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An extended period modeling of water supply systems using hydraulic simulators

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Abstract

Operators and managers of water supply systems (WSS) are now more concerned with the periodic pattern of water usage throughout the day (24 h) due to scarcity of resources. Hence, this study focuses on using the EPANET and WaterCAD simulators to perform hydraulic simulations of Calabar metropolis's water supply system (WSS) in the extended period simulation (EPS) mode. The results of EPANET and WaterCAD were statistically compared using analysis of variance (ANOVA). With a *p* value of 0.54–0.99, the results showed no significant difference between the values predicted using both simulators for each and every hydraulic parameter. However, there were changes in the hydraulic parameters coming from the time patterns when comparing anticipated values for the extended period (6 am, 12 pm, 6 pm, and 12 am). The highest-pressure violation of the system's minimum pressure criterion is 34% during the most crucial demand hour (6 am). In addition, (98%) of the system flow rate was above the 0.15 PLS specified for the system, while 100% of the velocity dropped below the system's approved minimum limit. As a result, the WSS may become clogged, decreasing overall system performance. The system requires strengthening for effective performance under different demand patterns.

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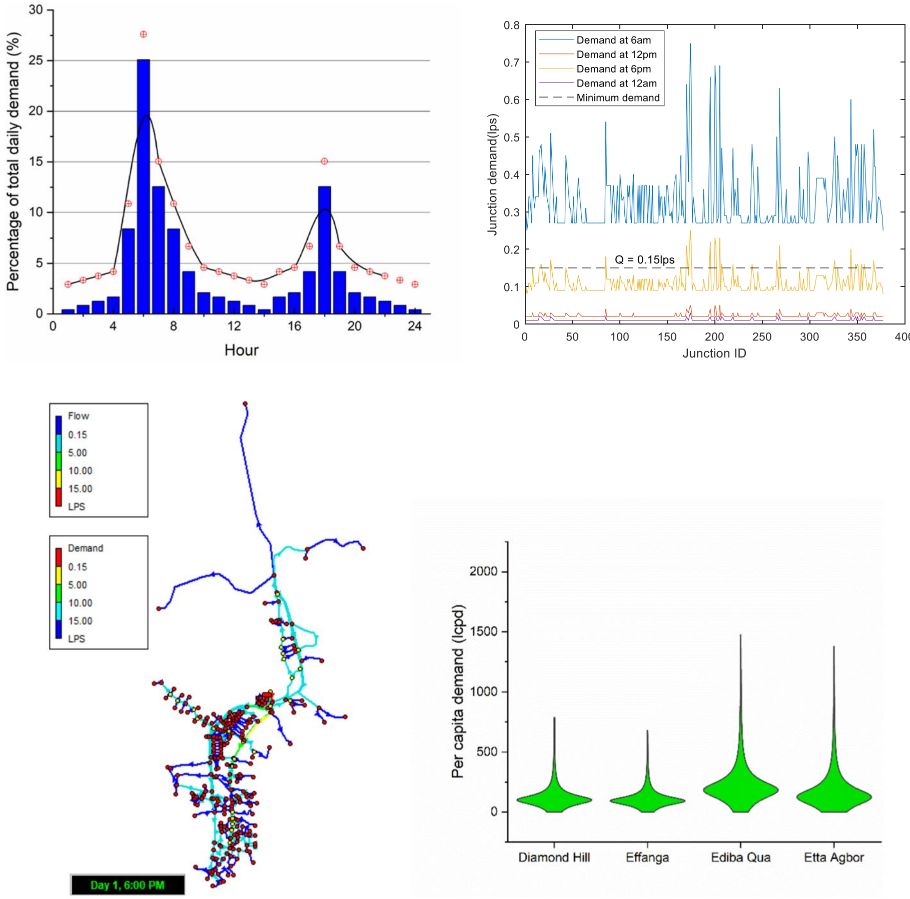
Graphical abstract



Keywords Extended period · Water supply system · EPANET · WaterCAD · Hydraulic parameters

1 Introduction

Though Nigeria is blessed with abundant freshwater resources, access to potable water for domestic applications remains a mirage. Even at the heart of the most urbanized areas, access to piped water is a luxury that only a privileged minority enjoys. The majority of municipal water supply facilities are plagued by inefficiencies caused by pipe breakage, leaks, water theft, poor pressure, insufficient and intermittent demand, and inaccurate and unsustainable water pricing that does not represent current economic realities. Yet, the safest option to offer consumers drinkable water in appropriate quantity and recommended quality is through a piped water supply (Ghorpade et al., 2021). Although water supply systems (WSSs) are designed following established standards and guidelines, their operation usually falls short of expectations (Abu-Madi & Trifunovic, 2013). For an efficiently designed and operating water supply system (WSS), best practices mandate that the water delivered to or consumed at various connection points (nodes) should match the demand pattern at those points over time. As long as the nodes are linked within the same supply network, the time series which depicts water delivery should typically reflect the time series showing the usage of water at each node. However, when there is some sort of disruption within the system resulting from a mechanical malfunction, variation in nodal demand, damages caused by earthquakes, or perhaps a sudden activation of a fire hydrant, nodal pressure reduction within the WSS can drop below acceptable minimum. When the pressure hits these low levels, the water supply in the affected nodes will decline as well (Paez & Filion, 2020). While WSSs are intended to function optimally, consumers are always assured of a potable and well-pressured water supply all through the day (wire et al., 2015).

The goal of WSS simulation is to offer quick and accurate solutions to differential-algebraic equations used to develop a WSS's mathematical representation and as a result, has become an extremely valuable tool in assessing WSS response to various operational actions (Paluszczyszyn et al., 2015). In WSS simulation, three types of techniques can be used: steady-state simulation, extended-period simulation, and transient simulation. Simulations of steady states show the operational state of the WSS, this implies that, the pressures and demands are not changing over time at any given point in the system. However, in a typical WSS, the loading conditions and states are highly variable during the course of the day. In many studies, an extended period simulation (EPS) is utilized to assess the functionality of a WSS over the long run (Bhave, 1988; Tabesh et al., 2004; Paez et al., 2018). This form of sophisticated analysis is generally used to monitor the pressure, fluxes, and water levels in a system and its stockpile repositories (reservoirs) at specified moments and under distinct pressure-driven states. This also allows for the monitoring of the adequacy of pressure, flow, and velocity in a framework exposed to different external, pressure-driven activities ranging from mundane, diurnal changes to the quick withdrawal of water for firefighting. By analyzing data on the pressure-driven performance and demands of the system over periods of 6, 12, 24, or 48 h, the designer can assess the system's ability to meet these varying operational needs in a reliable manner (Paluszczyszyn et al., 2015). Transient simulation provides the most reliable replica of a WSS because it incorporates transient assessment and analyses volatile flow scenarios. Due to the complexity of this methodology, its use has not been widely adopted as it is primarily suited for specific applications (Paluszczyszyn et al., 2015).

Simulating the complicated behavior of a water supply system (WSS) poses multiple challenges. Therefore, replicating a WSS in its entirety via an analytic-based method requires advanced techniques to address this complexity of various interacting components. However, a solution can be gotten for tree-molded networks by applying a flow continuity equation at all the nodes, but practically, WSSs are only occasionally perfect tree-molded networks. The evaluation of a water network in a loop design presents additional difficulties. Notwithstanding, several methods have been proposed over the last few decades to analyze a WSS. The most notable methods include: Hardy Cross' method (Cross, 1936a), method of linear theory (Wood & Charles, 1972), Netwon-Raphson technique (Shamir & Howard, 1968), linear graph theoretical approach (Kesavan & Chandrashekar, 1972), optimization techniques (Collins et al., 1978; Todini & Pilati, 1987). The approaches outlined above and their hybrid combinations have been applied to simulate pressure-driven systems, resulting in considerable advances to numerous well-known hydraulic modeling tools over extended periods. Some of the key simulation programs that have benefited from the introduction and improvement of diverse modeling methodologies are EPANET 2.0, WaterGEM, H2Onet, and WaterCAD (Agunwamba et al., 2018).

Several studies have been conducted on the use of hydraulic simulators for assessing system performance, as well as enabling robust network management. Mabrok et al. (2022) adopted EPANET to model and analyze a selected area in Kuwait by applying an extended period simulation model. In their study, an extended period simulation was performed to identify residents that were affected by the aging of water (water quality) in pipes at different time intervals (<24 h, 24–48 h, 48–72 h, > 96 h). In a genuine contextual analysis carried out in Italy, an extended period simulation (EPS) model was coupled with a few serviceability pointers that were utilized to assess the framework's performance during interferences brought about by isolated valves (Giustolisi et al., 2008). Paez and Filion (2020) made and tested a structure for assessing mechanical, water-driven, and firefighting durability in extended-period simulations (EPSs) under fluctuating scenarios. An extension of the global gradient algorithm (GGA) was used in a study by Todini (2011), to solve the concerns with unsteady state caused by varying head water storage systems, like tanks, in extended period simulations (EPS) of networks with loops for distributing water. Filion and Karney (2002) introduced a mixture model that productively tracks the full scope of pressure-driven conditions in a framework over an extended period, from consistent state to water hammer, by coupling a transient test system with a repository routing plan. Their model showed high routing efficiency and was proposed for distinguishing the critical state in a framework that will deliver the most serious overloads.

Calabar Metropolis water supply system was designed to perform under continuous water supply guidelines, but most time operates intermittently. To look at these varieties of water utilization over the day, an extended period analysis is vital. This paper presents an extended period model carried out in EPANET and WaterCAD which are equipped for demonstrating a large number of pressure-driven situations and modifying tank levels in a framework over an extended period. The model is partitioned into two sections, every one of which fills an alternate need: the first is a transient test system, which duplicates the pressure-driven conditions in a conveyance framework utilizing the full conditions of transient flow specific points in time; the second is a time-stepping plan that monitors coherence conditions in a system's tanks and reservoirs and updates water levels at each extended time step using pressure-driven gages (Filion & Karney, 2002). This study's fundamental contribution is to underscore the significance of long-term modeling of the Cross River water supply system (CWSS) all through the contextual investigation of four chosen zones in Calabar, which can be summed up in the accompanying sub-contributions: (i) An outline of the CWSS was introduced and explained – no published article has explained how the different phases of the interaction are connected. (ii) Building an EPANET/WaterCAD-based model of the CWSS hydrodynamics predicated on a rough map of the piping system, pressure check, siphon, water treatment plant, and water tank interconnectivity this was a necessary move toward providing a reasonable understanding of the effect of varying demand patterns on the municipal water supply. (iii) By leveraging the problem-solving capacity of time-series modeling and feedback control design principles, it was possible to capture acute hydraulic changes within the system using the hydraulic simulators.

2 Methodology

2.1 Study area

Calabar serves as the state's capital in Cross River, which is situated in the southern district of the State. It has coordinates between longitudes 8°19′30″E to 8°24′00″E of the Greenwich meridian and scopes 04°57′00″N to 5°04′00″N of the equator. Calabar lies in the tropical central zone of southern Nigeria, with high relative humidity, high temperatures, and a significant amount of rain. The region has yearly precipitation of 2759 mm and a typical yearly temperature of 26.1 °C. The city has a boundary that covers an area of 406 square kilometers (sq. km) and an expected populace of 605,000 in 2021 (NPC, 2016) with a growth rate of 4%. The principal wellspring of the water supply of Calabar metropolis is the great Kwa River which is situated on the east and the Calabar River on the west of the city. Calabar is located on a tenderly slanting plain with mean ocean levels fluctuating from 09 m (Eta Agbor) to 85 m (Ikot Effanga). The water is siphoned from the riverbank to the treatment plant, where it is dealt with utilizing different techniques. Ikot Effanga, Ediba Qua, Diamond Hill, and Eta Agbor distribution zones are the four fundamental zones for pipe-borne water appropriation in Calabar metropolis. