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EXPLORING OPTIONS IN THE DESIGN OF A WATER DISTRIBUTION NETWORK FOR FIREFIGHTING

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ABSTRACT

Exploring options in the design of a water distribution network for fire-fighting is presented. The method used was that of the gradient method embedded in the EPANET software. Analysis were carried out for a typical residential estate in Ebocha village. Input data such as fire water demand, pipe lengths, pipe diameters and assumed pump sizes were fed into the EPANET software. Results showed that the existing water distribution network for firefighting was inefficient with a negative pressure of -116.89 metre head when water was released for the purpose of fire-fighting. A total of 5 cases and 25 options of simulations were carried out for the proposed network for the residential area. The best option for the network simulation was that of case 7, option 2 which consisted of two Overhead tanks (OHT) of sizes 10 m ×10m × 2.7m, two submersible pumps of 35HP each and fire pump of 315 HP. The system is designed to automatically pump water 10 minutes after a fire incidence starts and this is possible because of the high aquifer yield in the locality.

Key words: Fire- Fighting, Water Distribution, Network Analysis and EPANET

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1. INTRODUCTION

A water distribution network for domestic use can hardly serve the needs for a fire fighting system. This is basically because of the pressure and the volume of water required by the system. For the purpose of fighting fire, water pressure must be maintained at a minimum of 350kPA and this value varies to about 75 psi depending on the distance of the hydrant and the height of the facility. The volume of water needed for fire-fighting is so large that recommended standards (NFPA, AGIP) states that a close river, stream or lake should be used for the supply. Under normal circumstances an overhead tank (OHT) that can achieve the required pressure and volume of water needed might not be structurally sustainable and for this reason pump(s) are required to help the system achieve its aim.

Recent studies have shown ground water yield in the southern part of Nigeria as high as $24m^3/s$ (Chattel, 2014). With this figure, the question arises if ground water is capable of satisfying the water requirement for fire-fighting when pumped directly during a fire incidence and if not how do we combine the options of pumps and tanks to achieve the best option that will satisfy the water volume and pressure requirement of the fire-fighting system.

In other to determine the required OHT, diameter of mains, pump sizes necessary to deliver water and foam to the most remote hydrants, we had to resort to a computer – aided simulation model EPANET which was developed by Luwis Ross in 2001.Originaly designed for the United States government but with its successes in design results, pressure was mounted for it to go public. EPANET is a computer program that performs extended period simulation of hydraulic and water quality behavior within pressurized pipe networks. A network consists of pipes, nodes (pipe junctions), pumps, valves and storage tanks/ reservoir. EPANET tracks the flow of water in each pipe, the pressure at each node and the height of water in the tank.

The hydraulic modeling capabilities of EPANET are as follows:

- Places no limit on the size of the network that can be analyzed;
- Computes friction head loss using the Hazen – Williams, Darcy – Weisbach or Chezy – Manning formulas;
- Includes minor head losses for bends, fitting, etc;
- Models constant or variable speed pumps;
- Models various types of valves including shutoff, check, pressure regulating and flow control valves;
- Allows storage tanks to have any shape; and
- Considers multiple demand categories at nodes, each with its own pattern of time variation.

EPANET has gained much popularity over the years because of its use of the Gradient method of analysis. The Gradient method of water distribution network analysis as presented by Todini and Pilati 1987 solve the flow continuity and head loss equations that characterize the hydraulic state of the pipe network at any given point in time. The gradient method is a method by which corrections are applied to assume velocity of flow until an acceptable hydraulic balance of the system is achieved. Works of Henshaw and Nwaogazie (2015) have done a extensive comparison on the successes of the gradient method over the popular Hardy Cross's method of solving water distribution problems. The EPANET software's fast convergence does not depend on the accuracy of initial velocity selected as it has been coded to start with a velocity of 1m/s.This study is aimed at using a sample study area to demonstrate different options in which a firefighting system can be satisfied. This is important because different environments will definitely pose their own unique properties.

A selection of references considered relevant to this work as it concerns hydraulics of water distribution and fire-fighting are Heafley and Lawson (1975), Jones (2013), Mays (2001), the National Fire Protection Agency (NFPA, 2010) and AGIP company specification (1996).

