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CIVIL & ENVIRONMENTAL ENGINEERING | RESEARCH ARTICLE

Estimating a municipal water supply reliability

O.G. Okeola[1]* and S.O. Balogun[2]

Abstract: The availability and adequacy of water in a river basin determine the design of water resources projects such as water supply. There is a further need to regularly appraise availability of such resource for municipality at a distant future to help in articulating contingent plan to handle its vulnerability. This paper attempts to empirically determine the reliability of water resource for a municipal water supply. An approach was first developed to estimate municipality water demand that lack socioeconometric data using a purpose-specific model. Hydrological assessment of river Oyun basin was carried out using Markov model and sequent peak analysis to determine the reliability extent for the future demand need. The two models were then applied to Offa municipality in Kwara state, Nigeria. The finding revealed the reliability and adequacy of the resource up till year 2020. The need to start exploring a well-coordinated conjunctive use of resources is recommended. The study can serve as an organized baseline for future work that will consider physiographic characteristics of the basin and climatic dynamics. The findings can be a vital input into the demand management process for long-term sustainable water supply of the town and by extension to urban township with similar characteristic.

Subjects: Civil, Environmental and Geotechnical Engineering; Engineering Economics; Engineering Management

Keywords: catchment; water demand; model; empirical; population

1. Introduction and literature review

1.1. Water resources assessment
Reservoir system is a requisite requirement for most urban water supply. Reservoirs for water supply are generally operated by a set of predetermined rules formulated on the basis of historical inflow, design storage capacity, and safe yield criteria (Moy, Cohon, & ReVelle, 1986). Inflow hydrology is an

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PUBLIC INTEREST STATEMENT

This work looked in to the reliability of water resource for a municipal water supply usage in Kwara State of Nigeria. An approach was first developed to estimate municipality water demand. Thereafter, hydrological assessment of River Oyun was carried out using Markov model and sequent peak analysis to determine the reliability extent for the future demand need. The findings indicated the reliability and adequacy of the resource up till year 2020, but for domestic usage only. The need to start exploring a well-coordinated conjunctive use of resources is imperative.

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important aspect of a reservoir operation studies. Seasonal demand may be relatively fixed, but in contrast, variation in natural streamflow between seasons may be highly variable. In evaluating reliability of water supply system, the availability of water must be compared with water demand. This is usually done by simulating water supply system using historic streamflows and anticipated demands. Fiering (Vogel, 1987) documented three principal shortcomings of strict use of the historical records, thus: (1) the analysis is based solely on the historical record and it is unlikely that some flow sequence will recur during the active life of the completed structure (2) the mass diagram does not help designer to establish or calculate the risk to be taken with regard to water shortages during period of low flow, and (3) the length of the historical record is likely to differ from the economic life of the proposed structure.

Sharma, Tarboton, and Lall (1997) concluded that it is very important to generate synthetic streamflow sequences to analyze alternative designs, operation policies, and rules for water resources systems and that the dependence structure of streamflow sequences is often assumed to be Markovian. In an earlier study, Itube, Mejia, and Dawdy (1972) and Yurekli and Ozturk (2003) noted that generating extreme values is most significant in design and planning. For general surface water resources systems, mathematical optimization techniques have been applied to the study of reservoir planning management as related to urban water supply in a single purpose reservoir and including irrigation, flood control, hydropower, etc. in a multipurpose reservoir with varying degree of success (Barnes & Chung, 1986; Guariso, Rinaldi, & Soncini-Sessa, 1986; Karamouz, Szidarovszky, & Zahraie, 2003; Martin, 1987; Moy et al. 1986; Strycharczyk & Stedinger, 1987).

Water resources infrastructure and policies are designed in part to reduce the risks inherent to climatically driven, variable water resources systems and are built for adaptation to climate variability (Kiparsky, Joyce, Purkey, & Young, 2014). The water supply planning and management philosophy has been based largely on the concept of firm yield which should exceed demand by some reasonable margin of safety (Cabezas & Wurbs, 1986). This work followed this philosophy in its water resources availability assessment approach and was based on the yield that can be achieved, and other reliabilities, given a streamflow sequence. The persistence of high flows and of low flows, often described by their correlation, affects the reliability with which a reservoir of a given size can provide a specified yield (Loucks, Stedinger, & Haith, 1981).

