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Olotu Yahaya, Unuigbe O.M., Eleta Paul.O., Stephen A.O.

Modelling Water Supply-Billing and Collection Systems for Effective Utility Distribution

Safe drinking water is a strong constraint to the attainment of Millennium Development Goals by 2020. The water supply coverage of 38.3% of the total population corresponds to 45 litres per person and an average supply period of 3.5 hours daily. This further explains the degree of water-stress in Ikare. Annual non-revenue of 18.3% represented $6.2 million USD which was lost to physical water loss, thus leading to gradual increase in operation ratio value of 1.05. Chlorination water treatment is cost effective for large water scheme than ultraviolent (UV) with a price index of $ 0.01 per 1m^3 of water. The predicted cost for plant with 5 million m^3 capacity. Increasing water supply coverage requires the reduction of non-revenue water and creates effective tariff system.

Keywords*: NRW, Supply, Water, Price, Coverage, Loss, Ratio, Cost, Population*

1. Introduction

Water development, supply and distribution system have typically been approached as an economic rather than engineering problem. Water supply managers and stakeholders are often applying price increase as water conservation tools, instead relying on price demand management techniques (Idogho et al., 2013). These include requirements for the adoption of specific technologies (such as low-flow fixtures) and restrictions on particular uses (such as lawn watering). Water resources are mobile, they flow, seep, and evaporate making it difficult to establish and enforce exclusive property rights, the basis of an exchange economy. The WHO minimum requirement is 40 litres per capita per day for all rural areas (Reddy, 1999). Forty liters of water is therefore a basic need for all households; but greater quantities of water are normal goods and eventually become luxury goods.

The same river can be tapped by many communities, firms, and recreational users as it moves through a landscape. In addition, water is a bulky commodity; its per unit value is low, making the costs of transportation and storage high relative to its overall value in use. With growing population and limited water resources, there is an increasing need worldwide to manage water resources better. This is especially true when all or nearly all water resources in a basin are allocated to various uses. Effective strategies for obtaining more productivity while maintaining or improving the environment must be formulated. Furthermore, water supply is highly variable in time, space, and quality. Storage reservoirs are often necessary to smooth supplies. Reservoirs to mitigate periods of shortage, as well as infrastructure to manage flooding, provide public benefits, often shared by multiple communities. In addition, drinking water reservoirs can also be used for other purposes, such as recreation, irrigation, and power generation.

Many of the water projects implemented over the last three decades in developing countries are considered failures (World Bank, 1992). Experts from a variety of disciplines have examined factors determining success. They identified knowledge of the health benefits of improved water supplies, affordability of tariffs, sensitivity by donors and the central government to local customs and beliefs, the ability to operate and maintain water systems by the local population, as well as community participation and local involvement in design and management as important factors for rural people to use improved water sources (Brookshire et al. 1993). Regarding the supply side, economic studies have emphasized the importance of improving project identification, design and construction, of understanding the institutions providing water and their tendency towards selecting capital-intensive enterprises and neglecting maintenance schemes, and of establishing strategic links between the water investment sector and other macroeconomic policies (Howe and Dixon 1993; Rogers et al. 1993).

There is a growing demand for water and sanitation services in developing countries due to growing populations, rising standards of living and per capita incomes, and rising awareness of health benefits of improved water and sanitation. However, the demand for water in rural areas is growing faster than the supply. In urban areas, consumers are better off and can afford to pay for the water and sanitation services provided, but in the rural areas, incomes are generally much lower and therefore cannot sustain an adequate provision of water (Mensah, 1998). Much effort has been put into trying to improve the water supply and sanitation conditions of rural communities in developing countries but these efforts have not resulted in the level of desired supply. The monthly tariff for water from household connections is low and with few connectors and low tariffs, little revenue is generated beyond subsidies provided by the government. Water authorities cannot afford to maintain such systems up to a level that is reliable and so the consumers are forced to supplement the pipe water from traditional sources (Singh, 1993).

