AN OPTIMAL APPROACH FOR URBAN WATER DISTRIBUTION IN NIGERIA

By

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ABSTRACT

Most Nigerian towns have water distribution networks designed by conventional methods, with the assumption that demand will be spread over 24 hours. In reality, the distribution system operates under intermittent supply conditions. The common problem is how to utilize the scarce water resources so as to minimize operating costs, maximize internally generated revenue, and ensure equitable level of service delivery. This paper presents the results of application of linear programming technique to solve such urban water supply management problem. A mathematical model, which optimizes conjunctive distribution of available production to end users at minimum cost, was tested with field data from Maiduguri North East Nigeria. Results obtained from the analysis shows that distribution/operation costs can be reduced by 28% with a saving of ₦0.76 per m^3. The method improves revenue from water sales by 45% without compromising standard and level of service delivery. The method proposed and used by this study is relatively simple and enables operation managers to collect data directly on the prevailing important local parameters and draw their own conclusion with high precision and without involving the cost of hiring consultants.

***Keyword:* Water Production, Intermittent Supply, Cost, and Revenue.**

List of some symbols used:

SWA=State Water Agency,

GDP= Gross Domestic Product,

SW= Surface Water

Qij = Quantity Supplied (assumed consumption), m^3/d

GW= Ground Water,

D_{jn}=Maximum Demand, m^3/d,

C_{ij}=Operational Costs, ₦/m^3,

N_s=No Supply, P_d=Dummy Production, m^3/d,

D_d=Dummy Demand, m^3/d,

R_{ij}=Internal Revenue, ₦,

RW= Rain Water,

P_n= Production, m^3/d,

L_{ij}=Level of Service, %,

t_{ij}=Tariff Rate, ₦ /m^3.

INTRODUCTION

In many regions of the world, water supply limitations are becoming one of the constraints to development. In most Nigerian towns and perhaps some other developing countries, the availability of potable water is often restricted or inadequate. Many authors (1,2,3) have attributed this to difficulties arising from depleted water resources, increasing, population, poor management, power cuts, funding, etc. The problem of water scarcity in urban areas is of particular concern because the quantity available is not generally sufficient to meet the demands of the population. Unlike rural communities, there may be no nearby alternative source such as natural spring or river, and private boreholes ownership may not be viable or too expensive. For example, in Markudi only 46 – 56% of the demand is satisfied by the public water supply distribution system (4). The situation is the same in Ibadan where less than 30% of the estimated 5 million populations is catered for in terms of public water supply(5). In Akure only about 20% was available for consumption from the State Water Agency (SWA) in 2001. Aluko(6), reported that in Lagos State demand has exceeded the available average production. He suggested that improving and sustaining services will require more efficient operation of the SWA. Ekpenyong and Bassey(7) observed that private water schemes have emerged as principal sources of water supply in Calabar. This is as a result of inability of the Calabar public water schemes to meet the demand of the population. Similar poor functional supplies have been reported for Enugu and Abia states (8).

Apart from the above low coverage, there is also the problem of sustainability. Many reasons have been identified as causing or contributing to the poor performance of the SWAs in providing sustainable water supply to consumers (2,9,10). These reasons include institutional problems, insufficient funding, inadequate tariff and collection systems, and sudden increase in costs of petroleum products, chemicals and electricity. The cumulative effect of such changes reflects in increase in unit cost of water production and distribution. As tariff remains low, SWAs are not able to pay for chemicals, electricity and other operation costs from their revenue generation. This results in erratic and unsustainable supply of the available resources.

One of the most common methods of solving or controlling the above problem is the use of intermittent supplies. For example, a WHO survey report (2) showed that in South East Asia, 91% of the systems are intermittent and that nearly all-Indian cities operate intermittent systems. However, this solution approach gives rise to insufficient pressure (some areas may have zero pressure), inequitable distribution of the available resources and short duration of supply.

The objective of this paper is to present and discuss the results of the theoretical analysis carried out to investigate on how to achieve least operating cost and increase in revenue without compromising equitable service delivery. It hopes to suggest affordable tariff conditions.

Problem definition/formulation

Many state urban water supply schemes in Nigeria have difficulty in providing enough water to meet increasing demands. These states lack the resources and political will to expand or invest in new surface water schemes. Therefore, most SWA have to manage their existing water supply schemes more carefully. The balance between water availability and demand in most cases depends on several factors such as rapid population growth, increasing industrial development, variation in climate and human activities.