1.2. Water demand

Estimating and forecasting water demand become necessary as the urban population dependent on public water supplies increases rapidly and new demands for water are not easily met. Considerable efforts have been put into the development of urban water supply projections in the last four decades resulted in a wealth of understanding and sophisticated forecasting techniques in this field. Different kinds of data-sets have been used ranging from household data to aggregated data. The quantity and type of data available determine which forecasting method should be considered for application. There is no absolute level of accuracy that is appropriate in all demand forecasting situations. However, it is important to understand the key determinants of water usage. According to Nieswiadomy (1992), a consensus on the proper estimation methodology has not been reached.

Arbués, García-Valiñas, and Martínez-Espiñeira (2003) give a state-of-the-art review on estimation of residential water demand with distinct attention to variables, specification model, data-set, and most common econometric problems. Wurbs (1994) earlier made a general characterization of water use forecasting by (1) the level of complexity of the mathematical relationships between water use and explanatory variables and (2) the level of sectoral, spatial, seasonal, and other disaggregation of water users. The complexity of the relationships, however, depends primarily on how many and which explanatory variables are included in the equations. A large number of studies of the demand for urban water have appeared in the literature since the classic Howe and Linaweaver study of 1967 (Martin & Thomas, 1986). The approach most widely used for water forecasting is the

per capita method, which assumes that the population is the single explanatory variable. It provides adequate explanation on water use and assumes other variables to be unimportant or perfectly correlated with population.

Other methods improve on this by considering many factors such as price, income, housing type, household size, and climate that are known to affect water use. The use of multivariate model reduces the degree of subjectivity in the analysis and makes better use of available data. The method includes variables observe to be significantly correlated with water usage and not necessarily those suggested by a priori economic reasoning. The disadvantages are that data requirements may be considerable and may be difficult to collect. These models reflect more of correlation rather than causation and consequently may omit potentially important relationship. The econometric demand model however differs in that they are based on economic reasoning and include only variables which are either expected to be causally related to or found to be significantly correlated with water usage. Econometric demand models are available mostly for residential water use and in the developed economies. A variety of econometric techniques which are based on semi-log equations are used to model residential water demand. These include ordinary least square, two and three stages least squares (2SLS, 3SLS), instrumental variables, generalized least squares, log–log model, double-log model, and discrete/continuous choice (DCS) (see e.g. Hussain, Thrikawala, & Barker, 2002; Mazzanti & Montini, 2006; Mitchell, 1999; Olmstead, Michael Hanemann, & Stavins, 2007; Schleich & Hillenbrand, 2009)

Stephenson and Randel (2003) estimate Rand water's demand in South Africa for 2000–2020 using statistical approach and obtained confidence limits for individual sectors. A decomposed demographic model was developed and used in predicting water demand until 2020. A wider uncertainty in future consumption was foreseen. Therefore, conservative planning was recommended for future water resource projects. This was to be achieved through low capital and operating intensive schemes. Cochran and Cotton (1985) used multiple regression models in a municipal water demand study for Oklahoma City and Tulsa, Oklahoma. The results indicate that price and per capita income were predictive variables for Oklahoma City's water demand, while only per capita income was found to be a predictor for consumption in Tulsa. Mimi and Smith (2000) and Khadam (1984) employed this approach in water demand studies for Rammallah and Khartoum, respectively. Both studies also found price and size of household significant, but the later was inversely (i.e. as household sizes increases, per capita water use decreases). Mylopoulos, Mentes, and Theodossiou (2004) applied a cubic functional form of an econometric model to study a residential water demand which allows the use of different price elasticities for different levels of water demand. The data used for the econometric analysis were obtained through a survey of consumers in the city of Thessaloniki, Greece. Panel estimation methods were then employed to estimate model parameters. The results showed that a cubic form of the demand equation can provide appropriate estimates of price elasticities for different "consumption groups" of residential customers.