2. Materials and methods

2.1. Water use system

The total water use within Ikare-Akoko is not the right measure of actual appropriation of the water resources in the region. Water resource being accessed from the neighbouring place such as Egbe (Egbe dam) is added to the total domestic water in Ikare-Akoko. Therefore water accessed from Egbe in Ekiti State is classified as imported goods which its cost of procurement would be factored. Total domestic water use is computed using the expression in equation (1):

$$TDWU = WSI + WIE \quad (1)$$

Where;

TDWU = Total domestic water use (m^3yr^{-1})

WSI = Water supply in Ikare (m^3yr^{-1})

WIE = Water imported from Egbe (m^3yr^{-1})

2.2. Accessibility of improved water supply

Water security in the 70 and 80s in Ikare Akoko related to availability and access to safe water, which is closely related to investment in supply infrastructure and the management of domestic water supply, and this varied across space and time. It also depends on the decision to use or not available sources of improved water, which is determined by price and income constraints as well as preferences, knowledge, and perceptions about water quality differences. However, the situation has changed. More than 45% of the water supply in the region is imported from Egbe in Ekiti State

2.3. Modelling water resource variables

Water resources modelling are done on different temporal and spatial levels, depending on the model's purpose. The variables considered in this model include:

i. Type of water supply system;
ii. Location/distance of distribution reservoir;
iii. Pumping energy;
iv. Metering accuracy;
v. Pipe burst and leakage;
vi. Ineffective and reliable database;

vii. Cost of water treatment; and variation of climatic system.

The combined integrated water supply and cost simulating model (CIWSCM) also considers these assumptions:

i. Minimum design of 50 litres of water per head per day;
ii. Maximum design of 120 litres of water per person daily; and
iii. Mean average of 85 litres of water per person daily.

The water supply models that captured different degrees of daily water demand in the region are structured as follows:

$$MmWD = Pi * Mmin * \mu \tag{2}$$

$$MaWD = Pi * Mmax * \beta \tag{3}$$

$$MenWD = Pi * Mmax * \varepsilon \tag{4}$$

Where;

MmWD = Minimum water demand (m^3yr^{-1})
MaWD = Minimum water demand (m^3yr^{-1})
MenWD = Mean water demand (m^3yr^{-1})
P_i = Population
$\mu = 0.80;\ \beta = 0.75;\ \varepsilon = 0.70$

Water supply coverage in Ikare-akoko is computed as follows

$$WSC = \frac{PSPW}{TPI} * 100 \tag{5}$$

Where:

WSC = Water supply coverage;
PSPW = Population served with water supply;
TPT = Total population of the region (Ikare-Akoko)

Production population and per capita water consumption are estimated using equations 6 and 7 respectively.

$$PCC = \mu \frac{TAV}{PS} \tag{6}$$

$$PP = \frac{AP}{PS} \tag{7}$$

PCC = Per capita consumption; TAV = Total volume of water sold (m^3); PS = Population served/covered; PP = Production population, AP = Annual production.

Plate 1. Map of Ikare-Akoko. Source: Google, 2013.

2.4. Physical Water Loss Using Pressure-Leakage Relationship (PLR)

Treated water designed to be supplied to a given region in most cases got lost as a result of pipe burst due to pressure variation, construction of infrastructure and some other related activities. The Pressure-Leakage Relationship Analysis is widely accepted in accurately estimating the real losses which in thus have negative impact system input and non-revenue water. The Power Law Formula in equation (5) is often used to compute Real Losses (Thornton, 2003).

$$Q_2 = Q_1 \times PCF \qquad (8)$$

Where:

P_1 = Pressure at point 1
P_2 = Pressure at point 2
Q_1 = Flow at P_1
Q_2 = Flow at P_2
PCF (Pressure Correction Factor) = $(P1/P2)^N$ (Thornton, 2008).

The expression in equation (3) was modified as follows:

$$Q_2 = KQ_1PCF \qquad (9)$$

Where the modification coefficient ***K*** is applied to adjust flow discharge due pipeline lock-outs, closed hydraulic valves. The values of N and K are 1.0 and 0.8 respectively. Equation (6) could mathematically be written as follows:

$$WL\rho = KWS\beta \qquad (10)$$

Where β = Pressure coefficient.

The cost of $1m^3$ of physical water loss is computed as follows:

$$CWL\rho = \mu KWS\beta \tag{11}$$

Where; μ is the cost index of \$6.25 per 1m^3 of portable water.

