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Extended period simulation (EPS) modelling of urban water distribution network

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Abstract

***A WaterCAD hydraulic network model of the existing Ikpoba Hill Benin City Water distribution network was constructed, calibrated and validated for extended period simulation studies using the network's physical, operational, calibration and validation data. The model was then applied to evaluate: (i) effects of fluctuating water demand on system storage over* 24 *hour period and (ii) level of service and storage conditions during and following an emergency condition e.g. fire. Our results indicate that the existing system storage capacity (*276m^3*) is inadequate to meet operational, emergency and fire requirements for the present and future needs of the system. However, increasing the existing system storage capacity to* 1300m^3 *at the same Hydraulic Grade Line (HGL) will meet the system demand up to* 2015.**

Keywords
EPS, Network model, WaterCAD, Steady state, Fire flow, and Hydraulic Grade Line (HGL)

1.0 Introduction

Steady state hydraulic Modelling provides a snapshot of the condition in a distribution system with the assumption that the hydraulic condition has reached equilibrium (Gullick et al, [5]). This assumption simplifies the analysis of a water distribution system and is useful to evaluate and determine the size of pipeline and supply facilities (Walski et al, [13]). However, in reality, water demands vary over time, pump operations are altered and pumps may fail in a sudden event like power failure. These temporal variations cause the pressure and flow distributions to change and hence water distribution system can be better modeled by Extended Period Simulation (EPS). An Extended Period Simulation (EPS) also known as quasi-steady state analysis is a simulation of the behaviour of water networks over a twenty-four period using deterministic input data. It consists of a series of steady state simulations and in an extended period simulation of a water network the dynamics of reservoir fill-up and depletion are used to update the inputs to the static solution in each successive time interval, hence in an EPS, the only dynamic variable are tank levels (Boulos et al, [2]; Rossman, [10]) which are being updated between steady state analysis.

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The dynamics of the reservoir depletion are modeled by a differential equation for the reservoir heads as a function of time. These differential equations are integrated in time using predictor corrector scheme in the form of a modified Euler procedure. Extended period simulation analysis is a useful tool for determining the effects of system changes over time and provides more information about system operation characteristics and how the water systems respond to changing demand. In order to better understand water system hydraulics and enhance system improvement design and to plan and prepare for emergencies, system specific studies are needed to adequately analyze the distribution system behaviour of how tank levels fluctuate when pumps are running, how tank water levels would drop during a fire and how demands change throughout the day. Thus, EPS analysis software has now become an available option in most hydraulic analysis software.

In this study, we undertake an Extended Period Simulation analysis of Ikpoba Hill Benin City Water distribution network using WaterCAD hydraulic analysis software. The specific objective of the investigation is to provide proper understanding of the hydraulic behaviour of the existing system in order to aid distribution system operation and planning and hence:

(i) Evaluate the effects of fluctuating water demand on system storage over a 24-hour period.

(ii) Evaluate the level of service and storage conditions in the system during and following emergency situation or demand (such as fires etc)

2.0 Study network and basic theory and governing equations of extended period simulation analysis

2.1 The study network

The network utilized for this study is the Ikpoba Hill Water distribution network, Benin City, Nigeria. Benin City is located approximately within latitudes 5^0-30'N and 5^0 45'N and longitudes 6^{0-} - **1**5'E and 6^0 – 30'E. It is the capital of Edo state Nigeria. The study network is one of the five major water networks serving the City. It is an independent water supply system incorporating areas some 3.5km East of Benin City across Ikpoba River. Areas covered by the system are Federal Housing Estate, Aduwawa Quarters, Agbor Road and environs, Old Army Barracks, Auchi road and environs with a present estimated population of 29,000 persons, land area of 180 hectares and 1734 consumer connections. The distribution system operates as a single pressure zone with customers at elevations ranging from 60 metres to 90 metres above mean sea level.

2.2 Basic theory and governing equation of an EPS

The Extended Period Simulation (EPS) involves a sequence of static solution linked by an integration scheme for different equations describing the reservoir dynamics. Static solutions require that the fundamental relationship of conservation of mass and energy mathematically describe the flow and pressure distribution within a pipe network. These laws are

(a) The algebraic sum of all of the flows at a node is zero. This implies that mass continuity is preserved at each node. If Q_{ij} is the flow from node *i* to node *j* and C_i is the injection or consumption at node i, then the following relation is satisfied.

$$\sum_{\substack{j=1 \\ j\neq i}}^{N} Q_{ij} + C_i = 0 \qquad (2.1)$$

(b) The algebraic sum of all pressure drops around any closed loop in the network must add to zero.

$$\sum_{loop} H_{ij} = 0 \qquad (2.2)$$

Whether loop or node equations are written for a network, there remains the problem of solving the resulting system of simultaneous non-linear equations. To compute nodal heads and pipe flows, a set of non-linear equation is solved by an iterative process. In EPS analysis an additional relationship describing changes in tank level due to inflow/outflow is needed.