2. MATERIALS AND METHODS

2.1. Study Area

The study area is a typical residential estate in EBOCHA village (5^0 28'40.52"N , 6^0 44'24.52"N) which comprises of residential blocks of rooms, a recreational center, military block, helipad and a messing facility .There are existing fire hydrants (14 numbers) which are not in working condition at the time of site visit. The perimeter of the entire area is 1942 metres. The terrain is fairly flat with a gentle undulating slopes and spot heights range between 18.2m minimum to 19.8m maximum. The temperature variation is within 22.2^0 C on a much clouded day to as high as 35^0 C on a very clear sky day. Figure 1 shows a map indicating the study area.

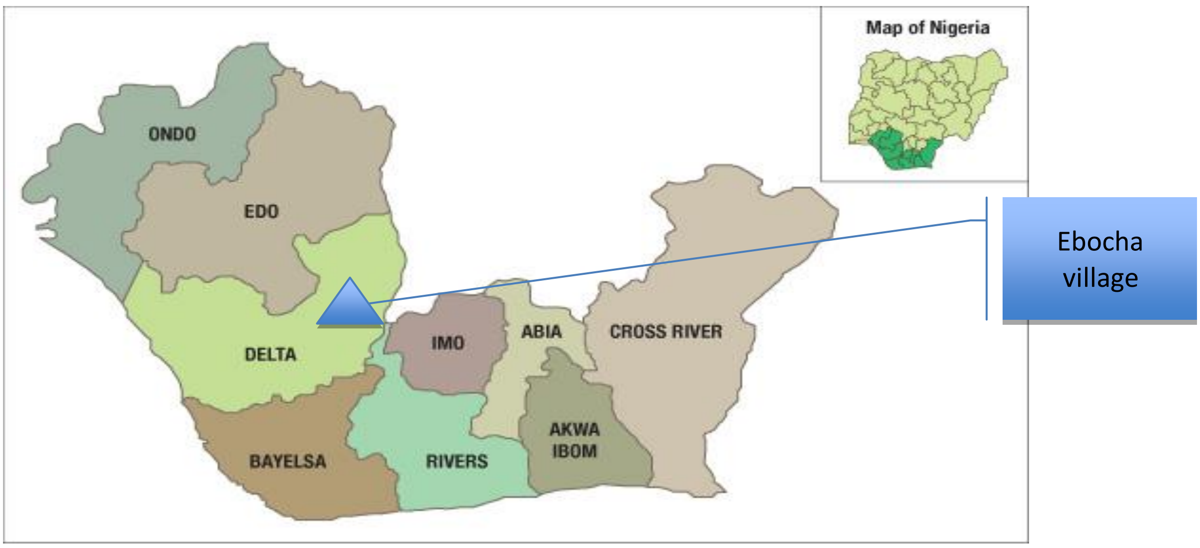


Figure 1 Map showing the study area.

2.2. Estimating Fire Water Demand

According to NFPA-15, 3.98 liter per minute (3.98 l/min) is recommended for every metre squared area or equipment used up area. The fire water demand should be designed to meet fire water demand for one hour duration and this change according to hazard level (high or low). After the determination of the individual water demand, the fire water facility is designed with the highest total fire water demand. The fire water demand can also be flexible depending on the assumption of number of fire out breaks at a time designed for. There are cases where there might be a fire outbreak in more than one location in a facility but all these considerations are basically design options.

According to the NFPA standards, Table 1 shows the fire water demand based on the existing structures in the new base residence.

Table 1 Fire water demand for structures in the study area.

FACILITY	AREA COVERED (m^2)	WATER DEMAND (l/min)
*Residential block (Largest block selected; residential blocks A and B)	2232	8883.4
helipad	324	1289.5
canteen	2192	8724.2
Military block	300	1194
Transformer unit	292.969	1166

*Residential block: Area covered by the largest residential block = 2232 m^2

The largest value of the water demand in Table 1 is selected as the design demand (NFPA 15).

Water demand per square meter = 3.98 l/min.

Water demand = 2232 $m^2 \times 3.98$ l/min/ m^2 = 8883.4 l/min = 148.06 l/sec.

By the NFPA standard fire water demand should be designed for a minimum of 1 hour; thus.

Water demand = 8883.4 l/min × 60 min/hr = 533,004 l/hr.

Fire water demand for the Ebocha new base residence = 533,004 l/hr ≡ 533 m^3/hr

2.3. Tank Sizing

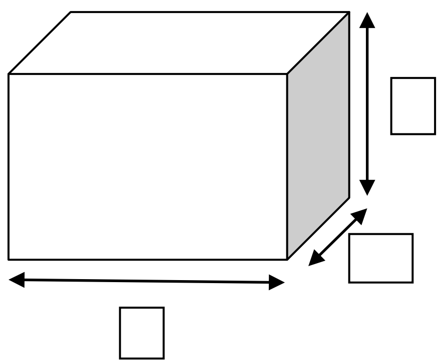
The size of the tank to hold the demand volume would be achieved by equating the volume of the proposed tank size to the hour fire demand calculated.

