ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
ISSN 1584 - 2665 (printed version); ISSN 2601 - 2332 (online); ISSN-L 1584 - 2665

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HOLISTIC DIAGNOSTIC OF AN URBAN WATER SUPPLY SYSTEM MANAGEMENT USING HYDRO–ECONOMICS MODEL

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Abstract: The paper demonstrated the application of a multicriteria decision analysis (MCDA) using integrated hydro–economic optimization model as the core diagnostic evaluation tool for a regional metropolitan water supply scheme in Kwara state, Nigeria. It presents a holistic investigation into a real–world operational sustainability of metropolitan water supply with the aim of facilitating exploration of insights into sustainability challenges that have burdened service delivery. A total of 20 water management scenarios were considered and four were identified as satisfactory considering a 95% reliability of flows as both realistic and secured for the schemes. They were based on the physical and hydrological capacity of the system, unaccounted–for–water (UFW), revenues, expenditure and institutional/management arrangement. The findings revealed that the scheme not financially viable to sustain service. However, scenario B1 with 95% inflow reliability, a 5% step incremental on revenue and 30% UFW results in the long term sustainability of service delivery. The study would serve as an organized baseline for future work, particularly in obtaining improved estimates for industrial, commercial, and institutional water use categories.
Keywords: Hydro–economic optimization, sustainability, water resources, analytic hierarchy process, Nigeria

1. INTRODUCTION

Water management all over the world is becoming increasingly complex and conflicts laden as water demands grow and involve several management strategies along with wide range of stakeholders and interests. The provision of potable water supply to a host of African countries' urban and suburban citizens for decades remained daunting. The important factors for effective water supply management are economic, socio–political and engineering [1]. In the last three decades many approaches were proffered and implemented towards finding a sustainable water supply provisions. These include [2,3] the focused on technology in the 60's, appropriate technology in the 70's and in the 80's, social issues emphasized. However during the 90's, it was capacity building at all levels, all functions and the wide range of organizations from national government agencies to local government, community based, and NGOs. The later 90s witnessed efforts at developing policy, legislation and institutional rationalization [4]. Nigeria is suffering from water poverty which is conditioned according to [5] on inability of citizenry to access or able to afford the cost of sustainable potable water at all time. There are some fundamental factors cited by [6]which are strongly contingent on Nigeria's poor water supply service delivery. Okeola [3] provides exhaustive overview of the challenges facing the sustainability of Nigeria's urban water supply. The United Nations formal declaration on human right to water in 2010 exacerbated the challenges. Despite all declarations and the moral burdens of these documents according to [7], the modus operand financing their implementation is a huge challenge this century. Sustainability is a holistic definition of evaluating performance of water utilities [8]. All problems link with sustainability of urban water supplies are wicked ones which according to [9,10] have no right answer. However, such problems are at intersection of science and values. There is uncertainty in all wicked problems including the problem of human rationality [11].

It is unrealistic searching for optimal solution in all wicked problems because they rarely exists, as it can only be better or worst. Instead it is appropriate to find compromise solutions. The commonly used holistic approach to solving wicked problem is Multicriteria Decision Analysis (MCDA). It is decision support tool, a forum within which several variables and models can be combined to incorporate all necessary interacting components that play a role in the decision making process [12]. The philosophical bases of multicriteria decision analysis are to provide insights into the nature of conflicts among objectives to reach consensus among stakeholders rather than eliminating the conflicts [13]. The MCDA differs in how ideas of multiple criteria are considered, application and computation of weights, mathematical algorithm employed in the model to describe the system of preferences of the individual decision making including the level of uncertainty embedded in the data set and also stakeholders' ability to participate in the process [14].

The MCDA methods have been effectively used in structuring several complex multiobjective problems within variety of fields and applications such as in urban water supply [15–17] and water resources planning and management [12,14,18]. Analytical Hierarchy Process (AHP) is a MCDA methodology that allows objective as well as subjective factors to be considered in a decision making process. AHP helps determine which variable have the highest priority that should be acted upon to influence the decision outcome. The reasoning is on the supposition that humans are capable of making relative judgments than absolute judgments and rest on three key principles: decomposition, comparative judgment, and synthesis of priorities [19].