2.3 Solution procedure for system of equations

The unknowns in a steady state hydraulic analysis are the flows along each pipe (Q) and the total energy head at each function node H. For a system with n-nodes and n-pipes, the total number of unknowns is n-nodes + n-pipes. Four simulation equations can be developed to solve for the unknowns. They can be expressed in terms of unknown pipe flows or nodal heads. All sets are non-linear due to energy loss relations and require iterative solution procedure.

Let the resulting system of simultaneous non-linear equation be denoted by

$$g_i = \left(X_1, X_2, \cdots, X_L\right) = 0 \qquad (2.3)$$

(X_i = 1,…,L). For the node equations, the X_i are the unknown heads, while for loop equations, they represent the unknown circulating loop flows. The simplest method for solving equation (2.3) is to consider one equation at a time as shown by the Hardy Cross method. One can solve the K^{th} equation for X_k, assuming that all other variables are temporarily fixed at their latest approximate values. If done by linearization, the correction, ΔX_k is given by

$$\Delta X_k = \frac{-g_i}{\partial g_k / \partial x_k} \qquad (2.4)$$

Where the right hand side is evaluated using the latest known estimates of all the other variables. When each variable has been updated in sequence, then one Hardy Cross iteration has been completed.

The Newton Raphson method is the most widely used iterative solution procedure in Network Analysis (Boulos et al, [2]). The Newton Raphson procedure is based on the simultaneous linearization of all solutions about the latest approximation to the solution.

$$g_i + \sum_{i=1}^{L} \frac{\partial g_i}{\partial x_j} \Delta X_j = 0, i = 1, \cdots, L \qquad (2.5)$$

A system of L linear equations in the unknown corrections, ΔX_j results. When these corrections have been solved for, and applied to improve the approximate solution, then one Newton iteration has been completed.

3.0 Extended period simulation methodology and input parameters

An EPS is a series of steady state simulation. It begins with an initial set of tank levels, a given demand distribution and duration and set of operation decisions. A steady state simulation is completed for the initial set of demand to determine the pressure and flow distribution including flow rates into/ out of tank.

Using the tank flow rates and demand duration, a mass balance calculation is completed to update the tank levels. The new tank levels are then used as the fixed grade elevation for the next steady state hydraulic analysis and time step.

3.1 Tank mass balance equations

Steady state flows are computed in all pipes with tank levels fixed at their elevations at the beginning of the simulation period. The flow rate into and out of tank is assumed constant over the duration of the steady state simulation.

The new tank level are computed using the tank mass balance equation below (Boulos et al, [2]).

$$\tfrac{d}{dt}\int dV = \frac{d}{dt}\left(A_T H_T\right) = A_T \frac{dH_T}{dt} = Q_{T,in} - Q_{T,out} \qquad (3.1)$$

where $Q_{T,in}$ and $Q_{T,out}$ are the tank inflow and outflow and A_T is the area of the tank, H_T is the tank water level.

For a discrete time step of duration Δt and a tank of constant diameter, equation (3.1) becomes

$$\frac{A_T H_{T,i+\Delta t} - A_T H_{T,i}}{\Delta t} = \left(Q_{T,in} - Q_{T,out}\right) \quad (3.2)$$

Hence,

$$H_{T,i+\Delta t} = H_{T,i} + \left(Q_{T,in} - Q_{T,out}\right)\frac{\Delta t}{A_T} \quad (3.3)$$

where $H_{T,I}$ and $H_{T,}\ i + \Delta t$ are the tank levels at the beginning and end of time step Δt respectively.

3.2 Construction of watercad (EPS) model of the network

An Extended Period Simulation (EPS) model of the Ikpoba Hill Benin City water distribution network was constructed for this study using WaterCAD version 6.0 software. The model was constructed in 3 steps of minimal model skeletonization (Walski et al, [13]), model building and model calibration based on the network's physical and operation data applying rules available in the literature (Walski et al, [13]; Pilipovic, [8]).

