Water Allocation in the Lower Niger River Basin, Nigeria using Water Evaluation and Planning (WEAP) Model

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Abstract

An important challenge of Integrated Water Resources Management (IWRM) is to balance water allocation between different users in a catchment area,The Niger River is a major source of water in the North Central States, Nigeria. There is need to determine water availability sustainability in an hydrological basin,the current and future demand in order to model the water resources and ensure optimal water allocation to various users in the area.This study uses a Water Evaluation And Planning (WEAP) modelthat systematically simulates natural water flows and water demands within a domainfor assessing various water demand and supply without compromising the ecosystem scenarios and arriving at a negotiated allocation, thereby providing a negotiated river condition and economic trade-off between water stakeholders.WEAP's ability to quantify water demand shortages serve as a key tool for the iteration process to assign appropriate economic tranches with corresponding land acreage and cropping patterns for sustainability.

Keywords

Integrated Water Resources Management (IWRM), Water Allocation, (WEAP), Ecosystems, Negotiated Allocation, Sustainable River Basin.

1. Introduction

The climatic and hydrologic processes that govern the generation and movement of water are highly complex and not fully understood (Vladimir et al., 2012). Water scarcity or decreasing water allocations in developing countries should drive and encourage decision makers to look for improved management alternatives. In the face of a changing climate and increasing demands on water resources, there is a growing need to simulate how water resources will be affected by natural or anthropogenic events.Many regions are facing formidable freshwater management challenges(SEI,2001). Allocation of limited water resources, environmental quality, and policies for sustainable water use are issues of increasing concern(Uitto, 2004; Conway et al., 2009), Conventional supply-oriented simulation models are not always adequate (SEI,2005). Increasingly, researchers and policy makers are advocating sustainable development as the best approach to today's and future water problems (Louks, 2000). Water managers and policy maker at the catchment level required models to forms a decision support system. In such models, hydrological data, water development projects, policy and other metaphysical aspects of catchment hydrology and socio-economic factors are analysed in an interactive computer based system (Prodanovic&Simonovic2007a,b;2010). The main objectives of the system are to maintain a sustainable source of water supply that provides optimum benefit to the population in the complete catchments by satisfying their personal needs while allowing them to undertake socio economic activities without unnecessarily damaging the environment and also to control the resource in a way that minimizes the impact of natural disasters (Charania, 2005).

The Niger River flows and its tributaries which have been the major water supply in the North Central hydrological area have witnessed reduction in volume over the years and conflicts often arise between the downstream and upstream users over the resource allocation. Different water uses, including domestic, commercial, industrial and agricultural takes place within the basin (Olomoda,2004). As population and economic activities increase, water demand also increases, which makes it imperative for water resources planners to look for a relatively new approach in managing the water demand challenges (Aristeidis, 2007). Also, there has been considerable pressure on ecosystem resources coupled with the climate change and severe droughts. These have contributed to the severe consequences on the status of the Niger River and its tributaries,its biodiversity, landscapes, key habitats and floodplains.

In this study, WEAP model is used to evaluate the impact of possible water demands on the water resources of Lower Niger River basin up to the year 2050. The study aims to evaluate the allocation of water upstream and its impacts on economic activities downstream. The basic hydrological and economic issues of upstream water diversion are reviewed and a model of upstream water diversion with downstream impacts was constructed. The model was adopted in the Tada-Shongafloodplain in North Central, Nigeria, in which the downstream losses from dams and other barrages constructed for agricultural production, fishing and hydropower generation. The impact on the recharge of shallow aquifers that are important for dry-season irrigation and water use by villages located outside the floodplain.

Over the last decade, an integrated approach to water development has emerged that places water supply projects in the context of demand-side issues, water quality and ecosystem preservation (Sieber and Purkey, 2007). In IWRM, there are three overriding criteria/guiding principles for decision-making (GWP, 2000): These are: economic efficiency in water use, equity and Environmental/Ecological sustainability. As a way to approach the management of water resources in a given geographical context, IWRM has been viewed to be a systematic process for the sustainable development, allocation and monitoring of water resources, which promotes more coordinated management of land, water, the river basin and upstream and downstream interests (UNW-DPC, 2010). Other issues and challenges in the North Central district include:

(i) Inability to evaluate the water management options under alternative scenarios of the future.
(ii) Only a top down supply driven and fragmented development of water exist.
(iii) Poor data base and management fragmented sectoral development, that led critically to near neglect of quality management of water;
(iv) Institutions with conflicting mandate which makes them referees and players in the sector, thus creating problems of accountability and transparency.
(v) Many dams are built with inadequate development control, no licensing and poorly managed, underutilized; and in many cases operated with no rule curves for reservoirs operations and with little or no maintenance.