Several past studies abound in developed countries on multipurpose water resources systems optimization models at regional, trans–boundary, small and large scale basin levels with focus on operational rules of reservoirs such as [18, 20–27] etc. There are limited studies on municipal water supply operations for examples [28–30]. Thus most existing models in the literature are largely driven by operating rules under prevailing water allocation practices but do not include measures for explicit economic viability and performance while maintaining a constant level of resource reliability. The authors attempted addressing this gap using hydro–economic model as the core tool in a MCDA setting.

A significant interdisciplinary attention focuses on integrating modeling for purpose of promoting efficiency and transparency in the management of water resources [31]. Most of these model combine hydrologic and economic aspect of water resources. However, integrated hydro–economic models facilitate evaluation based on changes in temporal and spatial allocation, physical and economic impacts on existing/alternative structural measures among competing water uses subject to environmental and institutional restrictions by the decision makers [31–33]. The stakeholders involve in water resources system operations, planning, and policy–making may benefit from the insights derive from integrated decision support systems (DSS) that is contingent on coupled sub–models of different domains through framework for data integration and models of various aspects of water systems [34]. However in original model design these aspects are not always considered. The issue of participatory role in water management models are gaining research interest [1]. This study also benefited from this concept.

Brouwer and Hofkes, [1,9,32,35] provide reviews of hydro–economic modeling exhaustively for compartmental and holistic approaches. In the former, the hydrological process and economic components are separately model. Thereafter, the output in either turns to input in another. While the later completely consider both in one integrated model. However, the adoption of either is a trade–off between holistic approach which require simplification of hydrological and economic modeling and the compartment approach along with its information transfer difficulties [36,37]. Hydro–economic modelling as fundamental concept found relevancy in several water resources management [23,36,38–40], river basin modeling/management [41,42], water policy [43] and environmental protection management [36,44]. This paper holistically addresses operational sustainability challenging facing an urban water supply with MCDA using hydro–economics model as the core evaluation tool. The holistic approach essentially facilitated consideration of relevant components and factors on their effect on sustainability of the water supply accomplishment. The insights from diagnostic effort is to assist in an informed improvement strategies.

2. MATERIAL AND METHODS

— Study area

The catchment of river Oyun is 830 sq.km [45] and lies within Kwara State, Nigeria (Figure 1). The catchment, oblong in shape and long compared with its breadth is between latitudes 8° 38' and 9° 50' N and between longitudes 8° 03' and 8° 15' E. The climate is the type common in the tropical savannah grasslands of Africa. There is not much climatic variation and insignificant hydrologic variation in the catchment. The river Oyun is the main river in the catchment and it is a sub–tributary of the river Niger. The river is the raw water source for the Regional Metropolitan Water Supply Scheme (RMWSS) at Offa in Kwara state. In 1964, a 7 meter high dam was constructed on the river and the height was raised by 2.75m in 1988 to increase the gross reservoir storage capacity to 3.5 Mm^3 and the active storage to 2.9 Mm^3 [46]. There are two separate treatment plants designed to serve 7 major towns and sub–urban settlements in four local government areas in the state. The dam serve the purposes of municipal, commercial, and industrial water supplies with the following features (Table 1). The Offa RMWSS was studied with the formulated model to give insight into service delivery challenges, future operations and the development of alternative system–improvement strategies.