The traditional method of forecasting industrial water use is the water requirement approach (Hanemann, 1998). This approach postulates that water use in an industrial establishment varies proportionately with the scale of production in that establishment. Scale is measured in terms of physical units of output, monetary value of output, or the size of labor force employed. There are two approaches. The first approach is a constant factor of proportionality which leads to the following forecasting Equations 1 and 2. In this approach, α_i and β_i are treated as constants. They vary by industry, i, but are fixed over all the establishments in an industry.

$$X_i = \alpha_i y_i \tag{1}$$

Alternatively,

$$X_i = \beta_i E_i \tag{2}$$

Table 1. Typical demand figure for commercial and institution establishments in urban areas	
Usage	**Demand allowance**
Small businesses, shops and offices	Up to 35 liter/capita/day (applied as per capita allowance to the whole urban population)
Offices	65 liters/day/employee*
Departmental stores	100–135 liters/day/employee*
Hospitals	350–500 liters/day/bed
Hotels	250 liters/day/bed
Schools	25–75 liters/day/pupil*

*Note: These figures should only be applied when the above are operating or open.
Source: Walliingford Ltd (2003).

where X_i is the water intake in an establishment in the ith type of industry, y_i is the production by the establishment, α_i is the water intake per unit of output in the ith type of industry, E_i is the number of employees in the establishment, β_i is the water intake per employee in the ith type of industry.

The second approach is more sophisticated. It relaxes the assumption of strict proportionality and postulates as follow:

$$X_i = \alpha_i y_i^\gamma \tag{3}$$

Alternatively,

$$X_i = \beta_i E_i^\gamma \tag{4}$$

where γ may or may not vary with industry i. Water use increases less than proportionately with scale of production if $\gamma < 1$, and more than proportionately if $\gamma > 1$. Dziegielewski (1988) found that a value of $\gamma = 0.7$ fit the data well for the US manufacturing industry. Several studies have reportedly found the number of employees to be highly correlated with water demand and therefore, in a unit use approach, may be used to estimate a water coefficient for a group of establishment (Cook, Urban, Maupin, Pratt, & Church, 2001).

For urban institutional and commercial water demand estimate where there is no available metered record, one estimation method is to apply a demand allowance on a per capita basis for various institutions and commercial buildings. Typical allowances for commercial and institutional establishment are as shown in Table 1. These allowances assume piped water connections and waterborne sanitation, and should be adjusted down where the establishments have a lower level of service for instance, standpipes, hand pumps, or VIP latrines in schools. Most of the sophisticated statistical and econometrical models are not entirely applicable in developing countries albeit the characteristic of developing economy. Oyegoke and Oyesina (1984) contend that in estimating design figures for water demand in developing countries, the philosophy should be to provided first for the basic needs and then incorporate various factors that may affect demand in the particular situation.

2. Water demand model formulation

The objective is to find simple relationship which accounts for as much of the variability of demand as possible. Hence, in the formulation of the model, water demand is addressed as basically non-irrigation demand which include the following principal determinant components typical of urban water requirement: residential, industrial, commercial, institution, and system losses. The forecasting relationship to estimate water demand is based on specific assumption reflecting the following local situation common in most developing countries:

- urban water uses are predominantly residential and commercial,

- water use is not metered, and

- fixed rates, independent on amount consumed, thus quantity has no correlation and causation with price.

The model is formulated to take into account the major uncertainty associated with water demand which is the population. Therefore, the per capita method is used and estimate of principal components incorporated. The justification for this are: (1) paucity of long-period socioeconomic data; and (2) no large contingents of seasonal residents. The total urban water demand U_{wd} forecast model is given in Equation 5.

$$U_{wd} = \gamma \left(x \left(P_t \left(1 + r \right)^n \right) + \sum_{j=1}^{m} \sum_{i=1}^{k} q_{ji} b_i \right)$$ (5)

where P_t is the population at present time t; U_{wd} is the water demand in cubic meter per day in year n; r is the rate of growth of population; n is the length of time for which the projection is made; x is the per capita water requirement in cubic meter for domestic/residential use; γ is a factor greater than 1 for system losses and contingent usage; q_{ji} is the estimated water requirement of establishment i per employee, pupil, or bed space in category j; b_i is the number of employees, pupils, bed spaces, etc.; m is the number of principal determinant components ($m = 1$ for commercial, $m = 2$ for institution, $m = 3$ for industrial); k is the number of establishment in commercial/industrial/institution categories.

3. Hydrological model formulation

There are two key approaches to simulate the variability of water resources potential in a hydrosystem including the uncertainty resulting from this. The first is based on historical time series while the other stochastic based. In other, to stimulate Oyun River Water Resources System, a synthetic hydrological system was generated using Markov model. A number of stochastic models have been considered in the literature for synthetic generation and forecasting of hydrological processes (Fortin, Perreault, & Salas, 2004; Karamouz et al., 2003; Loucks et al., 1981; Philipose & Srinivasan, 1995).

