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AN INNOVATIVE SIMULATION ALGORITHM FOR OPTIMISING THE COST OF COMMUNAL WATER SUPPLY SYSTEMS USING EPANET

AUTHORS:
T. A. Fashanu[1,*], C. Ndunaga[2], M. A. Ogundero[3], and O. Oluwatusin[4]

AFFILIATIONS:
[1,2,3]Department of Systems Engineering, University of Lagos, Akoka – Yaba, Lagos State, Nigeria
[4]Department of Mechanical Engineering, University of Lagos, Akoka – Yaba, Lagos State, Nigeria

***CORRESPONDING AUTHOR:**
Email: tfashanu@unilag.edu.ng

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Abstract

In this work, the EPANET software is used to parametrize the design, simulate and optimise the overall cost of building and running a reliable, sustainable and efficient communal Water Supply System. Considering a model community of forty houses with an average of six occupants per home, the developed optimization algorithm using the simulated annealing heuristics approach minimizes the total cost of continuous water distribution to the community through a system of pipe network in a way that satisfies the critical hydraulic rules and constraints for efficient water distribution. Thus, the controlled variables of the simulated system include volumetric flow, velocity and head loss. To realize the desired goal, the prototyped communal water distribution system was first simulated by water free fall i.e., only gravity feed under a peak demand flow condition. This facilitated the identification and localization of head-loss zones. Subsequently, virtual pump stations of various capacities were optimally introduced as boosters at identified nodal points to overcome critical head losses. The response of the system to varying capacities of the booster pumps was then used to analyse and determine the optimum capacity of the pump. Simulation outcome showed that the optimum least cost design for a sixty-year system's life cycle is achieved by using a combination of gravity and 5 hp (3.73 kW) pump with optimum pipe diameter ranging from 60 - 150mm.

1.0 INTRODUCTION

It is a well-known fact that water is critical to the existence and quality of life on earth. Thus, any disruption of its supply system, no matter how short lived, can induce untold discomfort or health-related issues. As a result, it is important that communal water supply systems are designed in such a way that they are robust enough to continuously deliver clean and safe to drink water, irrespective of prevailing circumstances [1]. Depending on body weight, health and other related conditions; for survival, the specified minimum volume of daily consumption of water in humans ranges between 3 to 6 litres [2]. On the whole, according to the World Health Organization (WHO) in 2003, an average person requires some 50 to 100 litres of water on a daily basis to satisfy all basic needs and minimize related health challenges. Thus, fifty litres of water is considered the basic daily requirement of an individual.

Growing populations, improvement in living standards and disposable incomes, and deeper understanding of the advantages of access to clean, safe water; hygiene and sanitation are all contributing

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to the increase in demand for water, especially in developing nations. In most of these places, rapid increase in demand for water is outpacing capacity to provide it. For example, on population, cities in underdeveloped countries are growing at a higher rate than those in wealthy industrialized countries [3]. This further widens the gap between demand and availability of water, in developing economies.

In the design of water distribution systems, it is important to ensure that the system meets the demands of end-users in terms of quantity and quality of supply for the entire period of the system's life. This is usually referred to as system reliability [4]. Since the demands of various categories of end-users are not exactly the same, their specifics should be critically considered during the design process. Most often, inability of water distribution systems to meet demand at an efficient pressure is often caused by inappropriate pipe sizing [5], failure to take into account real-time water consumption patterns of the target community in terms of population, and spikes in demand at certain periods of the day. Other issues are leaks and interruptions caused by pipe bursts. These are common occurrences. High pressure and flow typically result in bursts, water loss, and consequently, high maintenance costs [6]. Inadequate system design and implementation challenge the reliability and availability of WSS. This could be due to wrong assumptions, inadequate statistics, and input calculation errors. Again, these may result in high maintenance costs. Other responsible factors are improper sizing or prolonged supply interruption periods caused by failure [7]. Furthermore, bursts and leakages are most often associated with high levels of contamination in systems with insignificant or null pressures [8]. As a result, end-users may be exposed to some major health risks.