(vi) Absence of regulation as well as effective and transparent subsidy such that the poor pay many times more than their affluent neighbours that have piped connections;
(vii) Absence of effective floods forecasting and drought management (Olusina,andOdumade, 2012).

The solutions to water problems depend not only on water availability, but also on many other factors, among which are the processes through which water is managed, competence and capacities of the institutions that manage them, prevailing socio-political conditions that dictate water planning, development and management processes and practices.

Other factors are: appropriateness and implementation statuses of the existing legal frameworks, availability of investment funds, social and environmental conditions of the countries concerned, levels of available and usable technology(Jasper,2003). Therefore, the management are in dire need of effective management tool that recognizes the catchment area or river basin as the only logical unit to water resources management (Saha and Barrow,1981; Mody,2004; Burton, 2003). The allocation of water should, therefore, redress the effects of previous discriminatory legislation which did not provide social stability; thereby promoting economic growth. Adaptation of new modeling tool, the WEAP System allows for sustainable use of water resources. Its prospect entails: climate-driven, captures the integrated nature of system hydrology and system operations condition and the quantification of water shortages per region(Sieber et al.,2005).The objective of this study was to develop and apply an integrated water resources management model for water allocation in Lower Niger River Basin with the aim to assist planning, restore and rationally allocate water resources in any river basin with similar attributes to the study area.

2. The Study Area

The study area is Tada-Shonga irrigation catchment area located at Edu Local Government Area of Kwara State, Nigeria. 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 who are majorly smallholder farmers(www.kwarastate.com). A humid climate prevails within the study area with two distinct seasons (the wet and dry seasons). The wet season lasts between April and October while the dry season falls between November and March. The rainfall ranges between 50.8mm during the driest months to 2413.3mm in the wettest months(Ayoade,2013). The minimum average temperature throughout the state ranges between 21.10^{o}C and 25.00^{o}C while, maximum average temperature ranges from 30^{o}C to 35^{o}C (Met.Office,2007). Agricultural production is largely peasant and small-scale relying heavily on the use of manual labour equipped with crude implements, while fertilizers, mechanical implement, improved seeds and agrochemicals are also used to some extent (Ariyo, and Mortimore, 2011). The location of the study area is presented in Figure 1 while the catchment area is presented in Figure 2 and the schematic diagrammatical representation of the study area required in the model is presented in Figure 3

