THE HYDRAULIC IMPACT OF WATER SUPPLY NETWORK EXPANSIONS

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ABSTRACT

There is a general belief arising out of negligence on behalf of service providers, that water supply networks can be expanded indefinitely. Many water supply providers, in a drive to provide wide water supply coverage increase the number of customer connections through a massive network expansion. It has been observed in Kampala that with the expansion of the network, service levels have drastically dropped, with customers receiving intermittent water supply, and in many cases, not at all. This background prompted this research with the main aim of studying the hydraulic impact of the water supply network extensions. Specifically, the research was aimed at studying the effects of the expansions on pipe pressures, velocities, and flows and propose remedial measures in order to maintain satisfactory hydraulic properties. The methodology involved the assessment of the water supply situation before and after major extensions were made. Consumption patterns were generated from the block maps and water audits of the GIS records of Kampala Water. A simulation of the network was carried out using the EPANET-2 software. The modeling process involved data collection, system operation and monitoring, network schematization, model building, model testing and the analysis of the problem. Most notably, it was found that pressure zones are not well marked out and transmission mains were no longer functionally differentiated from distribution mains. Results from the study show a strong relationship between network extensions and reduced service levels.

KEY WORDS:

water supply network; hydraulic impact; simulation; pressures; velocity; flows; service levels

1.0 BACKGROUND

According to the Millennium Development Goals, water supply for all is emphasized. Water is a source all livelihood, an important constituent of living things, and a prerequisite for development (Linsley et al, 1979). There is need to provide water in sufficient quantities to the entire population, for growth, health and industry. In an urban setting, the importance of piped water supply cannot be over emphasized.

The National Water and Sewerage Corporation (NWSC), under the Water Statute of 1995, is mandated to provide water supply and sewerage services in the urban centers of Uganda. The corporation currently operates in 22 towns in Uganda. The social and political responsibility carried by the corporation to provide water and sanitation services in the urban centers of Uganda, on the one hand, and the desire to maximise revenue on the other, has in combination with increased demand, led to increased water connections.

In line with the NWSC objective of bringing services closer to the consumers, the corporation continued with its policy to extend its distribution network in all its areas of jurisdiction. As a result a total 294.6 km were extended bringing the total pipe network length to 2,733 Km. This serves a population of 749,297, short of the target of 1,208,544 (NWSC Annual Report, 2002/2003). However, cases of intermittent supply and no water have been increasingly reported in several areas. Areas that previously used to receive enough water especially prior to the introduction of the new connection policy nowadays receive intermittent supply at low pressures.

The effect of network extensions on the hydraulic characteristics of the network is not known. Lack of adequate knowledge about this impact hinders the explanation of water shortages in the network, and therefore, formulation of appropriate remedial measures. If the exact reasons for the reduced supply and the extents to which these reasons affect supply could be established, water supply in the study area would be managed better, and a more satisfactory customer service would be offered. This research was therefore carried out to explain the emergent reduced service levels, their relationship with the network extensions made and afterwards, formulate recommendations to remedy the current water shortage problem. Specifically, the main objective of the research was to study the hydraulic impact of the water supply network extensions with the following specific objectives: to study the effect of network size expansions on the pressures and suggest remedial measures; to study the effect of network size expansions on the pipe velocities and flows and suggest remedial measures; and to recommend the extent to which extensions should be made in order to maintain recommended hydraulic properties.

The research concentrated on Zone Eight, Kampala Area. This zone includes the part of Kampala that has Rubaga, Nateete, Busega, Wankulukuku, Makindye, Budo, Bulenga and Lungujja among others. The entire network of the zone, including all links, nodes and their elevations was studied. Further, the water demand and supply situation was studied. Hydraulic parameters that were studied include pressures, pipe velocities and flows.

2.0 METHODOLOGY

The method used involved three broad steps :

- Assessment of the water suppy situation, before two major extensions were made : 6-inch 12 km extension to Nabbingo, which supplies over 5000 people, and 6-inch 3 km extension to Bulenga supplying over 5000 people. This step invoved modelling of the network, and determining its hydraulic efficiency through assessment of the terminal pressures that customers would receive at their premises at the time.
- Assessment of the situation after the above mentioned major extensions were made.
- Assessment of the expected situation after more extensions were made especially Bulenga-Buloba and Nabbingo-Nsangi in the near future.