Physical network data consisting of pipe length, alignment, connectivity, material of make, diameter, age, location, geometry and size of tank, information on valves were obtained from water system map got from Edo State Water Board, the operator of the distribution system. Operational data were also obtained from the Water Board while the water demand analysis and computations were carried out using standard methods. Data on typical water usage pattern for Benin City was obtained from previous studies (Tahal, [11]). The skeletonised network is shown in figure 3.1 and it consists of 15 nodes, 25 pipelines ranging from 100mm to 300mm diameter, 3 functional boreholes and a 276m^3 capacity elevated storage tank

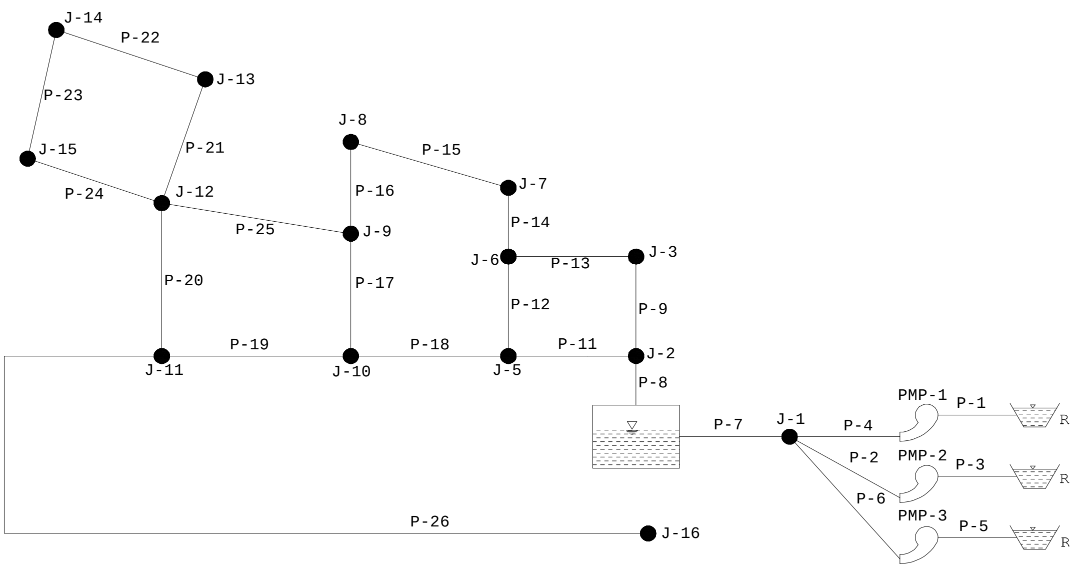

Figure 3.1: Skeletonization model of network

To use the base model as a predictive tool on the EPS node, it was calibrated and validated using calibration and validation data collected according to methods prescribed in the literature (Pilipovic, [8]; Hammer, [7])

3.3.1 Tank input data

Input data for the existing elevated storage tank in the distribution system is as presented in Table 3.1

Table 3.1: Elevated tank physical data

Parameter	Input Data
Elevation (ground)	91.50*m*
Maximum elevation	126*m*
Initial HGL	121*m*
Minimum Elevation	120.50*m*
Base Elevation	120*m*
Section Type	Circular
Diameter	8.0
Total Active Volume	276m^3

3.2.2 Nodal water demand

In practice, water consumption occurs along the pipe mains but as this exact state cannot be reproduced, it is simulated by aggregating individual consumptions at a node (Anyata, [1]) hence the consumption of water at each node constitutes the load. The water demand distribution within a network involves assigning the water demand to appropriate nodes and by this method, the effect of the total consumption exerted on the distribution system is readily seen and evaluated. To obtain the nodal demands for each node of figure 3.1, the total demand in the pipeline housing the node was split 50% to each end (Twort et .al, [12]) and using water demand analysis and computation procedures available in the literature (e.g. Walski et al, [13]; Hammer, [7]; Griffiths, [4])