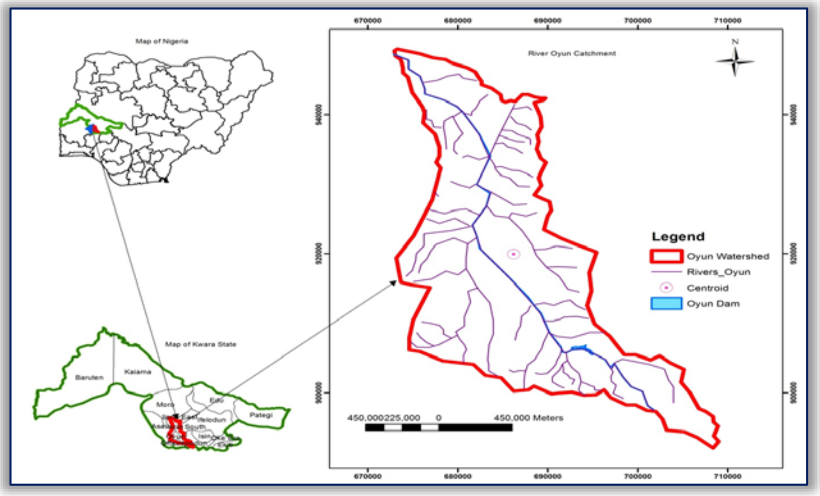

Figure 1. The delineated catchment study area

Table 1: Cogent Features of the Dam

Height of Dam	9.8m
Location	6Km north of Offa
Spillway crest elevation	406.58m.a.s.l
Spillway length	80m
Embankment	409.5m.a.s.l
Gross Storage volume	3.5M m3
Gross Storage volume	3.5M m3

— Methodological Framework

This study follows multicriteria decision analysis (MCDA) framework shown in Figure 2 which facilitate representation of system components and functional relationships.

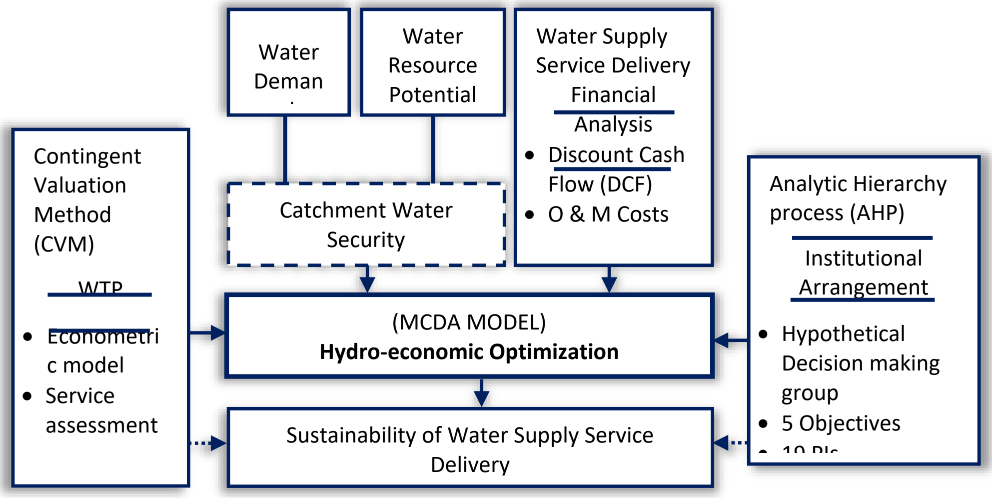

Figure 2. Methodological Framework

The figure encapsulate a descriptive and prescriptive models of natural, physical, economic, and social processes for the evaluation purpose. It begins with assessment of the catchment surface water resources to supply future water demands. The framework incorporate (1) hydrological assessment of water resources and water demand. (2) determination of stakeholders preferences and values from the syntheses of AHP (3) system viability and socio–economic assessment based on discount cash flow (DCF) from sectorial water uses and CVM respectively. The MCDA is escalated with hydro–economic optimization with which promising combinations identified with diverse actions with natural and human–made constraints such as availability of water resources and statutory rules [1]. Their integration in the framework was based on modular design already explained.

Using hydrologic time series approach, the adequacy of River Oyun impoundment for projected demand was carried and then determine the yield, reliability and storage–yield function. However for formulation of water demand model, the key uncertainty associated with it, the population was taken into account. Therefore per–capital method was adopted with the estimation from principal determinant components common with urban water demand (i.e. residential, industrial, commercial, institution, and system losses) are incorporated. The justification was that there is no large contingents of seasonal residents. The Contingent valuation methods (CVM) was adopted to estimate willingness to pay (WTP) for water supply service by the customer groups. The general motivation in adopting CVM is its ability to address a broad range of policy interventions including taken into account nonuse values. There existed several studies that established the CVM a good and reliable approach for WTP values for public policy decisions. The WTP measures the monetary evaluation of a service to its customer [47]. There are over 5000 CVM studies done in over 100 countries [48–52].