A model constructed using the EPANET 2 Soft Ware was used. EPANET is a computer program that performs extended period simulation of hydraulic and water quality behaviour within pressurized pipe networks. A network consists of pipes, nodes (pipe junctions), pumps, valves and storage tanks or reservoirs. EPANET tracks the flow of water in each pipe, the pressure at each node, the height of water in each tank, and the concentration of a chemical species throughout the network during a simulation period comprised of multiple time steps.

The modeling process involved the following steps: Input data collection, network schematisation, model building, model testing and problem analysis. Research criteria was determined, including minimum and maximum allowable pressures and velocities which were taken to be 1 bar (10mwc). Acceptable velocities would lie between 0.5-3.0 m/s. The Darcy-Wiesbach formula (Eq. 1) of calculating friction losses was used in the software.

$$h_f = \lambda \frac{l}{d}\frac{v^2}{2g} \qquad [1]$$

Where h_f =pressure loss (N/m^2); λ = D'Arcy-Weisbach friction coefficient; *l* = length of duct or pipe (m); *d* = hydraulic diameter *(m)*; and *v*=velocity (m/s).

Input Data Collection: The following data was collected: Layout of the system, reservoir features, topography, type of the system, population, flows, fire fighting demand, peaking factors and extensions being carried out currently, pressure tests were carried out to determine the actual pressures so as to aid the modeling process.

Water Demand: A special aspect of the model building process is the determination of nodal demands. A survey of numerous users spread all over the network was carried out and using an average household occupancy of six, and a daily per capita water consumption of 40l, their demand was concentrated into a limited number of pipe junctions in order to make the network presentation suitable for a computer model. The starting point is the calculation of the average demand. This yields the demand of a certain area, which has to be converted into demand at a point (pipe junctions). The next step is the conversion procedure based on the following assumptions: An even distribution of consumers and the border between the supply areas of two nodes connected by a pipe is at half of their distance.

Network Schematisation: The network was schematised by merging pipes of diameter less that 100 mm, concentrating demand at certain nodes, ignoring very small pipes, or those very far from the main pipes

Model Building: The model was then constructed in EPANET 2 software. Field data of residual pressures was compared with the model outputs. Calibration of the model of the existing system to field observed values was done for a range of operating conditions. Based on the projected development, future demands on the system were computed. The first trial solution was run, and its performance reviewed. The trial-and-error process was repeated until a technically feasible solution that meets the design criteria was reached. Flows, pressures and tank depletion rates, under both existing and future conditions, were simulated. Examination of the model for critical deficiencies in the system, such as low pressure or high velocity zones was done.

In the course of the research and the simulation process, the following assumptions were made:

- The contribution of leaks and bursts to pressure loss is negligible, since leakages are monitored and made good immediately.
- Local losses resulting from added turbulence that occurs at bends and fittings are neglected. Only friction losses were considered when calculating energy/heady losses.

3.0 PRESENTATION AND ANALYSIS OF RESULTS

3.1 Analysis of the operation of the Network prior to Major Extensions

This refers to the status of the network before major extensions to Budo and Bulenga were made. A schematized network map is shown in *Fig 1* below.