Volume = demand

$L \times W \times H = 533\ m^3$

Let L = W; $L^2 \times H = 533\ m^3$

For stability let $\frac{L}{H} = 3$; L =3H



$(3H)^2 \times H = 533$; $9H^3 = 533$; $H^3 = 59.2$ m; $H = \sqrt[3]{59.2} = 3.9$m

L=3×3.9 = 11.7m

The required size of tank to fight fire = 11.7 m × 11.7 m × 3.9 m

For a structurally stable system we recommend two overhead tanks.

Overhead tank (OHT) = 10m × 10m × 2.7m

2.4. Input Data for EPANET Simulator

The input data for the EPANET software are diameter of pipe (galvanized steel), spot heights of junction points, length of pipes, pipe roughness coefficient, height of OHT and pump characteristics. The network is modeled by varying capacity of main fire pumps, looped condition, submersible pumps, numbers of OHT, number of hydrants opened, position of hydrant opened and OHT heights.

3. DATA ANALYSIS

3.1. Network of Existing Fire Water System

With fourteen stand hydrants, two surface pumps and a surface tank of approximately 3m×3m×1.5m, the existing water distribution network was in poor state. The EPANET software was used to stimulate the network to identify any lapses or problems. Figure 2 shows the existing network. Table 2 shows result of the simulation.

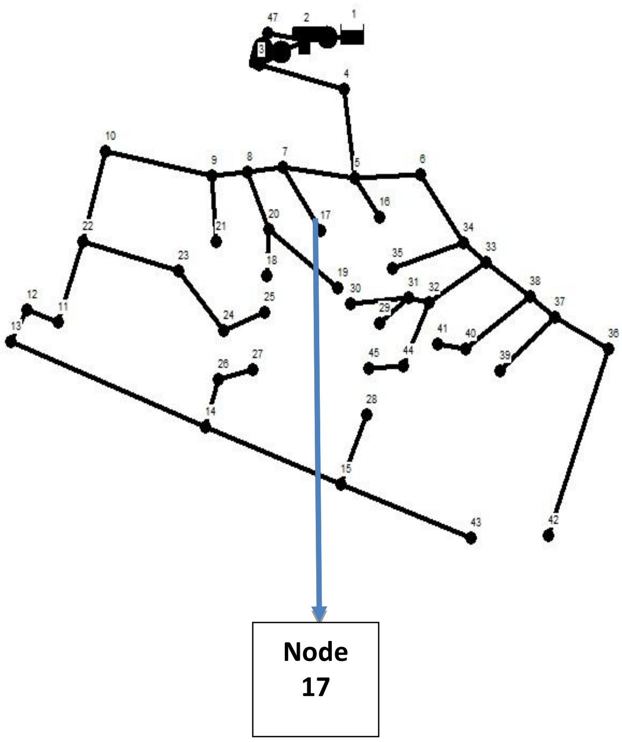


Figure 2 Existing network in the study area

Points to note for the simulation:

- One hydrant is opened;
- Fire incidence starts at 7AM and is to be fought for 1 hour; and
- Hydrant opened is that of junction 17 (see Figure 2)

Table 2 Results of simulation of existing network

BOOSTER PUMP CAPACITY		REFERENCE NODE 17 7 AM		REMARK
FLOW (LPS)	HEAD (m)	PRESSURE (m)	TOTAL HEAD (m)	
70	70	-116.89	-98.89	Insufficient pump pressure and Tank empties 10 minutes (7:10AM) into the fire fighting process.

3.2. Network of proposed firefighting system in the study area

Based on all relevant NFPA standards, hydrants are positioned in the new base in areas where they do not exist and where they are insufficient. The network of mains and sub mains were then developed and modeled to provide adequate water volume and pressure head during a fire incidence. Figure 3 shows the proposed network diagram for the Residential area.

