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ESTIMATING THE WATER BALANCE COMPONENTS WITHIN GURARA RESERVOIR USING REMOTE SENSING AND GIS TECHNIQUES

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ABSTRACT

The water balance components of Gurara reservoir were estimated as effective water resources development and management is crucial for sustainable economic growth and poverty reduction. In Nigeria, the Gurara reservoir with storage capacity of 700 mcm plays a considerable role in maintaining and developing activities within it surrounding catchment areas and in providing irrigation water for agriculture and for livestock and people. In addition, the reservoir provides approximately 70% of the total public pipe-borne water supplied to the Abuja water board treatment plant and its environs through diversion to the Lower Usuma Reservoir. An integrated Remote Sensing and GIS approach was used to estimate the runoff based on the Soil Conservation Service Curve Number (SCS-CN). The SCS-CN model produced an acceptable yield of monthly calibration/validation with NSE, PBIAS and R^2 values of 0.72/0.69, 0.72/0.67 and 4.0%/1.0% respectively in order to optimally manage the operational and hydro-physical dynamics of Gurara reservoir. From the findings, monthly observed water balance components were used for setting up a water balance model. The total annual water balance result indicates that total catchment runoff and direct precipitation respectively constituted 77.97% and 22.03% of the total inflows while spilled water, diverted water, evaporation, and evapotranspiration respectively amounted to 73.52%, 26.48%, 9.19 and 16.65% of the outflows. Theses result will help to enhance the knowledge of water resources of the reservoirs in order to improve their management in the context of multiple uses as lack of baseline data on reservoir operation hinders their optimal management.

KEYWORDS: *Water Balance, Gurara Reservoir Catchment, Water Use and SCS-CN model*

INTRODUCTION

Hydrological modelling provides a strong base to optimally investigate the hydrophysical dynamics of water resource, impacts of climate and landuse changes on water balance components. This is because hydrological models over time have been able to predict the hydrological processes that allow for detailed description of the hydrological cycle and provide opportunities for dealing with the hydro-climatic variables that fluctuate strongly in space and time. These models have increasingly been used by researchers as a means to apply the state of knowledge on reservoirs of interest, and provide valuable information regarding hydrological cycle on the existing and future surface water flow regimes. However, lack of data (stored water available, water volume consumption) can have a negative impact on water security and undermine the ability of the riparian population to effectively manage their water resources (Pekel *et al.,* 2016). This is the situation for many reservoirs in Nigeria which, despite being an important source of water for the city of Abuja which is largely unmanaged. In Nigeria, the Gurara Reservoir Catchment which hosts the Gurara Reservoir is been built to perform similar function an enclosed area for the storage of water to be used at a later date. The Gurara reservoir created by building a dam across the river Gurara providS approximately 70% of the total raw water supplied to the Abuja Water Treatment through the Lower Usuma Reservoir (Okunlola *et al.,* 2014).

Remote sensing has been a powerful tool to provide or complement information for water management (Garrido-Rubio *et al.,* 2020). In the Gurara Reservoir Catchment (GRC), it has been used for mapping water surfaces (Francis *et al.,* 2021). Remote sensing can be particularly useful for study locations where base line information is needed for further investigation However; the accuracy of different remote sensing techniques typically requires on-site data for model calibration and validation

When inflow and outflow records are not available to solve water balance equations, reservoir water level records can provide the information required to estimate the inflow and outflow if the records are carefully classified based on expert knowledge. The application of expert knowledge and supplementary information has been successful in solving hydrological inverse problems. For example, model parameter values are commonly constrained base on the understanding of the physical basis of the parameters and model structure (Gharari, *et al.,* 2014) and/or information derived from indirect observations. A model to predict the reservoir behavior such as a reservoir rule curve can provide information that can be used to constrain the parameter space of reservoir routing modeling (for inflow and outflow estimation), thereby increasing accuracy and reducing uncertainty in a reservoir water balance analysis. However, expert knowledge application has not been commonly employed to adequately estimate reservoir water balance components.

Water balance is a powerful tool for obtaining relevant data for reservoir management (Arsiso *et al.,* 2017), as a first step towards the development of an integrated system for GRC, this study assesses the water balance of the Gurara Reservoir to aid efficient planning, management and decision making in the reservoir. A water balance will quantify the total inflow and outflow using a long term data-driven approach as water moves through the catchment into and out of the reservoir (Alao *et al*., 2014). In this regard, the paper highlights how the water balance assessment could be used to optimize the benefits from a multi-purpose reservoir using the Gurara Reservoir as a case study to evaluate the uncertainty of the storage curve, estimate the stored volumes, and water flows, including inflow, withdrawal, and infiltration, using a water balance technique combined with remote sensing techniques.