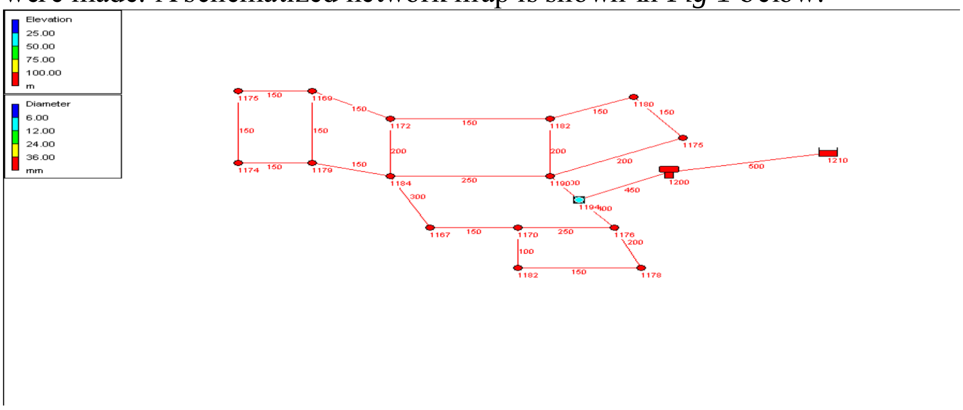

Fig 1: Schematised Pipe Network

3.1.1 Pressure

The pressures at the various nodes could satisfy the requirement of at least 1 bar. As can be seen from *Fig 2* below, these pressures were generally low, with a maximum pressure of less than 20m water column. *Fig 2* below shows the diurnal pressure variation of two selected nodes; 16 and 15. The nodes were selected because they were most critical since they formed take-off points for any major extensions.

With a head of at least 1bar, there is enough pressure to move the water against a head and frictional losses summing up to 10m. More water will therefore be delivered, since $q = Cp^{\gamma}$ Where q = flow rate, p = pressure, C = discharge coefficient and γ = pressure exponent. It can be seen that the flow rate enjoys a direct relationship with pressure. Therefore, with adequate pressure, the flow is adequate, too.

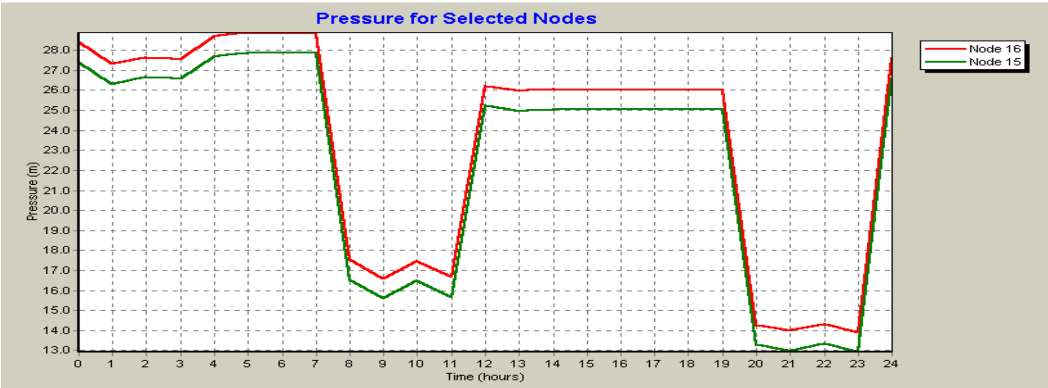

Fig 2: Diurnal Pressure Variations for Nodes

The plot in *Fig 3* below shows the diurnal demand variation at selected nodes. These nodes are critical because they lie at boundaries and could form joints for further extensions. Their hydraulic characteristics are therefore worth studying. Variable demands were observed between 4 l/s and 40 l/s. These demands were fed into the model to aid the simulation process. It can be seen that these demands are high, and require robust water supply to satisfy.

