DESIGN ANALYSIS OF WATER DISTRIBUTION PIPE NETWORK OF ROYAL VALLEY HOUSING ESTATE IN ILORIN USING ARC-GIS AND EPANET

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ABSTRACT

This report presents the use of Arc-GIS and EPANET to analyze simulate and design water distribution pipe network. The field work involved the use of structured questionnaire to obtain information on household demography and obtain water use. The corresponding data obtained was statistically analyzed with use of Stata 12.0 and Microsoft Excel software to establish a model for water use and to evaluate the variables that affect household water use. Google Earth and Arc-GIS software were employed to digitize the map of the study area in order to obtain the spatial information needed for analysis and design. The Water demand at individual node on the pipe network was estimated and used for simulation of the pipe network system. Allocation of buildings to the particular nodes that supplies water to them was carried out with the aid of Arc-GIS software with Voronoi diagram approach. Analysis and simulation was carried out with the aid of EPANET 2.0 software in order to obtain the minimum and maximum pressure, velocity and the flow in various pipes of the water distribution system. It was revealed that the estimated average volume of water used by individuals in the estate based on statistical analysis and questionnaire was estimated to be 90.7 l/c/d which is below the WHO standard of 120 l/c/d for an individual, the simulated minimum and maximum pressure for the study area were 6.67 m and 20.19 m, respectively which was found to be adequate to cater for the water supply to the household in the study area. The pipe diameter required for water distribution in the study area ranged between 75 mm and 100 mm for adequate water supply. The model developed in this research work is very useful for household water use prediction in the study area.

Keywords: Design, Distribution pipe network, Flow continuity, Head loss, Simulation.

1. INTRODUCTION

Management of limited water resources in fast growing cities is crucial in order to sustain the development of the economy. However, conjunctive management is increasingly challenging due to growing population hence, complicate the water distribution system in scale and operation. Water distribution systems are designed to provide water to consumers at certain desirable level of service which is sometimes defined as the minimum level of pressure at the critical point which is the lowest point of pressure in the system. However, according to Bhave and Gupta (2006) there could be other consumption requirement such as fire-flow requirements which could over ride the normal consumption requirements.

Jacobs and Strijdom (2009) ascertained that the stipulation of minimum pressure requirement during Water Distribution System (WDS) design is to ensure that consumers are satisfied. A pressure head that is 'too low' could result in operations and maintenance problems, with cost implication if any equipment is damaged such as collapse of pipe due to negative pressure. According to Ayanshola *et al*. (2015) providing sufficient water at adequate pressure to meet up with the growing demands is becoming more challenging in most cities of developing countries. This is due to the failure of the distribution system in most urban cities of developing countries. The Strengthening of the existing water distribution system or construction of a new system is however, inevitable for proper water distribution, this new construction might not necessarily go through the standard analysis and design procedure but the most important factor which is considered in the development of a new network system or refurbishment of an existing network system is the pressure management. This study is to carry out necessary analysis and simulation with the aim of determining the appropriate pipe sizes from a set of commercially available diameters that will satisfy the required pressure in every node which will further enhance a better pressure management for a better yield. Newbold (2009) affirmed that pipe network solution methods have evolved from applications where solutions to networks were solved by hand calculations. One of the earliest and most well-known solution methods is the Hardy-Cross method. This method was developed by a structural engineer to solve head-loss equations in a looped network, and is usually solved iteratively by hand calculations. This method requires a flow balance before the first iteration (the initial guessed flow directions do not need to be correct). However, this method is limited in the sense that it includes a trial and error procedure and also the process of analysis is a long and complex procedure. Once the availability of computer hardware became common place and algorithms that solve the entire network were developed, Todini and Pilati (1987) developed one of the most commonly used algorithms called the gradient method. This method allows a modeler to analyze large networks by solving a system of partly linear and non-linear equations that express the balance of mass and energy. An advantage of this approach is that all pipe flows and nodal heads are solved in each iteration. This allows the gradient method to converge on a solution in less iteration than a method such as Hardy-Cross. This solution method is used by EPANET and allows it to effectively simulate hydraulic parameters in a water distribution network. Rossman *et al.* (2000) developed the method for solving flow continuity and head loss equations in EPANET which is known as a hybrid node-loop approach. This approach is very similar to the solution method (the gradient method) designed by Todini and Pilati (1987) and was chosen over similar methods due to its simplicity. EPANET begins analysis by selecting initial flow estimates for every pipe in the system. These initial flow estimates are based on a velocity of 0.3048 m/s through the pipes and are not intended to satisfy continuity. The simulation capabilities of EPANET have been utilized by professionals and researchers in the design, management and operations of Water Distribution Network System part of which are Fabunmi (2010), Guidolin *et al*. (2010), Abubakar and Sagir (2013). Also, EPANET application is used in solving and optimizing water distribution network problems. The aim of this study is to analyse, simulate and design a water distribution pipe network system using ArcGIS and EPANET software. The hybrid node loop method developed by Rossman *et al.* (2000) was adopted due to its simplicity and its ability to solve hydraulic parameters at every node simultaneously, which greatly improves the probability of convergence, this makes its result more accurate as compared to other methods.

