 8.6%, Jul 13%, Aug 16%, Sept 14%, Oct 10.5%, Nov 9.2%, Dec 7.0%	100%	2
Farm 4 Dairy Cattle Crops	212 Prod. Units 170 ha	46 m^3/Prod.Unit/year 3500 m^3/ha	Jan 3%, Feb 2.8%, Mar 3.7%, Apr 5.8%, May 6.6%, Jun 8.6%, Jul 13%, Aug 16%, Sept 14%, Oct 10.5%, Nov 9.2%, Dec 7.0%	90%	2

The irrigation area water use was based on different monthly water use as defined as below: 3% in January; 2.8% in February; 3.7% in March; 5.8% in April; 6.6% in May; 8.6% in June; 13% in July; 16% in August; 14% in September; 10.5% in October; 9.2% in November and 7% in December (Figure 3).

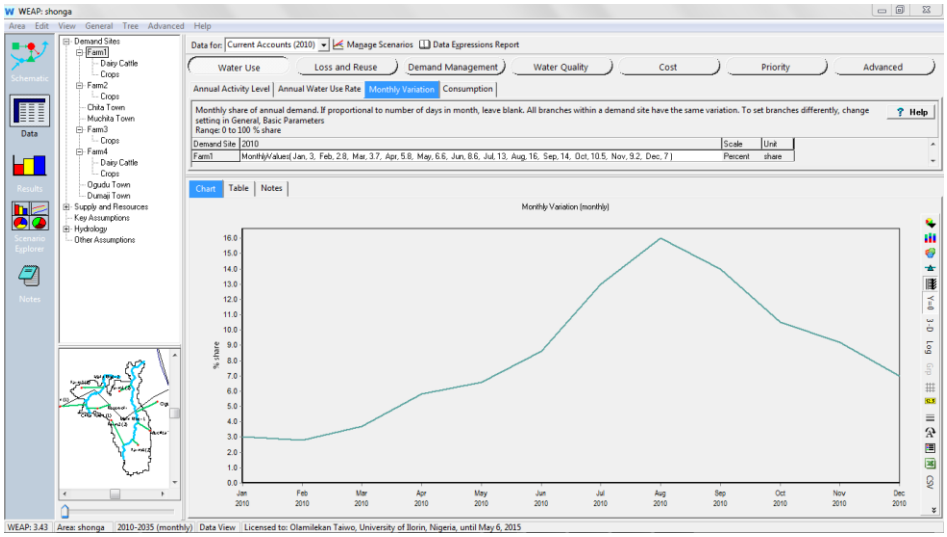

Figure 3: Monthly variations in water demand in the Shonga Watershed

The various population data of the towns were calculated using the expression builder in the model for populating the area population data obtained from the National Population Commission for the 1991 census.

2.5 Water supply resources

For this model, two main rivers and a local reservoir were considered as the available water resources in the watershed to all the demand sites. Table 3 depicts the projected monthly head flow for the main rivers.

Table 3: Monthly head flow for main rivers

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
Main River 2	1079	1027	938	1071	792	844	850	622	1208	1463	1445	1282	12621
Main River 1	1258	1343	1466	1272	1223	1147	896	1126	1576	1514	1372	1195	15388
Sum	2337	2370	2404	2343	2015	1991	1746	1748	2784	2977	2817	2477	28009

The rivers are labelled as Main River 1 and Main River 2, with the local reservoir labelled as Reservoir, as shown in Figure 4. The major sources of water are the two major rivers named Main River 1 and Main River 2.

Reservoir represents the main assumption considered for the area of water storage with a capacity of about 0.5 Mm^3. This was represented as only one component that was schematized in the model and named ‘RESERVOIR’.

Main Rivers: Data required by the model for the two main rivers in the area were obtained using the meteorological data obtained from Jebba Hydropower Generating Station for the base year 2010, considered in the model, and the projection period of 25 years considered in the model are shown in Table 3.

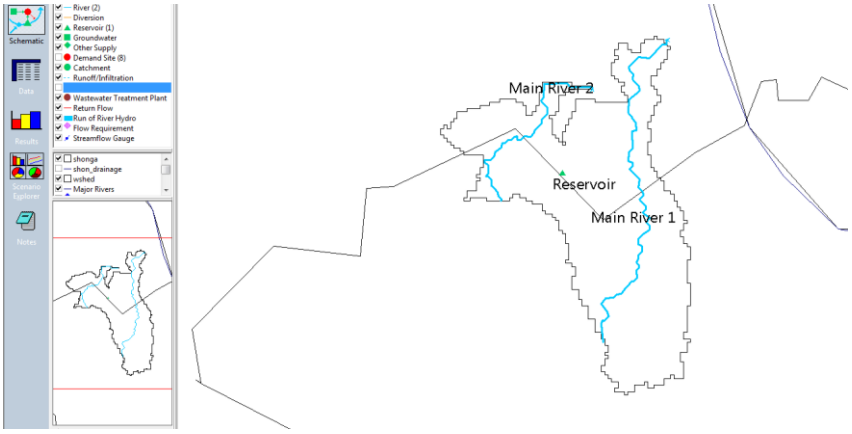

Figure 4: Available water supply resources in the model

2.6 Connecting the supply with the demand side

In configuring the WEAP, each water demand side must be satisfied by an accomplished connecting supply side through transmission links created from the main rivers and reservoirs (Supply Resources) to the towns and farms (Demand Sites). WEAP uses the highest preference level in distributing water from the supply side to all the demand side, except if the lowest level source does not have sufficient water to supply. The transmission links performed in the WEAP model show the links between the water demand and supply sites in the Shonga Watershed, are shown in Table 4.

Table 4: Transmission links between the water supply site and the demand site

S/N	Start Point	End Point	Priority
1	Main River 1	Farm 1	2
2	Main River 1	Ogudu Town	1
3	Main River 1	Muchita Town	1
4	Main River 1	Farm 4	2
5	Main River 1	Farm 3	2
6	Main River 2	Farm 2	2
7	Reservoir	Chita Town	3
8	Main River 2	Dumaji Town	1
9	Main River 2	Chita Town	1

Hence, there is a need for integrated water resources management in irrigated agricultural areas to improve crop yields and optimise the use of the available water resources.