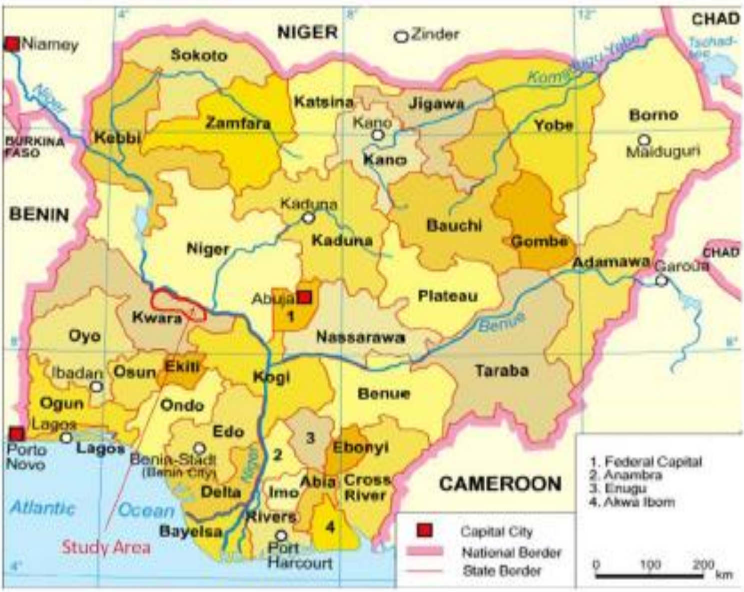

Figure 1: Map of Nigeria (with the 36 States) showing the study area

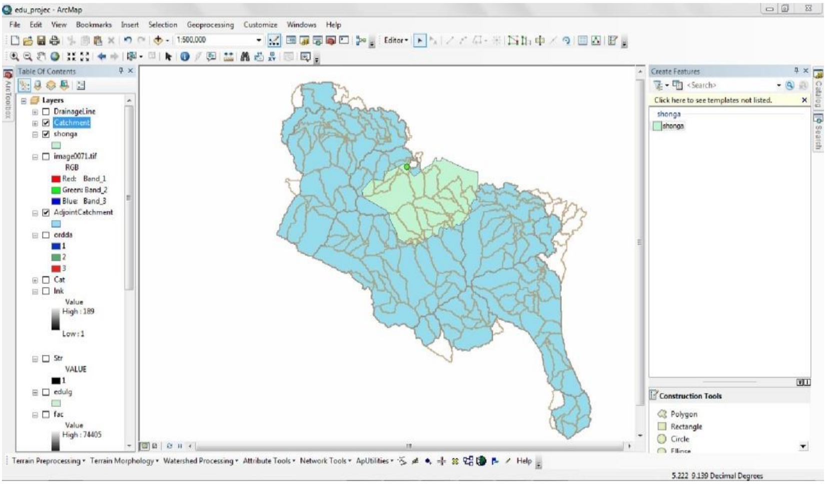

Figure 2 An ArcMap Interface showing Shonga Catchment in Edu Local Government Area

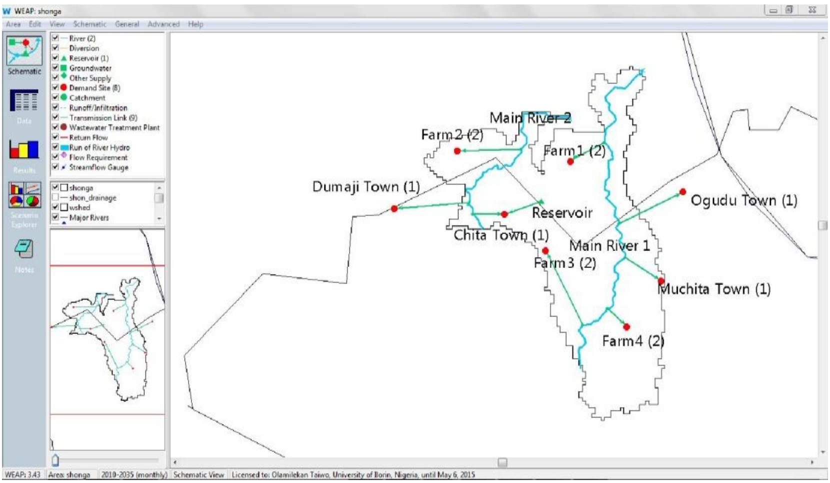

Figure 3.Depicts the schematic diagrammatical representation of the study area.

3. Materials and Methods

The study area was characterized by defining physical elements comprising the water demand-supply system and their spatial relationships, the study time period, units and hydrologic pattern. The area considered for the study includes various watersheds modeled as a Sub-basin as shown in Figure 3.For the study of water supply and demand, the main data required in the WEAP model are the quantity of available water, quantity of water used for domestic, for irrigation, breeding, and numbers of users (people and livestock), the cultivated area and evapo-transpiration (Sakka, 2010). Summarily, these data include the water resources and the 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 as presented in Figure 3 above.The objective of simulation with WEAP model is to maximize water delivered to various demand elements and in-stream flow requirements according to their ranked priority. Demand of the same priority is referred to as an equity group. 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 site in the WEAP model were selected and edited concerning water use, annual activity level, monthly variation and consummation for each activity. The various population data of the towns were calculated using the expression inbuilt in the model from population data obtained from the National Population Commission(NPC,1991) census.

The monthly variation is expressed as a percentage of the yearly value. The proportional number of days in a month for the different years is considered for the monthly variation at the different demand site. The values for all of the months have to sum up to 100% over the whole year. The monthly variation in the water use rate selected for the irrigated area is recognized in the following configuration: 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. This is presented in Tables 1 and Figure 4 for all the demand sites in the model.

Table 1 Input Data for Domestic Demand Sites for base year 2010

Demand Site	Population (persons)	Annual Water use rate (m^3/person/year)
Chita Town	1310	47815
Muchita Town	1577	57560.5
Dumaji Town	1532	55918
Ogudu Town	1350	49275