Hydrologic processes such as streamflow are oftenly well represented by stationary linear models such as autoregressive (AR) and autoregressive moving average models. These models are usually capable of preserving the historical statistics such as mean, variance, skewness, and covariance (Fortin et al., 2004; Philipose & Srinivasan, 1995; Shaw, 1988). The basic form of the AR model of order p, (AR, p), with constant parameters is (Philipose & Srinivasan, 1995):

$$Z_{v,\tau} = \sum_{j=1}^{p} \phi_{j,\tau} Z_{v,(\tau-j)} + \varepsilon_{v,\tau}$$ (6)

where the subscript v and τ denote the year and the period, respectively, $\{Z_{v,\tau}\}$ is the time series suitably transformed and standardized and has an expected value equal to zero, $\phi_{j,\tau}$ are the AR parameters, and $\{\varepsilon_{v,\tau}\}$ is the error term (white noise) and assumed to be uncorrelated.

The adequacy of the flow in Oyun River and the impoundment to meet projected demand was assessed using hydrologic time series modeling approach. The model uses monthly step and has its stochastic component handled by representing the inflow as a Markov process and the fitting of probability distributions to the inflows. The statistical parameters of the underlying population of historical streamflow are first derived and subsequently used to develop a stochastic model of reservoir inflows. The stochastic streamflow model provides large number similar sequences that are used to estimate the reliability with which a storage reservoir can deliver prescheduled quantities of water (Philipose & Srinivasan, 1995). The monthly streamflow is predicted up to the year 2020 using

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Markov. The 50 years inflows are used in the (1) estimation of the yield of the River Oyun (2) reliability of flow, and (3) the development of storage–yield function. The yield of the Oyun reservoir was subsequently determined using sequent peak method. The sequent peak model can be used to trade off capacity and yield given a mode of operation that does not allow failure (Moy et al., 1986).

4. Application of the models to study area

River Oyun is the source of water supply and the catchment (Figure 1) is oblong in shape and it is very long compared with its breadth. The climate of the catchment is the common type with the tropical savannah grassland of Africa. There is not much climatic variation and hence the hydrologic variation in the catchments is also insignificant (Adebosin, 1986). The water demand model was applied to water supply scheme in Offa Township, the headquarters of Offa local Government Area (LGA) in Kwara state. The Offa township is completely inside the catchment which lies entirely inside Kwara