2.7 Final construction of the model

When all the simulation steps required for the modelling with WEAP were finalized for the base year, inputting all databases concerning area location, demand and supply, then the objectives are formulated as follows:

The main objective of the study is to optimize water distribution systems among competitive users: domestic, agricultural, industrial, and hydropower uses. The analysis chooses the optimal net benefit derived from water users (Naira/m^2) and minimizes water irrigation use (m^3). The decision variable, which represents the total net benefit, is denoted by TNBi, (i = 1, 2, 3, 4) for domestic, industrial, agricultural/irrigation, and hydropower activities within the basin, respectively.

2.7.1 Objective 1: Maximize total net benefits

$$MaximiseTNB_i = \sum_{j-Ag} NB_{Ag,j} + \sum_{j-D\&I} NB_{NB\&I,j} \quad (1)$$

Where Ag-agriculture, D-domestic, I-industrial,

2.7.2 Objective 2: Minimize irrigation water use

60% of water is used for agricultural purposes [45]. Hence, to minimize water use in irrigation. Equation (2) presents it as a mathematical equation:

$$\text{Minimize } WU_{vol} = \sum_{i=1}^{n}(CWR_i \times A_i) \quad (2)$$

where WU_{vol} is the total irrigation water used in m3, and CWRi is the total annual estimated gross crop water requirements under flood irrigation, in mm, for crop i.

Using appropriate parameters, Equations 1 and 2 were modelled in WEAP; the in-built optimization driven by priority was used to arrive at the solutions. Figure 5 represents the final WEAP model setup for the Shonga Catchment.

Figure 5 shows the final WEAP Model for Shonga Catchment with its various transmission links and nodes that connect the various demand sites to the water supply resources in the area. The domestic demand sites have a higher priority than the farms.

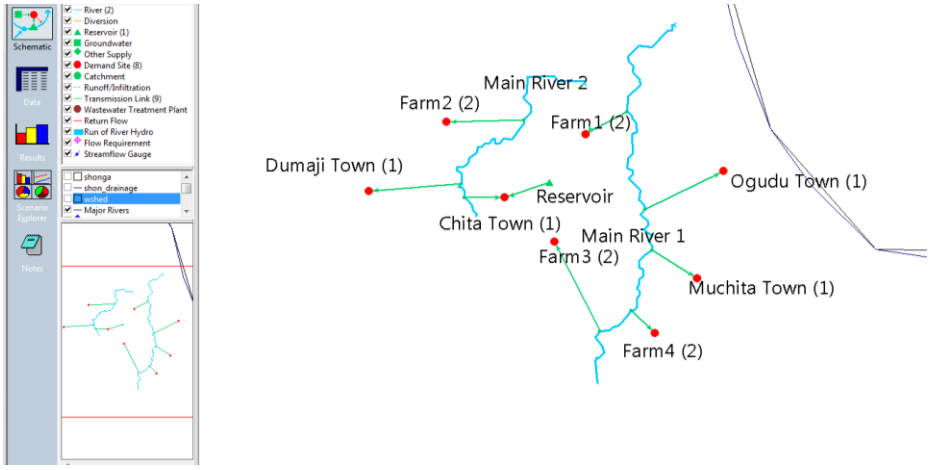

Figure 5: WEAP model for Shonga Catchment

2.8 Development of scenarios

Once a model has been built, it can explore various scenarios. The standard approach for every scenario analysis is to compare a baseline with one or more scenarios using predefined indicators. The development of the typical scenario model consists of three steps.

The "Current Accounts" year was chosen to serve as the base year of the model. All the data for the base year was input into this account.

The "Reference" scenario is established from the Current Accounts to simulate the likely evolution of the system without intervention.

Finally, "what-if" scenarios were created to alter the "Reference Scenario" and evaluate their effects.

The two scenarios developed in the simulation process for this study are listed below.
High Population Growth: This scenario was used to evaluate the impact of increasing the population growth rate of the towns from 3.2% to 6.4% and the livestock growth rate from 5.6% to 15.4% in the farms.

Managerial Policy: This scenario looks at the impact of strict water demand management practices in both the domestic and agricultural demand sites, thereby reducing their demand by 15%. Figure 6 depicts the WEAP Interface showing Input Scenarios Simulated.

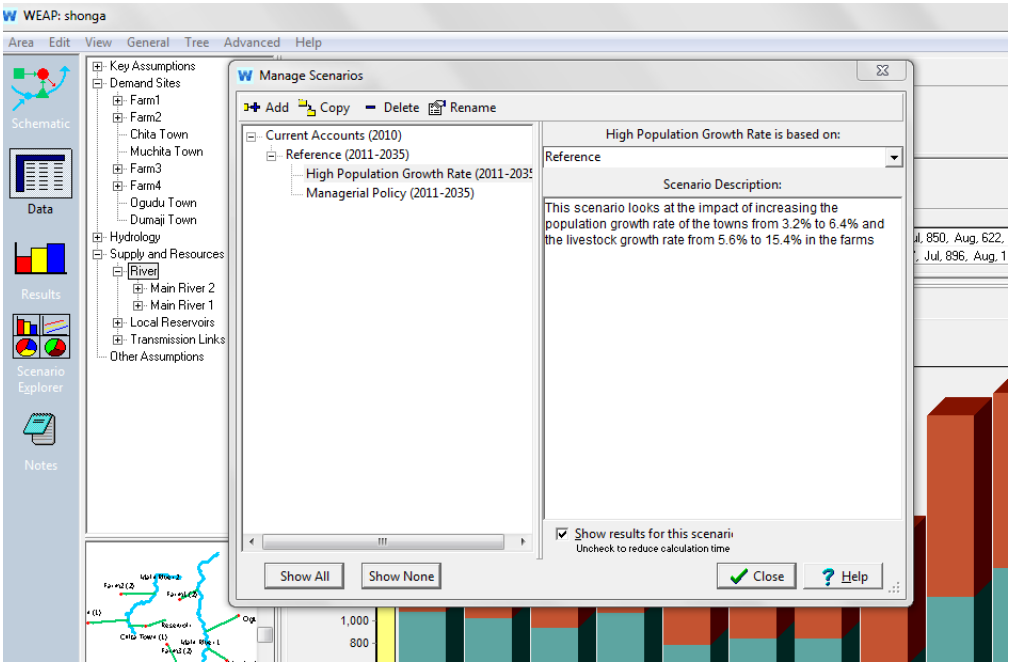

Figure 6: WEAP interface showing input scenarios simulated

3 Results

The analysis of the total net benefit is represented by TNBi, (i = 1, 2, 3, 4) for domestic, industrial, agricultural/irrigation, and hydropower activities within the basin, respectively. Each activity was solved separately. Considering the allocation of water at different dependability levels of 85%, 70% and 60% of the available total surface water. Most preceding water allocations were based on priority-driven approaches among the contending different users using different dependable flows as formulated in **Error! Reference source not found.**5. The percentage of dependable flow with realistic outflow is usually considered.