Material and Methods

Study Area

Gurara reservoir lies along the Gurara River at 9°05'N, 7°30'E. The reservoir cuts across Kachia and Kagarko Local Government Areas in Kaduna State. The Gurara river system flows northeast to southwest and turns southwards as it flows through Abuja, the Federal Capital Territory as illustrated in Fig 1.

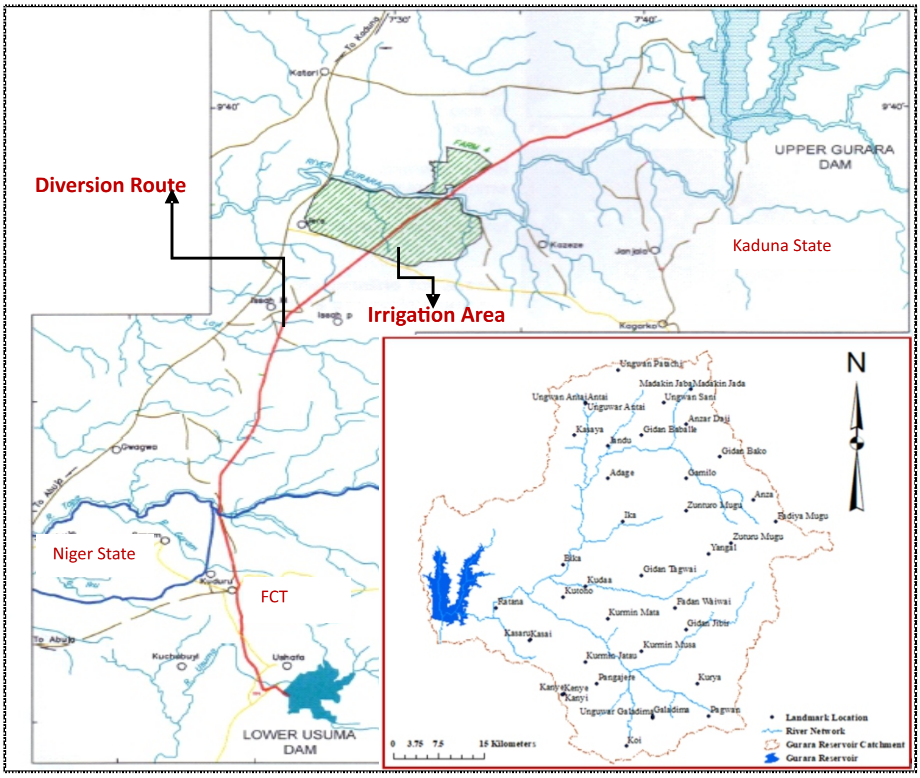

Figure 1: Map showing Gurara Reservoir Catchment Boundaries and Country Location.

The Gurara reservoir is multipurpose in nature, designed and constructed to transfer approximately 70% of 720 million litres of raw water per day demand to the Lower Usuma reservoir for onward forwarding to the Abuja water treatment plant. The inflow is from the Gurara River into the reservoir is the major source, while the diverted water to Abuja water treatment plant and Azare-jere irrigation farms is regarded as the major outflow of Reservoir Gurara. Prior to damming the Gurara River to create the Gurara Reservoir, there were six villages namely Atara, Akama, Asawa, Akwana, Dokah, and Kadah which were within the reservoir area, and one village (Maje) within the irrigation area all were relocated to a new settlement as their villages were submerged with water. The federal ministry of water resources and sanitation has been monitoring the water level and quality of Gurara reservoir since its operation from 2010.

The Climate around Gurara Reservoir Catchment

The climate within the Reservoir Gurara catchment experiences a typical tropical continental climate with distinct seasonal regimes, oscillating between cool to hot dry and humid to wet. These two seasons reflect the influences of tropical continental and equatorial maritime air masses which sweep over the entire Gurara Reservoir Catchment area. The influence of both air masses on the study area is determined largely by the movement of the Inter-Tropical Convergence Zone, a zone representing the surface demarcation between the two air masses. The interplay of these two air masses gives rise to two distinct seasons within the catchment, which are the dry, dusty, tropical-continental (cT) air mass originating from the Sahara region and the warm, tropical- maritime (mT) air mass from the Atlantic Ocean. The wet season is associated with the tropical maritime air mass, while the dry season is a product of the tropical continental air mass.