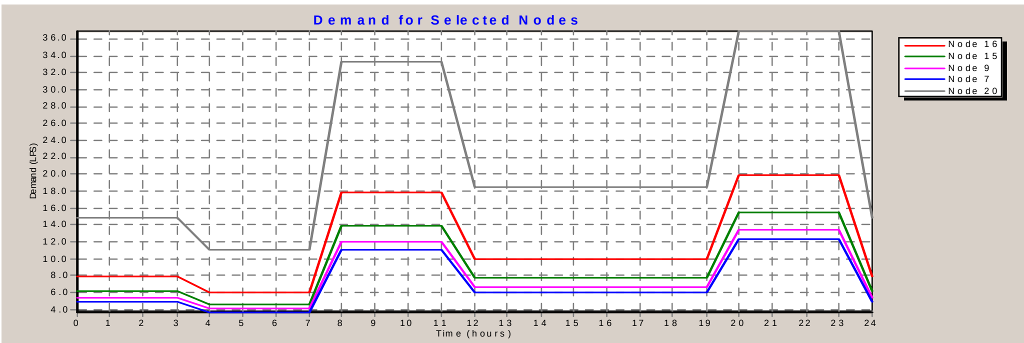

Fig 3: Diurnal Demand Variation for Selected Nodes

A plot that showed the variation of pressure between a node on the main where the connection was made and the pressure at house hold level clearly showed a negative slope, indicating declining pressure. This has been shown in *Fig 4* below.

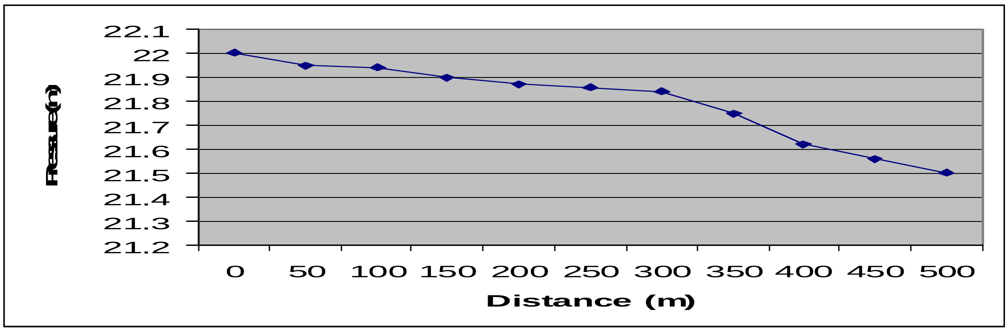

Fig 4: Pressure Variation Between the Node at the Main and at the Household

3.1.2 Velocity Variation

The velocities are generally very low, varying but below 1.5 m/s. *Fig 5* below illustrates further. These links are critical because they lie at boundaries and could form take off links for further extensions. Their hydraulic characteristics are therefore worth studying.

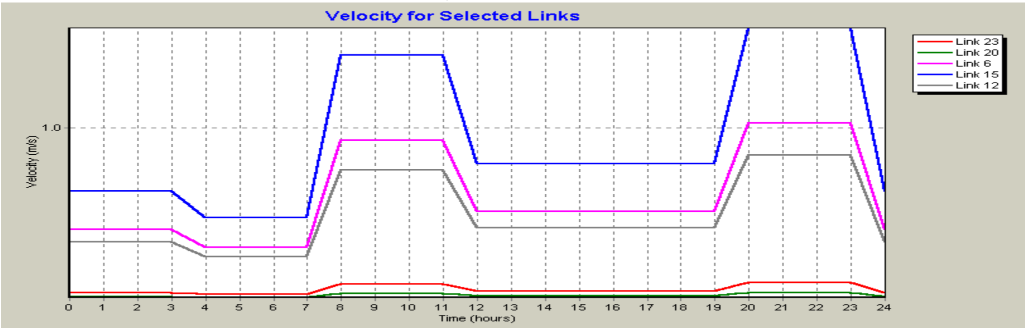

Fig 5: Velocity Variation for Selected Links

Upon implementing the extensions, the simulation showed a further drop in the velocities to averagely below 1.0 m/s. Recommended velocities should be between 0.5 and 3.0 m/s. Low velocities are undesirable because they lead to low pipe flows, since discharge is a function of velocity. **Discharge = Cross sectional area x Velocity**. Also low velocities are undesirable for reasons of hygiene.

A plot that showed the variation of velocity of flow between a node on the main where the connection was made and the velocity of flow at house hold level clearly showed a negative slope, indicating declining pressure. This has been shown in *Fig 6* below.