Table 5: Water allocation for Gross annual yield at 70% dependability

Details	Sub-total (cubic meters)	Total (cubic meters)
Net annual yield at 85% dependability of the total		8,322,906
Water requirement at outlet 1		
Industrial (10%)	856,804	
Domestic (20%)	1,813, 609	
Irrigation (60%)	4,840, 826	
The total of the water balance at 85% dependability	8,322,906	

The results of the crop irrigation schedule at Farms 1, 2, 3, and 4 show that Irrigation water use that account for (60%) uses 4,840.826; Domestic (20%) needs 1,813,609; Industrial was use which account (10%) 856,804 while regeneration for environmental and ecology (10%) usage account 730,194 m^3 for equitable trade off distribution.

Among the harvested responses, how efficient and realistic was the present employment method in meeting the various users' needs? And are these sources of water reliable and sufficient? The majority response was "Yes, at present, but not sustainable in the long run due to the mainstream being over-extracted, especially in the dry season for most communities". Respondent 9 says: "Main River 1 and 2 are the main sources and viable, but due to the ever-increasing demand, alternatives like rain harvest and artificial wetland are created to combat the effects of drought". Participants No. 3 and 10 stated: "Most main River sources are viable except where the water source is over-extracted. Thus, promotion of more efficiency in water use and non-wasteful use represents modern insight in the water allocation process, which is also sustainable. To this effect, the study evaluates the use of WEAP software for integrated water resources management at Shonga irrigated agricultural areas to improve crop yields and optimize available water resources.

4 Discussion

4.1 Model solution: Water resources available in the area

Using Table 6 as the data input for the base year 2010, Main River 1 and Main River 2 are the main sources of water to the study area, supplying the area with a total head flow of 15388 m^3/s and 12621m^3/s respectively for the base year 2010. Hence, a total head flow of 28,009m^3/s was available for distribution.

Table 6: Total annual water demand

Demand site	Annual demand (cubic metre)	Annual demand (cubic metre)
Year	2010	2035
Chita Town	47,812	105,083
Dumaji Town	55,914	122,889
Farm1	534,788	236,886
Farm2	1,052,100	3,556,144
Farm3	1,332,660	3,620,244
Farm4	605,956	446,829
Muchita Town	57,574	126,537
Ogudu Town	49,273	108,294
Total	3,736,077	8,322,906

From Table 6, the WEAP model was able to simulate present and projected water demand for the area. Agriculture, in particular farms 2 and 3, depicts the highest water use with 1,052,100 and 1,332,660 m^3 for the base year 2010 and likewise for the projected year 2035.

4.2 Unwater demand in the area

Table 7 depicts the total annual unmet water demand for the demand sites for the base year (2010) and the forecast year (2035).

Table 7: Total annual water demand

Demand site	Annual demand (cubic metre)	Annual demand (cubic metre)
Year	2010	2035
Chita Town	6,715	14,759
Dumaji Town	13,439	29,537
Farm1	132,026	58,482
Farm2	259,739	877,927
Farm3	329,002	893,752
Farm4	149,596	110,311
Muchita Town	13,838	30,414
Ogudu Town	11,843	26,029
Sum	916,199	2,041,212

While the study highlights unmet water demand (2.04 Mm^3) in future projections, which can mitigate through alternative water sources (e.g., groundwater, water recycling, desalination) to help bridge the supply-demand gap.

Figures 7 and 8 show the graphical representations of the total annual water met and unmet demand respectively.

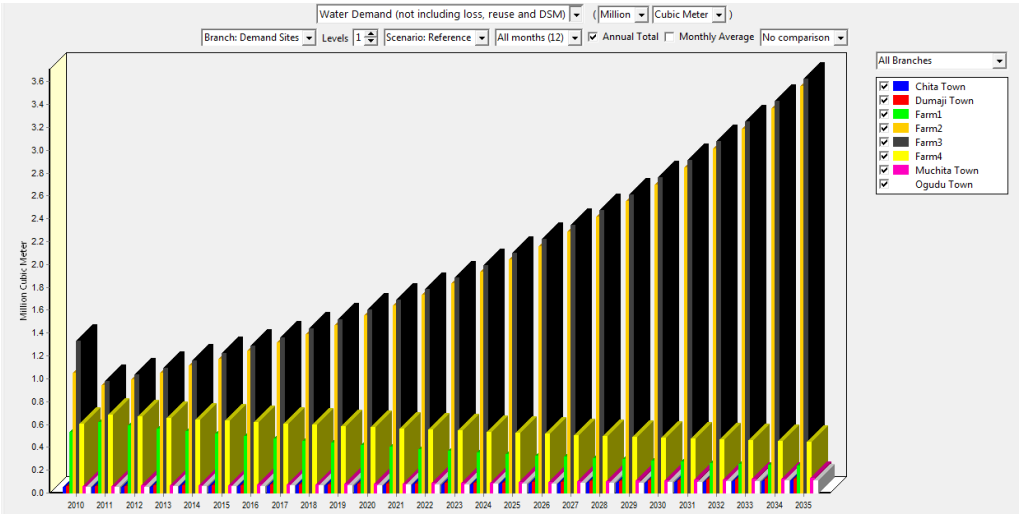

Figure 7: Total annual met demand

Figure 8 shows the total annual unmet water demand for the various users. The figure follows the same pattern as the met demand, which implies that future water demand should be put in place to meet the unmet water for the various users. Even though the domestic demand sites have been assigned a higher priority than the farms.

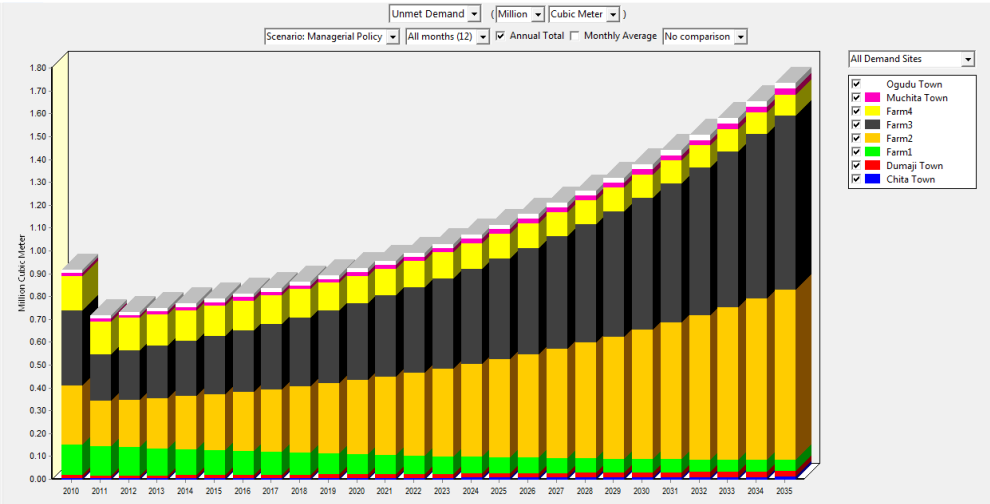

Figure 8: Total annual unmet demand

4.3 Effects of developed scenarios

For the simulation, three different scenarios were developed and their effects on the water demand were evaluated as is discussed in following sub-chapters.

4.3.1 High population growth

Table 8 depicts the projected population water demand for the year 2035, while Table 9 depicts the Total Annual Unmet Demand.

Table 8: Total annual demand due to high population growth for 2035

Demand sites	Normal population growth annual demand (cubic metre)	High population growth annual demand (cubic metre)
Chita Town	105,083	472,075
Dumaji Town	122,889	552,065
Farm1	236,886	243,971
Farm2	3,556,144	3,556,144
Farm3	3,620,244	3,620,244
Farm4	446,829	744,448
Muchita Town	126,537	568,457
Ogudu Town	108,294	486,499
Sum	8,322,906	10,243,904

Water Demand for Domestic can be calculated as in the following **Error! Reference source not found.**:

$$Q = (Wc \times N \times S_d) \times 365 \quad (3)$$

Where: $Wc = water\ consumed\ per\ person\ \left(taken\ as\ 135\frac{m^3}{d}\right)$; $N = Population$ and an adjusted seasonal difference in demand S_d (%).

Table 9: Total Annual Unmet Demand Due to High Population Growth for 2035

Demand sites	Normal population growth annual demand (cubic metre)	High population growth annual demand (cubic metre)
Chita Town	14,759	66,302
Dumaji Town	29,537	132,692
Farm1	58,482	60,231
Farm2	877,927	877,927
Farm3	893,752	893,752
Farm4	110,311	183,786
Muchita Town	30,414	136,632
Ogudu Town	26,029	116,933
Sum	2,041,212	2,468,257

Figures 9 and 10 show the graphical representations of the projected population's annual water demand and unmet water demand for the area.

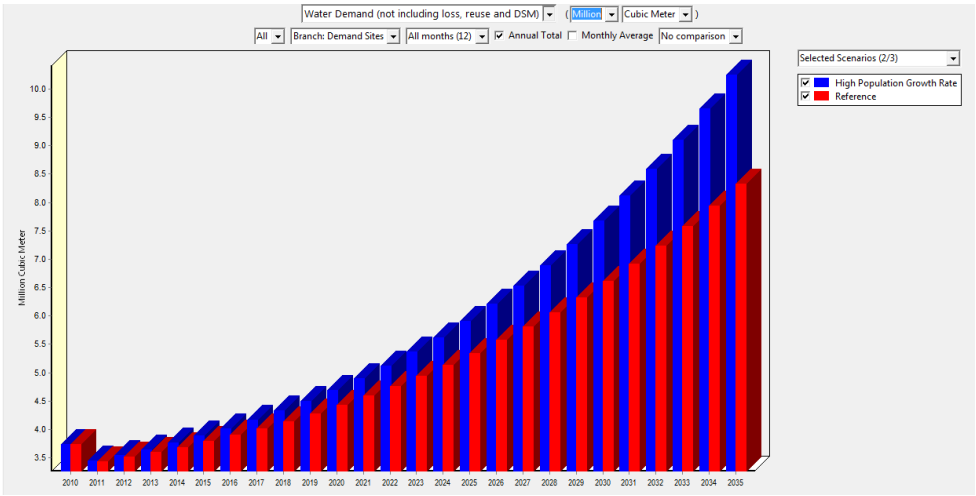

Figure 9: Total annual demand due to high population growth rate

Both the rise in annual water demand and unmet demand are associated with increased population growth, while their graphic representation follows the same pattern. This implies that policy decision makers need to make better reforms on how the projected Unmet water can be achieved.