The CVM from which WTP elicited is construed an indication of the demand from improved services delivery along with other sustainable potentials [53]. The adoption of double bounded dichotomous choice format (DDCF) was because it gives a better statistical efficiency of the WTP results. For water supply service delivery, WTP signifies maximum amount an individual would pay to alleviate averting expenditure and enjoy the benefit of quality service. Economic evaluation have traditionally been carried out with Discounted Cash Flow (DCF) methods [54]. The DCF techniques are generally proposed for evaluating profitability of various kinds of projects or services [55]. The financial net benefit adopted here provides a measure of the financial viability of the system operating entity. The method has been used in financial viability analysis in various fields for example Agricultures [56] and Water supply [57]. The DCF technique for investment appraisal was extended to evaluate the level of financial sustainability of RMWSS.

Analytic Hierarchy Process (AHP) prioritized institutional arrangement for sustainable water supply management strategies and their integration with various constraints aimed at optimizing sustainable water supply service delivery in the eye of stakeholders. The basic idea of AHP is that the factors in a complex system are grouped on different logic levels, forming a chain, or hierarchy, whereby the lower–level elements can be compared in pairwise matrices with respect to the higher level, and so on, so that finally the composite priorities of all levels are achieved [58]. The detailed procedure is available in [59]. Finally the framework is based on the modular design that connects independent sub models having them interacting within a single programme. The modularity approach increase the probability of convergence on optimal solution. It also facilitated scrutinizing each sub–field and independent update and development. The hydro–economic optimization was based on the development of a set of possible scenarios that offer a conceptual, realistic and strategic way to achieve sustainable water supply delivery considering the peculiarity of the study region. The use of scenarios to assess the future state of water resource systems in the medium term was also supported by the EU Water Framework Directive [60].

A scenario is not a forecast but rather a snapshot of how future could unfold [42]. We have defined a scenario in this model as an independent set of possible future hydrological inputs to the system flow sequences, time–sequence of correlated river flows, operation and maintenance (O&M) expenditure, revenues, and water production which occur per scenario. A total of 20 scenarios created. The MCDA framework examined the policy objective implementation by combining elements of hydrology and economics in the hydro–economics model objective. Two important assumptions with significant influence on the outcome are considered: (1) adoption of vertical equity policy which enable redistribution objective and thus enable authors to cater for the urban poor. (2) the center–piece of the nation water policy considers inter alia private sector in the participatory investment in water supply in a sustainable way.

— Model Parameterization and Formulation.

Operational sustainability is the main goal of municipal water supply service delivery. In Nigeria the managers of state or regional water supply scheme have to contend with political and financial pressure and hence make the cost of service delivery and the quantity of water produced the distinct decision variables. We have used monetization to convert a complex multiobjective management problem into a simpler single–objective problem [35]. If the service delivered by the municipal water agency is defined as [S] and is constrained by service function $S = f(H|\beta, \theta)$, where H is the natural system hydrology, β are the prevailing inputs and θ are the deliveries to customers' category. The β are operationalized as the utility's annual expenditures while the θ are operationalized as the utility's annual income from deliverable services. The model assumption is that the municipal water utility strives to maximize deliverable services with the possible produced treated water. Therefore, the objective function finds solutions that maximize annual service delivery (net benefits) via a trade–off between the cost and volume of treatable water. In order to develop the objective function, the revenue from all customer categories and expenditure on items of water production were expressed as unit volume of water treated and fitted with the Excel LOGEST function to obtain the logarithmic models using the operational parameters. The objective function is stated thus:

Maximize the annual net benefit of the service

$$S_{AB} = \mathrm{Max}[(Y_R) - (Y_E)] \times D \quad (1)$$

where:

SAB = Annual net benefit in Naira

$$Y_R = \exp\begin{Bmatrix} 0.82X_{1R} + 2.30X_{2R} + 2.77X_{3R} + 2.56X_{4R} + 3.02X_{5R} - 0.54X_{6R} \\ +4.58X_{7R} - 14.01X_{8R} - 1.65 \end{Bmatrix} \quad (2)$$

$$Y_E = \exp\{0.5207X_{1E} + 0.178X_{2E} - 0.1370X_{3E} - 0.7372X_{4E} + 0.4045X_{5E} - 0.094\} \quad (3)$$

YR = Annual revenue in Naira/m^3

YE = Annual expenditure in Naira/m^3

D = Annual treated water (m^3)

The solutions to the objective must satisfy the following constraints:

1. The mass balance Equation.

$$S_F = S_I + Q - D \quad (4)$$

where:

S_F= Reservoir storage at end of the year.

S_I=Reservoir storage at beginning of the year.

Q=Annual reservoir inflow at 75%, 80%, 85%, 90% and 95% reliabilities.

D=Annual reservoir withdrawal for the treatment plant.

2. Constraint on reservoir withdrawal defined as maximum and minimum releases.

$$D_{min} \le D \le D_{max} \quad (5)$$

3. Storages constraint defined as maximum and minimum storage

$$S_{min} \le S_F \le S_{max} \quad (6)$$

4. Constraint on annual revenue in Naira per cubic meter

$$X_{Rmin} \le X_{iR} \le X_{Rmax} \quad (7)$$

where iR is the revenue component type; i = 1, 2 … u. Where u = 8 i.e. there are eight components of revenue generation. These are industry, institution, commercial, public standpipe, water tanker, direct deduction, domestic and service connection.

5. Constraint on Annual Expenditure in Naira per cubic metre

$$X_{Emin} \le X_{iE} \le X_{Emax} \quad (8)$$

where iE is the expenditures component type; i = 1, 2 … v. Where v = 5 i.e. there are five components of expense identified. These are chemical, energy, pump maintenance, general administration and staff emolument.

— Model Solution

The model and its solution algorithm were developed in the Solver code of Microsoft Excel which provides a high–level language for representing the model in a compact and robust manner. The assumptions for the development of scenarios are:

- Figures on O&M costs and revenues are historical records made available by the Offa RMWSS authority and constituted the base–line values.
- The Oyun river dam has a usable storage volume of 2.9 Mm^3.
- By using the sequent peak analysis, it implies a mode of reservoir operation which doesn't allow failure [61]. Hence, 75%, 80%, 85%, 90% and 95% reliability of inflows were considered on normal, lognormal and log Pearson distribution models.
- Two broad water management scenarios A and B (Tables 2) were identified based on the physical and hydrological capacity of system, unaccounted–for–water (UFW), revenue, expenditure and management arrangement. Management options 1 and 2 as used in these scenarios were adopted from the results of the AHP. The WTP value results from the CVM considered for scenario B.

Table 2.Scenarios A and B

Scenario A	Implement option 1: Public Ownership and Public Operation
	75%, 80%, 85%, 90%, and 95% inflow reliabilities
	O&M practice remain status quo
	Very high UFW
Scenario B	Implement Option 2: Public Ownership and Private operation
	Implement Option 2: Public Ownership and Private operation
	Customers' WTP incentive
	Customers' reform–support incentive
	Efficiency improvement (via: for e.g. improved billing & collection system)
	Reduction in UFW and recurrent expenditure

3. RESULTS AND DISCUSSION

— Management of RMWSS under operational scenarios

The 20 feasible water management scenarios were run through the optimization model. Of these only seven (listed below) at 95% reliability of flow were identified to meet the policy objectives in terms of the operational financial and physical/hydrological system sustainability for the RMWSS. The seven scenarios are:

(A1) 95% inflow reliability, revenue and expenditure status quo, 60% UFW.
(B1) 95% inflow reliability, 5% stepped increment on revenue and 30% & 40% UFW.
(B2) 95% inflow reliability, 5% step expenditure reduction and 30% & 40% UFW.
(B3) 95% inflow reliability, 5% step incremental on revenue, 5% step reduction in expenditure, and 30% & 40% UFW.