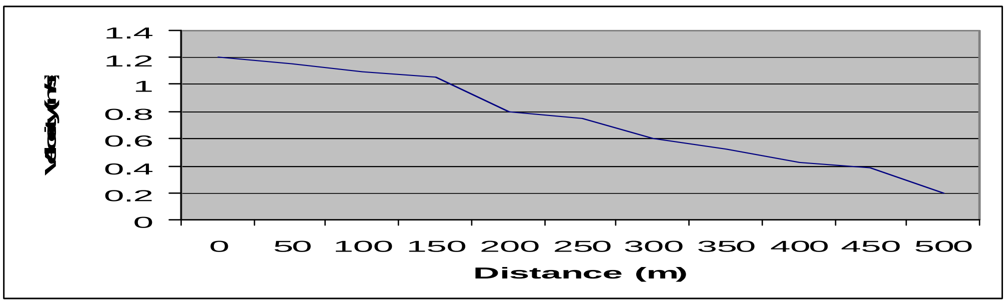

Fig 6: Velocity Variation between the Node at the Mains and at the Household

3.2 Recently Implemented Extensions

<u>3.2.1 Budo Extension</u>

This is a 12 km section that currently terminates at Nabbingo. It supplies a big community including secondary schools such as Kings College Budo, Trinity College Nabbingo and St. Lawrence School, among others, a total population estimated at 8000 (Bureau of Statistics, 2005), corresponding to, according to the prior-described procedure, an extra demand of 4.6 l/c/d. If this is added to node 16, which was thetake-off point for this extension, the effect of this extension can be assessed. As it is shown in *Fig 7*, the pressures generally fall. This shows that at the withdrawal points for the customers, pressures received are much less that 1 bar, if at all.

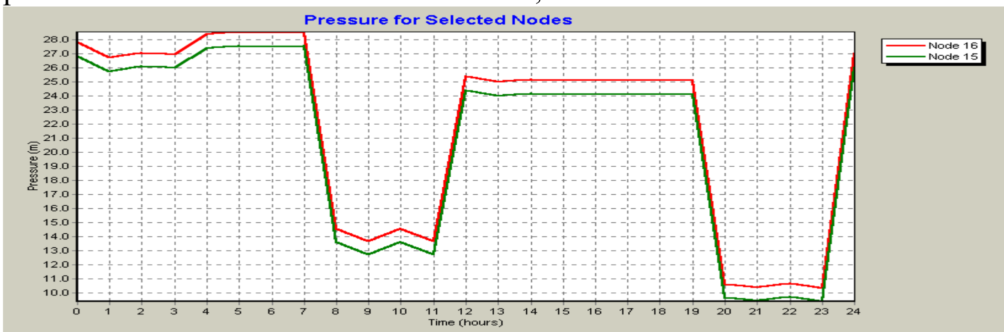

Fig 7: Pressure Variation for Selected Nodes

The increased demand after the new areas were added has been shown in Fig 8 below.

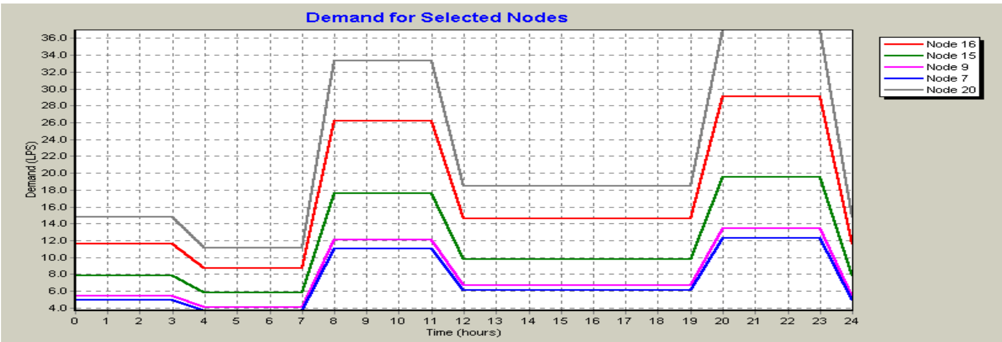

Fig 8: Demand Variation for Selected Nodes

Velocity variation after the new extensions were made is show in Fig 9 below. As can be seen, the velocities are low, mostly below 1 m/s.