1. DESCRIPTION OF STUDY AREA

The study area named Royal Valley is located in Ilorin, the capital city of Kwara State Nigeria is located between latitude $8^0 25^1$N and $8^0 32^1$N longitudes $4^0 30^1$N and $4^0 41^1$N. The town is situated in the eastern part of Kwara State. The entire metropolis of Ilorin presently occupied an area of about 89 km^2 (Adeleke, 2003). The population of the city was estimated to be 777,667 in 2007 as reported by Ayanshola *et al.* (2010). Ilorin has grown in terms of population due to the establishments of commercial undertakings, industries, financial institutions, public utilities. All these activities have resulted in the migration of people from rural areas of the state to the city. Ilorin is the heart of Kwara State in terms of economic, political and social activities. Figure 1 shows the map of Kwara State, Ilorin East Local Government Area (where the study area is located) and the digitized map of the study area.

Royal Valley Estate has 134 buildings with a population of about 674. The estate is gradually being translated and developed by a front liner in the building industry, International Business Bureau Limited. Because the ancient city of Ilorin, the state capital, spread conveniently within two nautical grids, the housing scheme has a strategically and serene positioning: the stretched out Savannah land bordering the Royal Valley Estate to the east is presenting the gentle flowing Asa River with potential sand deposits of beach advantage. To the east is the towering Sobi Hill which promises glamour of the Aso Rock for the Estate dwellers. To the west of this haven is the Rail line with a rare value as a transport means and possible novelty for its children population. To the north of this tangible concept is also the growing intension of Kulende-Sobi road by pass.

2. MATERIALS AND METHODS

The methodology of this study entails field data collection and analysis. The field work was carried out in order to determine the parameters that will be needed for simulation (such as length of link, nodal elevation, pipe diameter, and such as to be fitted into the pipe network system). In order to carry out simulation, the water demand at each node in the pipe network must be known. ArcGIS software was used to allocate demand to each node using the voronoi diagram. The information obtained from the ArcGIS software is the water demands at each node. The simulation of the pipe network is aimed at determining the pressure and discharge at every node. EPANET 2.0, a computer program that performs extended period simulation of hydraulic and water quality behaviour within pressurized pipe networks was used for the hydraulic simulation. According to Ayanshola et al. (2010) EPANET 2.0 is used for hydraulic simulation purpose amidst several commercial simulation models due to its ability to calculate nodal pressures, the easy accessibility to its source code for free of cost and also its ability to simulate large distribution networks with unlimited pipe numbers. The simulation results were the pressure, discharge and head with which the water is flowing within the system.

The area used for this study was Royal Valley Estate in Ilorin, Kwara State, Nigeria, a 500-unit residential estate with 134 residential houses available (figure 1). The skeletonised network layout for the study area is shown in figure 2 and data obtained from field work is shown in Table 1 and 2.