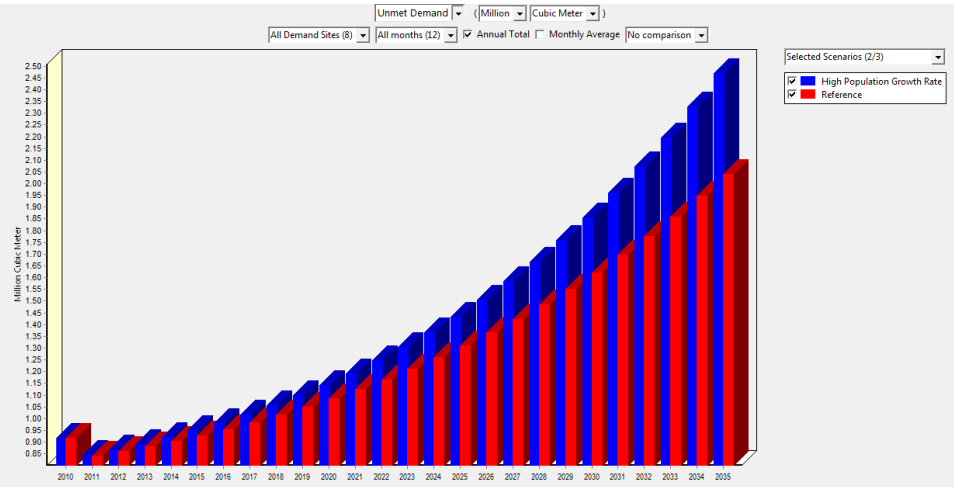

Figure 10: Total annual unmet demand due to high population growth rate

4.3.2 Managerial policy

The constant total water demand represents the actual water demand of the different water demand Sites, while the decrease in unmet demand is attributed to the adaptation policies and management strategies, which were aimed at reducing the actual amount of water being used in the demand sites. Table 11 depicts the total annual Unmet water demand if the suggested managerial policy is applied.

Table 10: Total annual unmet demand due to managerial policies for 2035

Demand sites	Normal annual demand (cubic metre)	Managerial policies annual demand (cubic metre)
Chita Town	14,759	12,545
Dumaji Town	29,537	25,106
Farm1	58,482	49,709
Farm2	877,927	746,238
Farm3	893,752	759,690
Farm4	110,311	93,765
Muchita Town	30,414	25,852
Ogudu Town	26,029	22,125
Sum	2,041,212	1,735,030

4.3.3 Water Management strategies and adaptation policies

Beyond water allocation modeling, the paper suggests improvement in public infrastructure to enhance public water supply, the implementation of promulgated water sector reform acts to achieve a sustainable water supply for the LNRB, while regulating the emergence of mediating agencies for conflict resolution among competitive users. Other valuable strategies should include the implementation of water conservation policies, both from the demand side and the supply side. In all, the role of community engagement and better sensitization cannot be

overemphasized in ensuring behaviour changes towards water wastage and conscious awareness in ensuring efficient use of the available water. Figure 14 depicts a graphical representation of total annual unmet demand due to managerial strategy application. This includes tariff payment on domestic users, which encourages users to be more conscious of using water sparingly and closing the tap when not in use.

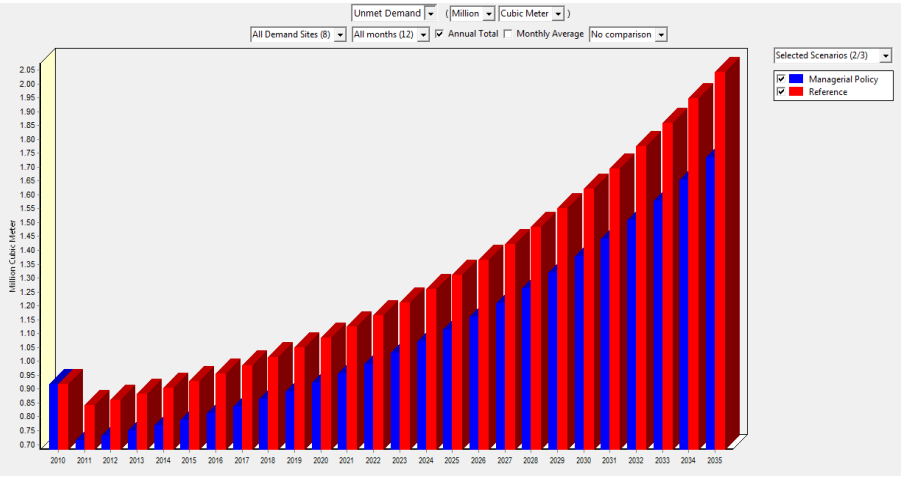

Figure 11: Total annual unmet demand due to managerial policies

The managerial policy application scenario accounts for a decrease in total unmet water demand experienced from a value of 2.04 million m^3 to 1.74 million m^3 As seen in Table 11, while Figure 14 shows the equivalence in graphical representations.

4.4 Simulated Water Allocation Summary to Various Users

Tables 11 and 12 below give the summary for the water allocation simulation for both the base year 2010 and the projected year 2025. The study of the various water demand components shows the need to treat the various demand components separately and apply appropriate managerial policy to address the water shortfall while improving the water supply side with intuitive initiatives management.

Table 11: Water allocation simulation summary for the project area for 2010

Inflow (cubic metre)		**Outflow (cubic metre)**		
Precipitation	2,815,101	Demand Site	Actual Demand	Consumption
Reservoir	4,777	Chita Town	47,812	41,097
		Dumaji Town	55,914	42,475
		Farm1	534,788	402,761
		Farm2	1,052,100	792,362
		Farm3	1,332,660	1,003,658
		Farm4	605,956	456,360
		Muchita Town	57,574	43,736

		Ogudu Town	49,273	37,430
Total	2,819,878	Total	3,736,077	2,819,878

Table 12: Projected Water Allocation Simulation Summary for the Project Area For 2035

Inflow (cubic metre)		**Outflow (cubic metre)**		
Precipitation	6,271,196	Demand Site	Actual Demand	Consumption
Reservoir	10,498	Chita Town	105,083	90,324
		Dumaji Town	122,889	93,352
		Farm1	236,886	178,405
		Farm2	3,556,144	2,678,217
		Farm3	3,620,244	2,726,492
		Farm4	446,829	336,517
		Muchita Town	126,537	96,123
		Ogudu Town	108,294	82,265
Total	6,281,694	Total	8,322,906	6,281,694

The total unmet water consumption increases from 2.82 Mm^3 to 6.28 Mm^3 for the projected 2035. Although the population projection scenarios show an increase from 2.4 Mm^3 to 2.47 Mm3 for water demand, while water supply in the area shows a decline from 6.27 Mm^3 in the projected simulated result (2035) to 2.82 Mm^3. Hence, policymakers would benefit from these water allocation projections to develop better policies because the projected water demand scenarios are expected to characterize the study area. Although the model shows the actual projected unmet water demand to be 8.32 Mm^3.The study advocates water augmentation measures through groundwater, water recycling, or desalination water treatment, which could help bridge the supply and demand gap. Turning all these water deficits into opportunities would still require the use of water technology devices to minimize leakages and to manage the allocable water resources reasonably.

