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Simulation Analysis for Rainwater Harvesting and Groundwater Withdrawal in Auchi, Nigeria

Shortage in supply of water for potable and non-potable applications and exponential world population increase is a strong constrain to Human Development Index and social-economic advancement in Nigeria. ClimGen (Version 4.1.05) was used to simulate and create large dataset of annual rainfall depth. Generated average annual rainfall from 1430 mm to 1600 mm was subjected to varying roof plan surfaces of 250 m^2*; 500* m^2*; 1000* m^2*; and 2000* m^2 *respectively. Simulation analysis showed that an average of 5,300*m^3 *of rainwater was harvestable and this value of water could only meet water demand of 170 people annually. The relationship of roof plan surface (RPS) and collected rainwater is very strong with* $R^2 = 0.84$ *and 0.95 respectively. Again, the volume of groundwater withdrawal increased from* $12.4\times10^4 m^3$ *to* $32.7\times10^4 m^3$*, this could only meet an annual water demand for 10,480 people representing about 6.2% of the population in Auchi. This development reveals that water supply from the alternative sources could not meet up to 6.3% of total water demand in Auchi and increasing water availability and accessibility to about 65%* **(**$31.3\times10^5 m^3$**)** *coverage requires integrated rainwater harvesting system and technically-based groundwater exploration mechanism.*

***Keywords**: potable, accessibility, rainfall depth, RPS, volume, demand, integrated*

1. Introduction

Water is an essential and precious resource upon which our ecosystem and agriculture production depend. However, water a natural resource of the world, constitutes 1,384 million cubic kilometres of which around 97.39 per cent (*i.e.*1, 348 million cubic kilometres) is in the oceans. Another 2.61 per cent (*i.e.,* 36 million km^3) is fresh water of this 77.23 per cent (27.82 million km^3) is in polar ice caps, icebergs and glaciers. Only small fraction of water resources (0.59% or 8.2 million km^3) of the earth is present in the ground, lakes, rivers and atmosphere and is useful to mankind. Whereas, more than 99 per cent of water present on the earth is not useful to agriculture (Anonymous, 2003).

Water scarcity is recognized as an increasingly severe problem with global implications (Sazakli et al. 2007).The distribution of water reserves is far from homogeneous, both geographically and temporally. Water scarcity is a characteristic of Estako-West, such as Auchi and its environs. This development will be complicated in Afuze, Otuo, Agbede, Jattu and Fugai that are projected to experience a reduction in their water resources in the coming decades due to the effects of climate variability, rainfall distribution and excessive infiltration.

The exponential increase in population and subsequent urbanization of Auchi has caused a major strain on waterways including complete loss of rivers and natural watersheds in order to create more structural facilities for the growing population. However, there is drastic reduction of watershed due to increase in development and urbanization of Auchi as a result of intake of Auchi Polytechnic, Auchi and the commercial activities. Water availability in Auchi is within the range of 500m³, this indicate that water a primary constraint to life. People in this region have developed techniques to meet their water needs and requirements. Rainwater harvesting is very common in this area. In addition, groundwater is somehow being harnessed. The problems of withdrawing water from groundwater system can be categorized as *technical-know-how* and *project finance*. The soil structural type in Auchi is *sedimentary* which is always very difficult to drill in the course of sourcing for underground water. It requires highly skilled drillers and engineers and the overall operation is capital intensive.

Having considered the complex situation being faced with water availability and accessibility in this region, alternative water sources such as rainwater and groundwater systems will be analysed to determine supplementary potentials of water supply and distribution in order to create a stochastically-based model veritable in proffering realistic measures of resolving water shortage by 75%.

2. Materials and Methods

2.1. Description of the study area

Auchi district falls in the central part of Estako-West, Edo State, Nigeria (Fig 1). It lies between the northern latitudes of 7, 0667 (74'0.012"N) and east longitudes of 6, 2667 (616'0.012"E). It is by Ipkesi, Jattu, Aviele and Warake. The average annual rainfall of Auchi is 1300 mm with a bimodal distribution. The first peak occurs in June-July while the second occurs in October. Plates below show various systems of rainwater harvest and distribution.

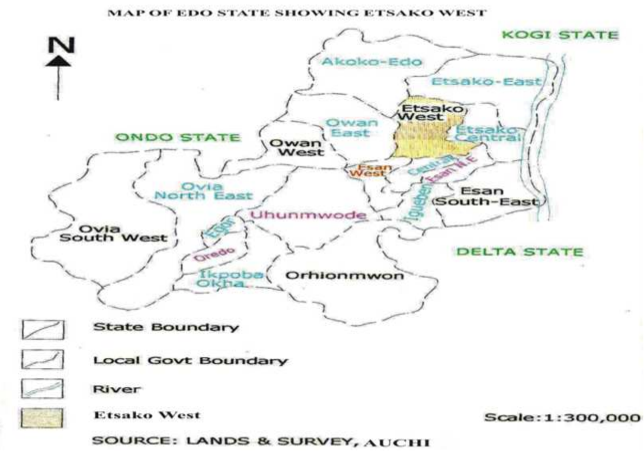

Figure1. Map of Auchi

Plate 1. Rainwater harvest from surface roof plan

2.2. Rainwater modelling

Rainwater harvesting systems are very flexible and alterable based on specific site needs. The main components for each system include a catchment area (rooftop), a gutter or downspout system, a cistern or holding tank, and a pump to re-distribute the water (Rainwater Management Solutions Inc 2007).

Rainwater harvesting in Auchi and its environs can be categorised in three methods: open air collection, collection from tree trunks and collecting from temporary gutters into square brick tank. In these areas, rainwater is collected from permanent roofs made of tiles, asbestos or tine sheet. The potential yield from rainwater is a function of the roof size, roof type and filter efficiency. The potential yield of rainwater and rainfall relationship for various roof materials such as steel, asbestos and concrete roofs is as follows:

$$P = 0.85RWs \tag{1}$$

$$P = 0.82RWa \tag{2}$$

$$P = 0.75RWc \tag{3}$$

Where:

P = Rainfall (mm)

RW = Harvested rainfall water (mm)

The potential yield of rainwater harvest is modelled as follows:

$$Rwh = \alpha \mu Rp \tag{4}$$

Where:

Rwh = Rainwater harvest (mm)

Rp = Roof plan size (m^2)

α = filter efficiency

μ **=** collection efficiency

For the purpose of this research study, α and μ are choosed as 0.94 respectively. Rainwater collection potential (gallons/month) for study area is calculated from monthly rainfall using the following equation (Cabell Brand Center, 2007):

$$Rwh = Rp * maR * \mu \tag{5}$$

Rwh = Rainwater (m^3)

Rp = Roof plan size (m^2)

maR = monthly average rainfall (mm)

μ = collection efficiency

2.3. Structural water usage

Structural water usage in this research study is the collection, storage, distribution and supply of 45% (16.5 m^3) of total water needed for per person annually for both portable and non-portable application from harvested rainwater. However, the productivity of this system is a function of these variables: catchment area per building- roof plan size (*CFP*); average rainfall depth (*ARD*); number of raining days *(NRD)*; capacity of storage tank (*CST*); population of the city (*P*); and climate variability (*CV*). This expression can be mathematically represented as follows:

$$Ps = f(cfp * ard * nrd * cst * p * cv) \tag{6}$$

Where: Ps = Productivity system

2.4. Groundwater Withdrawal

The total volume of water discharged from the aquifer cans hardly be estimated due to the inconsistency of water discharge, and complete absence of records in most cases. Field and physical contacts indicated an average mean discharge by 10 boreholes located in Auchi Polytechnic, Auchi, Maclean Water Company and others amounts to $1.43 \times 10^6 m^3$/annually.

2.5. Groundwater in Storage

Determination of the amount of water in the aquifer is done by relating aquifer thickness, the specific yield, and the area of the freshwater body. The can be expressed as follows:

$$St = T * Ya * A \tag{7}$$

Where:

St is the total water storage in the aquifer (m^3); T is mean thickness of the aquifer (m); Ya is the average specific yield; A is the total area of the freshwater aquifer.

2.6 Data collection and analysis

Data on rainwater collection and groundwater potentials from the selected locations based on the degree of water-stress situation within Auchi and its environs were obtained and subjected to validation using all the modelling expressed described in this research study. ClimGen software (Version 4.1.05) was used be to produce generated rainfall data to supplement direct data obtained from meteorological station. T-test and One-sample analysis were carried out on the validated data to test it level of significance and operation. Excel software and Sigma Plot were used for spread sheet calculations, graphical representations and calibration iterations.