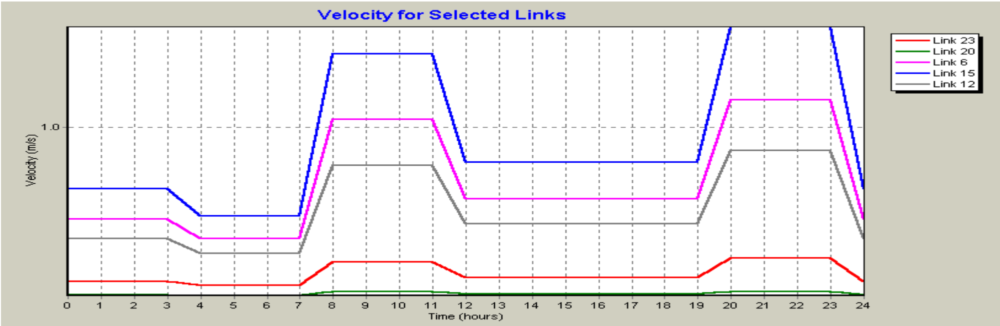

Fig 9: Velocity Variation for Selected Links

3.2.2 Pressure Test Done at Bulenga

For quality assurance and calibration purposes. A pressure test was carried out at Bulenga on a 6 inch main. It revealed pressures below 2 bars most of the time as can be seen in Fig 10. It should be noted that this point lies at the boundary of the study zone, and at this point, an 11 km extension has been planned.

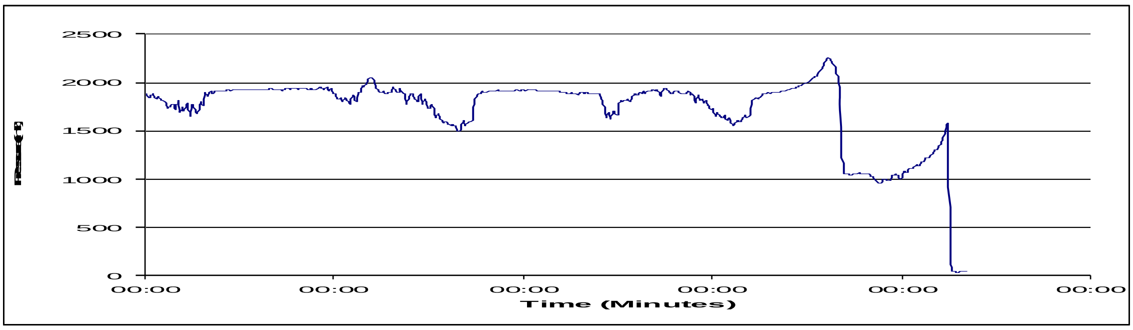

Fig 10: Pressure Test Done at Bulenga Trading Centre Between 8-11 August 06

In addition, several smaller extensions were carried out, and continue to be carried out. If the planned extensions next in line are implemented i.e. that is Nabbingo-Nsangi and Bulenga-Buloba, this will put another load of about 5 l/c/d on each of nodes 15 and 16. The program fails to run and therefore the research yields no positive results.

The failed simulation suggests that in reality, upon implementing the Nabbingo-Nsangi and Bulenga-Buloba extensions in the present circumstances, the pressure would not be enough to deliver the water, and water supply to these new areas would not be achieved. The present system, at the present flow cannot supply the new areas with water.

4.0 DISCUSSION OF RESULTS

4.1 Pressure and Head Loss

Pressures at nodes on the mains were modeled and measured. This gave a good indication of the terminal pressures expected at the consumer premises. If Pressures at these points were low, and indeed they were mostly less than 2 bars, it would be difficult to expect any better pressures at the consumer premises. No wonder in many homes very low pressures were evidently observed.

Before the extensions were made, the pressures at the various nodes could satisfy the then demand for most of the day, i.e. at least 1 Bar. This pressure was just adequate at the time prior to making extensions, and not after. Any extensions to be carried out later would lead to a significant drop in pressure. The thinking at the time is that as long as there is water in the pipe, as many consumers can be connected to the pipe as possible.