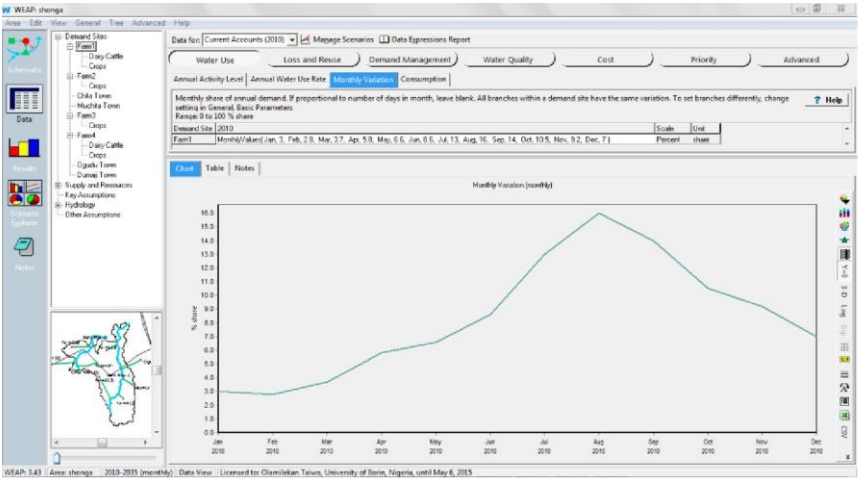

Figure 4: Monthly variations for water demand in the shonga watershed

3.1 Application of WEAP Model for Integrated Water Resource Management

The Water Evaluation and Planning Version 21 (WEAP21) is an IWRM model that attempts to address the gap between water management and watershed hydrology. The requirements for it to be effective in IWRM are: should be useful, easy to- use, affordable, and readily available to the broad water resourcecommunity (SEI,2001).WEAP21 integrates a range of physical hydrologic processes with the management of demands and installed infrastructure in a seamless and coherent manner(SEI,2005). It allows for multiple scenario analysis, including alternative climate scenarios and changing anthropogenic stressors, such as land use variations, changes in municipal and industrial demands, alternative operating rules, points of diversion changes, etc(Sieber and Purkey, 2007). WEAP21's strength is addressing water planning and resource allocation problems and issues. Importantly, it is not designed to be a detailed water operations model, which might be used to optimize hydropower based on hydrologic forecast,(Sieber et al.,2005). WEAP has been described WEAP as being comprehensive, straightforward and easy-to-use, and attempts to assist rather than substitute for the skilled planner. The model was used to estimate water supply resources and demand in the study area.

3.2 Water Supply Resources

For the purpose of this model, two main rivers and a local reservoir were considered as the available water resources in the watershed to all the demand sites. The rivers were labelled as Main River1, Main River2 and the local reservoir labelled as Reservoir as presented in Figure 5.

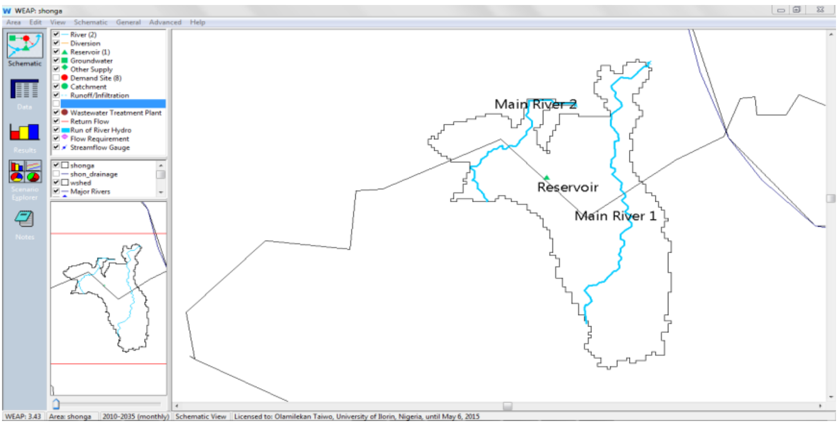

Figure 5 Available Water Supply Resources in the Model

Table 2 Monthly flow for main rivers (m^3/s)

	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

In the model, the reservoir is taken as small tanks schematized in the model and named 'RESERVOIR' with a storage capacity of about 0.5 x $10^6 m^3$and the 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 projection period of 25 years considered in the model are presented in Table 2.

The transmission links performed in the WEAP model applied to the Shonga watershed arepresented in Table 3.

Table 3: Transmission links between water supply site and demand site in the Shonga Watershed

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

The ultimate WEAP model for Shonga Catchment is presented in Figure 6.