4.5 WEAP Model Performance, Calibration and Validation Details

The WEAP model was well calibrated for the study area. Using the Soil Moisture Method, the sensitivity analysis of WEAP was done by fine-tuning the soil moisture (z1 and z2) input parameters to values that ensure that the basin simulated soil moisture levels follow a believable trend. A very high value of z1 indicates a wet period, signally soil water availability, while a low value of z1 signifies a very dry period. Hydrological calibration of the WEAP model was done through the collected monthly streamflow data (upstream of Jebba) for 10 years, which were validated with a match of simulated runoff. An empirical relationship obtained from another catchment that has precipitation and runoff data and lies in a hydro-meteorologically similar environment was used for the catchment validation process. Since the study area (Shonga) has no stage/discharge data for stream flow (unguaged station), a regression relationship was established between the hydro-meteorological station that lies in similar basins. This is given as Equation 4:

$$P = R + ET + \frac{\Delta S}{\Delta t} \quad (4)$$

Where: P = Precipitation
R = Runoff
ET = Evapotranspiration
$\frac{\Delta S}{\Delta t}$ = Change in storage over time

For a start, the precipitation and runoff data are tested by plotting precipitation and runoff against each other as depths, and a correlation in the form of a straight line is obtained. The mean annual runoff, R, a dependent variable, is expressed as Equation 5:

$$\text{Mean Annual Runoff, } R = a + b\,þ \quad (5)$$

Where, þ is the mean annual precipitation, an independent variable; "a" and "b" are empirical constants given by Equations 6 and 7.

$$b = \Sigma\,(R\text{-}R)(P\text{-}þ)/\,\Sigma(P\text{-}þ)2 \quad (6)$$
$$a = R - b\,þ \quad (7)$$

This method is used for estimating mean annual runoff for completely ungauged catchments. As shown above, the runoff and precipitation are known; we find the constants "a" and "b", and apply them to the ungauged catchment. The station used for this correlation analysis is Jebba Station along the River Niger, which has both stream flow and rainfall data. The correlation coefficient between rainfall and runoff for the River Niger at Shonga watershed is given by:

Correlation coefficient,

$$r = \Sigma\,(PR - nP\text{Jebba}\,R\,\text{Jebba})/\,[(\Sigma P2 - nP2\,\text{Jebba})(\Sigma R2 - nR2\text{Jeb})] \quad (8)$$

Where n = number of years of record, which is 25 years
P Jebba = Annual mean Precipitation for Jebba; 1100 mm
R Jebba = Annual mean Runoff of River Niger at Jebba; 2405.5 mm

The coefficient of correlation value of 0.922 shows that there is a strong linear connection between rainfall and runoff of the River Niger at Jebba, which can be transferred to the Shonga Basin.

The coefficients "a" and "b" obtained are –535.4 and 0.355, respectively.
The runoff equation is given by:

RShonga = -535.4 + 0.355PShonga

The Mean Annual Rainfall figure of Jebba is adopted as 1100 mm for the project site.
R = -535.4 + (0.555x 1100) = 75.1 mm

The catchment area, as measured using ArcMap software, is 295.8 km^2.
Mean Annual Runoff (Mm3) = 295.8 x 75.1 x 0.001. = 22.1Mm^3

A spatially distributed correlation was plotted between rainfall and runoff as depicted in Figure 12. The result of the simulation process between the simulated rainfall and the convolution runoff results looks 'reasonable' since there is no observed data from the watershed. The fitted runoff prediction shows observed similarity obtained for both the rainfall calibration and runoff validation for the location. The figure shows there is a good correlation between the historical observed flow and the simulated flow, indicated by the coefficient of correlation (r^2) and RMSE of 0.63 and 0.72, for the validation. The result indicates that the simulated WEAP experimental data are reliable, while the validation exercises are within the 95% confidence interval. The runoff validation for the locations could be useful to determine the quantity of water for peak flood and surface water availability for allocation.

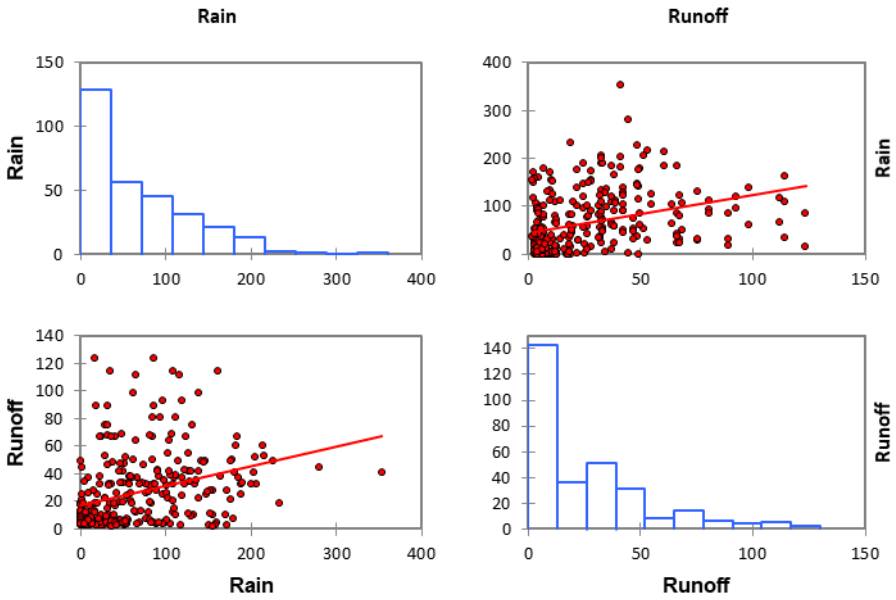

Figure 12: Correlation plot between rainfall and runoff for the validation period

Using historical data for model validation, an RMSE with a value of 0.72 denotes a good correlation result for the validation period 2010-1015, while still meeting the requirements of the ecosystem.