Therefore, the percentage of Non-Revenue Water (NRW) is expressed as follows:

$$NRW = \frac{TAP - TBLC}{TAP} * 100 \tag{12}$$

Where:

TAP= Total annual production (m^3); TBLC = Total billed consumption (m^3)

2.5 Cost of water treatment

The dominant use of chlorine in small water system may be due to historical reasons and a failure to modernize after the wide-spread availability in small and rural communities. Two-dimensional models are applied to estimate the cost of water treatment using chlorine and ultraviolent treatment. The other model relates chemical cost per unit of treated water to raw water supply characteristics. Per unit chemical cost is expressed as a function of cubic metre of water treated, turbidity, pH, a proxy variable for chemical contamination, and rainfall. Chlorine- ultraviolent model is summarized as follows:

$$C / Q_1 = a_i Q_i \beta_i + \zeta \tag{13}$$

Where;

C = Cost of water treatment;
Q = Volume of water to be treated
a_i = Multiplicative component coefficient
β_i = Exponential or elasticity component coefficient

Chemical water treatment model cost is estimated as follows:

$$Cost^{-1}/(m^3) = b0 + b1*(\textit{total Volume}) + b2*(\textit{turbidity*pH}) + b3*(\textit{turbidity*pH})^2 + b4*(\textit{turbidity*pH})^3 + b5*(\textit{contamination dummy}) + b6*(\textit{average annual rainfall}) \tag{14}$$

Where:

total volume is the number of cubic meter of water treated, *turbidity*pH* is the interaction multiplication of the difference in turbidity level between raw and treated water, times the pH level of the raw water, *contamination dummy* is a 0-1 dummy variable, where a one represents counties identified by the TWC as having potential or actual groundwater contamination, and serves as a proxy for chemical contamination of surface water supplies, and *average annual rainfall* is the annual rainfall for the county where the plant is located (Henderson, 1980).

3. Results and discussion

3.1.1. Water supply

Awara multipurpose dam at Ikare provides water at *45*litres per day per person to its consumers for an average of 3.5 hours per day, to 38.3 percent of the population in its service area. Sewerage service is available to only 7.4 percent of the population. Only 30.4 percent of consumption is metered and 9.3% are functioning. The operating ratio is almost unity and fairly reasonable. Average tariff of \$5.253/m^3 was estimated from 2004-2008; and thus increased from \$5.253/m^3 to \$6.25/m^3 from 2009 till 2013. This is very high and thus covers operating expenses well. One of the reasons for this is the volume of water lost known as physical or real loss which was represented as Non- Revenue Water (NRW). The percentage of NRW increased from 15.1% in 2004 to 18.3% in 2013 which corresponded to an annual loss of 6.2 million USD. Fig.3 shows that there is steady increase in the volume of water produce for a decade.

Table 1. Simulation results of water supply system

Year	Amax WD Mil.m^3	Amax WS Mil.m^3	% WSC	PCC	PP	APC mil.\$	% NRW	ANT mil. \$	UP	OPR	BL mil.m^3
2004	11	3.3	30	11.5	44.2	17.3	15.1	16.8	5.22	1.01	2.8
2005	11.1	3.5	32.1	11.9	44.1	18.4	15.9	18	5.32	1.02	3
2006	11.2	3.9	34.8	12.8	44.9	20.5	16.2	19.8	5.31	1.03	3.3
2007	11.8	4.4	37.3	13.7	45.2	23.1	16.5	22.2	5.32	1.04	3.7
2008	12.1	4.6	38.3	14.2	46.3	24.2	16.8	23.4	5.14	1.03	3.9
2009	12.2	5.9	48.4	17.8	47.1	36.9	17.1	35	5.91	1.05	5
2010	12.5	6.1	48.7	18.2	47.4	38.1	17.1	36.4	6.21	1.04	5.2
2011	12.9	6.2	48.8	18	46.9	39	17.3	37.1	6.32	1.05	5.3
2012	13.1	6.3	48.9	17.6	47.6	39.3	17.9	37.1	6.21	1.05	5.3
2013	13.3	6.5	49	18.3	48.9	40.6	18.4	38.5	6.21	1.05	5.5

Source: Simulation output, 2014

AMaxWD = Annual maximum water demand; AMaxWS = Annual maximum water supply; %WSC = Water supply coverage; PCC= production per capita consumption; PP = Production per population; APC = Annual production cost; NRW = Non-Revenue water; ANT = Annual tariff; UP = Unit operation; OPR = Operating ratio; BL = Billed water.