In many conventional water distribution systems, reliability is built in by increasing pipe density. However, this usually results in significant increase in setup costs. Basically, water supply systems are relatively very expensive to build and maintain [9]. Therefore, attempts should be made to optimize systems cost by minimizing energy and material wastages. This is in addition to deployment of system analysis, and effective design tools to develop robust cost-effective systems. To evaluate water distribution systems, a variety of widely available optimization and simulation tools are available [10]. For example, since increasing the pipe diameters means increased cost and lowered flow velocities [11], smart booster pumping stations could be strategically added to distribution networks to facilitate the use of optimum pipe diameters and increase systems' reliability. With this approach, gravity alone is used during the normal discharge flow. The pumping stations (PS) only set up complement gravity to meet peak demand conditions. Hence, the aim of the scheme developed in this work is to optimize the pipe network of a communal water supply system. The EPANET software is used to simulate the modelled system. The objectives are to minimize operational costs, as well as maximize the system's availability and reliability under the assumption of zero downtime. Hence, the objective functions and the corresponding constraints are appropriately formulated to address the aim.

The iconic model considered for this analysis is a twelve-node pipe network designed to serve a community with two thousand, eight hundred (2800) households, with an average of six occupants per household. Using network analysis, a mathematical model for optimising the functionality and availability of the designed pipe network was developed. Objective and constraint functions for the developed model were determined and solved using a cost minimisation approach. The optimum solution uses robust optimisation approach to determine the minimum possible sizes of pipes in the network such that reliability is not lost in the process of minimizing running cost. The scheme also investigates the response of the system to the introduction of pumping stations of various capacities to the network and their impact on reliability and system lifecycle costs. Thereafter, the developed model was simulated and validated using EPANET software.

EPANET is a well-known tool that is used to model, analyse, and evaluate networked systems, especially fluid distribution systems. Specifically, the software runs high-end simulations on WSS to show their performance and reliability across closed and pressurized communal networks. Its active modules or parts include pumps, pipes, valves, storage tanks, and reservoirs.

2.0 OVERVIEW OF OPTIMIZATION OF WATER SUPPLY SYSTEMS (WSSs)

Early study of optimization studies of WSSs may be traced back to the late nineteenth century. It was founded on the theory of economic velocity, which was eventually revised and replaced by the concept of achieving the system's minimal (annual) costs; precisely, the least-cost design approach [12]. The emergence of digital computers and its applications in network analysis facilitated many ground-breaking solutions of optimal water supply systems, especially between the 1960s and the 1990s. During the period, some notable contributions are the iterative solutions of [13] and the simulation packages developed by Rossman in [14] to solve simultaneous nonlinear networks. This laid the foundation for the application of analytical techniques for the solution of WSS design and its optimization. In WSS optimization research, applications of soft computational tools such as evolutionary algorithms, multi-objective optimization techniques, fuzzy logics, artificial neural networks, etc., have seen a significant increase in the last decade. It is particularly remarkable that most of these works addressed industrial, agricultural, or large-scale case studies for strong presentation of findings [15]. However, most researchers focused on more complicated systems. Subsequently, they make fewer simplifying assumptions, to get closer to more useful research outcomes [10].

On the other hand, [16] and [17] optimized pump operations utilizing hybrid genetic algorithms. About the same period, [18] effectively optimized pump performance on pipe networks by considering real-time flow, variable flow, and variable pump pressures design. In addition, pump scheduling framework was also used to determine the effectiveness of pump interventions. This analysis is divided into three levels;

i. High level-dynamic optimization of reservoirs;
ii. Moderate level static optimization of pump groups; and
iii. Low level-static optimization of individual pump station.

Design optimization in water supply systems may be specifically applied in one of four different stages: when designing new systems; when strengthening new or existing system, or when expanding and rehabilitating existing systems.

Not only did a large number of publications deal with design optimization issues, but they also looked at operational optimization challenges. This is an equally sensitive issue when considering the overall cost (i.e., including both capital and operating expenses). As a result, the operation cost of the system has been included in the present analysis. Design of functional systems that relied on the use of pipe diameters as the system's principal state variable dominates the literature. This is mostly due to historical considerations. However, it is worth noting that size of pipes was extensively considered in literature only at the initial stage. This was before the advent of parametric WSS modelling. Pumps, tanks, and valves, as well as a variety of performance requirements, such as water quality and operational factors are now critical considerations in the design and simulation of WSS. Recently, increasing attention has been placed on the evaluation of the robustness, reliability, and durability in WSS design and operation. This seems to be the accepted performance metrics for the foreseeable future.

3.0 METHODOLOGY

To proceed, this study developed a looped water distribution network. This is an adaptive design that accommodates redundancy, permits pipe failure, maintenance or change while still ensuring that all nodes within the network get water supplied to them. It also supports almost uniform pressures at all nodes within the network. This is more practical, especially when compared with dead-end designs which are characterised by extremely high pressures upstream, and rapidly reducing pressures as one goes further down the network.

