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Water Availability Analysis of Multiple Source Groundwater Supply Systems in Water Stressed Urban Centers: Case of Lodwar municipality, Kenya

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Abstract

Ensuring water security to urban population in fragile environments through interlinked systems of groundwater abstraction, storage and distribution of sufficient quantity is challenging especially to urban utilities situated in arid and semi-arid regions. The purpose of this research was to evaluate water delivery challenges for water utilities in fragile environment in Kenya. A systematic analysis of availability from each supply sub-components from source to consumer was carried out through water audit and network analysis by employing water flow measurement equipments and through pump performance analysis and by employing continuity equation and Bernoulli's principle to sections of the network. Results showed that water availability within a utility in such environments is contributed by seasonal variations between wet and dry affecting quantity at source, optimal design of supply infrastructure in this case better matching of solar power with the pump, using standard pipes and on optimal operational strategies employed to reduce losses within the network. Based on these findings, we conclude that with clear understanding of each subcomponent's contributions to entire water supply system and optimizing their design and operations, more people will be made water secure in all seasons in the fragile environments.

Keywords: Borehole • Availability • Water supply infrastructure

Introduction

Water supply distribution systems are faced with complex challenges and problems. Among the challenges is supplying sufficient water to a rapidly growing urban population coupled with changes in climate and aging urban water supply infrastructure, operational logistics and economic problems [1]. It has been acknowledged that with decreasing availability of water as a result of increased urbanization brings the challenges to authorities who cannot improve their infrastructure at the same pace with demand consequently the need to change the way they operate existing systems for significant improvements [2].

Urban centres globally are faced with problems of proving sufficient water to satisfy demand against limited and diminishing sources hence continuous search of most appropriate methods to manage water resources at their disposal equitably [3]. A study conducted in 10 urban sites located in arid and semi-arid regions in East Africa by REACH and to specific towns in Kenya by Daniel O. Olago reflects similar situations of stressed water supply systems with accessibility falling from 55% in 1990 to 45% in 2015 due to climate shock, urban population explosion and slow pace of infrastructure expansion contrary to the expected trend of wide coverage as a result of advancement in technology and methods of operations [4,5]. It is expected that strain to urban infrastructure will continue as population increases and therefore authorities need to find innovative approaches to deal with such stresses to the systems to ensure its accessibility which is a basic human right [6] and goal number 6 in sustainable development goals.

Solutions to water availability and accessibility can be both technical and non-technical [3], posit that not all solutions to water availability should be complex but suggest simple solutions which include efficiency at all levels of water supply systems such as water demand management, equitable and fair allocation of available water and supply infrastructure operations. Methods have been applied to solve the problems including optimization of components within the network or by optimizing entire network infrastructure [7,8], dissect elements of optimization within a supply network as pump operations, tank location, capacities and operational levels and isolation valves schedules.

Different approaches have been proposed and applied like [9] suggest that problems of water availability and accessibility can be addressed by enhancing supply sources and putting in place water allocation policy. Efficient water system management is able to fix most challenges to water system [3]. Good understanding of water supply system is required to inform utility operators on where within the system more emphasis should be laid [10]. A methodology by American Water Works Association has been adopted for this study for a detailed analysis of a water supply system with results and findings expected to inform decision on the best operational strategies which can ensure accessibility and water security [11].

At a global scale, studies in water security in arid areas are gaining prominence as in the supporting program for this program, namely REACH is a seven-year programme (2015-2022) led by Oxford University with international consortium of partners and funded with UK aid from the UK Government. On average 1/3 of water abstracted for urban supply is lost within the supply infrastructure and the loss varies from utility to utility [12]. The losses add to unaccounted for water and in Kenya, performance indicators for utilities with respect to unaccounted for water are set as <30% as good, between 30-35% as acceptable and >35% as poor [13,14] and on average, utilities record unaccounted for water as 41% which is poor and a sign of utilities facing challenges in performing their core mandates. The main aim of this study was to assess water delivery challenges of a water supply utility and to suggest measures of improvements. An audit and network analysis guided by International Water Association (IWA) tool (standard water balance) and pump characteristic analysis of the supply infrastructure was conducted for a case study of Lodwar Water Supply and Sanitation (LOWASCO) in Kenya.

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The study concludes that:

- water availability at source fluctuates with seasons and energy source but should be sufficient in both seasons
- water availability to consumers is not sufficient as a result of losses within the network and operation inefficiencies
- existing sources can support network expansion when effective loss control is put in place
- optimizing design and operations of entire water supply system can make more people within a fragile environment water secure.

Materials and Methods

Study area

The study area (is the County headquarter of Turkana County in Kenya lies within latitude 3°06'3" and 3°07'2" and longitude 35°35'220" and 35°36'360")". Lodwar municipality and it's environ has an estimated population of 75,726 [15] out of which only 40,504 are currently served by existing water supply infrastructure. The municipality is within arid and semi arid regions of Kenya and has been classified as one of the fragile urban centers [4]. Water supply source to the municipality relies entirely on ground water with some aging infrastructure which is as old as 35 years [16,17].