Characteristic water demands are average day demand (*Add*), maximum day demand (Mdd) and peak hour demand (*Pk.hd*). The average daily demand is the average daily water demand over a period of one year; the maximum daily demand represents the amount of water required during the day of maximum consumption in a year while the peak hour demand represents the maximum consumption hour in a given day. This information is required to analyze the peak capacity required of the distribution system, elevated reservoirs and high service pumps to be able to deliver the peak water demand during peak hour of the day. Peaking factors are applied to average daily demands as follows to obtain maximum daily demand and peak hour demands (Garg, [3])

$$Mdd = 2xAdd \quad (3.4)$$

$$Pk,hd = 2xMdd \quad (3.5)$$

The nodal water demand data for the future year 2015 utilized for this investigation was obtained by using the 2005 data as base. The 2005 estimated population of study area (28,760) was projected to the year 2015 (38,651) assuming annual growth rate of 3% while the2005 water consumption rate of 135 *lpcd* is assumed to increase to 150 *lpcd* in 2015. The 2015 nodal demand data is presented in Table 3.2

Table 3.2: Nodal Water Demand Data for 2015

Node Label	J-1	J-2	J-3	J-4	J-5	J-6	J-7
Add (e/s)	0.0	28.73	3.68	3.78	3.87	2.73	4.56

Node Label	J-8	J-9	J-10	J-11	J-12	J-13	J-14
Add (e/s)	6.58	4.93	2.44	7.03	4.54	2.53	2.39

3.2.3 Water demand pattern

Water demand in a distribution system fluctuates over time. There are wide variations in seasonal, daily and hourly water demand and within a day there are two demand peaks, one peak in the morning as the day's activities start and the other peak in the evening (Qasim et.al, [9]) hence, In addition to physical data about the tank, the temporal variation of water demand is supplied to the simulation model by a demand pattern (Walski et al, [13]). The demand pattern is a set of multipliers that vary with time and which is applied to a given base demand, most typically average day demand (as established in Table 3.2

).A typical pattern covers a 24 hour cycle to analyze tank level changes during an average day when designing a network. For this study the pattern given in Table 3 which reflects the temporal variations in water demand in the study area has been utilized following the guidance of a previous study done in the project area by Tahal Consulting Engineers (Tahal, [11]).

Table 3.3: Typical residential demand pattern for Benin City (Tahal, [11])

Time from start (hr)	3	6	9	12	1	18	21	24
Multiplier	0.4	1	1.3	1.2	1.2	1.6	0.8	0.5

3.3 Application of the model for eps studies

The base model of the network was constructed as a link-node connectivity of the network elements using WaterCAD tool pallete utilizing the field data collected and skeletonization exercise carried out. Data were entered into the model for each of the network element – Pipe size, type, length, and roughness coefficient were entered for each pipe element. Elevation, water demand data and pattern were entered for each junction. Tank and pump information were entered based on actual condition and capacity. Entered data were checked (Pilipovic, [8]) to ensure that potential errors are corrected and checked to ensure it is functioning correctly. Calibration and validation were carried out thereafter before it was used as a predictive tool in the EPS mode of analysis.

Two major investigations were carried out for the study network namely:

(i) Emergency loading scenario

(ii) Varying storage tank capacities.

3.3.1 Emergency loading scenario

In addition to the various types of loads expected, there is a possibility of emergency loading on any of the load nodes. This emergency could be due to a fire flow requirement, or a facilities failure. In order to simulate the behaviour of the network under such emergency condition, demand was imposed on the system to represent a fire demand of 20l/s for 3 hours (from 1800 hours to 2100 hours) at node J – 14, the most critical node for the network. The emergency demand of 20 l/s for 3 hours (from 1800hrs to 2100 hrs) was applied to node J-14 as reflected in the fire flow pattern is shown in Table 3.4

Table 3.4: Fire Flow Pattern

Time from start (hr)	18	21	24
Multiplier	1	0	0

3.3.2: Effect of varying water storage capacities

In order to evaluate storage management policies in the operation of the water distribution network and as well as to aid planning in evaluating alternative network reinforcement policies, simulations were performed for 4 different tank sizes as shown n Table 3.5.

Table 3.5: Simulation data for varying tank capacities

Storage Tank diameter (*m*)	**Active Volume (m^3)**
8 (Existing)	276
10	432
12	622
17.4	1300

3.3.3 Assessment of present and future storage needs of the system

Elevated storage reservoir should provide storage capacity to meet the following (Garg, [3]; Qasim, [9]) :(i) Operational storage (ii) Emergency storage and (iii) Fire storage. Operating storage is the storage capacity required to offset the differences between the distribution system demand and the high service pumping rates. The Emergency storage is the sufficient volume of water stored at distribution pressure to meet emergency requirements like temporary failure of the pumps, electricity or any other mechanism driving the pump, while fire storage is the component of the total reservoir storage that takes care of the requirement of water for extinguishing fires.