Data Collection

The dataset used for this study are categorized into three set and collected from various sources, and were used for further analysis concerning the water balance computation. The first set of data comprising climatic parameters was used for trend analysis and extreme changes in climatic scenarios. They comprise thirty (30) years meteorological data of rainfall, temperature, wind speed, sunshine hours and humidity data obtained from the Nigerian metrological agency (Nimet). The second set of data consisted of topography digital elevation models (DEM), with a spatial resolution of 30 metres ad downloaded from http://glovis.usgs.gov/, land cover, soils, and the reservoir's storage capacity for hydrological modeling especially runoff and production of hydrological maps. The third set of data collected included population and water demands from different water users, the Federal Ministry of Water Resources Nigeria and the National Bureau of Statistics.

Data Processing

The processing of the data, majorly the hydrological map was performed using Geography Information System (GIS) software to digitalize the area and produce the administration boundary map around the Gurara Reservoir Catchment. The first step involves delineating stream network and getting some relevant properties such as area, slope, flow length, stream network density, etc. With the availability of digital elevation models (DEM) at a scale of 1:10,000 and the GIS tools provided by the Kwame Nkrumah University of Science and Technology, watershed properties were extracted using automated procedures.

Water Balance Analysis

The approach for the water balance was estimated using the general water balance equation for reservoir developed by Shaw (1994). According to Domfeh et al., (2015), the application of the water balance equation is to describe how water level in a reservoir responds to various simulated inflow and outflow scenarios. The generalized equation of water balance is listed below as Equation 1.

?S/?t = P_Reservoir+? G?_In - E_Reservoir - ?ET?_P - Q_out + ?   1.

Where: $\frac{\Delta S}{\Delta t}$ is the change in storage over time, $P_{Reservoir}$ is the precipitation directly over the reservoir area, $E_{Reservoir}$ is the evaporation, ET_P is the potential evapotranspiration, Q_{out} is the outflow from the reservoir, G_{In} is inflow into the reservoir while η represents the uncertainties in the water balance arising from errors in the data and other terms, such as net groundwater flux or minor abstractions which usually cannot be accounted for directly (Ufoegbune *et al.,* 2011). The components of the reservoir water balance model are illustrated in Fig 2.

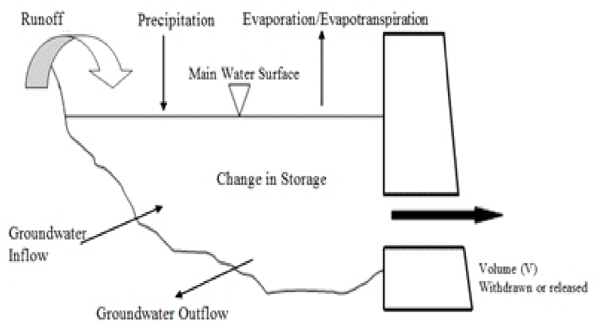

Figure 2: Schematic representation of the water balance components

Water Inflow

Precipitation (P)

Considering the relatively not very large surface area of the study area, the obtained precipitation data sufficiently represents the average rainfall over the catchment surface. Therefore, the average precipitation was computed from the average daily and monthly observed datasets.

Runoff

The inflow as runoff into Gurara Reservoir from the surrounding catchment was estimated using the Soil Conservation Service Runoff Curve Number (SCS-CN) method. This method involves determining the Curve Number (CN) which depends on the watershed's soil and cover conditions. This is represented as the hydrologic soil group, cover type, treatment, and hydrologic condition. The SCS runoff equation is

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad 2$$

Where:

Q = runoff (in), P = rainfall (in), S = potential maximum retention after runoff begins and = Initial abstraction i.e. all losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration.

is highly variable but generally is correlated with soil and cover parameters. According to (FMWR, 2014), through studies of many small agricultural watersheds within the study area was found to be approximated by the following empirical equation:

$$I_a = 0.2S \qquad 3$$

S is related to the soil and cover conditions of the watershed through the runoff CN by equation 3. The CN is a measure of the degree of imperviousness of the soil and how much soil responds to runoff generation in terms of volumes and rates for every rainfall event and has a range of values from 0 to 100. The value of 0 is for highly pervious surfaces and 100 for highly impervious surfaces. The expression for S is given in equation 4.

$$S = \frac{1000}{CN} - 10 \qquad 4$$

A composite Runoff CN of 75 % was adopted for this study based on previous study within the study area according to Jimoh and Ayodeji (2003). Based on Equation 2, 3 and 4, the Mean Annual Runoff over the catchment is estimated from Equation 5.

$$Q = \frac{(P - 0.6667)^2}{(P + 2.6666)} \qquad 5$$

Water Withdrawal

Open Water Evaporation Data.