There are three major sources of water in Nigeria; surface water, groundwater, and rainwater. We can reserve rainwater for rural water supplies. Water demands may arise from domestic and non-domestic needs. The total demand, quantity available and distribution/operation costs from each source may vary. The variation depends on the district ward or zone and the season (wet or dry season). Often people simply have to use less water. The first steps towards better use of limited available supply was evaluated by the following:

- Assessment of the surface and ground water resources.
- Assessment of the amount of water actually available for use from each source for each district.
- Assessment of water demands, consumption and losses for each district.
- Assessment of distribution costs of the available resources for each district.
- Incorporation of type of system (domestic/non domestic), type of consumer (metered/flat rate) in an optimization matrix. This will allow a scenario of water balance and revenue to be examined.

The management problems arising from these variations include:

- To determine what quantity of water to be pumped to each district from each source, so as to meet the various daily demand for the season at least cost (C).
- To determine the maximum revenue from each district for each consumption level (R).
- To determine the optimal (maximum affordable) tariff to be charged for each category of consumer (T_r)

The next approach for better use of the scarce and intermittent sources was attempted by the application of the mathematical optimization technique (11,12,13).

THE MODEL

The above formulation will go with the following assumptions.

- That the waterworks/pumping stations are in place.
- The distribution networks are interconnected to the district, etc.
- The server loss of pressure in the network common with intermittent supplies is accounted for.
- Corrective and preventive maintenance are conducted in such a way that water production is not interrupted as scheduled.
- Water bills are distributed and consumers are willing to pay as at when due.

Mathematical distribution (transportation):

The model relating the quantities of water from each source to each destination during each season of the year was derived as follows,

Let P_{ij} = Volume of supply, m^3/d.

D_{jn} = Projected demand for j district in n season

i =1, 2, 3 surface water, borehole water, rainwater.

j =1, 2, ... J where j is the number of districts.

n =1,2 periods of the year, dry or wet season.

For wet period we have three sources, five demands which gives 15 decision/variables. For dry season we have two sources, which gives ten variables.

Q_{ij} = quantity supplied or assumed consumption.

C_{ij} = cost of delivery unit volume of water from source to district j during the n season.

$$\sum_{i=1}^{n} P_{ijn} \geq D_{jn} \quad (1)$$

$$\sum_{j=1}^{n} P_{ijn} \leq Q_{in} \quad (2)$$

$$Q_{i} \geq 0 \quad (3)$$

$$D_{j} \geq 0 \quad (4)$$

If $Q_i = 0$, then $C_{ij} = 0$

For wet season, W_2;

$$\sum_{i=j}^{n} Q_{in} \geq \sum D_{jn} \quad (6) \text{ (expected ideal situation)}$$

For Dry season, W_1 ;

$$\sum Q_{in} \leq \sum D_{ij} \quad (7) \text{ (real existing situation)}$$

Substituting the above parameters into a linear program formulation gives:

Objective function as Y_1.

$$Y_1 = \sum_{i=1}^{n} C_{ijn} P_{ijn} \quad (8)$$

Minimize, Y

Subject to

$$\sum_{i=1}^{n} P_{ijn} \geq D_{jn}$$

The constraints in equations (1) and (7) implies that the total supply would be at least equal to the total demand in each period. This constraint may not hold for W_1. Hence the need for intermittent supply or rationing of distribution between the zones/districts.

Mathematical Optimization

In addition to adequate supply, SWAs are expected to generate enough revenue at least to cover their operation and maintenance costs. Therefore the method can be modified to maximize revenue from water sales (Assignment allocation). Since revenue depends on sales, an optimal level of service will encourage willingness to pay and maximize revenue.

Let X_{ij} be revenue of m_i to s_j

Where m_i ($i = 0,1, 2.......n$) = type of metered service connection installed in various districts/zones.

S_j ($j = 1,2 .... n$) = zones/districts

R_{ij} = Revenue to be generated from m_i at zone s_j (₦)

- The problem is to assign service type to zones so as to maximize the overall revenue through optimal service level.