Both the options B1 and B2 can be implemented with the arrangement of a management contract. For B1 implementation, a 5% revenue increment can be the starting point while in option B2 implementation, O&M expenditures be reduced through operational efficiency. Other revenue enhancements that would be possible in any private management are: (1) improved billing and collection system; (2) improved customer service relations; (3) reduction in UFW with programmes for leak detection and repairs, (4) illegal connection monitoring and prevention; and (5) integrated water resource management strategies.

The optimization results of the annual benefit with satisfaction in policy objectives and improved sustainable service delivery are shown in Table 3. The scenario A1 annual benefit was very low compare with B1 and B2 due to highly porous system with attendants UFW that does not contribute to service delivery. Another finding was that notwithstanding reducing O & M expenditure, it will not suffice in increasing annual benefit without some form of upward review of tariff. It can be observed in Figure 3 that annual benefits was highest for 75% reliability. However water supply very crucial in society socioeconomic and healthcare delivery, it is therefore instructive to sustain supply at 95% reliability and to sustain the "merited good" attribute of water for the sake of the metropolitan poor population.

— Operational Efficiency

The financial viability evaluation shows a negative NPV indicating financially non–viable schemes. However, the CVM survey revealed the citizenry already adopted some coping mechanisms through expenditures on table water, wells, boreholes etc. in response to poor level of service. This was the results of citizenry motivation in willing to pay more for improved water supply service has indicated in Table 3. The mean WTP was found at 70% higher than the prevailing tariff which give an expected monthly revenue of =N=21 million (1$ was approximate =N=150 in 2011). In practical term the empirical mean WTP amount gives a social benefit of a policy for the offered service. Thus the WTP may provide incentives for private sector involvement or for better government alternatives management of the utility. Therefore there is huge possibility for competition with possible gains in efficiency when infrastructure investment is separated from service operations. The results in Table 4 hypothetically indicates that there is a prospect of operational sustainability and financial viability for the scheme.

Table 3. Summary of scenarios optimization annual benefit for 95% inflow reliability

Scenario	UFW (%)	Annual benefit (N 'Billion/yr)	Treated water (MCM/yr)
A1	60	0.765	3.89
B1	30	1.98 – 22.64	6.86
	40	1.64 – 19.32	5.86
B2	30	1.35	6.86
	40	1.11	1.11
B3	30	1.98 – 22.64	6.86
	40	1.64 – 19.32	5.86

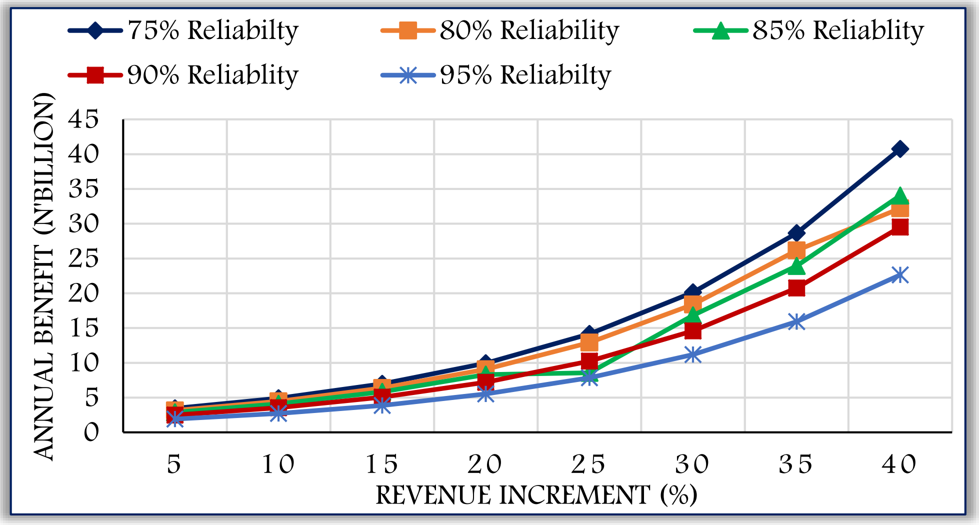

Figure 3. Relationship between percentage increase in revenue and inflow reliabilities at 30% UFW