Rapid population increase from 45,368 in 2009 [18] to more than 75,000 in 2017 [15] has been recorded in the municipality. This has led to higher water demand while common occurrences of droughts have left water services utility with a lot of challenges in attempting to satisfy demand. Pumps of varying capacities are installed in the boreholes and are driven by hybrid systems of solar energy and electric grid to reduce on cost of water production and each borehole is connected to storage tanks of varying capacities. An illustration of the boreholes and their respective storages within the study area is shown in Figure 1.

Methodology

To quantify amount of water that is being produced and supplied from each source of supply system, a detailed water audit using the International Water Association (IWA) standard water balance tool was carried out. The standard water balance provided a framework to quantify all water into and out of a supply area [19-21]. From the preliminary assessment of sources, master meters installed at the sources had either failed or were faulty due to age which according to World Health Organization (WHO), could not be relied upon due to possible errors that they are prone to record to the range of 50% hence could not be reliably used to determine production; for these reasons, measurements of production for each borehole were taken during dry and wet seasons using non-destructive flow measurement method using Ultrasonic flow meter which utilizes sound waves to determine velocity of a fluid flowing in a pipe [22]. Important pipe properties that were documented for the measurements were; internal diameter, material, wall thickness, lining materials if any, type of liquid flowing and transducers connection method.

Upon setting the pipe properties, spacing for attaching the transducers is automatically generated. This was followed by the attachment of transducers

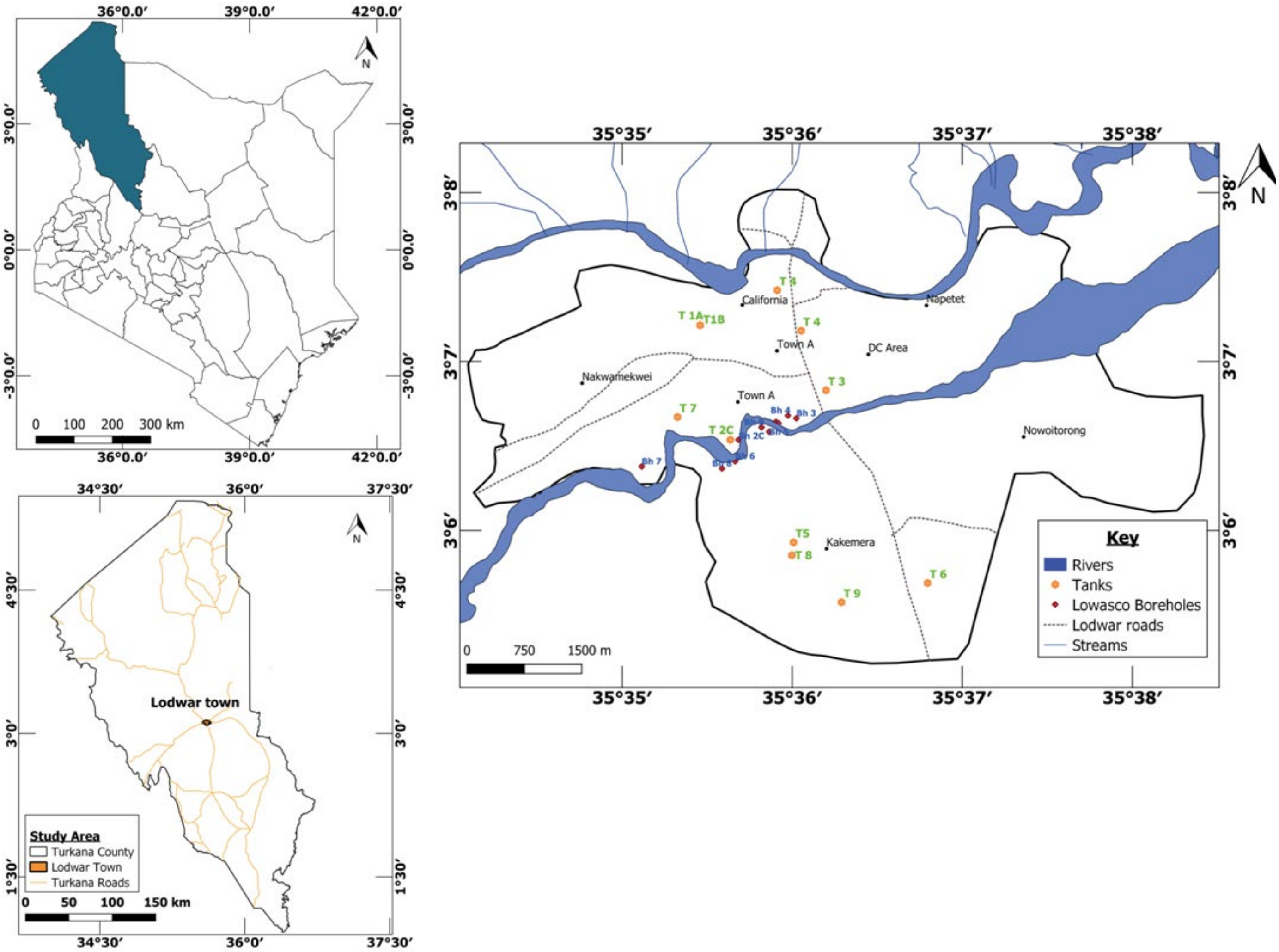

Figure 1. Map showing study area with boreholes and storage tanks for Lodwar Municipality.

in an upstream and downstream accordingly. Readings of discharge and velocity were taken when signal strength was greater than 85% for duration of 5 minutes at different times of pumping hours. The equipment had data logging capability and readings are stored for later download and analysis in MS Excel application. Borehole production measurements were done for power grid (mostly night time) and solar energy driven (daytime).