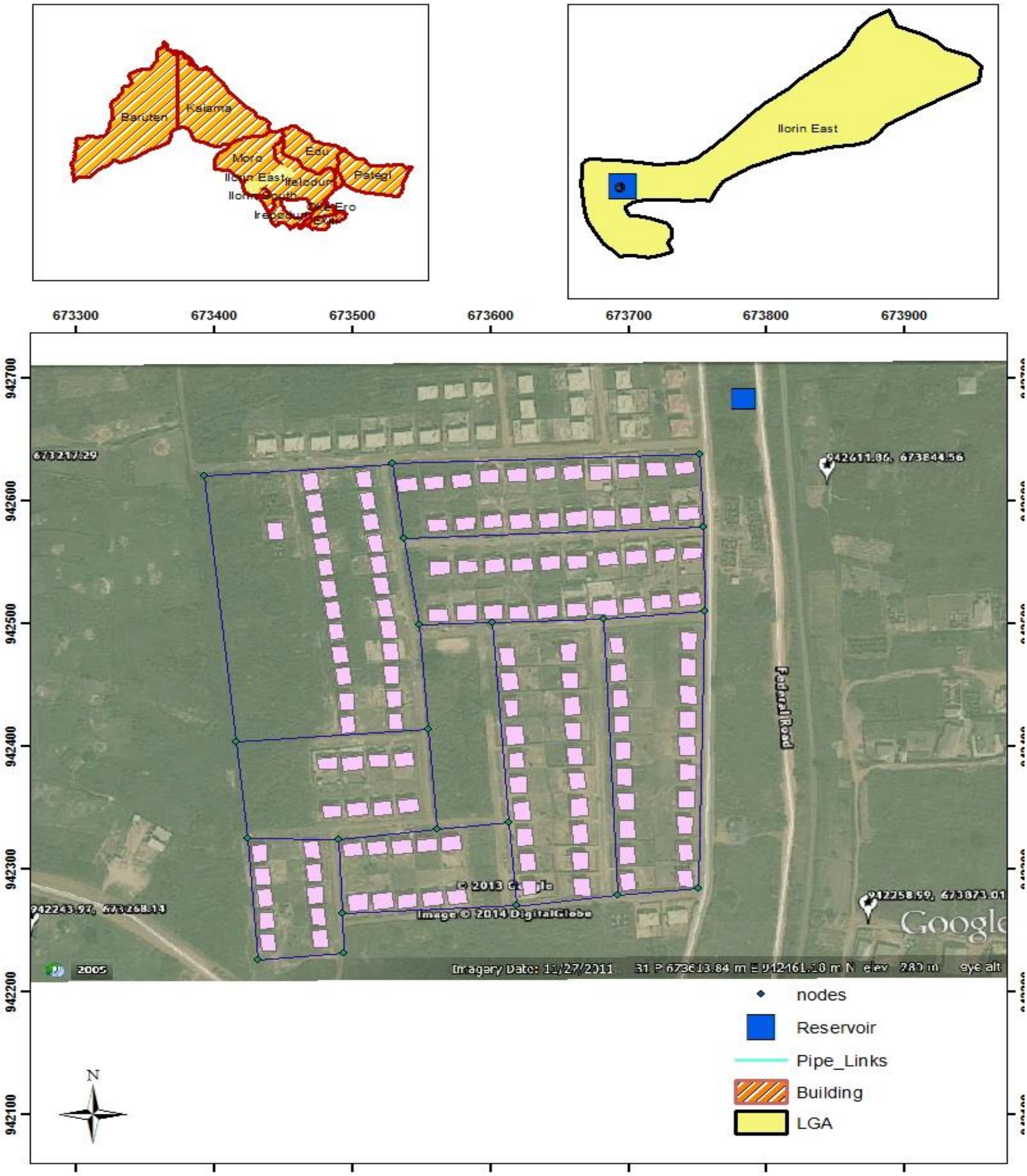

Figure 1. Map of Kwara State showing the local Government Areas

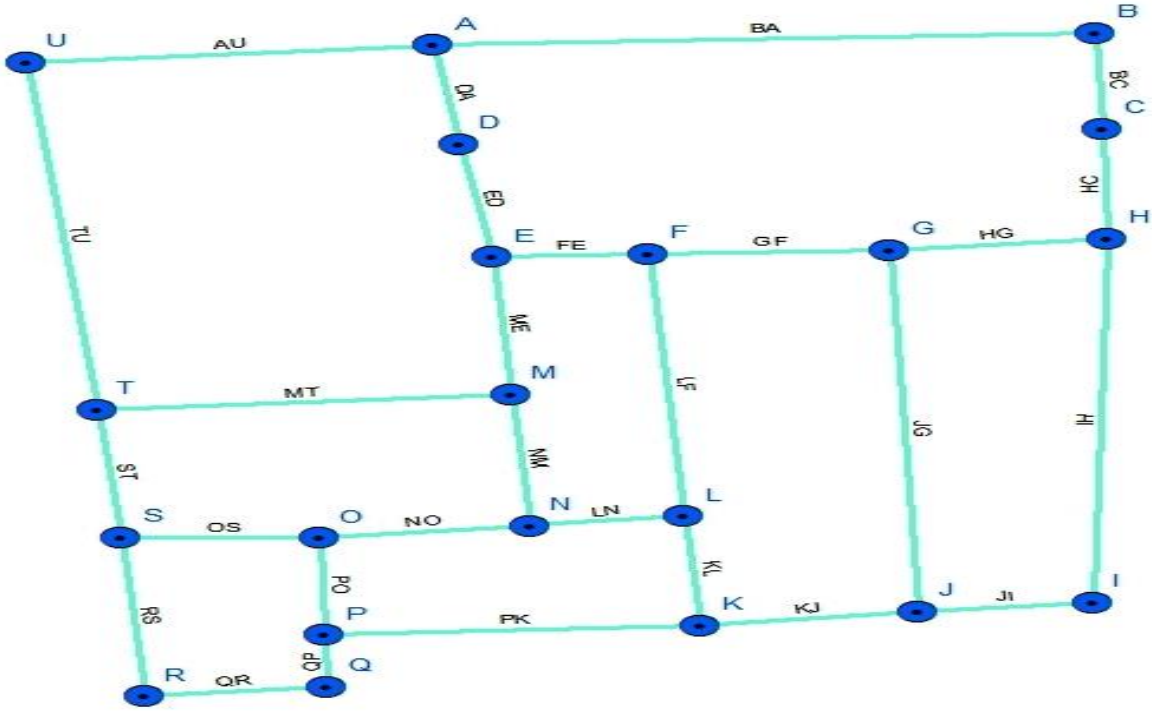

Figure 2. Skeletonized Pipe Network Layout for Royal Valley Housing Estate. Ilorin. Nigeria.

4. RESULTS AND DISCUSSION

The output result obtained for both the link parameters and the nodal parameters are shown in Tables 1 and 2. During the simulation, it was ensured that the residual pressure generated varied between 6 and 20 m as suggested by Ayanshola and Sule (2006) that this range of residual pressure has been found to be adequate for municipal water supply system.

Table 1: Link parameters and estimated average flow through them.

Links	Length (m)	Diameter (mm)	Roughness	Flow (l/s)	Velocity (m/s)	Unit Head loss (m/km)	Friction Factor
UA	32.31	75	100	-0.09	0.02	0.01	0.07
AB	50	75	100	-0.19	0.04	0.04	0.06
BC	52.17	100	100	0.47	0.06	0.05	0.07
AD	52.6	75	100	0.07	0.01	0.06	0.07
DE	58.52	75	100	0.17	0.04	0.08	0.08
EF	59.68	75	100	0.03	0.01	0.11	0.06
CH	60.24	75	100	0.29	0.07	0.15	0.07
GH	61.68	75	100	-0.16	0.04	0.19	0.08
FG	61.97	75	100	0.06	0.01	0.23	0.07
HI	66.2	75	100	0.09	0.02	0.25	0.08
JI	67.91	75	100	-0.07	0.02	0.28	0.09
GJ	68.28	75	100	0.03	0.01	0.3	0.08
FL	71.02	75	100	0.05	0.01	0.37	0.08
LK	71.45	100	100	-0.04	0.00	0.39	0.07
KJ	73.72	75	100	-0.08	0.02	0.45	0.08