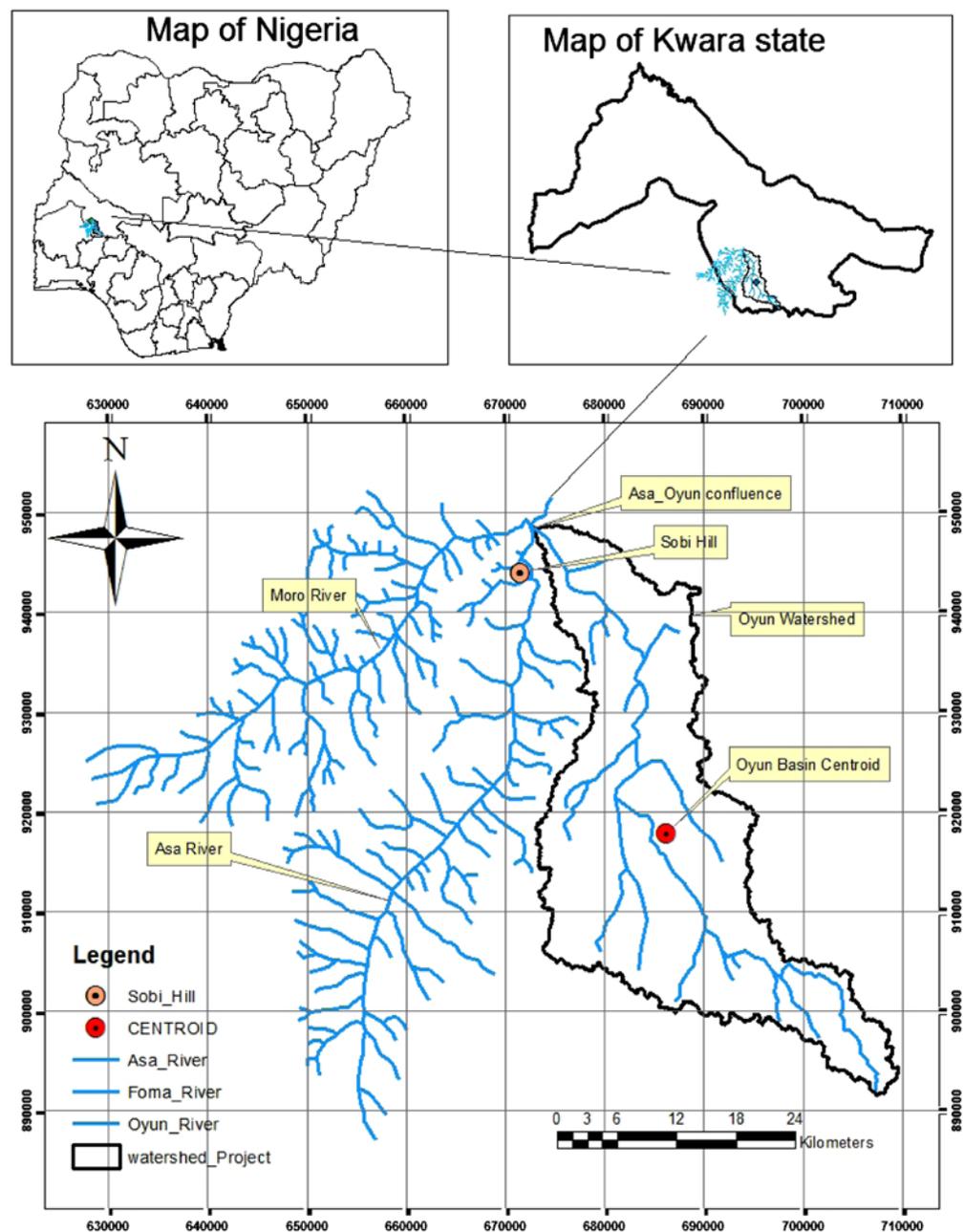**Figure 1. Map of Nigeria showing study area and delineated river Oyun catchment.**

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Table 2. Salient features of Oyun reservoir and dam	
Dam height	9.8 m
Location	6 km north of Offa
Catchment area (Adedayo, 2014)	830 km²
Spillway crest elevation	406.58 m.a.s.l
Spillway length	80 m
Embankment	409.5 m.a.s.l
Gross storage volume	3500000 m³
Net storage volume	2900000 m³

Source: KWWC (2009).

State of Federal Republic of Nigeria (Figure 1) between latitudes 8° 38′ and 9° 50′ N and between longitudes 8° 03′ and 8° 15′ E. Table 2 shows the salient features of Oyun reservoir and dam for a single purpose municipal water supply.

The yield of the Oyun reservoir was subsequently determined using sequent peak method. The sequent peak model can be used to trade off capacity and yield given a mode of operation that does not allow failure (Moy et al., 1986). Primary data on the customer categories connected to the public utility are collected from Kwara State Water Corporation (KWWC), the state-owned corporation responsible for municipal water supply. The standard water usages (Table 1) were used in the estimation of the principal components of water demand in the model based on the primary data and on the available numbers of individual components. The urban water demand was estimated as given in the model (Equation 5) and computed using C++ code.

5. Results and discussion

5.1. Water demand
The domestic, commercial, industrial, and institutional water demands between the periods 1996 and 2008 are estimated. The standard estimated water usage values in Table 1 are used in the estimation of principal components of water demand based on the available confirmed numbers in individual component. The domestic estimates are based on 120 lcpd and 2.83% annual population growth rate. The population projection was based on 1991 estimate (Okeola, 2000). Figure 2 shows the trend in the different categories of water demand for the period. Due to lack of reliable data on industry, commercial, and institutions for making future projections, the long-term water demand forecast for the year 2020 was limited to domestic demand (Figure 3). It was based on 2006 population census figures (National Population Commission, 2007).