It was realized that there is now no difference between transmission and distribution lines. Transmission lines have been converted into distribution lines with so many connections being made on the transmission lines. This immediately drops the head in the pipes, so that by the time distribution lines receive water, the head has dropped. Even the transmission main to the Rubaga reservoir has a connection to the Cardinal's residence, Rubaga Hospital and Rubaga Cathedral!

In situations like the Kampala one, it is not logical to expect a consumer to draw water directly from the main all the time. Yet in many homes in Budo, Nabbingo and Kyengera, this was found to be the case. If tanks could be availed in the homes to act as storage reservoirs to even out demand supply, this would remarkably alleviate on the problem.

Connections not withstanding, pipe sizes are chosen haphazardly. No rational criteria are followed. Therefore, it is not surprising to find a pipe connected today not satisfying customers a year later. In some cases, pipes too big for the network have been connected, thereby drawing much water from the network, and consequently creating dry zones in other areas.

Hydraulic calculations and considerations, as indicated earlier, need to be carried out. Low pressure pipes are tapped in the valley in many cases. These suck most of the water that would be used upstream, creating water shortages.

Water loses head after flowing for long distances. Therefore, to give it more energy, booster stations are needed. These would help boost the water pressures and add it energy to continue to flow. This is so especially at Bulenga where a pressure test was carried out, and revealed the pressure on the six inch main as not exceeding 2 Bars. The same is true at Budo.

The network is not rationalized. There are supposedly two pressure zones, but these are neither respected nor adhered to. So many interconnections are made, and it is no longer clear what high pressure and low pressure zones are supposed to mean. This weakness has got to be ironed out. Rationalization of the network would aid decision making on which and whether extensions should be made. This also requires optimum valve operation.

Planning extensions should be done professionally.

4.2 Velocity and Discharges

Upon implementing the extensions, the simulation showed a further drop in the velocities to averagely below 1.0 m/s. Recommended velocities should be between 0.5 and 3.0 m/s. Low velocities are undesirable because they lead to low pipe flows, since discharge is a function of velocity. Also low velocities are undesirable for reasons of hygiene.

In addition, several smaller extensions were carried out, and continue to be carried out. If the planned extensions next in line are implemented i.e. that is Nabbingo-Nsangi and Bulenga-Buloba, this will put another load of about 5 l/c/d on each of nodes 15 and 16. The program fails to run.

4.3 Optimisation of Pressure and Velocities

Hydraulic logic has its limitations. For example, a solution such as enlarging pipe diameters in an effort to increase discharge and which also reduces friction losses, consequently yields smaller velocities. Hence, it may appear difficult to optimise both pressures and velocities in the system. Furthermore, in systems where reliable and cheap energy is available, the cost calculations may show that the lower investment in pipes and reservoirs justifies the increased operational costs of pumping. Hence, there are no rules of thumb regarding optimal pumping or ideal conveying capacity of the network. It is often true that more than one alternative can satisfy the main design parameters. Thorough analyses should therefore be conducted for a number of viable alternatives, calculating the total investment and operational costs per alternative. In any sensible alternative, larger investment costs will lead to lower operational costs; the optimal alternative will be the one where the sum of investment and operational costs is at a minimum.

The first step is to adopt an appropriate distribution scheme. Pumping is an obvious choice in flat areas and in situations where the supply point has a lower elevation than the distribution area. In all other cases, the system may entirely, or at least partly, be supplied by gravity. Translated into practical guidelines, this means: maximum utilisation of the existing topography (gravity); use of pipe diameters that generate low friction losses; as little pumping as necessary to guarantee the design pressures; valve operation reduced to a minimum.

Besides maintaining the optimum range, pressure fluctuations are also important. Frequent variations of pressure during day and night can create operational problems, resulting in increased leakage and malfunctioning of water appliances. Reducing the pressure fluctuations in the system is therefore desirable. The design criteria for hydraulic gradients depend on the adopted minimum and maximum pressures, the distance over which the water needs to be transported, local topographic circumstances and the size of the network, including possible future extensions. The following values can be accepted as a rule of thumb (Bhave, 1991): 5-10 m/km, for small diameter pipes; 2-5 m/km, for mid-range diameter pipes; 1-2 m/km, for large transportation pipes.