Estimating evaporation is essential in water balance assessment. In this study area, the evaporation data was obtained from pan evaporation installed within the catchment and was made available by the Nigerian Meteorological Agency (NiMet) which was subsequently used for this study.

Groundwater Inflow and Outflow

Although the contribution of groundwater to the Gurara Reservoir is highly negligible, Francis *et al.,* (2021) reported in an earlier study that the contribution from groundwater into the Gurara reservoir is less than 4% of total inflow using on-site groundwater level measuring approach. The findings concluded that there is negligible groundwater outflow and inflow from Gurara reservoir. With no further substantive data supporting these findings, groundwater inflow and outflow were set to zero in this study for estimation of the water balance components because according to Francis *et al.,* (2021), the thick stiff clay at the bottom of the reservoir reduces seepage.

Water Outflow from Spillway

In the downstream of the catchment where the reservoir is located, there is no installed monitoring system to effectively estimate the quantity of water that leaves the reservoir through the spillway of the reservoir. Monthly spills were therefore estimated as an excess of the storage capacity.

Model Performance Evaluation

The performance of the models is assessed using a coefficient of determination (R^2), the NSE, and shown in Equation 6, while RSR is listed in

Equation 7 and PBIAS listed in Equation 8. The suitability of the models is estimated based on three criteria from Estimation of the performance factors. NSE representing fit-to-observations and RSR representing mass balance evaluation, fit-to-reality is performed to statistically determine the true representation of the hydrological processes using parameter. And PSBIAS representing fit-to-purpose is performed to assess the how far the models are capable to solve the problem (Awotwi *et al*., 2017)

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} (Q_i^{obs} - Q_i^{sim})^2}{\sum_{i=1}^{n} (Q_i^{obs} - Q_{mean}^{obs})^2} \right]$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n} (Q_i^{obs} - Q_i^{sim})^2} \right]}{\left[\sqrt{\sum_{i=1}^{n} (Q_i^{obs} - Q_{mean}^{obs})^2} \right]}$$

$$PSBIAS = \left[\frac{\sum_{i=1}^{n} (Q_i^{obs} - Q_i^{sim})}{\sum_{i=1}^{n} (Q_i^{obs})} \right] * 100$$

Where Q_i^{obs} and Q_{mean}^{sim} are the observed values and mean of the observed values respectively, while Q_i^{sim} and Q_{mean}^{obs} are the simulated values and mean of the simulated values.

Results and Discussions

Trend Analysis of Temperature and Rainfall

The estimated rainfall coefficient and aerial pattern of rainfall seasonality depicted in Table 2 are characterized by one wet and dry season during the year. From the rainfall coefficient analysis, the rainfall recorded in May and October are classified as small rain and account for 17.3% of the mean annual rainfall within the reservoir. This reveals that big rains with moderate concentration occur in June, July, August and September and accounts for 82.7% of the mean annual rainfall.

Table 2: **Rainfall Coefficient and aerial pattern within GRC (1988-2019)**

Months	Rainfall Coefficient Values	Season	Classification	Further Classification
Jan	0.0	Dry		
Feb	0.0	Dry		
Mar	0.0	Dry		
Apr	0.4	Dry		
May	0.9	Raining	Small Raining	
Jun	1.6	Raining	Big Raining	Moderate Raining
Jul	2.0	Raining	Big Raining	High Raining
Aug	2.4	Raining	Big Raining	High Raining
Sep	1.7	Raining	Big Raining	Moderate Raining
Oct	0.8	Raining	Small Raining	
Nov	0.0	Dry		
Dec	0.0	Dry		

This finding implies that within the study area, high concentration of rainfall is experienced in July and August which accounts for approximately 44.9% of the total rainfall. There are approximately six months of dry season contributing 4.1% of the mean annual rainfall, with 95.9% occurring in the wet season. The mean annual temperature and rainfall is illustrated in Figure 3, with temperatures occurring between 30.6°C – 36.5°C with the hottest period occurring in the months of March and April. The highest mean monthly temperature is observed in April with 36.5°C while the lowest mean monthly temperature is in December with 14.7°C. The results are in agreement with Awotwi *et al*., (2017), as temperature value for the typical semi-arid region. In the same manner, the mean annual rainfall of GRC area trend is high in July, August and September, which accounts for 52% of the total mean annual rainfall, whereas the minimum rainfall is observed between November and February. The total annual rainfall in the GRC has a duration is between five to seven months, from April – October. According to Awotwi *et al*., (2017), this period is under the influence of a Saharan high-pressure zone, while the northeastward harmattan wind brings hot, dry air and high temperatures onto the catchment during the dry season which begins in November and extends till February.