The operational storage for the system in the present (2005) and the future (2015) were assessed using analytical technique (maximum deficit and surplus method) (Garg, [3]). For 2005, with estimated population of 28,760, per capita water demand of 135 *lpcd* and 20-hr daily pumping rate of 194.13 m^3/hr, the Operational storage was obtained as 540m^3 and for the future (2015) condition with estimated population of 38,651, per capita water demand of 150 *lpcd* and 20-hr daily pumping rate of 289.89m^3/hr, the operational storage was obtained as 800 m^3.

Emergency storage required is taken as minimum of 20% of operational storage [3, 9]. Therefore, Emergency storage for 2005 condition is 108m^3 and for 2015 condition the minimum emergency storage required is 160m^3. Fire storage was assessed by using American water works Association (AWWA) recommended minimum value of 30 l/*s* for 3 hours. This yields a fire storage value of 324m^3. The summary of components of system storage capacities required for the present and future are presented in Table 3.6

Table 3.6: Summary of components of system storage capacities

Item	2005(Present)	2015(Future)
Operational storage	540m^3	800 m^3
Emergency storage	108 m^3	160 m^3
Fire storage (30l/s for 2hours)	324 m^3	324 m^3
Total required capacity	**972 m^3**	**1284 m^3**
Recommended Required Storage capacity	**1000 m^3**	**1300 m^3**
Existing system storage capacity	276 m^3	276 m^3
Additional storage required	**724 m^3**	**1024 m^3**

4.0 Result sand discussion

An EPS model of the system was run to model tank draining and refilling, check tank volumes and investigate system preparedness for special operations like fire emergencies and shutdowns. The EPS model calculates or gives information at each time step for every node, pipe, pump, tank or valve (Haestad methods, [6]). The graphical plots of the various investigations conducted are presented in figures 4.1 to 4.7.

Figures 4.1, 4.2, 4.3, shows how the different tank sizes perform in the EPS over a duration of 24 hours. The figure 4.1 indicate that the 270m^3 tank cannot keep up with peak demands at hours 10 and 18 hours during normal system operation as the tank falls below 10% full level during these times. This is indicative of inadequate storage capacity as the bottom 10% of the tank is typically held as non- operable except during emergencies (Qasim et.al, [9]). Figure 4.2 shows that the 432m^3 tank is depleted to about 40% full level at hours 10 and 16 in 24 hour periods of normal operation while figure 4.3 indicate that the 622m^3 tank is depleted to about 60% full level during critical hours of 11 and 16 in 24 hours of operation. Thus the 622m^3 tank performed better for the distribution system.

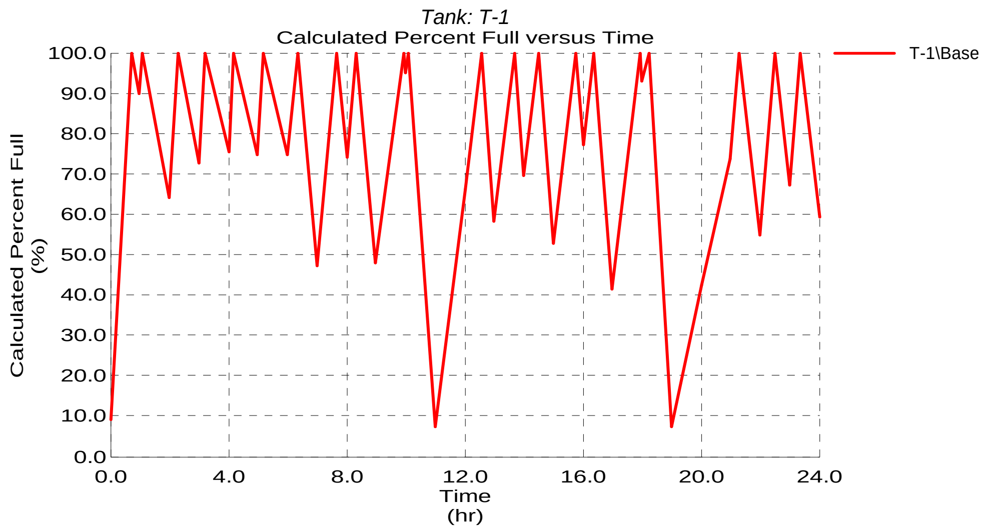

Figure 4.1: Calculated % full versus time for 8m diameter tank (276m^3)