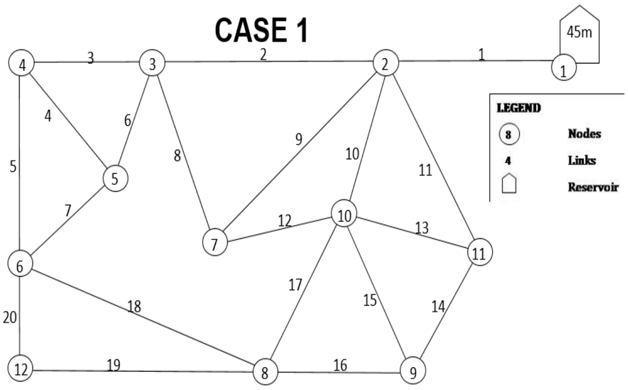

Figure 1: Design and network connection of the water supply systems on EPANET for case 1

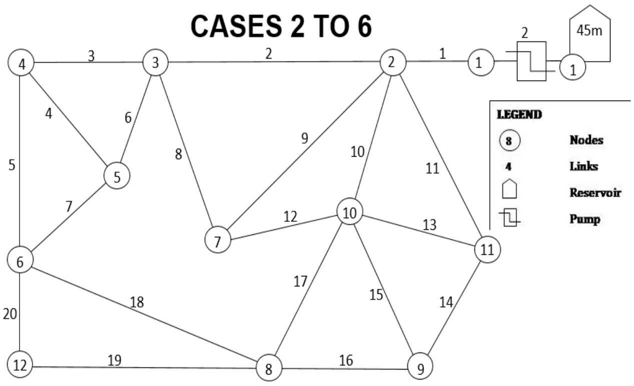

Figure 2: Design and network connection of the water supply systems on EPANET for case 2 to 6

3.1 Case Studies

The network was simulated in six case studies. In the first study, the network is fed exclusively by gravity by a single reservoir with a fixed elevation of 45m and comprises 20 pipes and 12 nodes. This schematic is shown in Figure 1. The network is assumed to be laid on a plane with uniform elevation and the reservoir is positioned 20m above datum. Therefore, all the nodes are assigned an elevation value of 20m. For case studies 2 to 6, a pumping station is integrated downstream of the reservoir as indicated in Figure 2. This pumping station is a contingency infrastructure that should only be used during peak demand.

The number of households served by each of the nodes are listed in Table 1 below. Given an average per capita water usage of 216 litres per day [19], and to account for an increase over time, average per capita usage of 250 litres of water per day was used for the calculations. Given that the local household average 5.1 persons per household [20], a population of 6 persons per household was used (since fractions of persons are difficult to quantify). The daily water demands per household was then 1500l/household/day and was used to generate the nodal water demands. A peak demand of 1.8 times the average was assumed.

Table 1: Nodes No of Households and Peak Demand at Nodes

Node ID	Ground Elevation (m)	Number of households connected to node	Peak Demand at nodes (l/s)
1	45	Reservoir	NA
2	20	304	9.5
3	20	256	8
4	20	320	10
5	20	176	5.5
6	20	288	9
7	20	208	6.5
8	20	240	7.5
9	20	224	7
10	20	144	4.5
11	20	368	11.5
12	20	272	8.5
13		Pump	0
TOTAL		**2800**	**87.5**

To protect the fittings at the nodes, a maximum pressure limit at nodes is introduced to limit the head pressure added by the pump. Therefore, to prevent pipe bursts and damage to the network due to excessive pressure, the maximum nodal pressure head is restricted to 60m at all times. This limits the capacity of the pump station that can be added to the network. Also, for availability of water to all households served by the system, the minimum pressure head at all nodes will be taken to be 20m. Network links and pipe characteristics for cases 1 and 2 are specified in Tables 2 and 3.