3. Results and discussion

3.1 Rainfall and rainwater collection

Table 1-5 show results of annual rainfall and harvested rainwater in some selected location within and around the study area over a period of 13 years (1999-2008). The results describe significance the relationship of roof plan sizes and volume of harvestable rainfall-rainwater collection. Average highest total rainwater of ($1.6m^3*10^2$) was captured using roof plan size ($100m^2$) with an average rainfall depth value of 1,660mm, while highest volume of rainwater ($31.2\ m^3*10^3$) was collected with roof plan size ($2000\ m^2$) and rainfall depth of 1,660 mm respectively. Analysis of harvestable rainwater from selected regions indicated that only ($5.3*10^2m^3$) of water could be captured on annual basis as shown in table 9. The capacities of overhead and underground storage tanks mostly used ranges between $1m^3$ to $5m^3$ for overhead storage tank, while underground reservoir usually being constructed with precast concrete ranges from $6m^3$ to $10m^3$ as shown in plate 1.

Table 1. Annual average rainfall and potential rainwater collection in Auchi (1996-2008) Roof plan size ($100m^2$)

Year	96	97	98	99	00	01	02	03	04	05	06	07	08
Rainfall (mm)$*10^3$	1.43	1.49	1.51	1.45	1.5	1.49	1.51	1.53	1.58	1.56	1.56	1.56	1.66
Rainwater Collection (m^3)$*10^2$	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.6

Source: Field study, 2012

Table 2. Annual average rainfall and potential rainwater collection in Auchi (1996-2008) Roof plan size ($250m^2$)

Year	96	97	98	99	00	01	02	03	04	05	06	07	08
Rainfall (mm)$*10^3$	1.43	1.49	1.51	1.45	1.5	1.49	1.51	1.53	1.58	1.56	1.56	1.56	1.66
Rainwater Collection (m^3)$*10^2$	3.4	3.5	3.5	3.4	3.5	3.5	3.5	3.6	3.7	3.7	3.7	3.7	3.9

Source: Field study, 2012

Table 3. Annual average rainfall and potential rainwater collection in Auchi(1996-2008) Roof plan size ($500m^2$)

Year	96	97	98	99	00	01	02	03	04	05	06	07	08
Rainfall (mm)$*10^3$	1.43	1.49	1.51	1.45	1.5	1.49	1.51	1.53	1.58	1.56	1.56	1.56	1.66
Rainwater Collection (m^3)$*10^2$	6.7	7	7.2	7.1	7.1	7.0	7.1	7.2	7.4	7.4	7.3	7.3	7.8

Source: Field study, 2012

Table 4. Annual average rainfall and potential rainwater collection in Auchi (1996-2008) Roof plan size (1000m^2)

Year	96	97	98	99	00	01	02	03	04	05	06	07	08
Rainfall (mm)*10^3	1.43	1.49	1.51	1.45	1.5	1.49	1.51	1.53	1.58	1.56	1.56	1.56	1.66
Rainwater Collection (m^3)*10^2	13.4	14	14.2	13.7	14.2	14	14.2	14.4	14.8	14.8	14.6	14.6	15.6

Source: Field study, 2012

Table 5. Annual average rainfall and potential rainwater collection in Auchi (1996-2008) Roof plan size (2000m^2)

Year	96	97	98	99	00	01	02	03	04	05	06	07	08
Rainfall (mm)*10^3	1.43	1.49	1.51	1.45	1.5	1.49	1.51	1.53	1.58	1.56	1.56	1.56	1.66
Rainwater Collection (m^3)*10^2	26.9	28.1	28.5	27.4	28.5	28	28.5	28.8	29.6	29.6	27.2	27.2	31.2

Source: Field study, 2012

Water resource data and statistics are often provided on a per capita basis. This represents an average across the entire population, giving the impression of equality in the availability of the utility. The calibration result in figure 1 and 2 show the relationship between rainwater collections (***RW***) and roof plans (***RPS***) as outputs, while annual rainfall depth of 1430 mm represents the input. Strong relationship exists between average water collection and surface area or roof area of collection with ***R^2=0.844 and R^2=0.955*** respectively***.*** This indicates that the volume of rainwater could be significantly increased by increasing the roof plan surface areas.

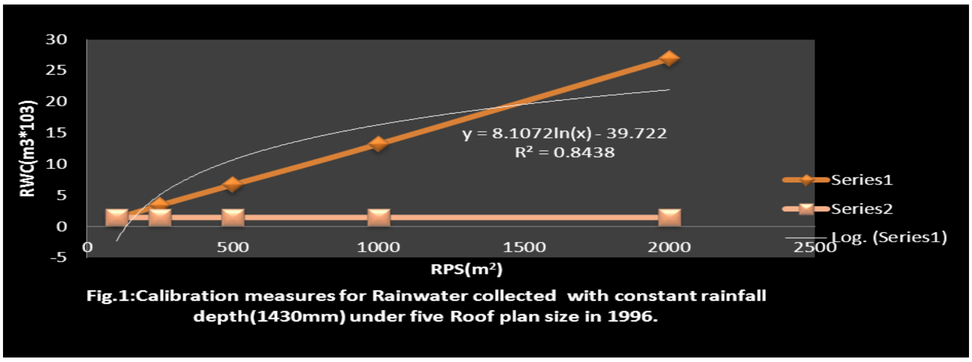

Fig.1:Calibration measures for Rainwater collected with constant rainfall depth(1430mm) under five Roof plan size in 1996.