Population served has intermittent water supply. Both chlorine and UV tests carried out shown that 22 and 18% passed the residual tests from 320 water sample taken respectively. Higher percentage of NRW occurred through physical loss such as pipe burst and breakages. In most cases pipe break-burst are not always reported and this increased the volume of water and percentage of non-revenue water on real-time analysis. Average annual cases of 1,234 pipe break-bursts were reported, while 215 pipe breaks were repaired immediately and 534 pipe breaks were attended thereafter leading to more loss of water and revenue.

Reducing water losses would require full metering of all production sources and all connections including public water points to determine the real extent of losses.

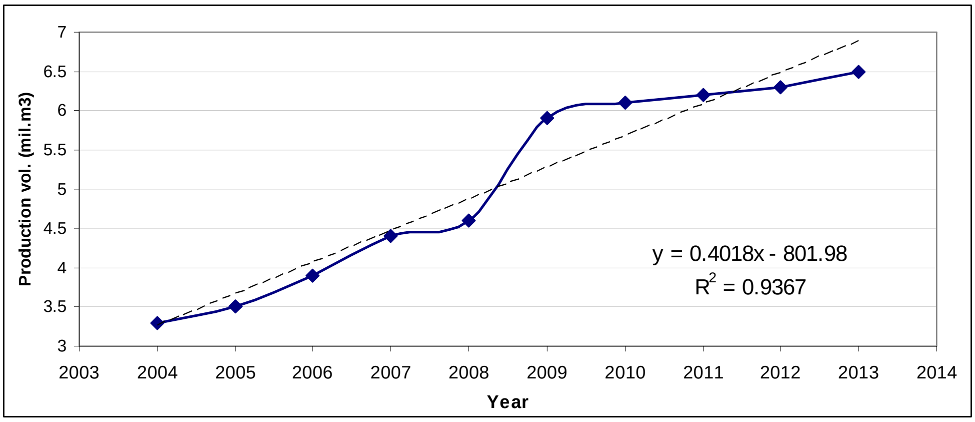

Figure 1. Production rate

3.1.2. Sensitivity analysis for water treatment

A global economic treatment analysis of this nature has a number of uncertainties and weaknesses. From source studies, there was insufficient information on the treatment cost and the available data was simulated to comprehensive analysis. Annual chlorination UV costs of 66 and 81.6 million USD were estimated in 2004. The treatment costs increased to130.1 and 140.6 million USD. Hence multi-way and probabilistic sensitivity analyses shows ultraviolent (UV) treatment is costly than chlorination by 10%. Based on the cost function, UV cost for $1m^3$ is higher with \$0.01 than the chlorination test. However, chlorination test for treatment plant less than 5000 m3 is more expensive \$25 over UV treatment.

Table 2. Simulation results of Water Treatment Cost Source Simulation output 2014

Year	ACC(mil.$)	CLD(mil.Mg/l)	AUVC(mil.$)	UVD(mil.mil/cm^2)
2004	66.0	16.5	74.3	462.1
2005	72.1	17.5	81.6	490.2
2006	78.2	19.6	88.3	546.2
2007	88.3	22.2	97.9	616.4
2008	92.1	23.4	100.9	644.3
2009	118.3	29.5	128.4	826.1
2010	122.2	30.4	131.6	854.3
2011	124.6	31.1	135.2	868.4
2012	126.3	31.5	135.9	882.3
2013	130.1	32.5	140.6	910.7

ACC(Mil.USD) = Annual cost of chlorine; CLD = Chlorine dose; AUVC= Annual cost of Ultraviolent treatment; UVD = Ultraviolent dose

Table 3. Estimated cost function for UV and Chlorination Treatment Based on Simulation Analysis