Velocity range can also be adopted as a design criterion. Low velocities are not preferred for hygienic reasons, while too high velocities cause exceptional head-losses. Standard design velocities are: ± 1m/s, in distribution systems ± 1.5 m/s, in transportation pipes; 1-2 m/s, in pumping stations.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The research enabled improved understanding, and quantification of the exact impact that water supply expansions have on network hydraulics. Data was collected and converted into usable forms. A model was built and simulation carried out. The science of the parameters that affect flow and pressure was analyzed and understood.

In the research, the key indicators of customer satisfaction were chiefly pressure, velocity and head loss. The findings of the research show that according to the current water production, even already existing customers cannot be guaranteed reliable supply of the pressures of at least 1 bar at all times in some sections of Zone 8.

i. The research intended to study the relationship between network expansions and the pressures. Pressures were found to fall with an increase in extensions. Terminal water pressures at most customers' premises were less than one bar, considering that at the nodes pressures are just about 20m. The hydraulic grade line between the nodes and the ultimate point of consumption continuously falls. It should be remembered that the recommended terminal water pressures should be at least 20m. Fallen pressures are due to higher abstractions from the network, attributed to high demand. The discharge from the pipes is much higher than intended. Head loss increases with discharge according to the Darcy-Weisbach formula. Higher pressures can be achieved by regulating the amount of water going out of the network. This is by regulating the extent of extensions to consumers. The fallen pressures can also be revived by installing booster stations at strategic locations. Proper marking and observance of hydraulic pressure zones would also help manage water supply in the respective areas.

ii. Pipe velocities were also found to fall with increasing extensions. Pipe velocities are low, generally below 1.0 m/s, and this affects the quantity of water received by the customer. Since Flow rate (discharge) = Cross sectional area x velocity, flow is majorly a function of velocity, the area being constant. Velocity range can also be adopted as a design criterion. Low velocities are not preferred for hygienic reasons, while too high velocities cause exceptional head-losses. The best solution would be to increase the capacity of the production plant and the sizes of the transmission and distribution mains.

iii. Reliability of supply is low. Customers receive intermittent supply, and others hardly ever receive water, to the extent that these areas are labeled "dry zones".

iv. Extensions should be carefully planned before execution. The design criteria for hydraulic gradients depends on the adopted minimum and maximum pressures, the distance over which the water needs to be transported, local topographic circumstances and the size of the network, including possible future extensions. Going by the then situation, no major extensions should be made on the network. Instead, rationalization of the network has got to be carried out. By this, some pipes may be replaced with different pipe sizes, and valves have got to be optimally operated.

5.2 Recommendations

As a recommendation for further research, a network simulation and optimization model for the whole of Kampala should be built, studied and used for planning extensions and suggesting remedies to water shortage cases. Other Recommendations include:

- The Unaccounted-for-Water component through leakages and water thefts should be seriously fought.
- The production capacity of the treatment plant should be increased.
- Booster pumps should be installed at points where extensions will start from.
- Planned extensions should be made after careful considerations.
- All customers ought to have tanks in their homes, to provide storage that shall guarantee supply during low supply hours. This was found lacking especially in areas of Kyengera, Budo and Bulenga.
- Transmission mains should be left intact, and no consumer connections should be made on them, otherwise they lose head, and become distribution mains.
- Hydraulic pressure zones should be mapped out to give guidance on the number and nature of consumers that can be connected to the respective mains.

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Surges (hydraulic transients) in water supply systems are usually caused by opening, closing or regulating valves or pumps starting and stopping. Water hammer, a result of hydraulic transients, will occur when the total surge pressure exceeds twice the value of the static pressure in the system when the fluid is at rest. Provide a surge analysis (IDS clause 7.6.6 â€“ Surge and Fatigue Re-rating of Plastic Pipes) appropriate to the pipeline e.g. pipes close to control valves require more detailed analysis or the selection of pipe materials that are not susceptible to surge and fatigue.