Due to the complex nature of the distribution network, measurements were first carried between the borehole production points and the entries to storage tanks to establish any losses from production to storage. Borehole and storage tanks locations and elevations were captured by Germin GPS and validated by Garuda smart phone application. The flow rates of visible leaks at the valves and joints were measured using bucket and stopwatch. Aspects that could not be measured, such as major pipe bursts were estimated through inflow rates. To detect invisible ground leakages or suspected illegal connections in an area, flow measurements were taken for two sections of the pipeline and the law of conservation of mass applied to determine continuity in the flow;

$Q = AV$

Where,

Q = Discharge, A = Cross-Sectional area of pipe, and V = Velocity of fluid flow.

Where the flows were inconsistent, leak detection equipment was used. Capacities of masonry storage tanks were determined through measurements by tape measure and the formula;

$V = \pi r^2 h$ applied to compute actual volumes,

Where,

V= volume of the tank in m^3, r is radius of the tank and h is the height of the tank.

For steel storage tanks, capacity validation was achieved through physical counting of the panels which are of standard measurements of one meter then the formula for volume,

$V = l^* w^* h$ applied to compute actual volumes,

Where,

V = Volume of tank, l = Length of tank w = Width of tank and h = Height of tank in meters.

Flow measurements within the network were carried out between boreholes to storage tanks for rising mains and between storage tanks to the consumer nodes for the distribution lines on selected parts of the network. To compare performance of the two sources of energy (electric grid and solar), production from boreholes was recorded at specific times of the day when the energy source was solar and when energy was from the electric grid.

Data collected using the ultrasonic flow meter was downloaded to MS Excel for editing and analysis. Determination of demand and zonal water use pattern using Peter Gleick Basic" Water Requirements for Human Activities: Meeting Basic Needs" recommended minimum per capita of 50 litres per person per day for developing countries was applied [23]. Network analysis was conducted to establish pressure variations within key control points of the network through

$$P_2 - P_1 = \rho g h_1 - \rho g h_2 - \frac{1}{2}\rho v_2^2 - f_h \rho g$$

Application of Bernoulli's principle,

Where, P_1 = Pressure at the tank P_2 = Pressure at the tap,

$$\rho g h_1 = \text{elevation head}, \frac{1}{2}\rho v_2^2 = \text{kinetic head}, f_h \rho g = \text{friction head}$$

and pump characteristics for pumps used in each borehole were obtained through measurements and through document reviews which were used together with corresponding pump curves.

Results and Discussion

Water availability status at boreholes

There is a direct relationship between flows in river Turkwel and water levels in the boreholes drilled along the river and the basin experiences two rainy seasons, March-June (long rains) and October-December (short rains) [24]. Results of production by all the boreholes in different seasons of wet and dry illustrate corresponding decline as shown in Figure 2 which corresponds to the flow volume in the river. Production in the month of May which is wet season is comparatively higher for most boreholes except for boreholes 4 and 7. Borehole 4 production was affected by a borehole which was sunk within a radius of 2 meters away. The reduction in production shows that the new borehole might have interfered with its productivity. Borehole 7 was discovered to have a pump with faulty impellers while borehole 2C had not been drilled by February 2017 which is a dry season and borehole 3 being the highest producer at 60 m^3/hr in wet season and 50 m^3/hr in dry season.

Table 1 shows demand distributions in different supply zones where Kanamkemer with the highest population of 13776 and daily demand of 688800 litres is being served by three boreholes 9, 5 and 6 to have benefits of looped networks which according to Loan Sârbu, enhances reliability of water supply system. Borehole 3 being the highest producer serves three supply zones, D.C. area, Nowoitorong and Napetet [25].

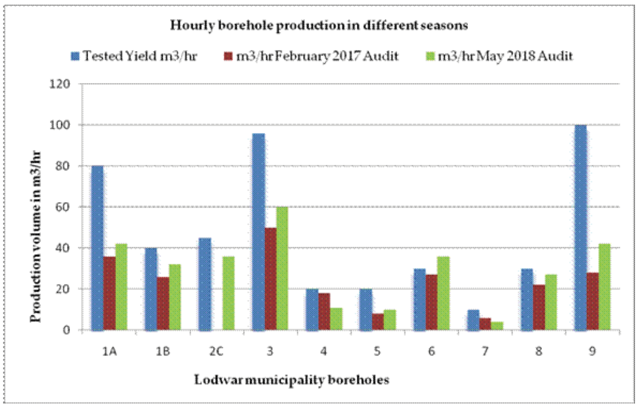

Figure 2. Hourly borehole production in both dry and wet season compared to test yields.