Table 2: Pipe Characteristics for Case 1

Link ID	Start Node	End Node	Length (m)
1	13	2	360
2	2	3	738
3	3	4	522
4	4	5	435
5	4	6	462
6	3	5	312
7	5	6	351
8	3	7	552
9	2	7	783
10	2	10	531
11	2	11	624

Table 3: Pipe Characteristics for Case 2

Link ID	Start Node	End Node	Length (m)
12	7	10	387
13	10	11	330
14	11	9	294
15	9	10	276
16	9	8	285
17	10	8	285
18	8	6	950
19	8	12	840
20	12	6	738
21	1	13	0

3.2 Mathematical Model

As stated earlier, the overall goal of this work is to simulate a WSS design that optimally minimizes the total setup and running costs associated with a closed communal water supply system over the lifetime of the system, without compromising good service delivery. To proceed and ease computational development, the following assumptions are made;

i. The projected lifetime of the system is 60 years, with each year consisting of 365.25 days
ii. Pumps (where installed) only come up during peak discharge hours. They are off at other times of the day.
iii. Peak water demand lasts for only 3 hours every day.
iv. The pipe materials are selected and the system operated such that the probability of pipe failures is negligible throughout the operational lifetime of the system.
v. Turnaround maintenance cycle for the pumps is once every two years. Lubrication and other maintenance costs within the periods between maintenance are also assumed to be negligible.
vi. Overall operational cost of the system is considered as a constant, hence it is neglected in the analysis.

Thus, to compute the cost of the system, the following considerations were made;

$$Lifetime\ costs = Pipe\ setup\ costs + pump\ setup\ costs + energy\ costs + operation\ costs + maintenance\ costs + downtime\ costs + environmental\ costs + decommissioning\ costs \tag{1}$$

If operational, downtime, environmental and decommissioning costs are neglected in equation (1), then

$$Lifetime\ costs = Pipe\ costs + pump\ setup\ costs + energy\ costs + maintenance\ costs \tag{2}$$

Since this work is aimed at cost minimisation without loss of functionality and reliability, the objective function for Equations (1) and (2) is formulated as;

$$Min \sum_{i=1}^{NPI} C\,pipe_i(D_i)L_i + \sum_{j=1}^{NPU}(CSp_j + CEp_j + CMp_j) + \sum_{k=1}^{NN} C\,td_k \quad \in Dcom \tag{3a}$$

$$\left(Min \sum_{k=1}^{NN} td_k\right) \ \forall\, k \ni td_k \simeq 0 \tag{3b}$$

Where, *NPI*: Number of pipes in the network; *Cpipe$_i$(D$_i$)*: Unit cost of pipe *i* as a function of its diameter D_i, (in \$/m); *D_i*: Diameter of pipe *i*; in mm; *L_i*: Length of pipe *i*, in m; *NPU*: Number of pumping stations in the network; CSp_j: Setup cost of the pumping station (PS) *j* in \$; CEp_j: Energy cost of the pumping station (PS) *j* in \$; CMp_j: Maintenance cost of the pumping station (PS) *j* in \$; $Dcom$: Set of commercial pipe diameters available; *NN*: Number of nodes; Ctd_k is downtime cost.

For the EPANET simulation, the objective function as outlined in Equation (3a) includes: cost of the pipes and cost of the pumping stations in terms of setup, energy and maintenance costs. However, Equation (3) ensures that system availabilty is optimized. Also, the simulation period in this work is less than the lifespan of the distribution network, hence, decommissioning cost is excluded. Non hazardous pump and pipe materials are considered, and the source of energy is also considered clean and renewable, hence, environmental cost is neglected.

The optimization model uses candidate diameter for each pipe based on a set of available commercial diameters. This is given by Equation (4) and it guarantees the assignment of only one commercial diameter for each pipe through Equation (5).

$$D_i = \sum_{d=1}^{ND} YD_{d,i}\, Dcom_{d,i} \quad \forall i \in NPI \tag{4}$$

The no loss condition inside the pipes stipulates that,

$$\sum_{d=1}^{ND} YD_{d,i} = 1 \quad \forall i \in NPI \tag{5}$$

Where; ND: Number of commercial diameters; $Dcom_{d,i}$: Commercial diameter *d* assigned to pipe *i*; $YD_{d,i}$: Binary variable to represent the use of the diameter *d* in pipe *i*.

As used in this work, commercial data of the pipes, and their Hazen-Williams (H-W) coefficients are listed in Table 4 below.

Table 4: Commercial Data of Pipes and their Hazen-Williams Coefficients

Diameters (mm)	Unit cost (\$/m)	H-W coefficients
60	75	100
80	80	100
100	87	100
125	93	100
150	103	100
200	115	100
250	132	100
300	150	100
350	172	100
400	196	100
450	222	100
500	250	100
600	320	100

The setup cost of the pumping station, which include the unit cost of pump and installaton cost is obtiained from data made available by the US State of Michigan [21] and compounded using the averge annual inflation rate of 2.0% to get the current prices. The pumps are assigned an efficiency of 75% when the head gain by running the pump is calculated. The pump information is presented in Table 5.