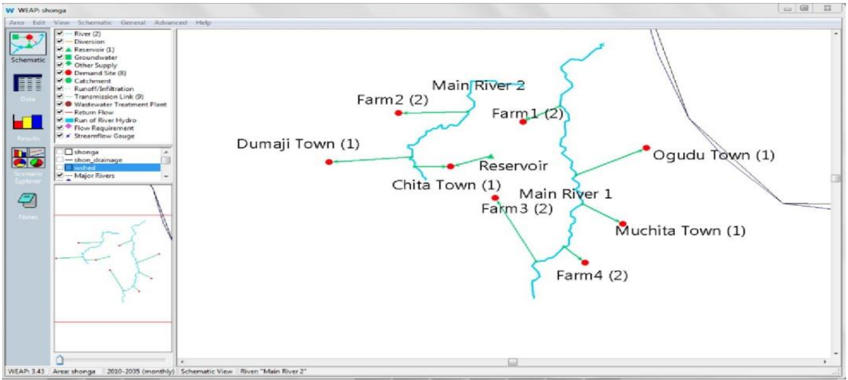

Figure 6 WEAP Model for Shonga catchment

3.3 Development of Scenarios

The development of typical scenario models consists of three steps;

(i) "Current Accounts" 2010 was chosen to serve as the base year of the model. All the data for the base year were input in this account.
(ii) "Reference" scenario is established from the current accounts to simulate likely evolution of the system without intervention.
(iii) 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;

(i) 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 thelivestock growth rate from 5.6% to 15.4% in the farms.
(ii) Managerial Policy: This scenario look at the impact of strict water demand management practices in both the domestic and agricultural demand sites; thereby reducing their demand by 15%.The interface of the scenario is presented in Figure 7

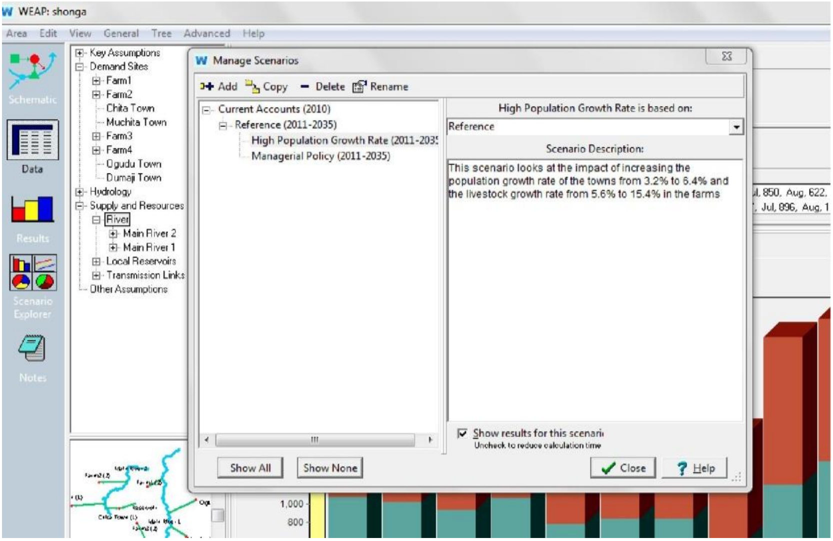

Figure 7: Scenarios interface

4. Results and Discussion

The results of the simulation carried out for the modeled area using year 2010 as the base year and for 25 years forecast period using WEAP software are discussed in this section.

4.1 Water Resources Available in the study Area

Using data in Table 2 as the input for the base year 2010, a total head flow of 28,009 x $10^6 m^3$/swas available, with Main River 1 and Main River 2 being the main sources ofwater to the study area supplying the area with a total head flow of 15388x $10^6 m^3$/sand2621 x $10^6 m^3$/s respectively for the base year 2010.

4.2. Water Demand in the Area

The quantity of water demand and unmet water demand respectively for the demand sites for the base year (2010) and the forecast year (2035) are presented in Tables 4 and 5.

The total water demand for the base year in the study area was estimated to be 3.74x 10^6 m^3/sand for the forecast year was projected to be 8.32 x $10^6 m^3/s$; while the totalunmet demand was estimated at 0.92 x$10^6 m^3$/sfor 2010 and 2.04 x $10^6 m^3$/sfor 2035.

Table 4 Total Annual Water Demand

Demand Sites	Annual Demand Year 2010	Annual Demand(m^3) Year 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

Table 5 Total Annual Unmet Demand

Demand Sites	Annual Demand(m^3) Year 2010	Annual Demand (m^3) Year 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
Total	916,199	2,041,212

Figures 8 and 9 is the graphical representations of the total annual water demand and unmet demand respectively.