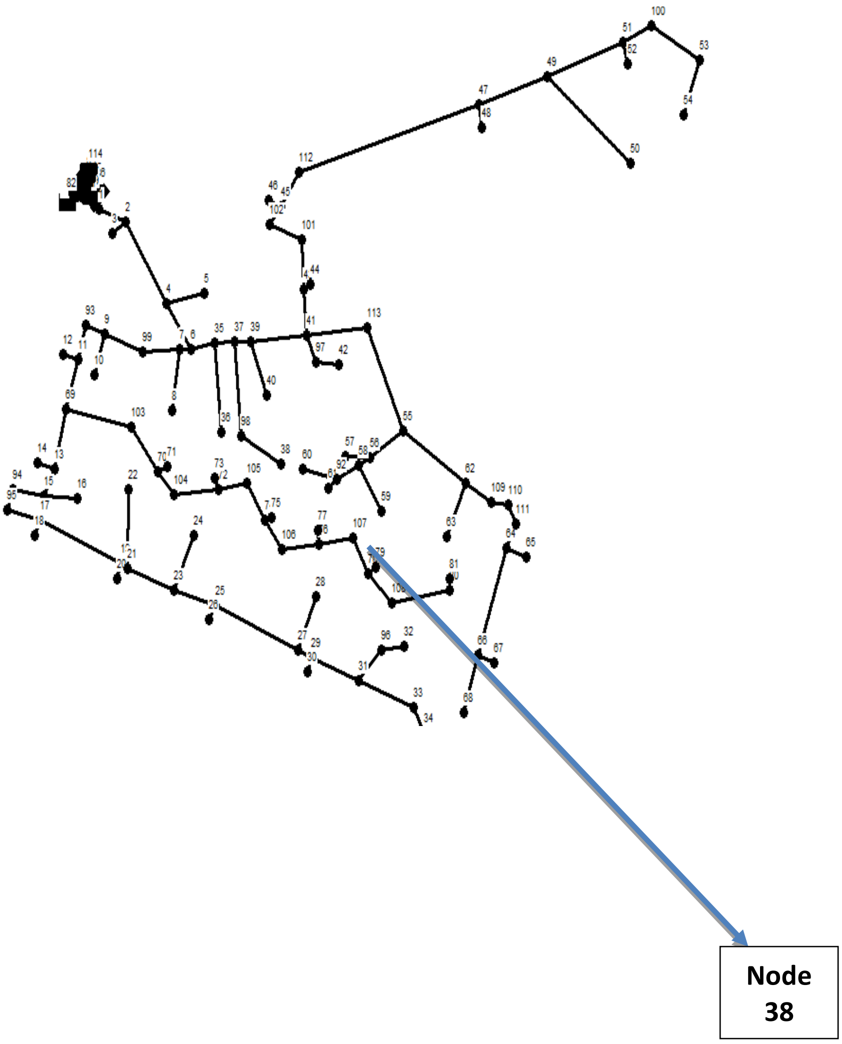


Figure 3 Proposed network for the New Base

CASE 1: Points to note for the simulation:

- One hydrant is opened;
- No closed loop;
- 1 number tank with size 10.2m × 10.2m × 3m;
- Fire incidence starts at 7AM and is to be fought for 1 hour; and
- Hydrant opened is that of junction 38 (see Figure 3).

OPTION 1: Providing a 5 metre height OHT

The network is simulated based on the conditions stated above and Table 3 shows the results.

Table 3 Results of simulation of case 1- option 1

BOOSTER PUMP CAPACITY		REFERENCE NODE 38 7 AM		REMARK
FLOW (LPS)	HEAD (m)	PRESSURE (m)	TOTAL HEAD (m)	
150	150	-148	-130	Insufficient pump
200	200	-70.94	-52.94	Insufficient pump
250	250	3.89	21.89	Insufficient pump
260	260	18.35	36.35	Insufficient pump
265	265	25.55	43.55	Insufficient pump
270	270	32.73	50.73	Insufficient pump
275	275	39.88	57.88	Sufficient pump but Tank empties 40 minutes into the fire-fighting process.

3.3. Discussion

The existing network in the residential area has not been able to serve its purpose as the operators via personal interactions complained of the insufficient pressure and weak pumps. The system was simulated and the results showed a negative pressure of 116.89 metres and the volume of water was insufficient as the simulation showed the existing surface tank empty 10 minutes into the firefighting incidence.

The water fire-fighting distribution network for the study area has been designed and presents a total of 7 cases and 25 options (See Table 4).Also the summary of all the simulations (Cases & Options) are graphically shown in Figures 4 and 5, respectively. The interpretation of both figures must be taken together to be meaningful; for instance, Figure. 4 for any case and option yields a particular pressure and correspondingly in Figure 5, the main pump capacity is read. The conditions are spelt by NFPA can be confirmed from both plots if met. With detailed analysis, recommendations are made from this poll of options of which design would stand the test of time.