Figure 1.

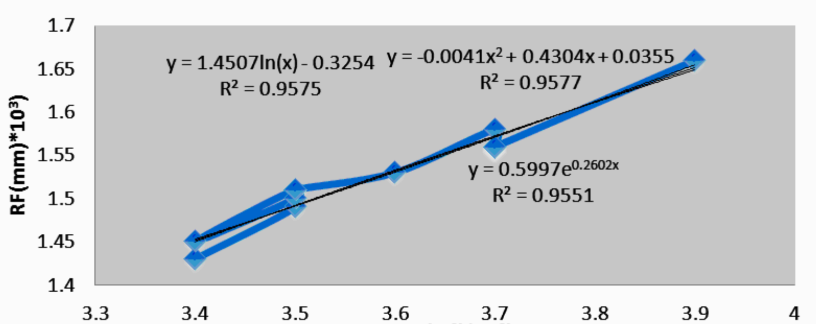

Fig 2: Averge rainfall depth (RF) and rainwater (RWC) harvested from roof plan size (250m²)

Figure 2.

In addition, magnitude of annual rainfall depth is a strong indicator influencing the volume of rainwater collection. The results of One-Sample Statistics and One-Sample Test show the significance of rainfall depth and rainwater collection at 0.05 level of significance. However, the correlation is well established in figure. 3 with ***R^2=0.59*** and ***0.61*** using power, logarithm and polynomial expressions. Again, there is no strong connection between the volumes of water captured and period of harvest as indicated in figure. 4.

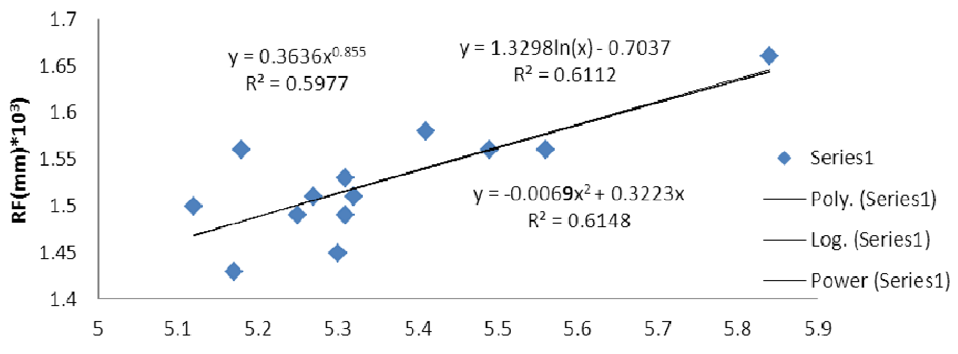

Fig.3: Rainfall depth and average volume of rainwater collected

Figure 3.

Table 7. One-Sample Statistics for Rainfall and Rainwater collection

	N	Mean	Std. Deviation	Std. Error Mean
Rainfall (mm)	5	10.3000	10.31431	4.61270
Rainwater collected (m^3)	5	770.0000	767.78903	343.36569

Table 8. One-Sample Test for Rainfall and Rainwater collection

	Test Value = 0.5					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
	Lower	Upper	Lower	Upper	Lower	Upper
Rainfall (mm)	2.125	4	0.101	9.80000	-3.0069	22.6069
Rainwater collected (m^3)	2.241	4	0.089	769.50000	-183.8360	1722.836

Table 9. Cumulative average annual potential rainwater collection in Auchi

Nr.	Year	Rainwater collection ($m^3 10^3$)
1	1996	5.2
2	1997	5.3
3	1998	5.3
4	1999	5.3
5	2000	5.3
6	2001	5.3
7	2002	5.3
8	2003	5.3
9	2004	5.4
10	2005	5.6
11	2006	5.2
12	2007	5.5
13	2008	5.5