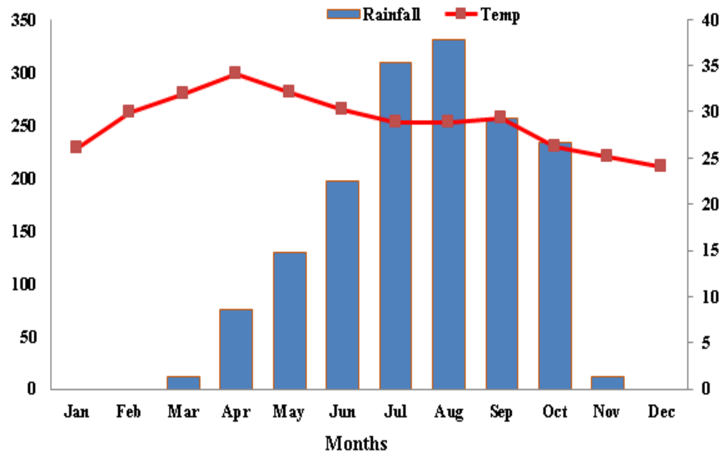

Figure 3: Rainfall and temperature relationship (1988- 2019)

The dry season sets in from early November till March with no trace of rainfall all through its duration. The mean monthly rainfall is highest in the month of August with a value of 294.8 mm using the summarized mean monthly temperature and rainfall relationship for the period 1988 to 2019 within the GRC. Although the recorded maximum temperature occurs only in April, high temperature values are also observed during the wet seasons.

Evaporation Losses

Estimating evaporation is essential in water balance assessment. The mean monthly evaporation within the GRC was obtained using the Pan Evaporation method installed at the Gurara gauging station and the plot is presented in Figure 4. The trend of evaporation is similar to that of the mean monthly precipitation with the lowest mean monthly evaporation occurring in August (2.3 mm) corresponding to the month of peak rainfall and highest in March (12.9 mm). The total annual water loss by evaporation within the GRC is estimated at 2533.4 mm.

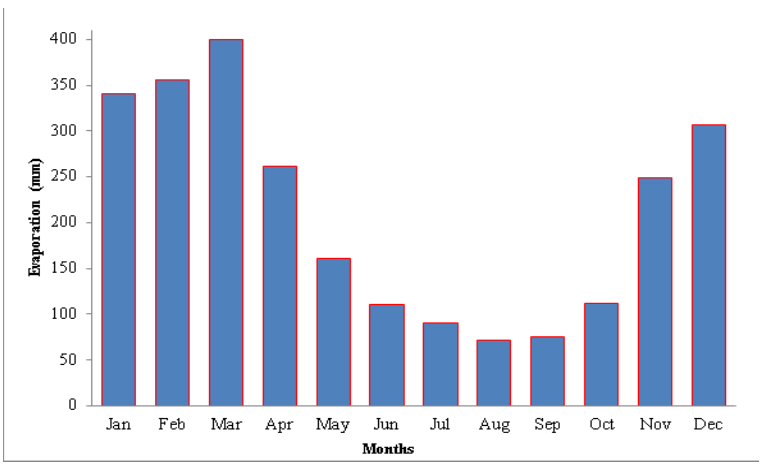

Figure 4: Mean monthly evaporation within the GRC (1988 - 2019)

Calibration and Validation of Surface Runoff

The calibration and validation of the observed surface runoff performed using the SCS-CN-based model is illustrated in Figure 5. A direct comparison of monthly observed and predicted runoff for the calibration and validation was performed. The output parameters were adjusted to reproduce the measured calibration data as representative as possible without any concern for the verisimilitude of the observed values. The model was run for the years 1978 through 1991, the year runoff data were last collected within the GRC. A random sample of half of those years was used to calibrate the model and a sample consisting of the remaining years coupled physical runoff measurement on the River Gurara were used to validate it and their final value listed in Table 3.

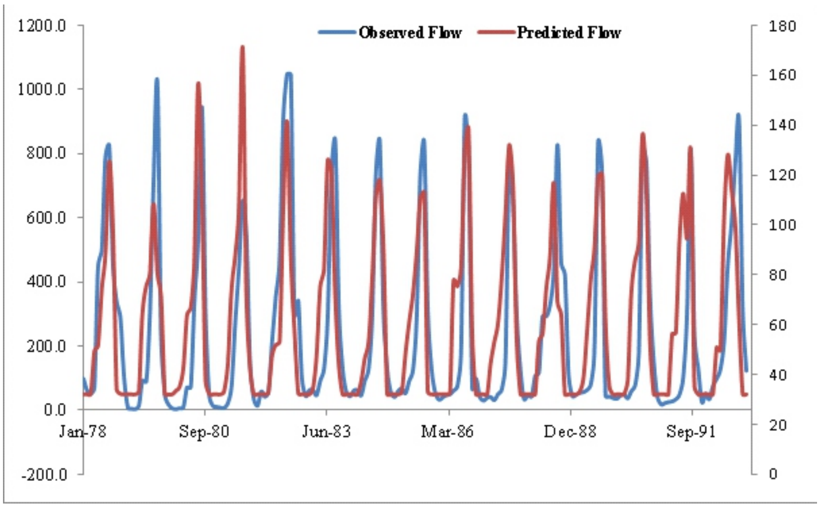

Figure 5: Modeled flow fit on the predicted flow for the period (1978 to 1991) within the GR

Table 3: Statistical analysis of observed and simulated runoff within GR (SCS-CN model)

	Average monthly inflow											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Standard deviation	11	15	15	12	37	46	103	216	245	126	48	20
Coefficient of variation	0.82	1.54	1.97	1.09	0.85	0.56	0.50	0.46	0.49	0.48	0.71	0.75
median	12	6	4	7	31	71	190	436	435	246	55	23
Maximum runoff	83	122	123	90	179	238	562	1322	1573	607	247	105
Minimum runoff	12	10	10	11	13	16	17	156	102	28	17	15

Accordingly, the result obtained from the SCS-CN method for runoff modeling on the Gurara Reservoir Catchment otherwise called the Upper Gurara Catchment which is a sub-basin within the Gurara River Basin. The statistical analysis reveals a good match between observed and predicted runoff values with R^2 being more than 0.5 as listed in Table 4. According to Moriasi *et al.,* 2007), a good fit between observed and predicted dataset uncovers usually in a minimum error variance between the two data sets. The dependability of the model was additionally affirmed by PBIAS values which were within the scope of ± 10 %, again demonstrating a very good performance of the model and NSE values of more than 0.72, thus further demonstrating the reliability of the SCS-CN modeling approach for runoff computation. Although it should be noted that the SCS-CN developed model is not a physical model as such it shouldn't be expected to yield usable results outside the range of runoff for which it was calibrated.

Table 4: **Model calibration and validation performance**

Stage	Statistics Indicators		
	NSE	PBIAS	R^2
Calibration	0.72	-0.04	0.70
Validation	0.69	-0.01	0.72

Irrigation Water Demand

The estimated outflow for irrigation farms within the GRC for the purpose of estimating the water balance components from the Gurara reservoir is listed in Table 5. A maximum of one cropping season was currently been practiced and fully in operation comprising of three (3) farms with smaller units as blocks thereby requiring a lot of water from the reservoir.

Table 5: **Water demand for the irrigation farms**

Irrigation Farms	Gross Area (ha)	Net Irrigated Area (ha)	Hourly Water Demand (m^3/hr)	Actual Daily water Demand (m^3/day)
Farm 1	1,344.0	1,075.1	2,688	32,256
Farm 2	1,292.6	1,034.1	2,772	33,264
Farm 3	1,579.2	1,263.4	3,780	45,360
Pilot Farm	2,000.0	2,000.0	5,983	71,796
	6,216.0	5,373.0		
Total for Farms 1, 2, 3 and Pilot Farm.			15,223(m^3/hr)**	182,676 (m^3/day)*

(Source: Modified from NIAF, 2014: Authors Estimations).

The irrigation period is during the dry season which lasts for a period of five (5) months. During this period, water is supplied continuously to the irrigation farms for 12 hours daily excluding Sundays before the commencement of the next wet season. The daily average water released for irrigation was computed based on a water depth of 5mm on average with net irrigation considered to be 85% of the gross area.