Case 1 simulations present design conditions of one hydrant open at a time at node 38, no closed loop in the network (see Fig 3), 1 number OHT of size 10m × 10m × 3m, and fire incidence begins at 7AM and is fought for 1 hour according to the NFPA standard. The simulation varies OHT from a 5 metre height to 20 height with options 1 to 4. Option 1 provides a 5 meter OHT that shows that the fire water pump is sufficient for the network and water finishes in the tank forty minutes into the fire-fighting exercise (7:40 AM). Option 2 provides a 10 m OHT to see the improvement and an improvement in the pump capacity is recorded as 1,278 HP capacity pump. Options 3 and 4 further provide 15 and 20 me OHT but there was no significant improvement as the pumps sufficient for the network were still the 1278 HP capacities.

Case 2 simulation uses all the conditions of case 1 except the additional tank of the same capacity as in case 1 provided. Option 1 to option 4 present OHT of 5 to 20 metres and all show the same improvement in terms of sufficient volume of water for fighting the fire incidence for 1 hour.

Case 3 simulation uses all the conditions of case 2 except for the additional hydrant opened at node 34. Option 1 shows that for a 5 m OHT provided, the fire-fighting pump sufficient for the network is 4,832HP capacity pump and water finishes at 40 minutes into the fire-fighting incident (7:40 AM). Options 2, 3 and 4 show improvements in the pump capacity as that of 4,324 HP is sufficient for the network.

Case 4 adds 2 more OHT to the conditions of case 3 and the total number of OHT provided are 4 of the same size (10m × 10m × 2.7m). Option 1 to option 4 present OHTs of 5 to 20 metres and all show the same improvement in terms of sufficient volume of water for fighting the fire incidence for 1 hour. The pumps provided in case 3 are still sufficient for the network.

At this point of the design it was seen that providing an OHT above 10 metres does not add a significant improvement to the system in terms of reducing the pump capacity sufficient for the network. With this, case 4 option 2 was then selected for further analysis in terms of position of hydrants opened noting that the most critical hydrants are those of nodes 34, 54, 81 and 68 which are the furthest hydrants from the OHT (see Table 5).

Table 4 Results of all the cases and options from the simulations

S/N	Simulation case/options	Number of hydrants opened/position	Number of OHT/height/ size of each	Number of Submersible pump /capacity	Main fire pump capacity (HP)	Loop(s) considered	Pressure at most remote point	Remark (fail/pass)
1	Existing case	1/node 17	Nil	1/1.5 HP		Nil	-116.89	fail
2	Case 1 option 1	1/node 38	1/5meters (10×10×3)	1/43.83HP	1,325.97	Nil	39.88	fail
3	Case 1 option 2	1/node 38	1/10meters	1/43.83HP	1,278.20	nil	37.72	fail
4	Case 1 option 3	1/node 38	1/15 meters (10×10×3)	1/43.83HP	1,278.20	nil	42.73	fail
5	Case 1 option 4	1/node 38	1/20 meters (10×10×3)	1/43.83HP	1,231.30	nil	40.55	fail
6	Case 2 option 1	1/node 38	2/5 meters (10×10×3)	2/43.83HP	1,325.97	nil	41.55	pass
7	Case 2 option 2	1/node 38	2/10 meters (10×10×3)	2/43.83HP	1,278.20	nil	39.40	pass
8	Case 2 option 3	1/node 38	2/15 meters (10×10×3)	2/43.83HP	1,278.20	nil	44.39	pass
9	Case 2 option 4	1/node 38	2/20 meters (10×10×3)	2/43.83HP	1,231.20	nil	37.21	pass
10	Case 3 option 1	2/node 38 & 34	2/5 meters (10×10×3)	2/43.83HP	4,832.7	nil	68.3	fail
11	Case 3 option 2	2/node 38 & 34	2/10 meters (10×10×3)	2/43.83HP	4,383.4	nil	37.25	fail
12	Case 3 option 3	2/node 38 & 34	2/15 meters (10×10×3)	2/43.83HP	4,383.4	nil	42.22	fail
13	Case 3 option 4	2/nodes 38 & 34	2/20 meters (10×10×3)	2/43.83HP	4,383.4	nil	47.23	fail
14	Case 4 option 1	2/nodes 38 & 34	4/5 meters (10×10×3)	4/43.83HP	4,832.7	nil	70.24	pass
15	Case 4 option 2	2/nodes 38 & 34	4/10 meters (10×10×3)	4/43.83HP	4,383.4	nil	39.1	pass
16	Case 4 option 3	2/nodes 38 & 34	4/15 meters (10×10×3)	4/43.83HP	4,383.4	nil	44.09	pass
17	Case 4 option 4	2/nodes 38 & 34	4/20 meters (10×10×3)	4/43.83HP	4,383.4	nil	49.12	pass
18	Case 5 option 1	2/nodes 34 & 54	4/10 meters (10×10×3)	4/43.83HP	6,849.10	nil	43.71	pass
19	Case 5 option 2	2/node 34 & 54	4/10 meters (10×10×3)	4/43.83HP	6,849.10	nil	136	pass
20	Case 5 option 3	2/nodes 54 & 68	4/10 meters (10×10×3)	4/43.83HP	23,188.10	nil	87.61	pass
21	Case 6 option 1	2/nodes 54 & 68	4/10 meters (10×10×3)	4/43.83HP	8,591.42 HP	Joining 34 & 68	97.42	pass
22	Case 6 option 2	2/nodes 54 & 68	4/10 meters (10×10×3)	4/43.83HP	6,312.06 HP	Joining 34& 68, 80&109	60.46	Pass
23	Case 6 option 3	2/nodes 54 & 68	4/10 meters (10×10×3	4/43.83HP	1,578.02 HP	Joining 34&68, 80&109, 38&60, 59&63, 18&119.	38.9	Pass/ Recommended
24	Case 7 option 2	2/nodes 54 & 68	2/10 meters (10×10×3)	2/45 HP	1,578.02 HP	Joining 34&68, 80&109, 38&60, 59&63, 18&119.	37.03	Pass/ Recommended
25	Case 7 option 1	2/nodes 54 & 68	1/10 meters (10×10×3)	9/45 HP	1851.98 HP	Joining 34&68, 80&109, 38&60, 59&63, 18&119.	54.15	Pass/ Recommended