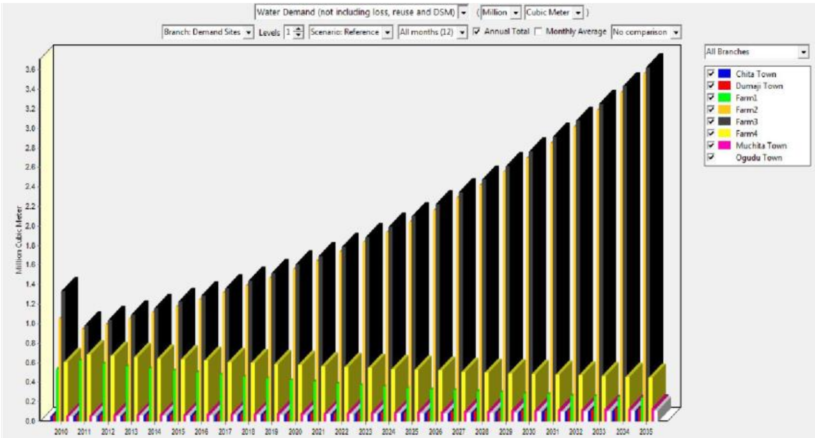

Figure 8: Total annual water demand

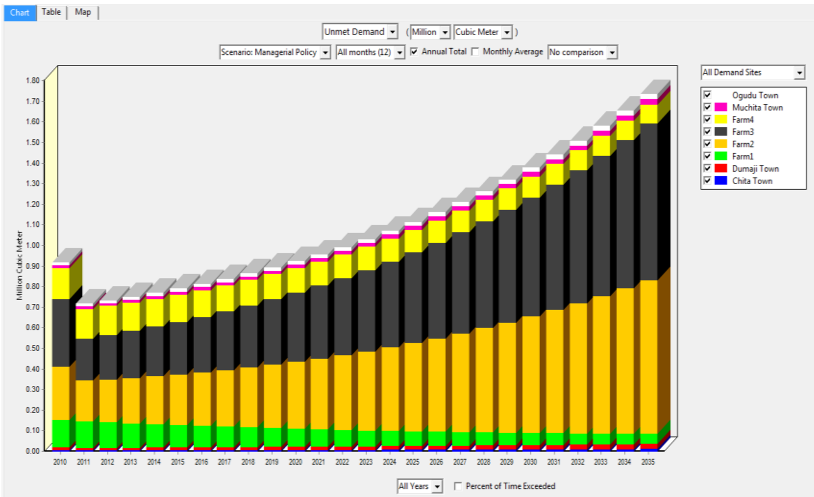

Figure 9: Total annual unmet demand

4.3. Water Resources Model for the Area

The model for the water resources available in the area designed on the WEAP interface can be seen in the Figure 10 with the major sources of water to the area being the two major rivers.

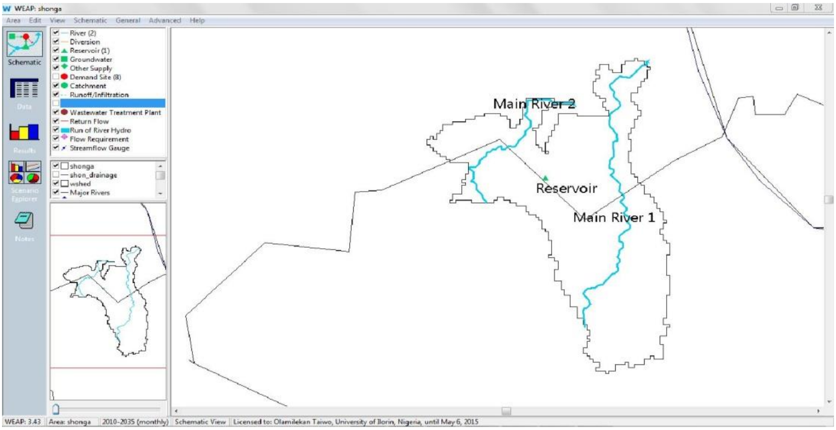

Figure 10: Available water supply resources in the area

4.4 Water Allocation Model of the Area

Various transmission links and nodes which connect the various demand sites to the water supply resources in the area have indicated in Figure 3. The domestic demand sites have a higher priority than the farms. The effectsof developed scenarios for the simulation areof three different scenarios develop on the water demand. They were evaluated as follows:

4.4.1 High Population Growth

As presented in Tables 6 and 7, the total water demand for the demand sites is observed to experience an increase from $8.32x10^6m^3$ to $10.24x10^6m^3$ at the end of the forecast year; while the total unmet water demand also increased from $2.04x10^6$ $m^3$to$2.47x10^6$ m^3. The rise in demand is attributed to the increase in population of people in the towns and the cattle in the farms. Figures 11 and 12 depict the graphical representations of the total water demand for the demand site.