The total revenue is $\sum_{i=1}^{n} \sum_{j=1}^{n} R_{ij} X_{ij}$

Problem definition:

Determine $X_{ij} \geq 0$ ($i,j = 1,2 ....n$) so as to

$$\text{Maximize } Z = \sum_{i=1}^{n} \sum_{j=1}^{n} R_{ij}\, x_{ij}$$

Subject to the constraints:

$$\sum_{i=1}^{n} Xij \geq 0 \quad , j = 1, 2, ... n$$

$$\sum_{j=1}^{n} Xij \geq 0 \quad , I = 1, 2, ...n$$

Application:

The model is illustrated by considering Maiduguri water supply area in Borno State, North East Nigeria. Maiduguri has been chosen because of available and accessibility of data and the first author's experience as a staff of the Borno State Water Corporation (BSWC). The project is necessitated by the fact that in the last 20 years there has been increasing evidence that the intensity of ground water abstraction in the area is not sustainable [1,9]. Reduced assess to groundwater, caused by decline in water table or the failure of wells in the dry season affects performance of the SWA in terms supply services and sustainable revenue generation. Addressing the problem has been challenging to the authorities. Against this background the authorities installed a surface water supply scheme as a solution to the problem. In spite of this laudable measure, the availability of water is often inadequate or restricted to some zones due to difficulties as stated in the introduction of this paper.

The city has two major sources of supply. There are five distribution zones. Zones 1, 2 and 5 (Figure1) receive supplies from both surface and ground water sources while Zones 3 and 4 are served by borehole water supplies only. The total water production and demands for each zone has been reported in the literature (9,14). The data for revenue and percentage of population was obtained from the SWA and previous study report.

Computation

The Vogel's Approximation method (11) was employed to find the initial basic feasible solution for minimum operation cost. The transportation table is represented in Table 1. The VAM was used because it takes into account not only the least cost but also the cost that just exceeds the least cost and therefore yields better initial solution. The iteration was repeated in four steps to obtain an optimal basic feasible solution.

RESULTS AND DISCUSSION.

Generally, an optimal network design is the one that can supply sufficient quantity to consumers at adequate pressure at least cost. The supply or consumption was computed as production less losses. The losses consist of **unaccounted for water**, which was estimated to be at least 10% of production (9,14), unaccountable losses are mainly caused by: thieves who siphon water at night, leaking pipes and wrong meter reading (15,16).

Table 1 showed that during W_1 the value of the D_m exceeded the supply. Therefore a dummy production variable (P_d) of 37.73×10^3 m^3/d was introduced to take up the short fall in supply. In W_2 the supply exceeded the demand. A dummy demand variable (D_d) of 9.81×10^3 m^3/d was applied to absorb the excess. In practice the P_d can be achieved by increasing the number of productive boreholes especially in zones 3 and 4. Less quantity should be treated for supply for W_2. This will reflect in lower operation and maintenance cost for the 3 months of W_2 or 25% of the year. Alternatively, ground reservoirs may be provided to take up the supplies.

Results obtained from the analysis showed that the average distribution cost can be reduced by about 28%, without compromising standards. This implied a saving of ₦ 0.76 per m^3 of water delivered when compared with other estimates by Coopers and Lybrand (16).

The operation implication of this prediction is that more people can benefit from the supply even with less quantity or duration of supply (i.e. intermittent or rationing conditions). The allocation of sales in Table 3 shows that the tariff rates are higher for M_1 and M_5 but these consumers have low population or number of connection. An application example is presented in Table 4. Based on the results of the computation the following tariff allocation factors will produce maximum revenue without affecting the level of service.

Model Testing.

The comparison in Figure 2 provides a useful measure of the accuracy of the model result. The precision of the model was attested by the high correlation coefficient, which was fund to have coefficient of determination (R^2) = 0.94

However, in implementing the above results another factor should be introduced to compensate for those who may not be able to pay due to inflation and their poverty level (17). The rate for M_1 and M_5 should not be reduced because these categories of consumers have high affordability capacity and willingness to pay (16).

CONCLUSION

A study was carried out to find a feasible solution to urban water supply in Nigeria, using data from Maiduguri. Result from the analysis showed that application of linear programming to water distribution management could guarantee optimal and sustainable supply, improve revenue and minimize operating costs.

It is recommended that more of such investigation be extended to other towns by a computer simulation technique. The work will be useful to operation engineers in water distribution planning and management.