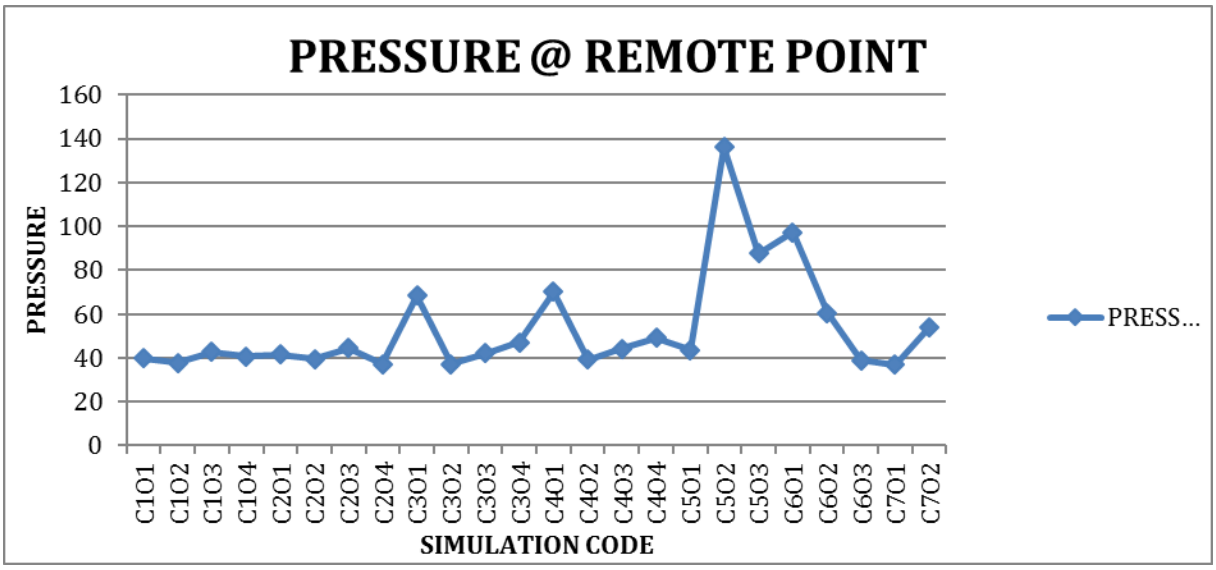


Figure 4 Pressure distributions of options (C1O1 – case 1 option 1)