5 Conclusion

Considering the extent of the uneven water allocation in the study area, the study has employed the WEAP model to simulate and forecast projected future allocable water to different users while ensuring the sustainability of LNRB. The study has been able to simulate current and projected near-year water demand, evaluate optimal water allocation to different users, and suggest measures for its effective and efficient management. The WEAP model performance and validation were satisfactory when assessed with a similar basin that lies within a similar

hydro-meteorological area, with a correlation value of 0.89 between rainfall and runoff during the validation period 2010-2015. Decision makers and water resource managers would find the study valuable in assisting water allocation planning and ensuring sustainable catchment management. No doubt, improvement in infrastructure provision, implementation of water conservation policies, and mass campaign through community engagement as part strategies for effective strategies for water use will go a long way in managing the area sustainably. Future studies for the area should harmonize the possibility to share data more freely between the beneficial users, thereby making previously static databases dynamic. Also, future research could explore the socioeconomic consequences of the catchments' water scarcity experience and other associated effects.

Acknowledgments

This research received no external funding. The authors would like to acknowledge the staff and student colleagues at the Department of Water Resources and Environmental Engineering, University of Ilorin, Nigeria, who helped with the data collection. We are indeed grateful for the constructive comments and suggestions from an anonymous reviewer, which have improved the presentation of the paper. Opinions expressed and conclusions arrived at, are those of the authors.

Abbreviations

The following abbreviations are used in this manuscript:
Water Evaluation and Planning (WEAP)
The Lower Niger River Basin (LNRB)
Decision Support System (DSS)
Water Demand Management (WDM).
Integrated Water Resources Management (IWRM)
'Hydrology, Environment, Life (aquatics), Policy and Sensitivity' (HELPS)
Digital Elevation Model (DEM)

References

[1] Yang, D., Yang, Y. and Xia, J., 2021. Hydrological cycle and water resources in a changing world: A review. *Geography and Sustainability*, 2(2), pp.115-122.

[2] Liu, S., Shi, H. and Sivakumar, B., 2020. Socioeconomic drought under growing population and changing climate: A new index considering the resilience of a regional water resources system. *Journal of Geophysical Research: Atmospheres*, 125(15), p.e2020JD033005.

[3] Liu, S., Shi, H. and Sivakumar, B., 2020. Socioeconomic drought under growing population and changing climate: A new index considering the resilience of a regional water resources system. *Journal of Geophysical Research: Atmospheres*, 125(15), p.e2020JD033005.

[4] Mehrazar, A., Massah Bavani, A.R., Gohari, A., Mashal, M. and Rahimikhoob, H., 2020. Adaptation of water resources system to water scarcity and climate change in the suburb area of megacities. *Water Resources Management*, 34, pp.3855-3877.

[5] Amoo, O.T., Nakin, M.D.V., Abayomi, A., Ojugbele, H.O. and Salami, A.W., 2020. System dynamics approach for evaluating existing and future water allocation planning among conflicting users. The International Archives of the Photogrammetry, *Remote Sensing and Spatial Information Sciences*, 44, pp.45-51.

[6] Liman, H.M., Nwaerema, P. and Yisa, J., 2021. Impact of Climate Variability on Reservoir Based Hydro-Power Generation in Jebba Dam, Niger State, Nigeria. *Hydro Science & Marine Engineering*, 3(1), pp.1-6.

[7] Emigilati, A.U., 2020. Socio-Economic Impact of Jebba Hydro Power Dam on Some Downstream Communities In Niger 738

[8] Krause, P., Biskop, S., Helmschrot, J., Flügel, W.-A., Kang, S. and Gao, T. 2010. Hydrological system analysis and modelling of the Nam Co basin in Tibet. *Advances in Geosciences*, 27: 29.

[9] Dai, T. and Labadie, J. W. 2001. River basin network model for integrated water quantity/quality management. *Journal of Water Resources Planning and Management*, 127 (5): 295-305.

[10] Azevedo, L. G. T. d., Gates, T. K., Fontane, D. G., Labadie, J. W. and Porto, R. L. 2000. Integration of water quantity and quality in strategic river basin planning. *Journal of Water Resources Planning and Management*, 126 (2): 85-97.

[11] Labadie, J., Baldo, M. and Larson, R. 2000. MODSIM: Decision support system for river basin management. Documentation and user manual, Fort Collins.

[12] Draper, A. J., Munévar, A., Arora, S. K., Reyes, E., Parker, N. L., Chung, F. I. and Peterson, L. E. 2004. CalSim: Generalized model for reservoir system analysis. *Journal of Water Resources Planning and Management*, 130 (6): 480-489.

[13] Wooldridge, M. 1999. Intelligent Agents. MIT Press

[14] Zagona, E. A., Fulp, T. J., Shane, R., Magee, T. and Goranflo, H. M. 2001. RiverWare; A Generalized Tool for Complex Reservoir System Modeling. *Journal of the American Water Resources Association*, 37 (4): 913-929.

[15] Fereidoon, M., Koch, M. and Mousavi, J. 2014. A sequential Simulation-Optimization Model for Water Allocation from the multi-reservoir System in the Karkheh River Basin System, Iran. In: Proceedings of 11th International Conference on Hydroscience & Engineering, ICHE Hamburg.

[16] Tiwary, P., Jha, M. K. and Venugopalan, M. 2010. Decision Support System: Concept and Potential for Integrated Water Resources Management. In: Natural and Anthropogenic Disasters. Springer, 503-535.

[17] McKinney, D. C. 2004. International survey of Decision Support Systems for Integrated Water Management, Technical Report: Agricultural Pollution Reduction Activity in Romania. Bucharest, Romania: US Agency for International Development.

[18] Warer, D.H.I., 2004. Environment. MIKE BASIN 2003: A Versatile Decision Support Tool for Integrated Water Resources Management Planning. 2004]. http://www. dhigroup. com/Software/Warer Resources/MIKEBA-SIN/References.Bangash, R. F., Passuello, A., Hammond, M. and Schuhmacher, M. 2012. Water allocation assessment in low flow river under data scarce conditions: a study of hydrological simulation in Mediterranean basin. *Science of the total environment*, 440: 60-71.