Table 6: Total annual demand due to high population growth for 2035

Demand Sites	Normal Population Growth Annual Demand (m^3)	High Population Growth Annual Demand (m^3)
Chita town	105,083	472,075
Dumajitown	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
Total	8,322,906	10,243,904

Table 7: Total annual unmet demand due to high population growth for 2035

Demand sites	Normal Population Growth Annual Demand (m^3)	High Population Growth Annual Demand(m^3)
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
Total	2,041,212	2,468,257

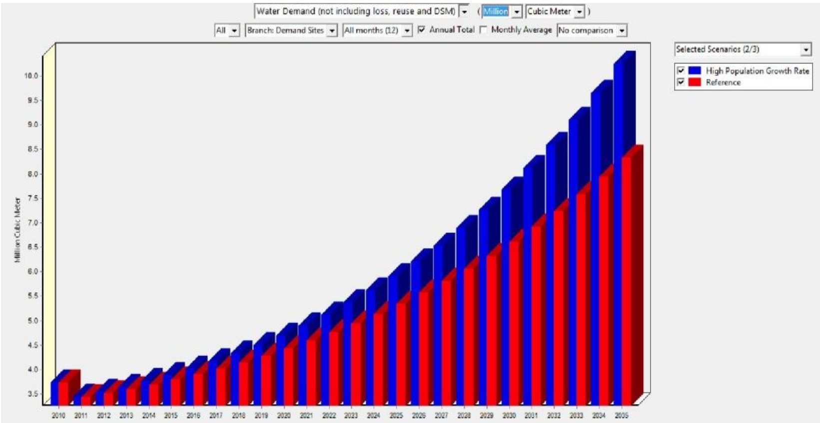

Figure 11: Total annual demand due to high population growth rate

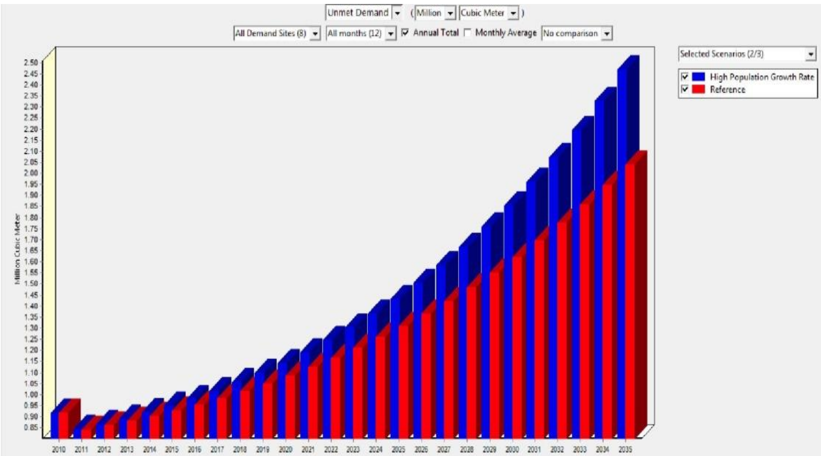

Figure 12: Total annual unmet demand due to high population growth rate

4.4.2 Managerial Policy

The total water demand for the demand sites remains the same at the end of the forecast year and managerial policy scenario (8.32 x $10^6 m^3$); while the total unmet water demand experienced a decrease from a value of 2.04 x

$10^6 m^3$ to 1.74 x $10^6 m^3$ aspresented in Table 8. The constant total water demand is due to the fact that this represents the actual water demand of the demand sites, while the decrease in unmet demand is attributed to the demand management policies which were aimed at reducing the actual amount of water being used in the demand sites. Figure 13 shows the graphical representations.

Table 8 Total annual unmet demand due to managerial policies for 2035 (m^3)

Demand sites	Normal Annual Demand (m^3)	Available Quantity (m^3)	Umet Demand (m^3)
Chita town	14,759	12,545	2,214
Dumaji town	29.537	25,106	4,431
Farm 1	58,482	49,709	8,773
Farm 2	877,927	746,238	131,689
Farm 3	893,752	759,690	134,062
Farm 4	110,311	93,765	16,546
Muchita town	30,414	25,852	4,562
Ogudu town	26,029	22,125	3,904
Total	2,041,212	1,735,030	306,182