EM	75.17	75	100	0.07	0.02	0.52	0.08
MN	79.88	75	100	0.04	0.01	0.77	0.09
NL	80.93	75	100	-0.03	0.01	0.81	0.07
UT	81.83	75	100	0.08	0.02	0.86	0.09
TM	85.69	75	100	0.02	0.01	0.89	0.08
TS	99.11	75	100	0.05	0.01	0.9	0.09
SO	125.27	75	100	0.03	0.01	0.93	0.09
ON	136.2	75	100	-0.03	0.01	0.96	0.09
SR	139.49	75	100	0.02	0.00	0.99	0.11
RQ	163.51	75	100	0.01	0.00	1	0.00
OP	216.4	75	100	00	0.00	1.01	0.00
PQ	217.28	75	100	00	0.00	1.05	0.00
DC	221.97	75	100	-0.16	0.04	1.08	0.07
PK	225.17	75	100	-0.03	0.01	1.11	0.09
BRE1	226.16	75	100	-0.67	0.15	1.17	0.05

Table 2: Nodal parameters and estimated demand through them.

Node	**Elevation (m)**	**Base Demand(l/s)**	**Demand (l/s)**	**Head (m)**	**Pressure (m)**
U	271	0.01	0.01	291.19	20.19
A	275.21	0.04	0.04	291.19	15.98
D	276.62	0.06	0.06	291.19	14.57
E	277.15	0.06	0.06	291.19	14.03
T	271.65	0.00	0.00	291.19	19.53
S	272.28	0.01	0.01	291.19	18.9
O	274.37	0.05	0.05	291.19	16.81
N	276.5	0.04	0.04	291.19	14.68
M	276.75	0.06	0.06	291.19	14.43
B	284.29	0.01	0.01	291.19	6.92
C	283.85	0.02	0.02	291.19	7.35
F	279.88	0.04	0.04	291.19	11.30
G	281.58	0.07	0.07	291.19	9.60
H	282.82	0.04	0.04	291.19	8.37
L	279.37	0.06	0.06	291.19	11.81
R	271.32	0.01	0.01	291.19	19.06
Q	272.75	0.00	0.00	291.19	18.43
K	279.75	0.01	0.01	291.19	11.43
P	275.85	0.04	0.04	291.19	15.33

J	282.75	0.02	0.02	291.19	8.43
I	284.51	0.02	0.02	291.19	6.67
RE1	291.25	-0.67	-0.67	291.19	0

The larger the tank capacity, the more stable the pressures in the distribution system will be, irrespective of fluctuations in demand or changes in pump operation. The result of this study conformed to the hydraulic principle above. According to figure 3, the nodal elevation is inversely proportional to the residual pressure at the node. This is a valid hydraulic principle as the residual pressure becomes lower at higher altitude in the supply zone. In order to acquire the desired pressure in each junction of the pipe network system, a suitable elevation of high altitude must be obtained for the location of the distribution reservoir. This will allow water to flow from high altitude to lower altitude at a very suitable and required pressure at nodal points.

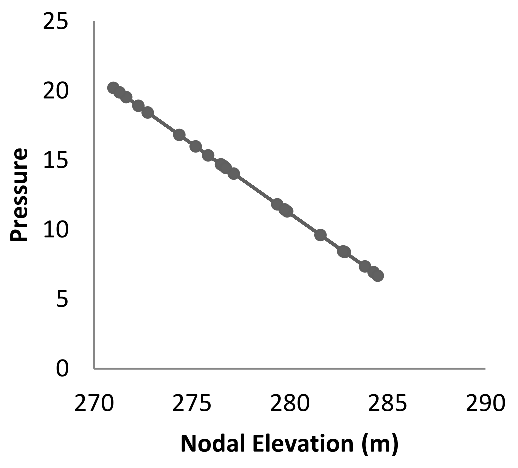

Figure 3. Plot of Pressure against Nodal Elevation

Pressures at nodes B, C, I which are at the intake nodes, after simulation, were low, (mostly less than 10m). This is due to the nodal elevations of the area, because these points are at higher altitude in the zone of supply. Low pressure pipes are tapped in the valley as seen in figure 4. These draw most of the water that would be used upstream creating water shortages at the upstream. Therefore, it is seen from figure 5 that the nodal pressure at the terminal points of the network analysis (node U, T, S, R) are higher in value as more pressure is required to pump water to these areas of the pipe network to give it more energy. In other cases, where the pressure is not high enough to satisfy the demand at its node, booster stations are needed, these would help boost the water pressures giving it additional energy to continue to flow.