Table 1. Shows boreholes serving demands for different supply zones.

Zone Name	No. of Connections	Assumed 6 persons per connection	Daily demand @ 50 litre per capita	Boreholes serving the zone
D.C. Area	275	1650	82500	
Nawoitorong	1118	6708	335400	
Napetet	874	5244	262200	Bh3, BH6
Town A	436	2616	130800	Bh1A, 1B, 4
Town B	304	1824	91200	
California	589	3534	176700	Bh1A, 1B
Nakwamekwi	1052	6312	315600	Bh2C, Bh7
Kanamkemer	2296	13776	688800	Bh9, 5, 8
Total	6944	41,664	2,083200	
Source (LOWASCO 2017)				

About 80% of the boreholes run on hybrid energy pumping system of solar and grid power. Grid power operates for about 14 hours especially in the night while solar power operates for about 8 hours during the day. An analysis of each borehole production during dry season under the two different power sources is given in Table 2.

Results in the Table 2 show limited storage capacities compared to water produced on a daily basis which is a potential source of major water losses as a result of overflows from storage tanks [22]. Boreholes 1A and 1B are connected to one tank of less capacity compared to their combined production. Borehole 4 pumping is only by grid while borehole 5 pumping is only by solar power hence the values of zero in their respective rows in the table. According to LOWASCO Borehole Status quantity of water billed in the month of February 2017 through metered connections and flat rate was 92422 m^3 but according to field results of production assuming optimal operation was 175392 m^3 implying that 47% of water produced could not be accounted for [16]. As per the performance report of Water Services Regulatory Board: A Performance Report of Kenya's Water Services Sector for year 2017, the utility had unaccounted for water of 40% and the disparity could have arisen due to different methods of data collection [13]. Limited storage capacities may contribute to more water losses through tanks overflows.

Figures 3, 4 and 5 illustrate that water availability also depends on the energy source used in pumping. A comparison of quantity achieved at the peak of solar power and grid power which is fairly stable show that boreholes 1B, 1A 3 and 7 have perfect matches in production meaning that quantity produced by both sources should be the same however, Figure 4 and Figure 5 demonstrate

Table 2. Water availability at each borehole for the month of February 2017.

Borehole	February 2017 Production in m^3 by Solar pumping	February 2017 Production in m^3 by Electric pumping	Total February 2017 Production in m^3	Total daily production in m^3 for February 2017	Tank Capacity Installed in m^3
1A	7168	12544	19712	704	300
1B	9408	16464	25872	924	
2C	6720	20160	26880	960	250
3	13440	23520	36960	1320	200
4	0	4312	4312	154	60
5	2240	0	2240	80	72
6	5376	14112	19488	696	85
7	1008	2240	3248	116	72
8	5152	10584	15736	562	60
9	4480	16464	20944	748	150
Total	54992	120400	175392	6264	1249

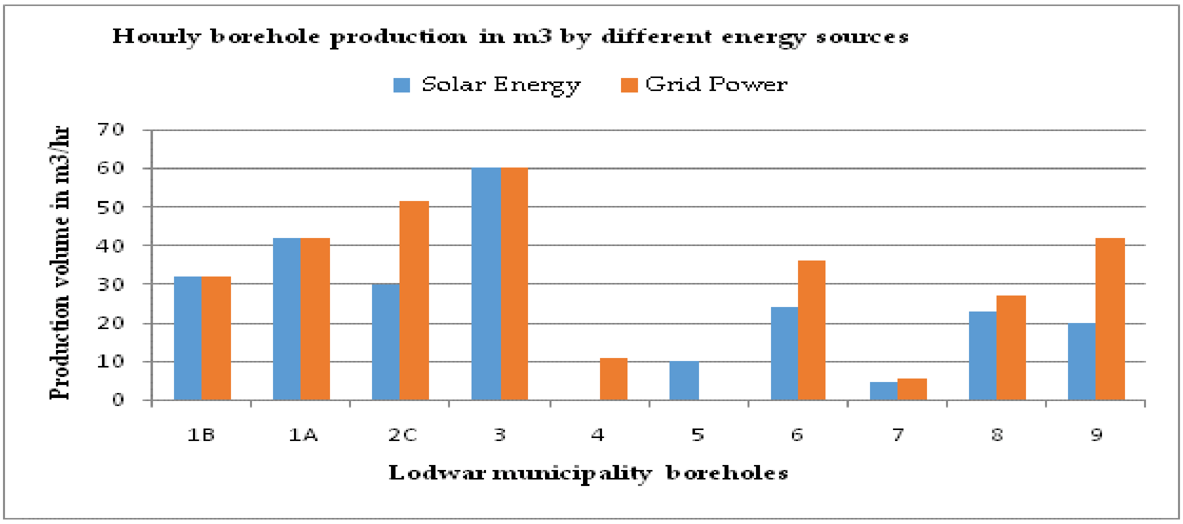

Figure 3. Comparison of borehole water production under different energy sources (solar and grid energy).