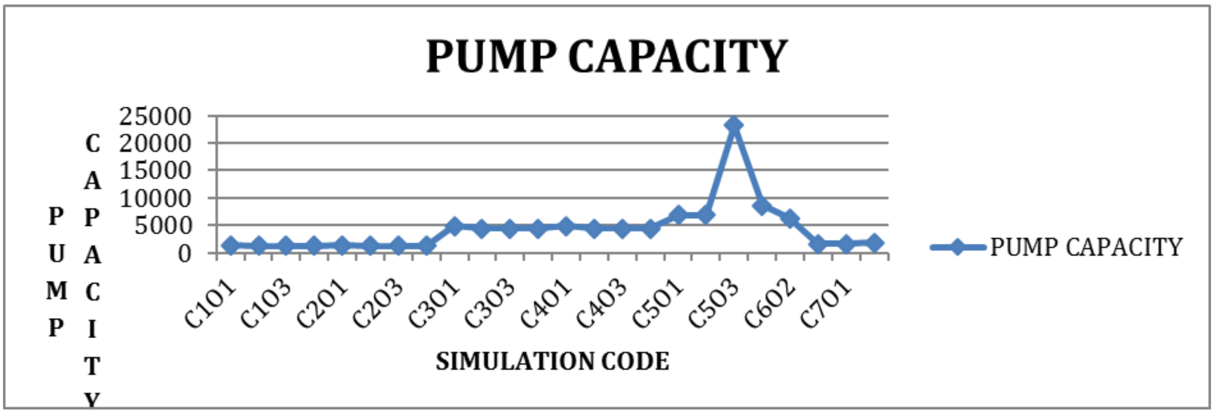


Figure 5 Pump capacities of options (C1OP – case 1 option 1)

Table 5 Critical nodes and distances from OHT

S/N	NODE NUMBER	DISTANCE FROM THE OHT POSITION (m)
1	34	827
2	54	814
3	81	704
4	68	624
5	38	264

Case 5 option 1 considers all the conditions of case 4 option 2 except that the hydrants opened are those of nodes 34 and 54 instead of nodes 38 and 34. The pump sufficient for the network is a 6,849HP capacity. Option 2 considers hydrants opened at nodes 34 and 68 and the pump capacity is 6,849 HP. Option 3 considers hydrants opened at nodes 54 and 68 and the pump capacity rised to 23,188.07 HP. With this it is seen that the hydrants of nodes 54 and 68 are the most critical points of all the points presented in Table 5.

Case 6 considers all the conditions of case 5 option 3 except that it creates loop in the network system to see the level of improvement made. Option 1 creates a loop by connecting nodes 34 and 68 and the pump sufficient for the network is improved from 23,189 HP to 7408 HP.

Option 2 further creates additional loops by joining nodes 80 and 109 and the pump capacity improves from 7,408 HP to 6313 HP. Option 3 creates all the possible loops putting into consideration as built structures in the residence. Loops were created by joining nodes 38 and 60, nodes 59 and 63. Nodes 18 and 119 were created and jointed (see Figure 6). The pump efficiency was improved from a capacity of 7408 HP to 1578 HP.

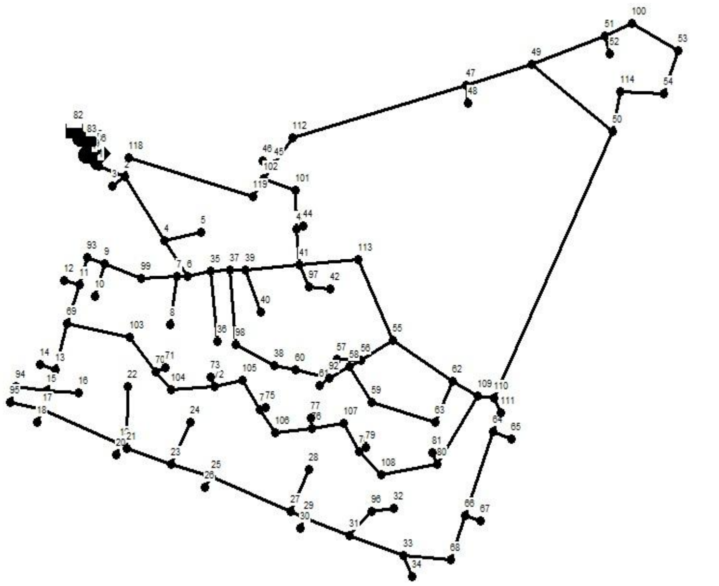


Figure 6 Diagram showing loop created by joining nodes 38 and 60, 59 and 63, 18 and 119.