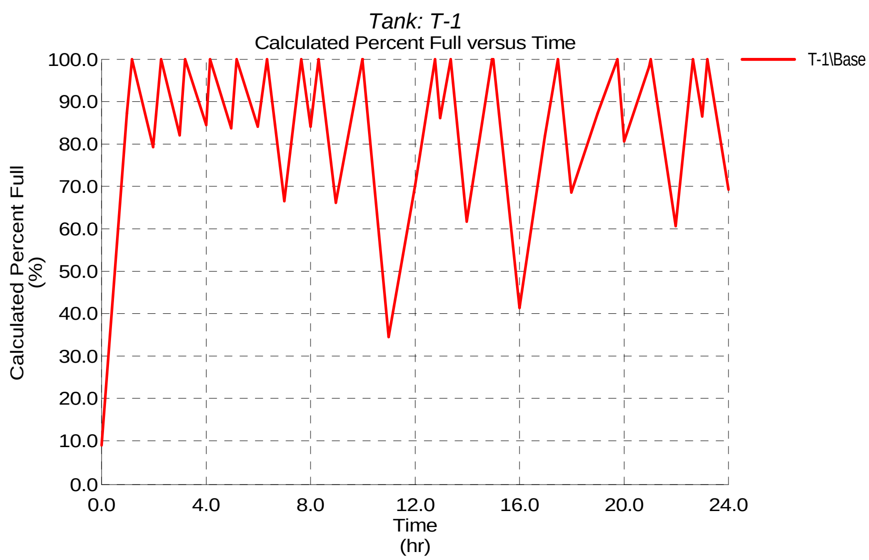

Figure 42: Calculated % full versus time for10m diameter tank (432m^3)

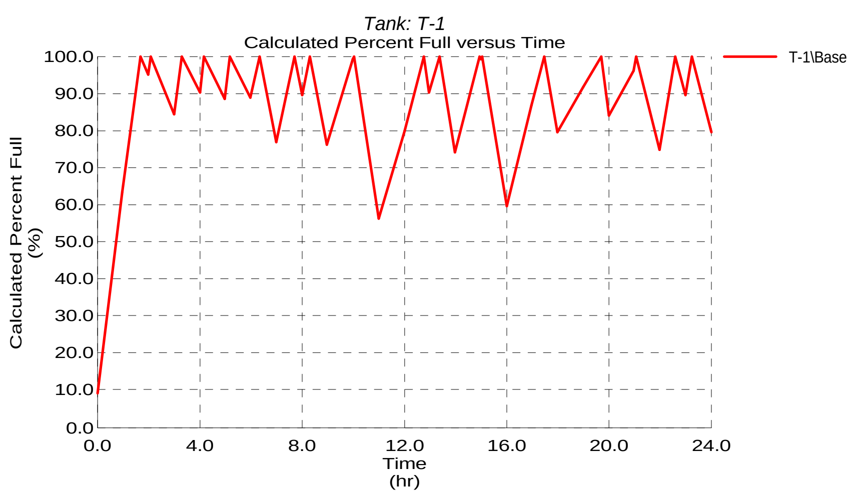

Figure 4.3: Calculated % full versus time for12*m* diameter tank (622*m*^{3})

Figure 4.4 is the simulation utilizing 1300m^3 tank. It is seen that the tank is depleted to 80% full level at the present day demand condition indicating satisfactory operational condition at the storage level.