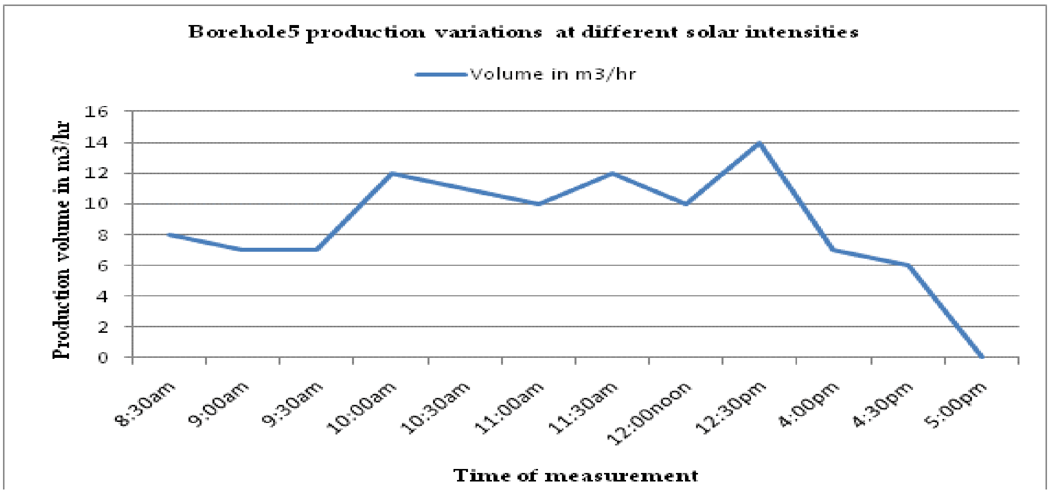

Figure 4. Time variation of borehole production in m^3 under solar energy.

erratic pumping by solar due to other weather factors such as cloud cover which may affect performance. In cases where solar pumping does not match grid power pumping, there is likelihood of improper design or a sign of fault with the solar modules such as boreholes 6, 8 and 9 in Figure 3.

Borehole 9 in Figure 5 illustrates effects of mismatch between solar power and pump capacities whereas in the same Figure 5, borehole 3 shows stability as a result of proper design where solar power matches with pump capacity leading to relative stability in production.

Water availability status at storage tanks

Storage tanks in water supply systems stabilize flow and balance distribution during peak demand [22]. Table 3 illustrates quantity of water that reaches storage from source. Deliveries of borehole 1A and 1B to the tank fluctuates due to the occasional diversion of water through stand pipes for authorized bulk purchase. To obtain stable flows for analysis, measurements of flows were taken only during grid power pumping and therefore borehole 5 which is not on grid could not be monitored. It was discovered that out of the 10 liters of water pumped per second from borehole 6, none reached the tank for distribution and indicator of either design problem, leakages along the rising main or illegal connections on the rising main pipe.

Water availability by connection density

Water is provided through pipe connection to the piped system either by individual connection, communal within a compound or through water kiosks [17]. Distribution of connection points within a zone theoretically indicate availability and from Figure 6, Kamankemer has the highest number of connections at 2296 with daily per capita of 688800 liters which according to results of daily production for both wet and dry seasons in Table 4 should comfortably be supplied by the three boreholes 9,8 and 5. When production from all boreholes is compared to regional demand in Table 4, all regions should have sufficient supply during all seasons a fact supported in a study report given done by Radar Technologies International, suggesting that seasonal groundwater level variation in the boreholes below alluvial deposits in Lodwar town is minimal and therefore to increase percentage coverage within the service area which currently is 57% according to latest performance report of Water Services Regulatory Board: A Performance Report of Kenya's Water Services Sector current availability can support expansion in the supply regions [14,26]. However, this expansion cannot be realized when there is excessive quantity of unaccounted for water within the supply network as demonstrated in Table 5 where water produced from borehole 6 cannot be accounted for.

Head loss associated to length and pipe materials is more for steel pipes than the losses in HDPE pipes as indicated for borehole 9 in Table 5 and therefore it can be deduced that for efficient delivery of water, HDPE pipes should be preferred over steel pipes [27]. Results of network analysis concurred with the flow measurements at the end nodes of the distribution network of borehole 2C and 7 discovered that there is an unstable pressure level within the network which hinders water from reaching the end nodes of the network. In Figure 7, Lokurono kiosk which is at end of network, a 5litre bucket took 20minutes to fill while no flows were recorded at IDP and Islamic kiosks even with control valve for the fully opened.