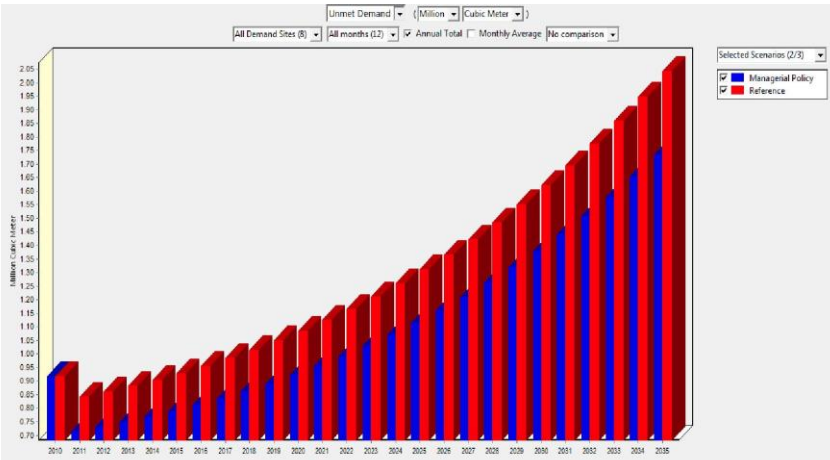

Figure 13: Total annual unmet demand due to managerial policies

4.5 Validation of the Model

The catchment area has no stage/discharge data for stream flow (unguaged station), hence a regression relationship was established between the hydro meteorological station of similar basins. An empirical relationship was obtained from another catchment that has precipitation and runoff data and lies in a hydro meteorologically similar environment (Jebba) to correlate the principal runoff parameters in order to determine the quantity of water for peak flood and surface water availability for allocation(Olukanni andAlatise, 2008). The precipitation and runoff data are tested by plotting precipitation and runoff against each other as depths, a correlation in form of a straight line was obtained. The mean annual runoff, R, a dependent variable is expressed as:

$$R = a + b\,þ \qquad (1)$$

Where, þ is the mean annual precipitation, an independent variable; “a” and “b” are empirical constants given by

$$a = R - b\,þ \qquad (2)$$

$$b = \Sigma\,(R\text{-}R_{jebba})(P\text{-}\,þ\,)/\,\Sigma(P\text{-}\,þ\,)^2 \qquad (3)$$

This method was used to estimate the mean annual runoff for completely ungauged catchments. The runoff and precipitation data are known, the constants “a” and “b”, for ungauged catchment were obtained and adopted for Shonga.

The station used for this correlation analysis is Jebba Station along River Niger which hasboth stream flow and rainfall data. The correlation coefficient between rainfall and runofffor River Niger at Shonga watershed is given by equation 4.

$$r = \Sigma\,(PR - nP_{Jebba}\,R_{Jebba})/[(\Sigma P^2 - nP^2_{Jebba})(\Sigma R^2 - nR^2_{Jebba})] \qquad (4)$$

Where, n = number of years of record which is 25years, P_{Jebba} = Mean Annual Precipitation for Jebba; 1100mm, R_{Jebba} = Mean Annual Runoff of River Niger at Jebba; 2405.5mm. The correlation coefficient of 0.922 was obtained, this shows that there is a strong linear relationship between rainfall and runoff of River Niger at Jebba which can be transferred to the Shonga Basin.The coefficients “a” and “b” are obtainedas –535.4 and 0.355 respectively. The runoff equation is given by:

$$R_{Shonga} = - 535.4 + 0.355P_{Shonga} \quad (5)$$

The Mean Annual Rainfall value of Jebbawas adopted for the study site as 1100mm. R = -535.4 + (0.555x 1100) = 75.1 mm The catchment area as measured using ArcMap software is 295.8km^2 and the Mean Annual Runoff (Mm^3) = 295.8x 75.1 x 0.001. = 22.1x10^{6}was obtained for Shonga catchment.

4. Conclusion

IWRM Domestication Process in Nigeria is a viable transition to water sustainability, the results obtained from this study shows that the water supply resources in the area was not sufficient to meet the water demand in the Shonga Catchment for the year 2010, and also will be less sufficient by the year 2035. These can be seen as a result of the unmet water demand that was recorded through the simulation process for all of the demand sites in the study area.The model was able to simulate and forecast for several years (2010-2035). The results look ‘reasonable’ since there is no observed data from the watershed for statistical validation. However using the Water Balance equation as a validation criteria, the correlation coefficient between the simulated rainfall and convolution runoff was 0.92 and 0.86 for sub basin (outlet) from nearest station with similar characteristics.The model provides a framework for local adaptation in maintaining spatially and temporally varying demand and supply information,useful for future planning and analysis with water managers and other stakeholders within the basin.

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