[19] Yates, D., Purkey, D., Sieber, J., Huber-Lee, A. and Galbraith, H. 2005a. WEAP21: A Demand-Priority-and Preference-Driven Water Planning Model: Part 2: Aiding Freshwater Ecosystem Service Evaluation. *Water International*, 30 (4): 501-512.

[20] McCartney, M. and Arranz, R. 2007. Evaluation of historic, current and future water demand in the Olifants River Catchment. South Africa. Research Report 118. International Water Management Institute (IWMI), Colombo, Sri Lanka.

[21] Perera, B., James, B. and Kularathna.M. 2005. Computer software tool REALM for sustainable water allocation and management. *J Environ Manag*, 77: 291-300.

[22] Bangash, R. F., Passuello, A., Hammond, M. and Schuhmacher, M. 2012. Water allocation assessment in low flow river under data-scarce conditions: a study of hydrological simulation in Mediterranean basin. *Science of the total environment*, 440: 60-71.

[23] Verma, S.K., Prasad, A.D. and Verma, M.K., 2022. An assessment of ongoing developments in water resources management incorporating SWAT model: Overview and perspectives. *Nature Environment and Pollution Technology*, 21(4), pp.1963-1970.

[24] Abbas, S.A., Bailey, R.T., Almahawis, M.K., White, J.T., Arnold, J.G. and White, M.J., 2024. Calibration guide for watershed modeling with distributed groundwater modeling: application for the SWAT+ model. *Hydrological Sciences Journal*, 69(13), pp.1777-1796.

[25] Merga DD, Adeba D, Regasa MS, Leta MK (2022) Evaluation of surface water resource availability under the impact of climate change in the Dhidhessa Sub-Basin, Ethiopia. *Atmosphere* 13(8):1296. https://doi.org/10.3390/atmos13081296

[26] Mortezaeipooya, S.S., Ashofteh, P.S., Golfam, P. and Loáiciga, H.A., 2022. Evaluation of water supply system performance affected by climate change with MODSIM modeling and reservoir efficiency indicators. *Arabian Journal of Geosciences*, 15(19), p.1580.

[27] You, S.B., Stawnychy, M.A., Cacchione, P.Z. and Bowles, K.H., 2024. Using the Outcome and Assessment Information Set to Measure Patient Health Status in Research: A Systematic Review. *Journal of the American Medical Directors Association*, p.105044.

[28] Salimi, M., Sattari, M. T., & Parsa, J. (2024). Simulation of Nahand reservoir water allocation and its performance evaluation under inflow increase and decrease scenarios using the water evaluation and planning (WEAP) model. *Water and Soil Management and Modeling*, 4(2), 295-310.

[29] Ashofteh PS, Kalhori M, Singh VP (2024) Water resources management considering groundwater instability affected by climate change scenarios. *Phys Chem Earth* 135(March):103606

[30] Kifle Arsiso B, Mengistu Tsidu G, Stoffberg GH, Tadesse T (2017) Climate change and population growth impacts on surface water supply and demand of Addis Ababa, Ethiopia. *Clim Risk Manag* 18(July 2017):21–33.

[31] Letcher, R. A., Jakeman, A. J. and Croke, B. F. W. 2004. "Model development for integrated assessment of water allocation 709 options.". *Water Resour. Res.*, 40 (W05502) 710

[32] Cai, X., Ringler and Rosegrant, M. W. 2006. *Modeling water resources management at the basin level: methodology and application* 711 *to the Maipo River Basin*. Research Report, No. 149. Int'l Food Policy Research Institute (IFPRI), Washington DC:

[33] Ward, F. A., Booker, J. F. and Michelsen, A. M. 2006. "Integrated economic, hydrologic and institutional analysis of 713 alternative policy responses to mitigate impacts of severe drought in the Rio Grande Basin.". *J. Water Resour. Plann. Manage*, 132 (6): 488–502.

[34] Deng, L., Guo, S., Yin, J., Zeng, Y. and Chen, K., 2022. Multi-objective optimization of water resources allocation in Han River basin (China) integrating efficiency, equity and sustainability. *Scientific Reports*, *12*(1), p.798.

[35] Yates, D., Sieber, J., Purkey, D. and Huber-Lee, A. 2005. WEAP21—A demand-, priority-, and preference-driven water planning model: part 1: model characteristics. *Water International*, 30 (4): 487-500.

[36] Lange, M.D., Merrey, D.J., Levite, H. and Svendsen, M., 2005. Water resources planning and management in the Olifants Basin of South Africa: past, present and future.

[37] Zuo, D., Xu, Z., Peng, D., Song, J., Cheng, L., Wei, S., Abbaspour, K. C. and Yang, H. 2015. Simulating spatiotemporal variability of blue and green water resources availability with uncertainty analysis. *Hydrological Processes*, 29 (8): 1942-1955.

[38] Aristeidis, A. (2007) "Water Demand Management and Water Conservation Potential and Limitations in Katerini, Greece". Water Engineering and Development Centre, Department of Civil and Building Engineering

[39] UNW-DPC. 2010. 'Integrated Water Resources Management. Capacity Pool'. UN-Water Decade Programme on Capacity Development, . Bonn, Germany

[40] Charania, S., 2005. Integrated water resources management with reference to developing countries. In *FIG Working Week* (pp. 16-21).

[41] Davis, M.D., 2007. Integrated water resource management and water sharing. *Journal of Water Resources Planning and Management*, *133*(5), pp.427-445.

[42] Un-GWP, (2007). Un-Water and Global Water Partnership, Road-mapping for Advancing Integrated Water Resources Management (IWRM) Processes. Status Report on Integrated Water Resources Management and Water Efficiency Plans, Prepared for the 16th session of the Commission on Sustainable Development.

[43] Katusiime, J. and Schütt, B., 2020. Integrated water resources management approaches to improve water resources governance. *Water*, *12*(12), p.3424.

[44] Liman, H.M., Nwaerema, P. and Yisa, J., 2021. Impact of Climate Variability on Reservoir Based Hydro-Power Generation in Jebba Dam, Niger State, Nigeria. *Hydro Science & Marine Engineering*, *3*(1), pp.1-6.

[45] Amoo, T.O., 2018. Integrated hydrological modelling for sustainable water allocation planning: Mkomazi Basin, South Africa case study (Doctoral dissertation).