Table 4. Aggregation of WTP to households' population

Item	WTP	Number of Household	Total Monthly Revenue (in Million Naira)
Sample average	995	19322	19.23
Mean WTP	1100	19322	21.250
Median WTP	1150	19322	22.222

— Service Quality Assessment

The quality of service from the perspective of various customer groups are carried out with questionnaires. The assessment was based on key parameter: Shortages, Water quality and Averting measures. We look into how many days water are available in a week; population that depends on secondary sources of wells and boreholes; those applying additional treatment and the type/purposed of secondary storage facilities. The result indicated most households not comfortable with the quality of water received and often applied additional treatment such as boiling and filtering before consumption. The rationing of water to consumers is an indication of shortages in the supply while the adoption of coping mechanism is a manifestation of unreliability of supply and unsatisfactory water quality. As such, expenditures are incurred on purchase of table water, storage facility, secondary treatment, and alternative sources of water.

— Water Resources

The available safe annual flow is 6.8 Mm^3 from the 50 years streamflow record analysis that is available 95% of the time. Using sequent peak analysis, the maximum monthly draft from Oyun reservoir is 1.67 Mm^3 for reservoir capacity of 3.07 Mm^3 with net volume of 2.9 Mm^3. However, 1.67 Mm^3 monthly draft will still be met. The water resources assessment predicted up to the year 2020 using Markov model gave the average annual flow of river Oyun at the dam as 6.9 Mm^3 and the highest flow occurs in September and October. The current total annual estimated water demand is 8.2 Mm^3 out of which 5.9 Mm^3 are for domestic usage along with consequential inadequacy after 2020 especially for domestic purpose. Hence the need to start exploring a well–coordinated conjunctive use of resources. The commercial, institutional and industrial sectors have respectively 1.33 Mm^3, 0.92 $Mm^3$and 0.053 Mm^3 water demands.

4. CONCLUSIONS

This paper presents the first holistic investigation into operational sustainability of a regional water supply in Kwara State, Nigeria. MCDA was used in diagnosing a comprehensive sustainability of a RMWSS based on scenario development. This encapsulated in–depth study within individual modules of: (1) water resources (2) water demand and (3) service delivery. The AHP and CVM facilitated explorative insights into the problem from the perspective of various stakeholders and allows for informed economic and managerial decision–making in the scenario development. A total of 20 water management scenarios were considered in the optimization modeling of the operation. Of these seven were identified to be satisfactory with a 95% reliability of flows.

Our key finding placed financial sustainability the panacea to a much more sustainable urban water supply service delivery on a long term. It is imperative to adopt appropriate public private partnership arrangement in outsourcing of operations to attain a high level of service delivery which can be a stepping stone in the direction of service improvement by introducing competition since our CVM results corroborated with this. The economic theory of consumer utility maximization agreed with the result of WTP. Toward the initial step on sound financial management improvement and cross–subsidization of the urban poor, a strong economic price should be implemented for industries, commercial enterprises and other VIP residential areas.

Our study revealed that deliberate involvement of stakeholders and water literacy campaign on issues of water supply will facilitate transparency, support, and interest in measures to improve service delivery at all time. Our finding also indicated that the government performed the role of a provider and regulator simultaneously thereby compounded the problem of sustainability of urban water supply. We suggested therefore the role of government be limited in policy formulation to ensure services are provided as done in the case of telecommunications sector. We have provided a flexible MCDA framework that combine stakeholder participation in quantifying WTP and preferences in regard to management objectives with core hydro–economic model which can be applied in any catchment–based in the rest of the country. We hope to expand the scope of this study especially on conjunctive usage of water resources strategies and obtaining improved estimates of industrial, commercial, institutional water requirement.

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ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
ISSN 1584 ‐ 2665 (printed version); ISSN 2601 ‐ 2332 (online); ISSN‐L 1584 ‐ 2665