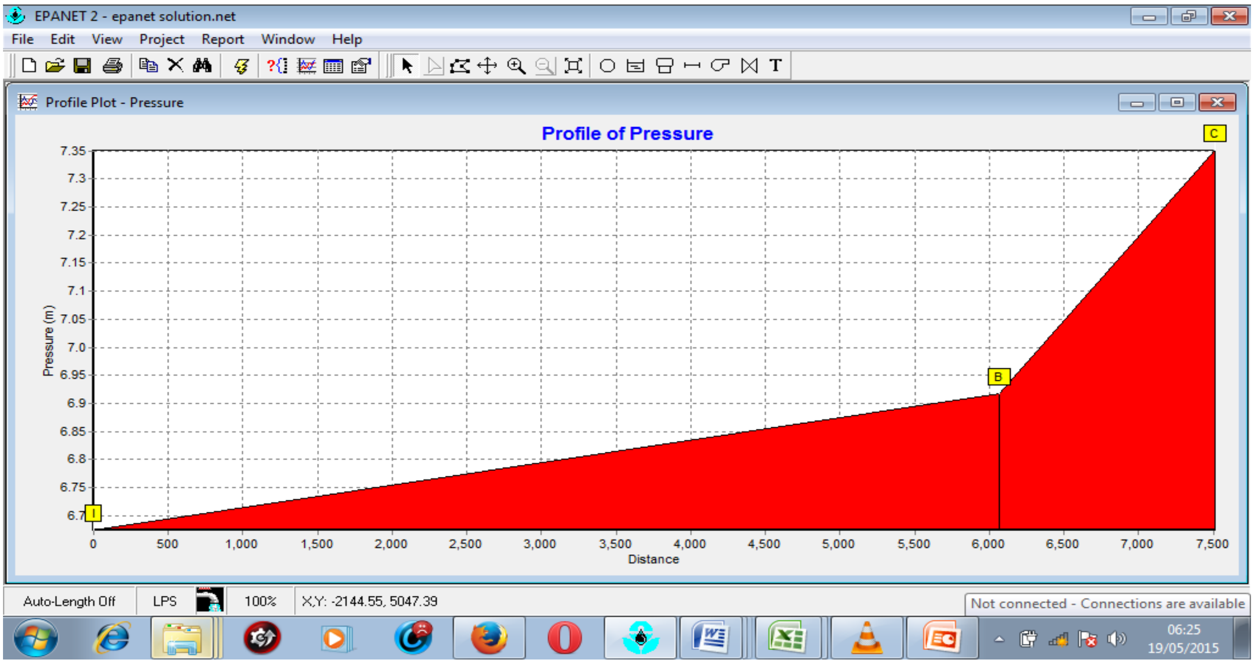

Figure 4. Low Pressure Zones (node B, C, I)

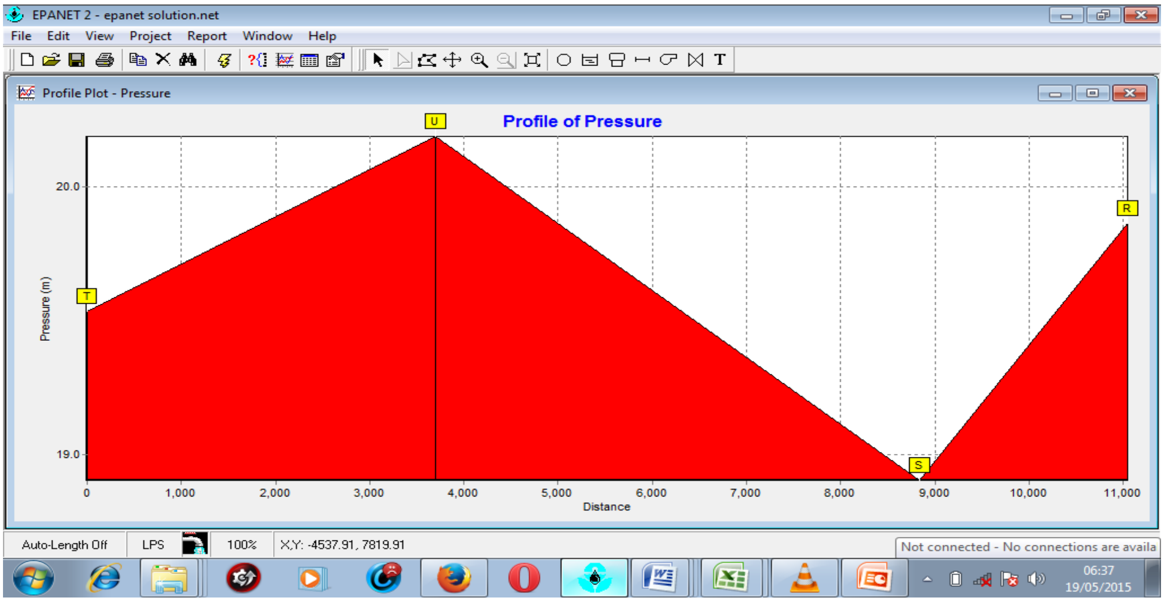

Figure 5. High Pressure Zones (node T, U, R)

Table 2 shows the pressure of the pipe network layout at the various nodes. The pressures obtained at various nodes were a function of the topography of the area under consideration and the pressures are higher at lower elevations. The minimum pressure was 6.67 m at the highest elevation of 284.51 m at node I and the maximum pressure obtained was 20.19 m at the lowest elevation of 271 m at node U. The average pressure in the entire network is 13.5 m. According to Ayanshola and Sule, (2006), adequate residual pressure range for municipal water supply system during peak demand condition should be within a minimum 5m and maximum 70m hence, the values of minimum residual pressures obtain are quite adequate for the residential area under consideration. In cases whereby higher heads are required, the elevation of the reservior can be increased to attain desired residual pressure.

Figure 6 shows the pressure distribution in the pipe network system. The highest range of pressures are 10−15 m and 15−20 m at 33% and the average pressure for the entire network is 13.5 m. Figure 7 is a contour map showing the spatial variation of the pressure in the study area while figure 8 relates the pressure contour map to the various water demand zones on the study area. Areas enclosed by nodes S, O, N, P, Q, and R show a higher pressure variation.