Source: Field study, 2012

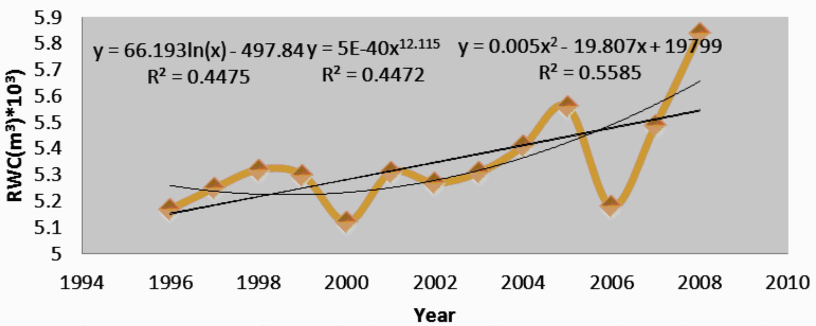

Fig. 4: Average volume of rainwater collected at selected areas in Auchi

3.2 Harvestable rainwater, water demand and use

Potable uses for rainwater include: drinking water; cooking; bathing, and washing dishes Non-potable uses for rainwater include household cleaning; irrigation; toilet flushing; pond/landscape use; fountains; vehicle washing (Cabell Brand Center, 2007). Table 10 shows water collection, demand and use pattern in the selected locations using different house specifications. It clearly showed that only 3.4 % of average water demand per house (AWDH) could be provided by rainwater. However, with record of annual rainfall depth and number of raining days, if rainwater water is technically captured, the potential application can increase to 65.5% for every house specification. The volume of water collection depends on the structural and hydraulic sizing of the catchment and storage. Distribution subsystems could be considered using an average rainfall depth and the area of the harvesting surfaces.

Table 10. Harvestable rainwater and water Demand-Use System

House specification	AWA(10^3m^3)	NC	AWDH(10^3m^3)	PWU (10^3m^3)	NPWU (10^3m^3)
HA	5.3	4	124.1	53.4	70.7
HB	5.3	6	186.1	80.1	106.1
HC	5.3	8	248.2	114.2	134.0
HD	5.3	10	310.3	139.6	170.7

Source: Field study, 2012

HA:	House A; HB:House B; HC: House C; and HD: House D
NC:	Number of occupants
AWDH:	Average water demand per house
PWU:	Potable water use
NPWU:	Non potable water use

3.3. Groundwater potentials

For community water supply systems, groundwater is almost always the preferred source (Ball, 2001). Surface water sources are very likely to be contaminated and much more subject to seasonal fluctuation (Blankwaardt, 1984). Table 11 shows average annual water withdrawal from boreholes in selected locations in Auchi. There is progressive increase in the number of boreholes (***15***) and annual water withdrawal (***$12.4 \times 10^4 m^3$***) in year 1996 to *39 number of NBH* and *$32.7 \times 10^4 m^3$ of AWW* respectively in 2008. Groundwater withdrawal represented 2.6% in 1996 and 6.8% in 2008 for total water demand in Auchi. This increase is highly insignificant and thus many constrain and problems (such as reduction in Human Development Index, outbreak of cholera and some water related diseases e.t.c) have reported to have associated this acute water shortage in this region.

Table 11. Estimated annual underground water withdrawal in Auchi

Year	NBH	AWW ($m^3 10^4$)
1996	15	12.4
1997	17	13.9
1998	20	14.7
1999	25	18.1
2000	27	20.1
2001	23	20.3
2002	26	22.1
2003	30	24.5
2004	32	26.2
2005	38	27.3
2006	40	29.0
2007	41	31.6
2008	39	32.7

Source: Field study, 2012

Hint: ***NBH***: Number of borehole: ***AWW***- Available water withdrawal

3. Conclusion

Steady increase in world's population is responsible for the pressure on the demand for safe drinking water. Meeting the increasing demand for the limited utility, alternative water sources of rainwater harvesting and groundwater potential were considered. The outputs of itineration system for both groundwater and rainwater harvesting system indicated that only 9.8% of total water demand could be achieved from these sources. The identified water sources if technically harnessed would meet expected water required. The total capacity utilization of the created storage capacity is relatively small compared to the size of roof plan surface which determines the volume of rainwater runoff. As a result of this, most of the harvested rainwater spilled off the storage tank and becomes unavailable for both potable and non-potable applications. The potential benefits of rainwater harvesting are not widely appreciated and this should be addressed through an educational and technological advancement programme. Again, it is financially high to develop groundwater exploration in this region due to its sedimentary soil formation. Improving water accessibility and distribution to about 65% **($31.3\times10^{5}m^{3}$)** of required water demand in Auchi using alternative water sources (Rainwater harvest and groundwater potential), the rainfall catchment areas and storage tank must designed and simulated for maximum possible rainwater runoff.

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