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Table 1 **Distribution Costs**

ZONE j / SOURCE i	W_1					W_2					
	1	2	3	4	5	1	2	3	4	5	P_n $\times 10^3$ m^3/d
S_w	C_{ij} 2.7	4.14	Ns	Ns	1.12	2.7	4.14	Ns	Ns	1.12	57.0
G_w	4.53	6.77	4.7	4.51	1.88	4.53	6.77	4.7	4.51	1.88	13.5
R_w	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2
D_{ij} $\times 10^3$ m^3/d	24.5	42.88	17.28	16.63	6.93	12.18	18.24	12.95	12.22	5.1	MN

Ns = no supply

Table 2: Types of Service Connection used in the Computation

TYPE		CONSUMPTION RATE $\times 10^{-3}$ m^3/d
M_1	High metered G.R.A type	350
M_2	Multi connection for medium density housing Estates	155
M_3	Single/yard stand tap	85
M_4	Public stand tap	27
M_5	Non-domestic	15

Source: Ndubuisi (1999)

Table 3. Allocation of Water Sales

S_j / M_i	Sales zones						
	1	2	3	4	5	Rates #/m^3	
m_1	7.0	12.8	6.6	6.8	6.9	15	
m_2	10.0	13.8	10.2	10.0	10.3	4	
m_3	43	40.3	40.6	40.0	41.5	4	
m_4	38	30.1	24.1	24.0	24.3	2	
m_5	2.0	3.0	18.5	19.2	17	30	

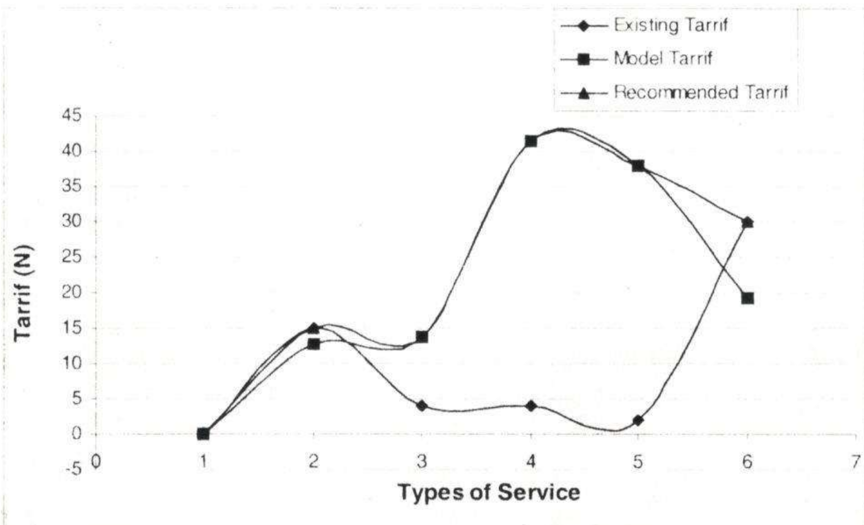

Figure 2. Comparison of Model result and Existing Tarrif.

Table 4. Application Example

m_i	1	2	3	4	5
m_1	7.0	12.8	6.6	6.8	6.9
m_2	10	13.8	10.2	10.0	10.3
m_3	43	40.3	40.6	40	41.5
m_4	38	30.1	24.1	24	24.3
m_5	2.0	3.0	18.5	19.2	17

=

m_1	5.8	0	6.2	6.0	5.9
m_2	3.8	0	3.6	3.8	3.5
m_3	0	2.7	2.4	3	1.5
m_4	0	7.9	13.9	14	13.7
m_5	17.2	16.2	0.7	0	2.2

a

b

m_1	5.8	0	5.5	6.0	4.4
m_2	3.8	0	2.9	3.8	2
m_3	0	2.7	1.7	3	0
m_4	0	7.9	13.2	14	12.2
m_5	17.2	16.2	0	0	0.7

=

m_1	5.8	$\boxed{0}$	5.5	6.0	4.4
m_2	3.8	$\boxed{0}$	2.9	3.8	2
m_3	$\cancel{0}$	2.7	1.7	3	$\boxed{0}$
m_4	$\boxed{0}$	7.9	13.2	14	12.2
m_5	17.2	16.2	$\cancel{0}$	$\boxed{0}$	0.7

c

m_1	5.8	$\boxed{0}$	3.8	4.3	4.4
m_2	3.8	$\boxed{0}$	1.2	2.1	2
m_3	0	2.7	0	1.3	$\boxed{0}$
m_4	$\boxed{0}$	7.9	11.5	12.3	12.2
m_5	18.9	17.9	0	$\boxed{0}$	0.7

=

d

m_1		$\boxed{0}$			
m_2		$\boxed{0}$			
m_3	$\cancel{0}$		$\cancel{0}$		$\boxed{0}$
m_4	$\boxed{0}$				
m_5			$\cancel{0}$	$\boxed{0}$	

Maximum Sales=(12.8x0.35)+(13.8x0.155)+(41.5x0.085)+(38.2x0.027)+(19.2x0.045)

=₦808, 635:00

Table 5: Recommended Tariff allocation factors for Maiduguri

Type of service Connection	M_1	M_2	M_3	M_4	M_5	R x 10^3 ₦/d	increase%
Existing rate (₦)	15.0	4.0	4.0	2.0	30	473.0	-
Model result (₦)	12.8	13.8	41.5	38.0	19.2	808.6	41.5
Recommended ((₦)	15	13.8	41.5	38.0	30.0	874.2	45.9

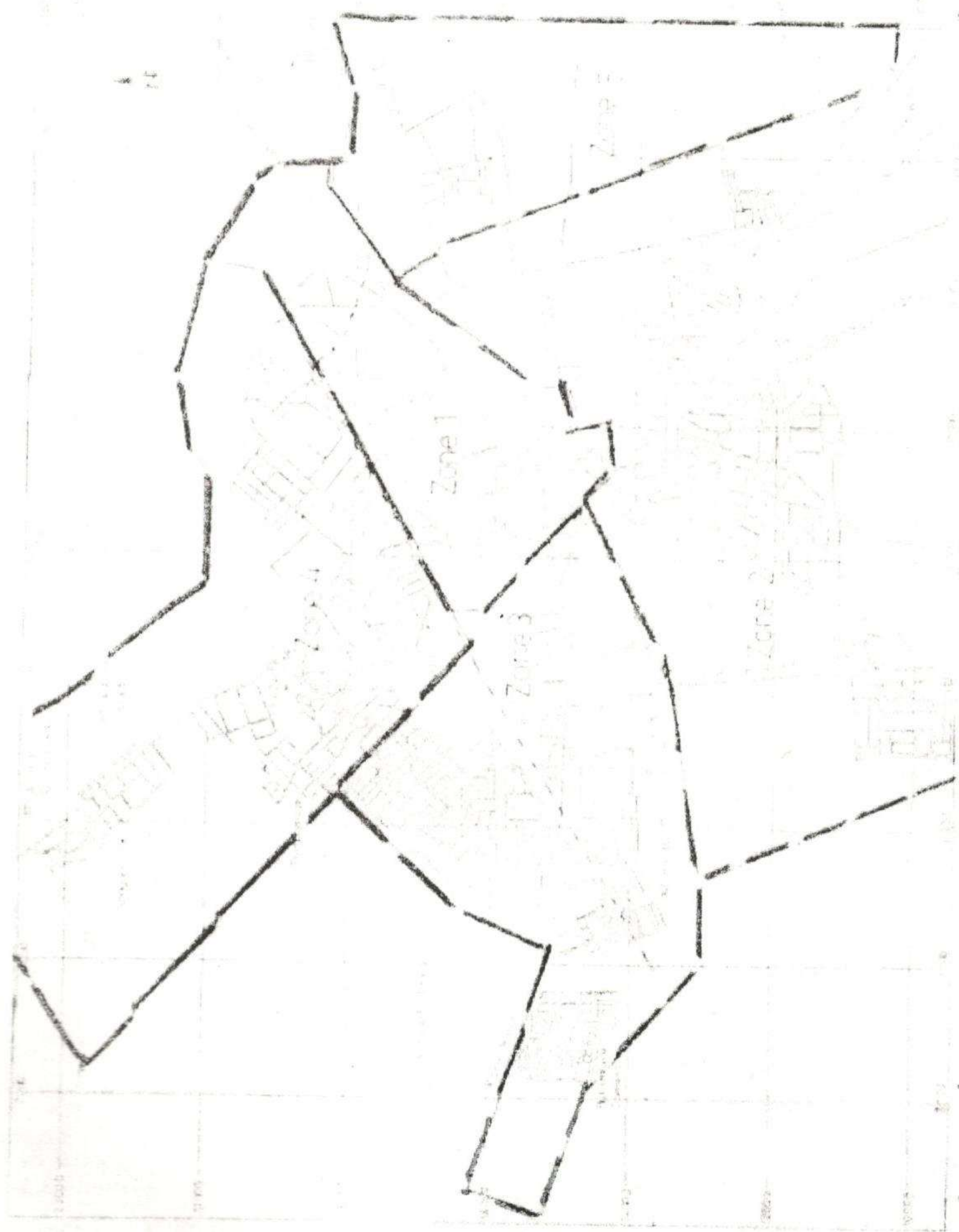

Figure 1. Water distribution zones in Maiduguri: Source: Tahal (1995)