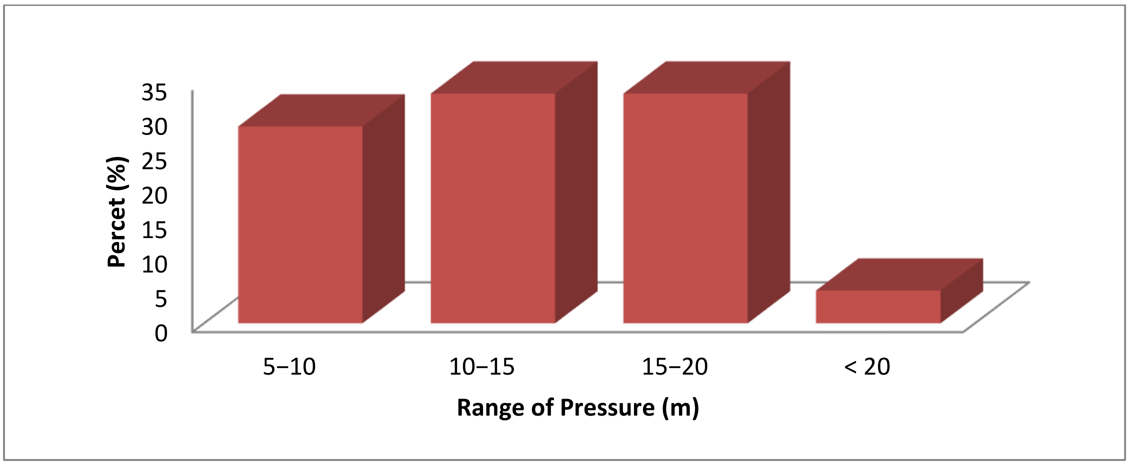

Figure 6. Pressure Distributions.