Table 5: Pump Information

Pump Rating (hp)	Pump rating (kW)	Normalized current cost (\$)	Head gain (m)
1.5	1.12	2220.99	0.98
5	3.73	3510.60	3.26
7.5	5.59	3976.30	4.89
10	7.46	4893.35	6.52
15	11.19	6197.29	9.77
30	22.37	9206.38	19.55

The energy cost of the pumping station is given by:

$$CEps_j = T_E \times Rp_j \times t_{r,j} \quad \forall\, j \in NPU \tag{6}$$

Where; T_E: Energy tarrif rate (\$/kWh); Rp_j: Power rating of pump *j* (kW) used in the system; $t_{r,j}$: Total time (hours) for which pump *j* is in operation.

Energy tarriff rate of \$0.17/kWh was used for the energy costs calculation. The maintenance cost of the pumping station for each cycle is taken as 25% of the setup costs of the station.

3.2.1 The constraints equations

For robust optimization of the objectives formulated in equation (1) to (6), the model includes a different set of constraints.

$$\sum_{i=1}^{NPI} I_{n,i}\, Q_{i,s}\, C = QC_n \quad \forall n \in NN; \forall s \in NS \tag{7}$$

$$\Delta H_{i,s} = K_i Q_{i,s} \alpha \quad \forall i \in NPI; \ \forall s \in NS \tag{8}$$

$$PMAX_n \geq P_{n,s} \geq PMINadm_n \quad \forall\, n \in NN; \ \forall\, s \in NS \tag{9}$$

$$D_i \geq D\min_i \quad \forall i \in NPI \tag{10}$$

Where; *$I_{n,i}$*: Incidence matrix of the network; *$Q_{i,s}$*: Flow in pipe *I* for case study *s*; *QC_n*: Consumption at node *n*, (l/s); *NS*: Number of case studies; $\Delta H_{i,s}$: Head loss in pipe *i* in case study *s*; K_i α: Coefficients that depends on the physical characteristics of the pipe *i*; *$P_{n,s}$*: Pressure at node *n* for case study *s*, (in m); $PMAX_n$: Maximum pressure at node *n*, (in m); $PMINadm_n$: Minimum admissible pressure at node *n*; $D\min_i$: Minimum diameter for pipe *i*, (mm).

Equation (7) ensures material conservation and nodal continuity. It demands that the total flow into a node must equal the total flow out of the node; Equation (8) determines and incorporates the head loss of through the pipes; Equation (9) is used to limit the pressure of the nodes and Equation (10) keeps pipes diameters in range and avoids a network bars.

Multiple case studies were considered and simulated to find the least-cost design of the network:

i. Case 1: Gravity fed system
ii. Case 2: Gravity fed system with an installed pump of 1.5hp for use during peak demand times
iii. Case 3: Gravity fed system with an installed pump of 5hp for use during peak demand times
iv. Case 4: Gravity fed system with an installed pump of 7.5hp for use during peak demand times
v. Case 5: Gravity fed system with an installed pump of 10hp for use during peak demand times
vi. Case 6: Gravity fed system with an installed pump of 15hp for use during peak demand times

Case 6 is considered the upper limit of the simulation. Since a higher pump capacity would raise a modal pressure above the set maximum head pressure and endanger the network.

4.0 SIMULATION RESULTS AND DISCUSSION

Performance analysis of the designed water distribution system was simulated with the system's identified state variables. These include pressure, head, elevation, pipe diameter, and pipe length. Pipe diameter and length affect head loss [22]. In particular, this work considered various systems configurations to improve the availability and reliability of water delivery to a community during regular and peak demand circumstances, at an optimum cost. As outlined in Section 3.2, the optimization model's objective function incorporates pipe and pumping station costs (i.e., installation, energy tariff and maintenance cost).

In case study 1, increasing pipe diameter increases network resilience and reliability. In the other case studies, complimenting the reservoir head with the pump station increases network resilience and reliability. In case studies that incorporated pump stations, the maximum nodal pressure was considered to be 60m. This constraint limits the pump capacity to avoid potentially excessive pressure in the network. The combined gravity and pump fed cases ii to vi allowed optimum choice of pipe parameters compared to the pure gravity loading condition in Case 1.