Disinfection Type	Average cost function	Predicted cost ($) for plant with capacity (5 million m^3)
UV Dose 140 mj/cm2	Y = $4.1016x^{0.9923}$	0.034
Chlorination (5 mg/L)	Y = $0.28x^{0.9915}$	0.562

Source: Simulation output, 2014

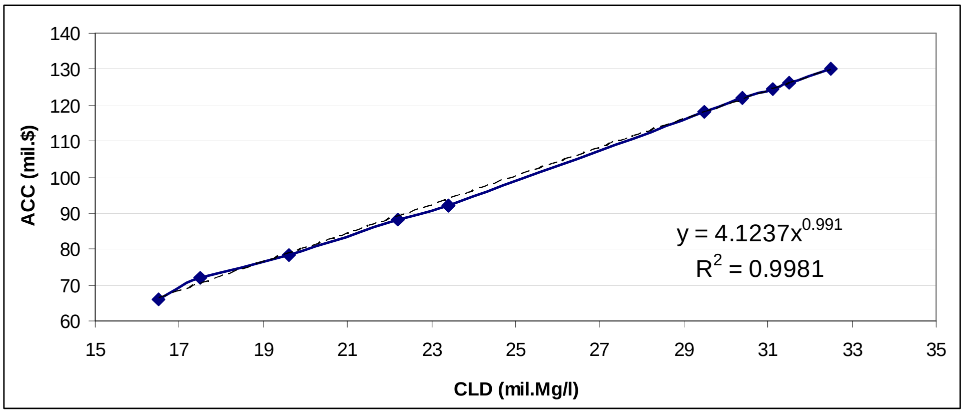

Figure 2. Chloride Water Treatment Cost Calibration

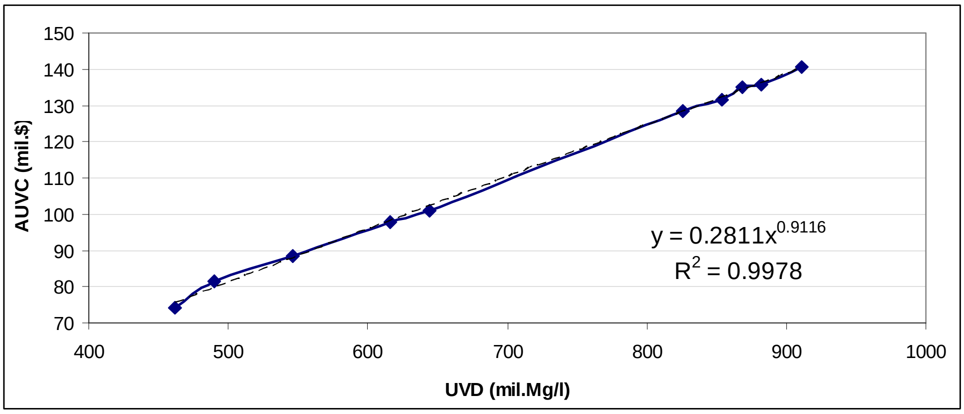

Figure 3. UV Water Treatment Calibration

4. Conclusion

Meeting the Millennium Development Goal on safe drinking by 2020, the overall, Ikare's water utilities will have to increase water availability to 14 hours, increase coverage (65%) to and the supply of water to their consumers. Ensuring this requires, non-revenue water must be reduced to improve the volume of billed water through effective repair and monitoring of pipe break and construction. Service connections and production sources should be metered to discourage the flat-rate tarrif system that is heavily rooted in this part of the country. Tariffs increase should bring revenues to a level to cover operation and maintenance expenses and fund expansion and service improvements. Operating ratio should be brought to about 0.80 or lower by raising tariffs or reducing costs.

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Addresses:

- Olotu Yahaya, Department of Agricultural & Bio-Environmental Engineering, Auchi Polytechnic, Auchi, Nigeria
- Unuigbe O.M., Department of Agricultural & Bio-Environmental Engineering, Auchi Polytechnic, Auchi, Nigeria
- Eleta Paul.O., Department of Agricultural & Bio-Environmental Engineering, Auchi Polytechnic, Auchi, Nigeria
- Stephen A.O., Department of Civil Engineering, Auchi Polytechnic, Auchi

Corresponding author: realyahaya@yahoo.com