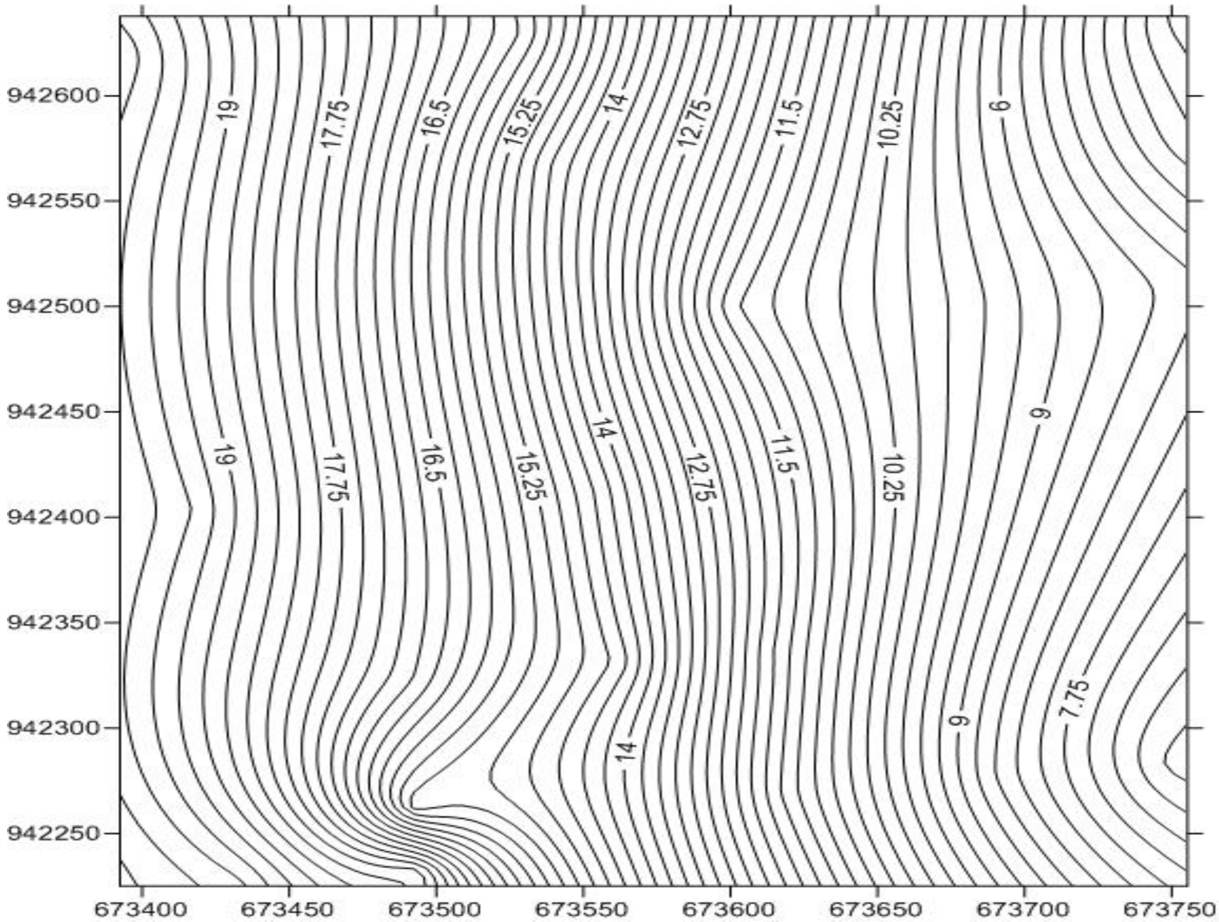

Figure 7. Pressure Contour Map

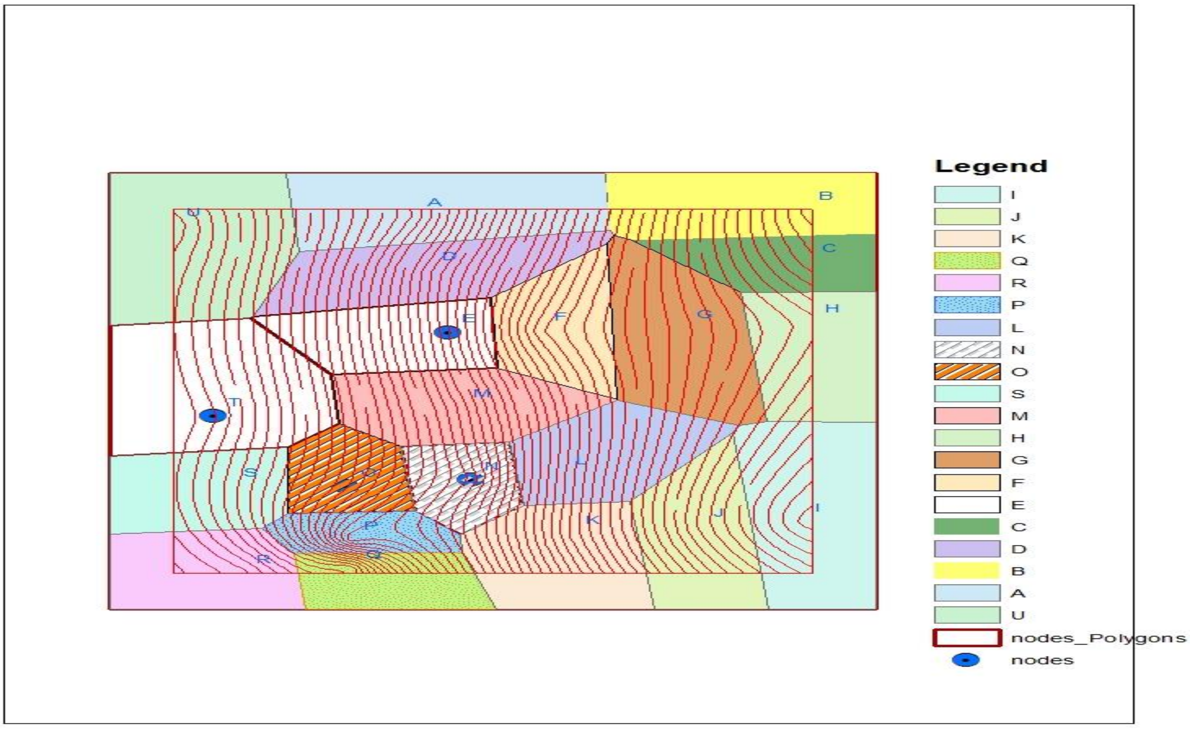

Figure 8. Spatial Variation of Simulated Pressure for Different Demand Zones.

Figure 9 compares the pipe length and the head loss along the pipes. Head loss is a factor that is dependent on the force and the length with respect to the weight of fluid. The analysis indicates that the head loss increases with increase in pipe length. It shows an initial steady increase in unit head loss as pipe length increases from 1- 20 m followed by a rapid increase in unit head loss as the pipe length increases above 20 m.

The velocities are generally very low, varying but below 0.5 m/s. Figure 10 illustrates the variation of velocities generated at different links and the corresponding flow. The velocity was at peak between 2 and 5 l/s discharge, and beyond a flow of 5 l/s, the velocity begins to fall gradually. The results show that the velocities are averagely below 1.0 m/s as shown in figure 11. Recommended velocities should be between 0.5 and 3.0 m/s[11]. From table 4.8, it can be seen that all the velocities obtained from the simulation fall below this velocity range. However, low velocities are undesirable because they normally lead to blockage of the pipe while, extremely high velocities increase head loss. To avoid low velocities especially at boundary links where higher flows are demanded it is advisable that pipe length and pipe diameters should be reasonably chosen.