Case 7 option 1 considers all the criteria of case 6 option 3 except that a single OHT of size 10m × 10m × 2.7 m replaces the recommended 4 OHTs of the same sizes (10m × 10m × 2.7m). This option tries to eliminate the clustering and cost of OHT. With this a pump of 1852 HP was sufficient and a submersible pump of 395 HP was also sufficient for the reservoir and it starts pumping when the fire incident begins. To actualize case 7 option 1 a well recovery test must be carried out in order to verify that the aquifer's yield is up to $533m^3/hr$ and even at that a submersible pump of 395 HP is equivalent to 9 number 45 HP pumps. Results of well recovery test according to Chattel in 2014 shows that the water yield in the Niger Delta region can be as high as 24 m^3/s. This means the ground water is capable of giving out 86,400 m^3 in an hour which is 163 times what we require to satisfy the water requirement in this study. Finally Case 7 option 2 considers all the criteria of case 7 option 1 except that two OHTs of sizes 10m × 10m × 2.7m replaced the recommended 1 OHT (10m × 10m × 2.7m). This option tries to reduce the number of submersible pumps provided in option 1. With this a pump of 1578 HP was sufficient and a submersible pump of 90 HP (2 number 45HP) was also sufficient for the reservoir and it starts pumping when the fire incident begins.

4. CONCLUSION & RECOMMENDATIONS

4.1. Conclusion

The following conclusion can be reached based on this research:

- The large water storage requirements for fire-fighting can be made less by utilizing the advantage of high ground water yield and pumps as the study presents. This can effectively help in space management as water storage facilities take large space;
- The most efficient water distribution network especially for fire-fighting purposes must be completely looped.
- The existing water distribution network in the study area failed when simulated. The negative pressure in the system was -116.89 metres and the water finished 10 minutes into the simulated fire incidence; and
- Case 7 option 2 is the best option from the analysis. With 2 number OHTs, 2 number submersible pumps of 45 HP each and a fire pump of 1578 HP, this option tries to strike a balance between the number of pumps and OHT required by the system.

4.2. Recommendation

Given the detailed analysis case 7 option 2 is recommended, Viz: two 10 m high OHT of size 10m × 10m × 2.7m each, 2 submersible pump of 45 HP capacity, a fire fighting pump of 1,578 HP capacity, a jockey pump of 1.8 HP for the residential fire-fighting system (See Figure 7 and Table 6).

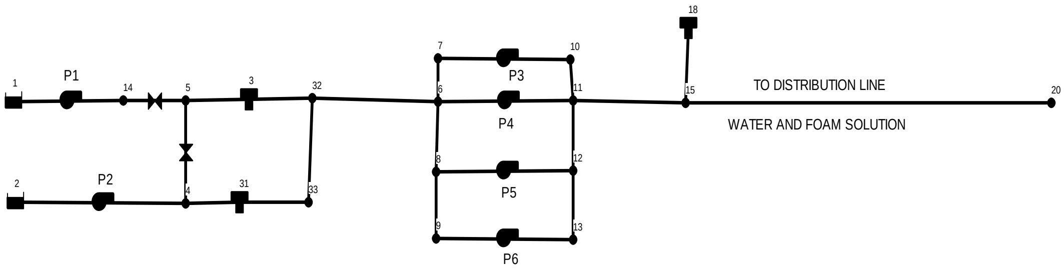


Figure 7 Representation of how the proposed network will work

Table 6 List of components on Figure 7

LABEL OF INTEREST	COMPONENT NAME	DESCRIPTION
1	Reservoir	in this case it is borehole of maximum 30 m depth
2	Reservoir	in this case it is borehole of maximum 30 metres depth and
P1	Submersible pump	It's a submersible pump of 45 HP capacity (50 LPS/ 50 metre head)
P2	Submersible pump	It's a submersible pump of 45 HP capacity (50 LPS/ 50 meter head)
3&31	Over Head Tanks (OHT)	each size is 10m × 10m × 2.7m
18	Concentrate tank (GP)	3,000 liters capacity
P3	Main fire pump	Its capacity is 1578 HP
P4	Main fire pump	Its capacity is 1578 HP
P5	Jockey pump	Its capacity is 1.8 HP
P6	Jockey pump	Its capacity is 1.8 HP
15	Mixing device	Responsible for mixing foam and water

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NFPA 24 - for firefighting water distribution system

NFPA 11- for firefighting foam

NFPA 20- for firefighting water pumps

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