The Water Balance

The comparison of the water balance components is illustrated in Figure 5 typical of a multipurpose reservoir, which comprises the major driver for withdrawal beside the outflow as the spill and the water diversion rate. Multipurpose reservoirs are often associated with huge open water evaporation losses usually considered as wasteful and hence, resulting in significant losses especially shallow reservoirs. On the other hand, direct rainfall serves as a significant contribution to the open water surface. According to Awotwi et al. (2017), in a study of the Volta Basin Water Balance, one hundred percent of the rain falling onto the reservoir reaches storage while only nine percent of the water falling on the uplands runs into the reservoir, while evaporation and reservoir rainfall is approximately one-third of runoff and likewise about a third of the outflow. In the water balance of the of the Gurara reservoir as illustrated in Figure 6, direct precipitation on the open surface water contributes immensely to balance for the open surface water evaporation.

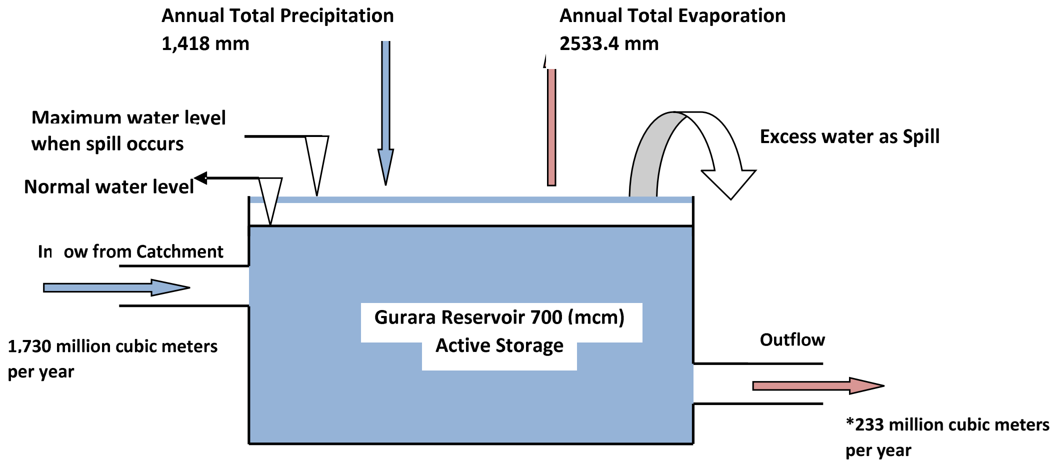

Figure 6: Water balance components (*Authors Calculation)

The long-term tendency of the annual and seasonal variations of precipitation, inflow, population and water level is illustrated in Figure 7. From the illustrative plot, peak annual mean runoff corresponds with the peak annual mean precipitation. The monthly mean precipitation increases from January to September and then decreases from October to December and a similar pattern are illustrated for the runoff.