In Table 6, analysis of pump performance to deliver water to the storage tanks is carried out by considering borehole depth whereby to achieve vertical pumping head, location of pump is assumed to follow recommendations of Grundfos which states that "the bottom of the motor should never be installed lower than the top of the well screen or within five feet of the well bottom"

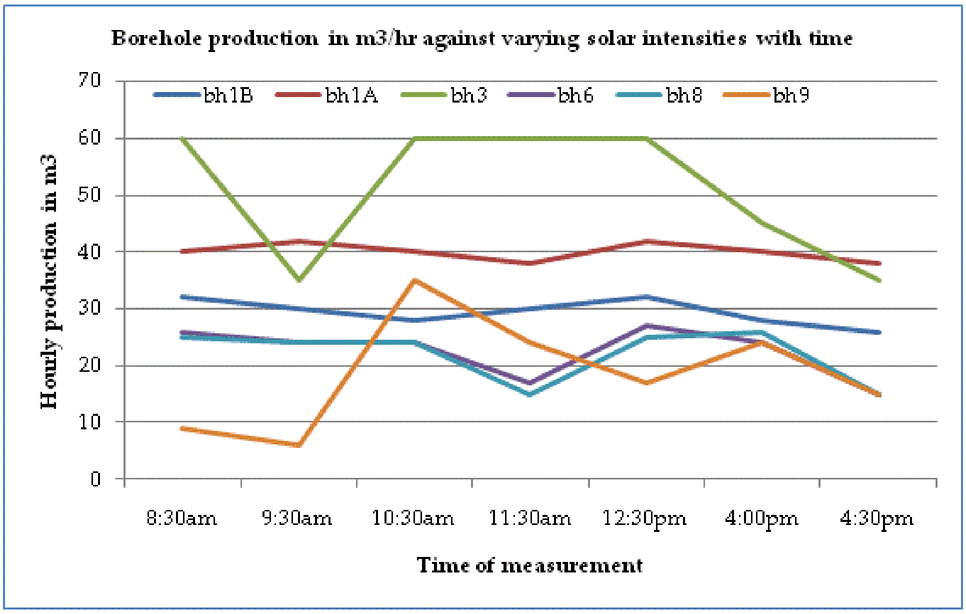

Figure 5. Borehole water production variation with solar intensities.

Table 3. Borehole to tank production analysis under electric grid energy.

Borehole	Measured production in (L/s)	Length of rising main in (m)	Rising main material	Diameter of rising main in inches	Fluid flow velocity in (m/s)	Total friction head loss(m)	Measured delivery at tank (L/s)
1A	11.7	1800	Steel	6	0.64	5.18	3.6 or 7.2
1B	8.9	1800	Steel	6	0.48	3.06	2.8 or 5.8
2C	10	900	Steel	4	1.22	14.21	7.8
3	16.7	1000	Steel	6	0.91	5.51	14.4
4	3.1	2400	Steel	3	0.63	14.81	0.2
5	N/A	3600	Steel	3	N/A	N/A	N/A
6	10	4600	Steel	4	1.22	72.17	0.0
7	1.1	1400	Steel	2	0.50	9.35	0.6
8	7.5	1900	Steel	4	0.98	20.00	4.4
9	11.7	2400	HDPE	6	0.64	6.58	5.6

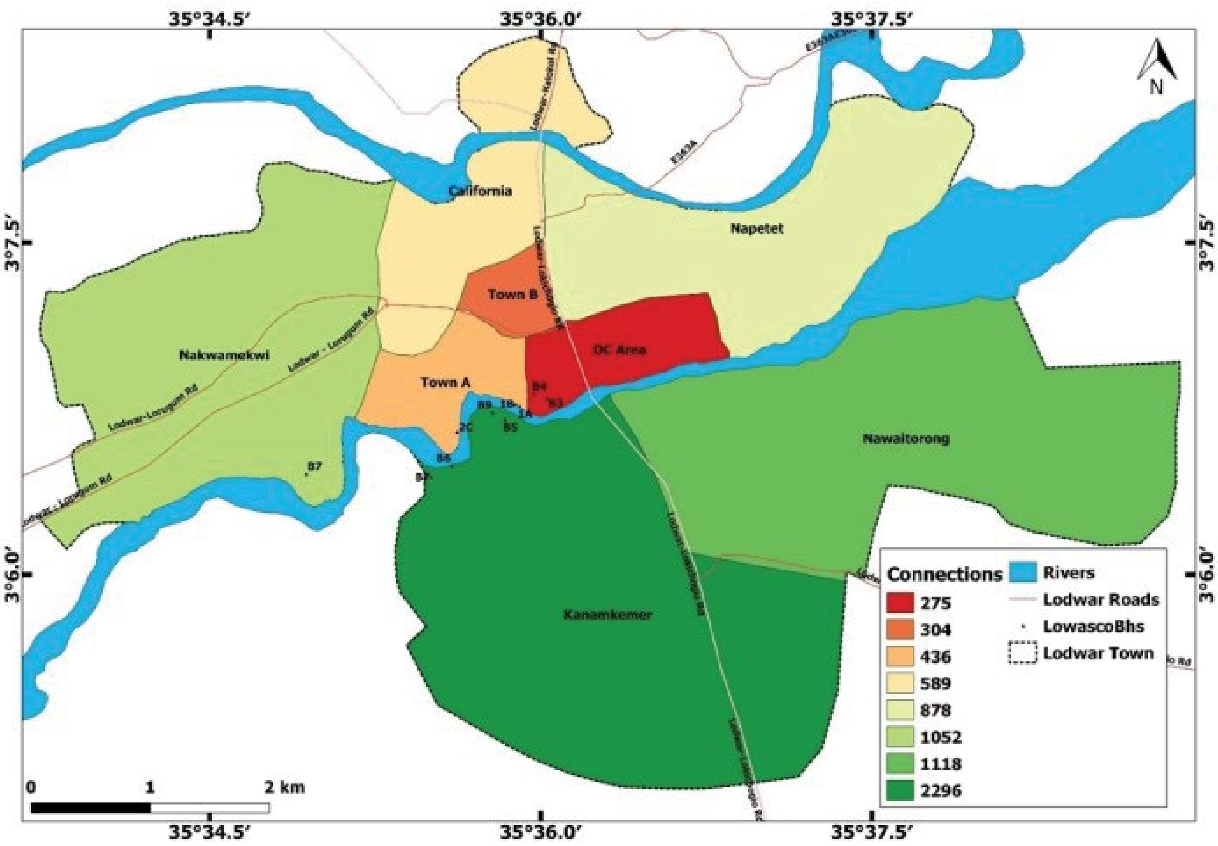

Figure 6. This is a figure, showing number of connections in each supply zone.

Table 4. Seasonal borehole production against zonal demands.

Borehole	Hours of Production	Daily Production in liters (wet season)	Daily Production in liters (dry season)	Zone Name	Daily demand @ 50litres per Capita	Boreholes serving the zone
3	20	1,200,000	1,000,000	D.C. Area	96,250	Bh3
				Nawoitorong	391,300	
6	20	720,000	540,000	Napetet	305,900	Bh3, Bh6
1A	20	840,000	720,000	California	206,150	Bh1A, Bh1B
1B	20	640,000	520,000	Town A	152,600	Bh1A, Bh1B, Bh4
4	18	198,000	324,000	Town B	106,400	
7	16	64,000	96,000	Nakwamekwi	368,200	Bh2C, Bh7
2C	16	416,000	-	Nakwamekwi		Bh2C, Bh7
5	8	80,000	64,000	Kanamkemer	803600	Bh9, Bh8, Bh5
8	20	540,000	440,000	Kanamkemer		
9	12	504,000	336,000	Kanamkemer		
Total		5,202,000	4,040,000		2,430,400	

Table 5. Total head loss along rising mains as per [27] chart. N/A – not applicable, pump not connected to grid power.

Borehole	Measured production in (L/s)	Length of rising main in (m)	Rising main material	Diameter of rising main in inches	Fluid flow velocity in (m/s)	Total friction head loss(m)	Measured delivery at tank (L/s)
1A	11.7	1800	Steel	6	0.64	5.18	3.6 or 7.2
1B	8.9	1800	Steel	6	0.48	3.06	2.8 or 5.8
2C	10	900	Steel	4	1.22	14.21	7.8
3	16.7	1000	Steel	6	0.91	5.51	14.4
4	3.1	2400	Steel	3	0.63	14.81	0.2
5	N/A	3600	Steel	3	N/A	N/A	N/A
6	10	4600	Steel	4	1.22	72.17	0.0
7	1.1	1400	Steel	2	0.50	9.35	0.6
8	7.5	1900	Steel	4	0.98	20.00	4.4
9	11.7	2400	HDPE	6	0.64	6.58	5.6

and should ensure it remain submerged at the lowest water table to provide highest output [22,28]. In Table 6, pumps performances under measured flow in column (D) have been obtained from pump performance curves provided by the pump manufactures [29,30]. Once maximum pumping head is obtained from the curves, the value is compared to the total dynamic head to ascertain if water being pumped will be able to reach the storage tanks. From the results, only borehole 6 pump is not able to pump water to the tank a fact supported by the findings shown in Table 7 where delivery to the tank is zero [31].

From the Figure 7, pressure at the new concrete tank labeled A, control chamber B, water kiosks C and D were analyzed to determine and validate residual head at the open taps.

Flows between points BC and CD could not be measured since distribution pipes are buried in the ground. Point B is the control junction and the pressure was computed from the formula [27] frictional loss = 1 m/ km per m/s velocity.

At nodes C and D results found minimal flow at the tap as a result of low pressure but at the junction residual head was 11.19 m which is sufficient to supply all nodes with appropriate allocation schedule in place.

Table 6. Total dynamic head computation for production pumps as per [28-31].