5.2. Water resources
Using sequent peak analyses, the Oyun reservoir storage–yield function is: $y = 0.977s^{0.4037}$; where s is storage in Mm³. The storage–yield function is well correlated with coefficient 0.97. The probability of exceedance that corresponds to the 75, 80, 85, 90, and 95% reliabilities of flow is as shown in

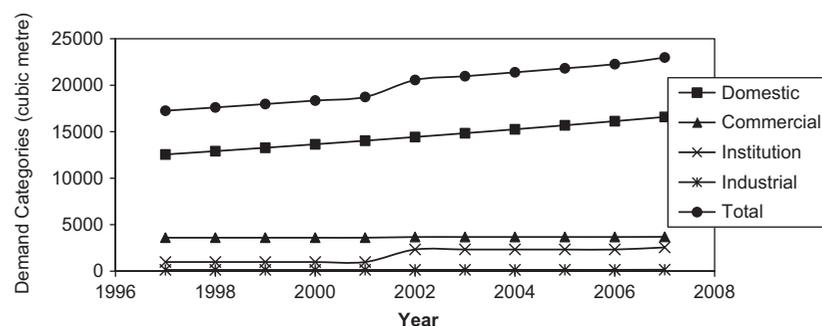**Figure 2. Offa water demand trend between 1996 and 2008.**

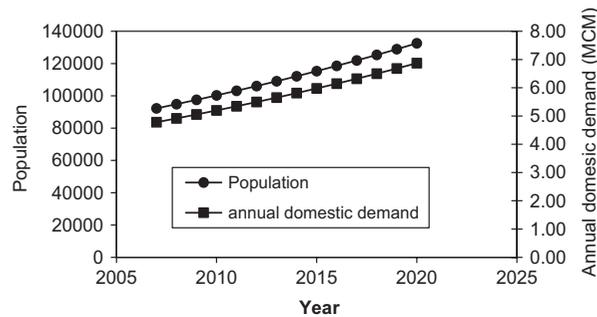**Figure 3. Projection of Offa population and annual domestic demand.**

Table 3. Flow frequency distribution for Oyun River (Mm³)			
Exceedence probability (%)	**Annual flow (Mm³)**		
	Normal	**Log normal**	**Log Pearson**
99	1.38	7.59	7.82
95	6.83	9.86	9.23
90	9.79	11.37	11.42
85	11.73	12.30	12.83
80	13.09	13.02	13.36
75	14.61	14.15	13.91

Table 3 at normal, lognormal, and log Pearson distribution models. The probability of exceedance is the difference between the percentage and correspondence percentile. For example, the reliability of the flow with 10% percentile is 90%, which implies that it has 90% frequency of reoccurrence. A high value of flow has high return period (low probability of reoccurrence and therefore a low reliability), while a small value of flow has low return period (high probability of reoccurrence and therefore a high reliability).

From the result of the analysis on the 50-year record, the available safe annual flow for the river is 6.8 Mm³. This is the volume that is available 95% of the time. The sequent peak analysis result shows that the maximum monthly draft possible from Oyun reservoir is 1.67 Mm³, for a reservoir capacity of 3.07 Mm³. However, the net volume of the reservoir is 2.9 Mm³. Practically, the 1.67 Mm³ monthly draft will still be met. The monthly stream flows are predicted up to the year 2020 using Markov model. The water resources assessment shows that the average annual flow for the River Oyun at the Oyun dam is 6.9 Mm³. The highest flow occurs in the month of September and October. The current total annual estimated water demand is 8.2 Mm³ out of which 5.9 Mm³ is for domestic usage only. This water source can still meet the demand of the domestic consumers but will not be adequate beyond the year 2020. There is a steady growth in the population and water demand up till year 2020 as shown in Figure 3.

6. Conclusion and recommendation

There are numerous programs for the short term aimed at improving water supply in Offa using underground water sources. The agencies involved in this program are Rural Water Supply Agency of the State government, UNICEF, ADP, LNRBA, and the Offa and Oyun LGAs. These programs should be managed and coordinated such that they are integrated into centralize system for effective conjunctive usage and thus improved upon the short-term measure.

On the long term when the demand exceeds the resource capacity, planning for new resources is the best solution. There are two ways to go about it in this case. One is to increase the height of the dam so as to increase the impounding capacity. The other is interbasin water transfer. This is the

physical transportation of water out of one river basin to another basin. They both require adequate technical feasibility studies covering hydrological, geotechnical, geological, and socioeconomic investigations.

The study can serve as an organized baseline for future work, particularly in obtaining improved estimate for industrial, commercial, institutional water use categories, and planning conjunctive uses of water resources. The findings of the study can be a vital input into the demand management process for long-term sustainable water supply of the town and by extension to urban township with similar characteristic in Nigeria and third world countries.

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