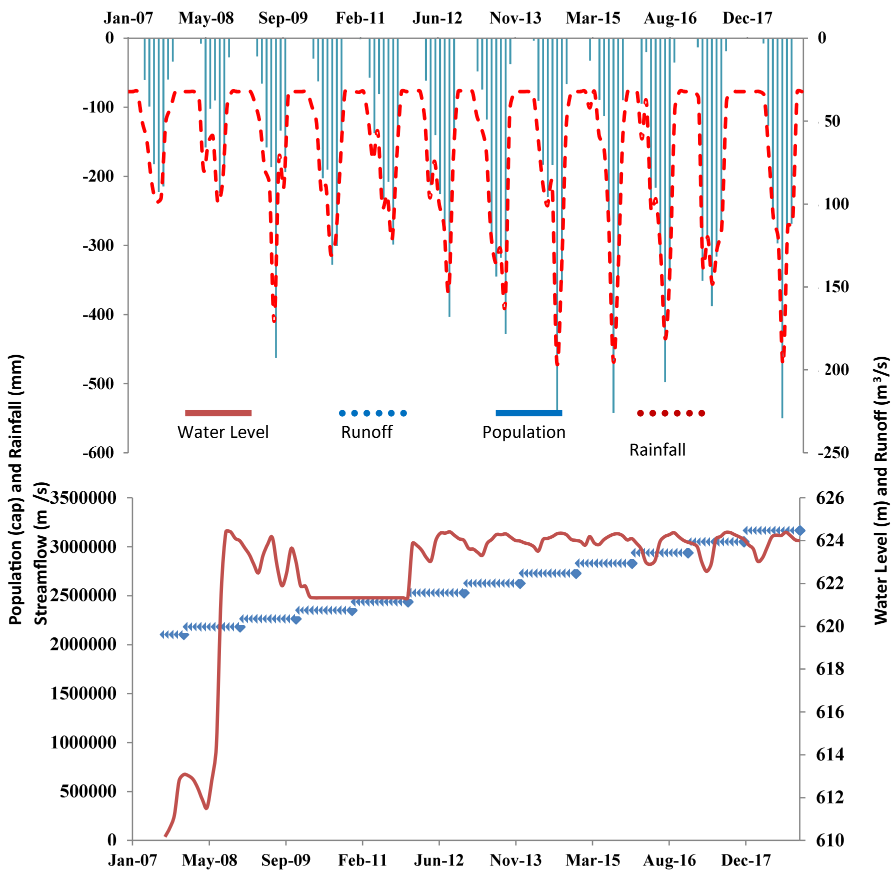

Figure 7: Variability of mean monthly runoff, water level, precipitation and population within the GRC

The plot shown in Figure 7 further revealed a downward trend in water level as the population increases. This can be explained as population growth increases, resulting in more water being diverted and resulting in lower water levels. According to Francis *et al.,* (2021) the mean month water level at the Gurara reservoir usually lowest during the dry season of increased water diversion operation which ends in June before the commencement of the wet season when the water levels return to its peak. This result is in agreement with Jimoh and Ayodeji (2003), suggesting that the Gurara reservoir diversion has influenced the water level with a view of having negative water balance anomalies in the future from the Gurara reservoir, which serves as the source fr the water diversion operation, The estimated percentages of the water balance component in the Gurara reservoir are listed in Table 6.8, showing the major inflow is from direct runoff and precipitation contributing approximately 77.97 % of the total inflow within the GR.

The computed percentages of the water balance component within the Gurara reservoir are listed in Table 6, showing the major inflow is from direct runoff and precipitation contributing approximately 77.97 % of the total inflow within the reservoir.

Table 6: Mean annual water balance from 2007-2019 as estimated within GR

Inflow		Outflow			
(Percentage of Total Inflows)		(Percentage of Total Outflows)			
Total Runoff	Direct Rainfall	Evaporation and	Evapotranspiration	Water withdrawal/Diversion	Spillway
77.97 %	22.03 %	9.19 %	16.65 %	26.48 %	73.52 %

The fact is that the surface water level in the Gurara reservoir in December before the diversions is greater than that of the post diversion periods indicates that the Gurara reservoir has been affected significantly water withdrawal from the Gurara reservoir as diverted water can be influenced by the water level difference between the Gurara reservoir and the Lower Usman reservoir. Accordingly, to Ibrahim and Isiguzo (2009), reports that river discharge for the downstream riparian population has seen a decreased after the reservoir started full-capacity diversion from 2010.

Having studied the state-of-art water balance components within the Gurara reservoir, it can be inferred that the interconnection between Gurara reservoir and the water balance components becomes more complicated during a water diversion operation within the catchment. However, we were able to look at the water balance components from different standpoints. From this study, three scenarios emerge regarding the water balances themselves: (a) Observable variations in precipitation be capable of producing larger changes in surface runoff. (b) Land cover change is critical in the partitioning of water within the catchment: (c) Spatial variation in water balance component needs adequate description within the catchment to increase our confidence in making a logical conclusion on the balance.

Major Concerns from Water Balance

From the estimated water balance component within the reservoir, there are three significant concerns emerging for consideration. First, the reduced drawdown evident in low water levels during water diversion outflow from the reservoir has and continually causing negative consequences for the water users downstream of the reservoir. Secondly, as the population of Abuja continues to increase, water demand becomes a major discussion among stakeholders requiring an effective water management mechanism for optimal allocation.

Conclusions

In this study, the water balance study allows us a first look at the hydrological response using a remote sensing, remote sensing and GIS approach in the Gurara Reservoir Catchment which is a sub–catchment within the Gurara River Basin to draw a logical conclusion.

1. The available water quantity is large; with an active storage of 700 million m^3
2. The surrounding catchment exhibits a season and annual trends depicting sinusoidal behavior, resulting in changes in surface runoff due to variability in rainfall, hence, land cover changes within upland areas of the reservoir is of major importance needing attention
3. Drone imaging and water balance techniques can enable monthly reservoir monitoring to provide information on stored volume, inflow, withdrawal, and infiltration.

The framework proposed in this paper can be replicated in other reservoirs of similar functionality in the Nigeria northwest region, which might be the main source of water for a local riparian population, such as Gurara reservoir.

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