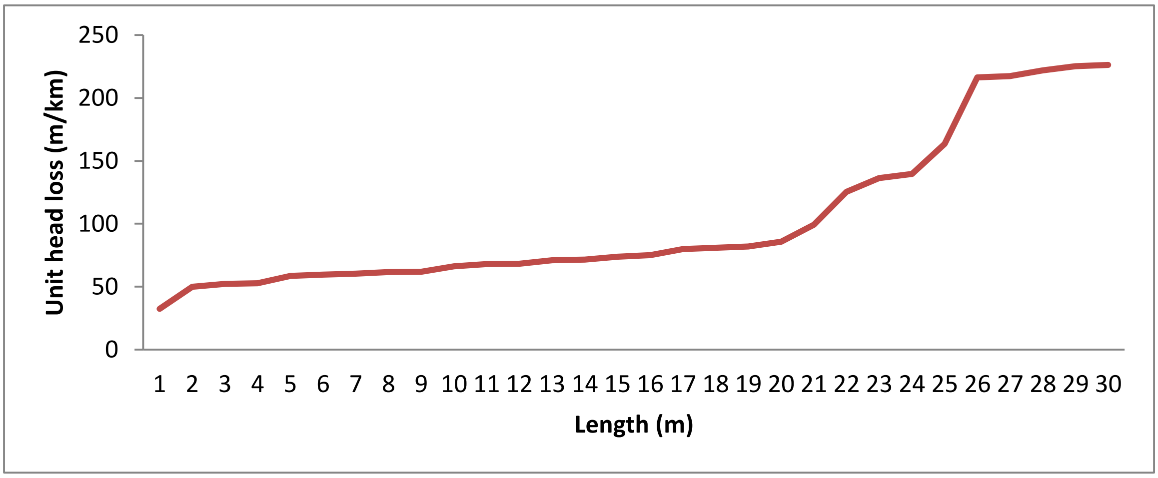

Figure 9. Variation of Pipe Length with Head loss

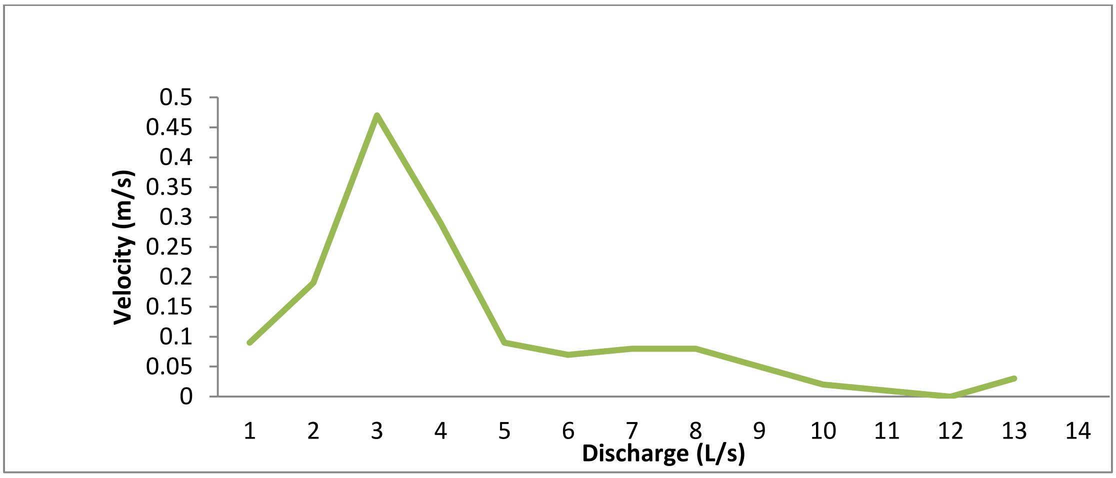

Figure 10. Variation of Velocity with Discharge in Links at Boundaries

5. CONCLUSION AND RECOMMENDATIONS

This research work has shown that water distribution pipe network is not available at Royal Valley Estate hence, the system requires new design for adequate water supply for the estate. The buildings present in the study area are not connected to municipal water supply thus, implies that all the households in the estate depend on private source (bore hole or shallow well) for water supply which may not be adequate to supply the needed quality and quantity of water to the citizenry in the study area.

The average volume of water used by individuals in the estate was estimated to be 90.7 l/c/d as against 120 l/c/d recommended by WHO. A formulated model was used to evaluate the water use and it was established that household population has the greatest effect on water use as compared to other significant variables. Other significant variables found to have significant effect on water demand include age of household head and household water source. All the households in the estate are not connected to municipal water supply.

The purpose of water distribution system is to ensure that water reaches consumers in good quantity and quality, for this purpose hydraulic analysis and simulation was carried out to obtain minimum and maximum pressure, velocity of flow in the pipe network system in order to ensure proper functioning of the water distribution network. The hydraulic simulation carried out revealed that the maximum and minimum pressure in the water distribution pipe network system is adequate but the velocity of flow is below the required standard as suggested by some researchers however, proper choice of pipe length and pipe diameters will take care of the challenge.

The growth and development of Royal Valley Estate is highly dependent on the availability of water that provides utilities and services necessary for improved standards of living. The present water supply system in the estate is inadequate as all households in the estate are not connected to municipal water supply and not all households can afford an adequate private source of water supply.

The formulated model developed by this research work is very useful for household water use prediction and also the results obtained from the analysis and simulation is very useful for future optimization of the water distribution system of the study area.

Recommendations

As a recommendation for further research, a network optimization model for the design of Royal Valley Estate water distribution network should be built. Studies should also be carried out for proper planning of the water distribution network in case of future extension of the network to guide against water shortages. Other Recommendations include:

i). Presently there is inadequate water distribution tank that supplies water to the various household in the study area, from the water consumption information obtained from the study area, the average water consumption per house hold is 433 l/c/d, hence a water storage tank of not less than ten (10,000 litres) capacity should be provided for the water supply of the estate, this will also cater for future extension.

ii). It is recommended that the pipe diameter required for water distribution in the study area should be ranged between 75 mm and 100 mm for adequate water supply.
iii). The formulated model developed in this research work can be used to develop a prediction of household water consumption in other areas with similar demographic pattern.
iv). From the simulation results, it was observed that there are low pressure zones at high elevated points of the study area, booster pumps should be installed at those point to enhance sufficient supply of water to those areas.
v). Government should provide a means by which the estate can be connected to municipal water supply this will go a long way to ease the households in the study area of water stress.

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