Borehole A	Borehole Depth in (m) B	Pump model installed C	Production in (L/s) D	Maximum pump head in (m) E	Vertical pumping head=(B-1.52) F	Total friction loss in (m) G	Elevation in (m) between borehole to tank H	Total dynamic head in (m) =F+G+H
1A	18.6	SP46-7(11KW)	11.7	105	17.08	5.18	35	57.26
1B	18	SP30-13(11KW)	8.9	88	16.48	3.06	35	54.54
2C	17	SP46-7(11KW)	10	112	15.48	14.21	17	46.69
3	21	SP46-12(18KW)	16.7	130	19.48	5.51	21	45.99
4	20	SP14-17(4KW)	3.1	130	18.48	14.81	22	55.29
5	17	SP8-25(3.7KW)	N/A	N/A	15.48	N/A	N/A	N/A
6	32	SP30-13(11KW)	10	70	30.48	72.17	37	139.65
7	36	SP14-17(4KW)	1.1	145	34.48	9.35	13	56.83
8	24	SP30-13(11KW)	7.5	106	22.48	20.00	35	77.48
9	30	C-SJ95-7(37KW)	11.7	110	28.48	6.58	40	75.06

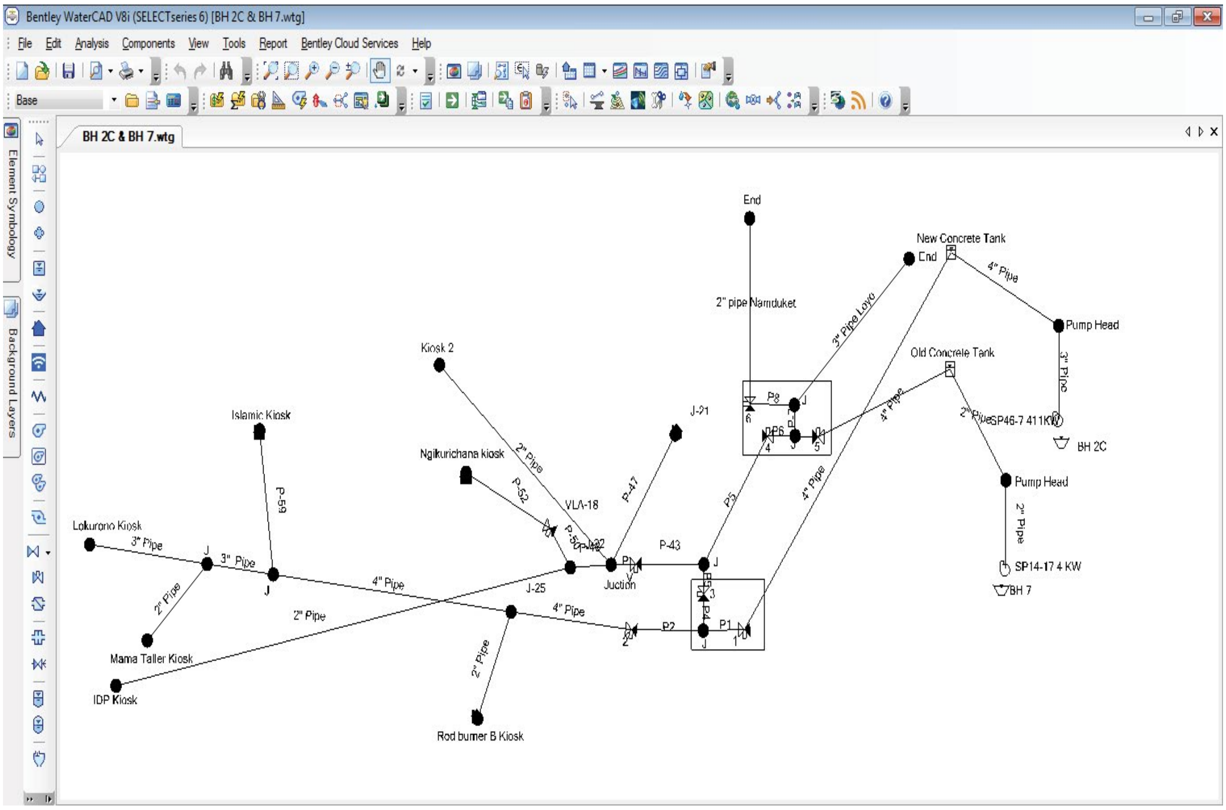

Figure 7. This is a figure showing schematic diagram of network for borehole 2C and 7.

Table 7. Pressure variation between tank and control chamber.

Node	Elevation in (m)	Length between nodes in (m)	Measured flow velocity in m/s	Total friction loss in (m)	Residual head at node in (m)
A	519	-	-	-	-
B	506	1007	1.8	1.81	11.19
C	497.6	1700	-	-	-
D	500.8	3300	-	-	-

Conclusions

The study concludes that:

- Availability at source fluctuates with seasons and energy source but should be sufficient in both seasons
- Availability to consumers is not sufficient as a result of losses within the network and operation inefficiencies
- Existing sources can support network expansion when effective loss control is put in place.

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Author Contributions

S.D. conceived the idea and designed the project. He also co-wrote the manuscript C.O.M. carried out field data collection and analysed all the related data and wrote the original draft. D.O.O. review, editing and acquisition of funds. P.M.A.O. is a research supervisor. All authors discussed the results and contributed to manuscript preparation.

Conflicts of Interest

The authors declare no conflict of interest.

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