The decision variables of the robust optimization model are:

- Case study 1 – pipe diameters;
- Case studies 2 to 6 – pipe diameters and pumping head of constant velocity pumps

Tables 1 to 6 outline the case study results. For each case study, the tables reveal the commercial diameter selected for each pipe (mm), the pressures at the nodes (m), and the overall cost of the solutions. The tables indicate that reliable solutions entail increasing certain pipe diameters and pumping heads to achieve the minimum desired pressure at the nodes. This implicitly increases the costs. However, the effect of reduction in pipe sizes can be offset by an increase of the applied pumping head.

Using the optimization model developed and outlined in Equation (1) to (6) and the constraints developed in Equations (7) to (10), the EPANET software was used to simulate the flow pattern for Case studies 1 to 6. As stated earlier, to simulate the outcome of case study 1, larger pipe sizes were used than in the subsequent cases. Instead of employing increased pipe diameters, the PS increases the head at the reservoirs to ensure network supply for Case studies 2 to 6. The following results were obtained for each of the case studies.

Table 6: Simulated Nodal Configuration, Pipes Diameters and Lengths for Cases 1 to 6

Link ID	Start Node	End Node	Length (m)	Diameter (mm)					
				Case Study 1	Case Study 2	Case Study 3	Case Study 4	Case Study 5	Case Study 6
1	13	2	360	300	300	300	300	300	300
2	2	3	738	300	300	300	250	250	200
3	3	4	522	250	200	150	150	125	200
4	4	5	435	60	60	60	60	60	60
5	4	6	462	150	80	80	125	125	125
6	3	5	312	200	200	200	200	200	125
7	5	6	351	150	150	150	150	150	125
8	3	7	552	80	80	100	100	100	60
9	2	7	783	200	125	60	60	60	80
10	2	10	531	250	250	250	200	200	200
11	2	11	624	200	150	100	100	100	100
12	7	10	387	125	100	60	60	60	60
13	10	11	330	80	100	125	125	100	80
14	11	9	294	100	80	60	80	60	60

15	9	10	276	125	125	100	100	100	80
16	9	8	285	100	60	60	60	60	60
17	10	8	285	200	200	150	200	150	150
18	8	6	950	100	80	60	60	60	80
19	8	12	840	200	200	125	125	125	125
20	12	6	738	125	150	150	150	125	125
21	1	13	0	0	0	0	0	0	0

However, the outcome of simulating each of the six case studies using EPANET gave the following data at the nodes:

Table 7: Table of Pressure Heads at each Node(m)

		Pressure (m)					
Node ID	**Demand (L/s)**	**Case Study 1**	**Case Study 2**	**Case Study 3**	**Case Study 4**	**Case Study 5**	**Case Study 6**
1	-87.50	0.00	0.00	0.00	0.00	0.00	0.00
2	9.50	22.06	23.04	25.32	26.95	28.58	31.83
3	8.00	21.09	22.00	23.87	23.46	25.12	24.10
4	10.00	20.72	21.33	21.49	20.88	21.35	22.69
5	5.50	20.72	21.40	22.87	22.54	23.94	21.53
6	9.00	20.26	20.37	20.78	20.71	21.38	20.87
7	6.50	21.37	21.32	20.52	20.15	21.83	20.84
8	7.50	20.48	20.84	21.75	21.91	22.09	23.71
9	7.00	20.47	20.48	20.78	20.18	20.83	20.02
10	4.50	21.16	21.56	23.68	22.43	24.18	26.89
11	11.50	20.99	20.64	21.44	20.61	20.84	20.34
12	8.50	20.03	20.32	20.08	20.07	20.02	20.28
13	0.00	0.00	45.98	48.26	49.89	51.52	54.77

Table 8: Itemised Pump Costs (US $)

	Case Study 1	**Case Study 2**	**Case Study 3**	**Case Study 4**	**Case Study 5**	**Case Study 6**
Setup costs ($)	0.00	2,220.99	3,510.60	3,976.30	4,893.35	6,197.29
Energy Costs ($)	0.00	12,517.85	41,688.90	62,477.47	83,377.81	125,066.71
Maintenance Costs ($)	0.00	16,657.43	26,329.50	29,822.25	36,700.13	46,479.68
Total Pump Costs ($)	**0.00**	**31,396.26**	**71,529.00**	**96,276.02**	**124,971.28**	**177,743.68**

Table 9: Components of Life Cycle Total Costs (Pipes and Pumps) for Cases 1 to 6

	Case Study 1	**Case Study 2**	**Case Study 3**	**Case Study 4**	**Case Study 5**	**Case Study 6**
Pipe Costs ($)	1,080,996.00	1,032,022.00	973,104.00	961,689.00	942,219.00	928,582.00
Pump Costs ($)	0.00	31,396.26	71,529.00	96,276.02	124,971.28	177,743.68
Total Costs ($)	**1,080,996.00**	**1,063,418.26**	**1,044,633.00**	**1,057,965.02**	**1,067,190.28**	**1,106,325.68**

The relative economic cost of building the water supply system is simulated in cases I to VI in terms of pipes and pumps prices indicated in Figures 3 and 4.

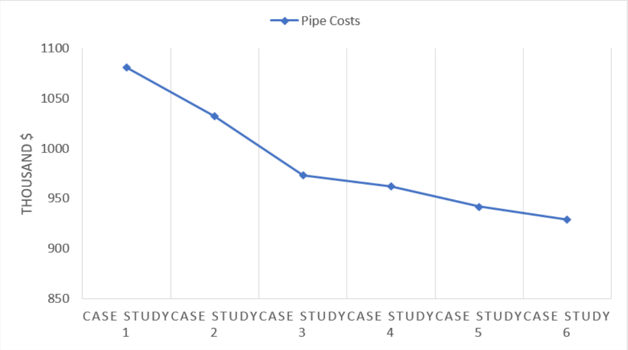

Figure 3: Profile of Pipe Costs Relative to Case Studies

Since no pressure booster pump is used in case I, as expected, case study 1 has the highest overall cost of pipes compared to the others. In this case, reliability is obtained by increasing the diameters of the pipes. As expected, Case 1 uses the largest pipe diameters, and it incurred the maximum cost of pipes.

Similarly, addition of pumps and gradual increase in pump capacity from one case to the other results in decreasing pipe cost. However, as the pump capacity increases beyond 5 hp (3.73 kW), the rate of decrease of pipe costs with respect to increase in pump capacity diminished noticeably.

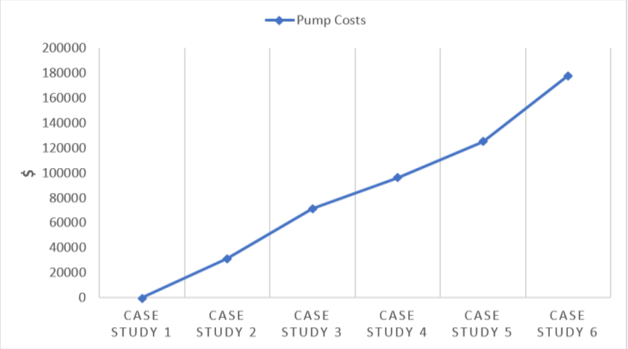

Figure 4: Profile of Pumps Ratings and Life Cycle Total Cost for Cases 1 to 6 (US Dollar)

https://doi.org/10.4314/njt.v42i4.4

An almost-consistent rate of pump cost increase with increasing pump capacity is observed. The components of pump costs for each of the case studies are shown in constituent units on Table 8. From Figure 5, apart from case study 2 where maintenance costs account for over 50% of the total pump costs, for the other case studies involving pumps, (i.e., Cases 3 to 6), energy costs are the largest contributors to pump costs. This ranges from 58% of pump costs in case study 3, to about 70% in case study 6. The relative total costs ($) for each case study (pipes and pumps) over the entire lifecycle as seen on Table 9 are presented in Figure 6.

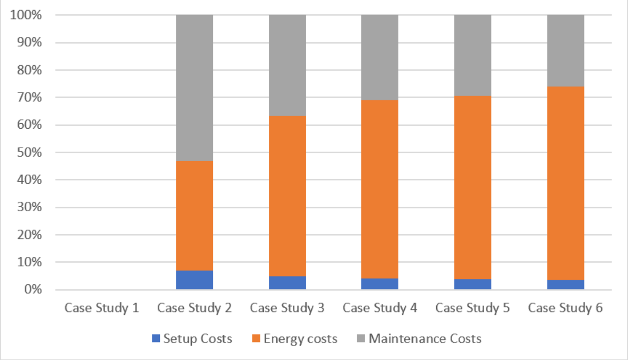

Figure 5: Percentage Analysis of the Components of Overall Pump Costs for Case Studies 1 to 6

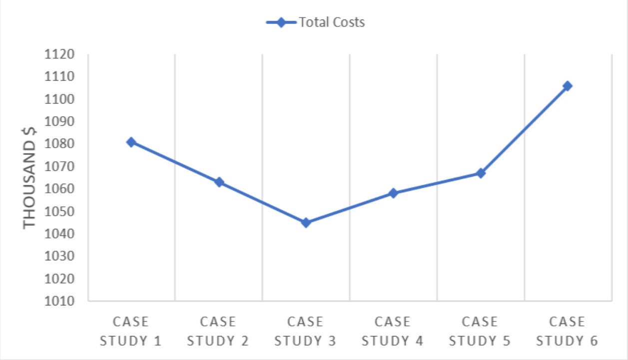

Figure 6: Comparative Life Cycle Total Costs for Case Studies 1 to 6

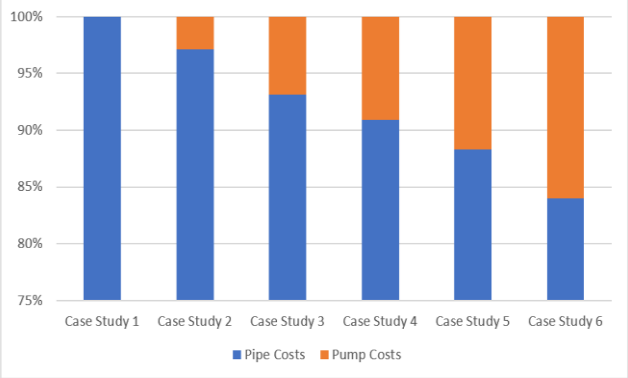

Figure 7: Percentage Analysis of Life Cycle Total Cost of Components for Case Studies 1 to 6

As indicated in Figure 6, pipe costs constitute a significant part of the overall costs even in cases with higher capacity pumps. As shown in Figure 7, the cost of pipe ranges from 100% of total costs (Case study 1) to about 84% of the total costs (case study 6). It is evident that moving from case study 1 (no pump) to case study 2 (1.5 hp pump) and then to case 3 (5 hp pump), total cost decreases linearly. However, increasing pump capacity beyond 5 hp leads to a jump in total cost. Meanwhile, the total cost of cases 4 and 5 remained less than that of case study 1 i.e., the gravity fed system.

Case study 6 shows a marked steeper increase in total costs, its costs are much higher than the gravity fed systems. It can also be projected that higher pump capacity will lead to pronounced cost increments with diminishing effect on pipe costs. From all the case studies, case study 3 (5 hp pump) gives the least lifetime cost for the model, while still satisfying all requirements and constraints. Hence, case study 3 is the recommended optimum systems configuration for water supply systems to service the modelled (illustrative) community that is earlier described in this work.

This work considers both gravity feed and pump stations in simulating and optimizing the water distribution system. Increasing the pipe diameter and integrating pump stations affects the network resilience and reliability. Also, the optimization model presented provides a cost-effective approach for planning water distribution networks.

5.0 CONCLUSION

This work applied the EPANET pipe distribution network toolbox to improve decision making in communal water supply systems design and optimization. The software and the developed optimization model facilitated virtual simulation of the operations of the conceptual system to realise reliability, availability and sustainability at optimum cost during the system's lifetime. With the help of six case studies, the functionality and applicability of this soft optimisation technique has been established. Two alternative solutions were used to assure the reliability of the water supply systems: In the first case, just expanding the pipe diameters was sufficient. However, in the other case studies, the system was designed for typical operating circumstances while also including pumping stations of various capacities to deal with peak demand.

This strategy for enhancing a water distribution system also evaluates, in terms of costs, the solutions obtained by the different case studies in order to determine the most cost-effective option while maintaining network resilience. The case studies that were employed to analyse the model resulted in the following conclusions; Loss of reliability of a water supply system which results from selecting pipes with smaller diameters can be offset by introducing a pressure booster pump station. This reduces the cost of pipes for the network, but increases the pumping costs. For our modelled configuration, optimum total cost of the designed system was achieved with the use of a 5hp (3.73 kW) pump with linkage pipe diameter ranging from 60 - 150mm.

The study highlights the effectiveness of the EPANET software in decision-making for water supply system design.

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