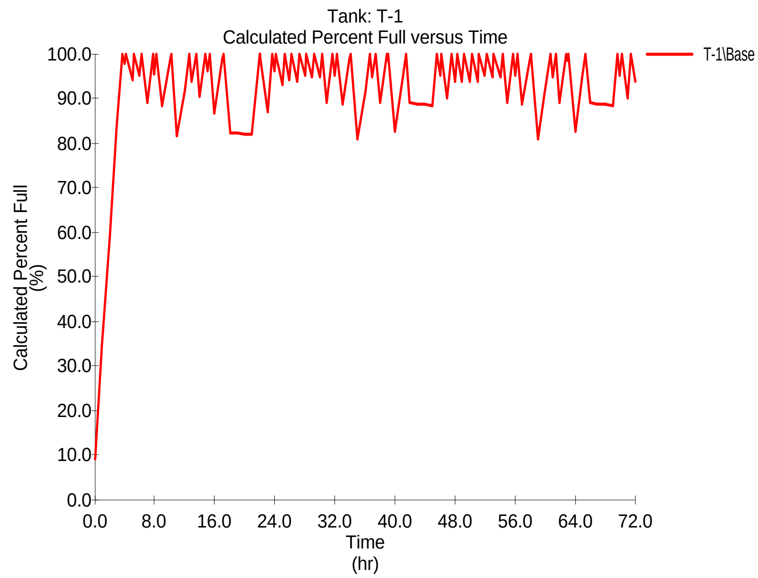

Figure 4.4: Calculated % full versus time for 17.4*m* diameter tank (EPS) - 2005

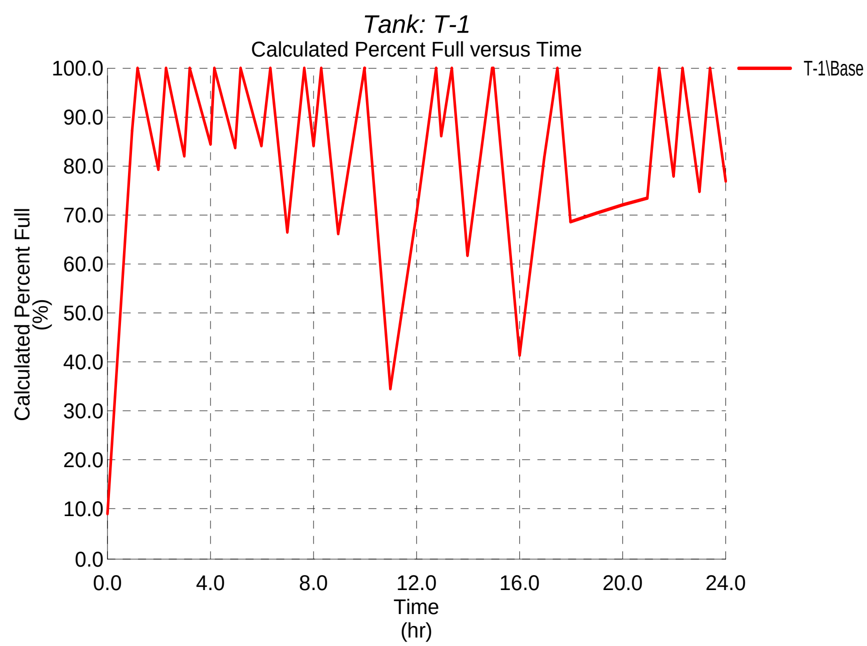

Figure 4.5: Calculated % full versus time for 10*m* diameter tank with fire demand

Figures 4.5, 4.6 and 4.7 displays the graphical plots of the simulations of emergency conditions when fire demand is applied at node 14 (critical node) during the period 18 to 21 hours for the 432m^3, 622m^3 and 1300m^3 tank respectively. The graphs show that 432m^3 tank is depleted to between 35 and 40% full level at the worst case during hour 11 and 16 in 24 hour periods. For the 632m^3 tank, the tank is depleted to 60% during fire emergency at the present day demand level.

Figure 4.7 shows the application of the 2015 demand level and the fire demand on the 1300m^3 tank. The graph shows that the tank is depleted to 40% full level at peak time. This is expected as the system is expected to be upgraded at this period. Our simulations also reveal that the existing tank in the system cannot stand any fire emergency as the simulations show unstable and unbalanced condition when fire demand was applied indicating that the existing tank is of inadequate capacity.

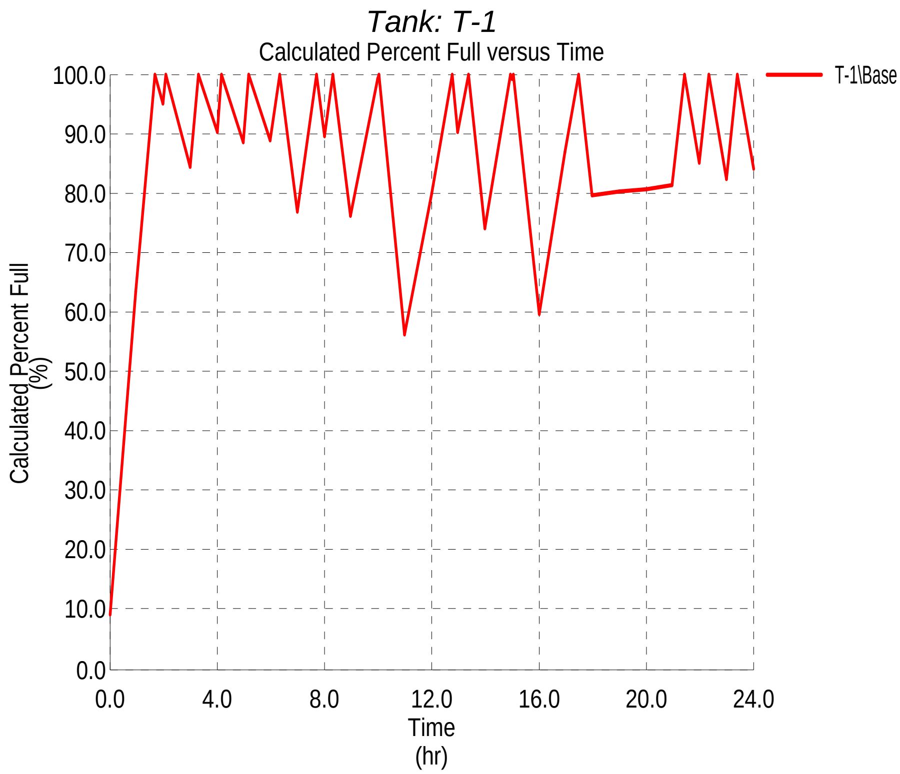

Figure 4.6: Calculated percent full versus time for 12*m* diameter tank with fire demand

This is corroborated by summary of the analysis presented in Table 3.6 which shows the components of required system storage capacity for both the present day (2005) and the future (2015). The table shows that the total storage capacity required for the present day is 972m^3 while that required for the future year (2015) is 1284m^3 indicating that the existing storage capacity of 276m^3 is inadequate to meet the storage requirements of the present and future year. For the system to have adequate storage capacity, additional storage capacities of 724m^3 and 1024 m^3 are needed for the present day and future year respectively. It is however suggested that the future additional storage of 1024m^3 should provided at the present time in order to have ample storage capacity. This could be achieved by matching the top overflow elevation of the new tank with that of the existing tank and located in the lowest pressure area.

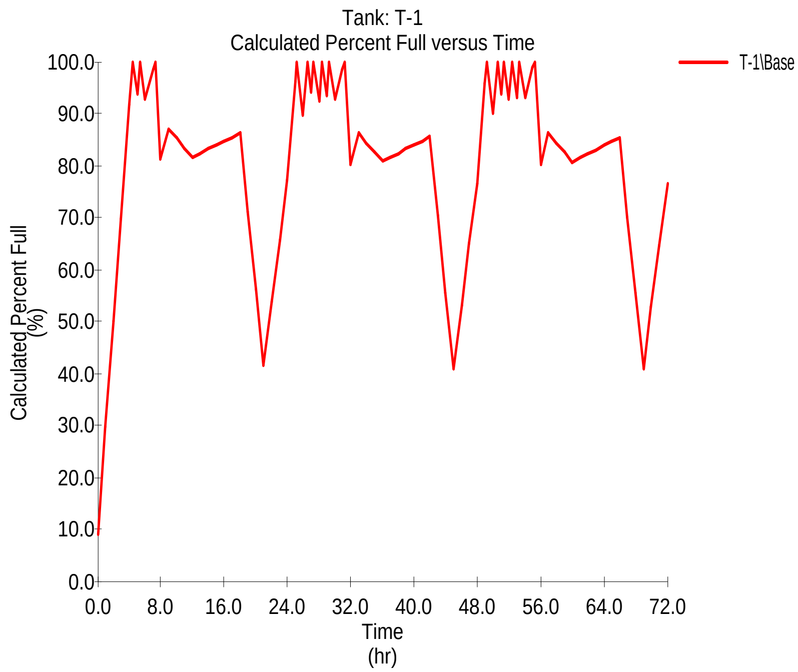

Figure 4.7: Calculated % full for 17.4*m* diameter tank (EPS) – 2015

5.0 Conclusions

The following conclusions may be drawn from this study

(1) EPS simulation capability is a useful tool in computer aided planning and operation of water distribution networks. In operation, results of the simulation can be used to evaluate storage management policies whereas in planning it can evaluate alternative network reinforcement policies.

(2) The system studied has inadequate water storage facility as it has insufficient capacity to meet operational, emergency and fire fighting needs of the system.

Consequently it is recommended that the storage facility be increased to $1300m^3$ by augmenting the existing system storage capacity with additional capacity of $1024m^3$ to meet the requirement of the future demand up to the year 2015.

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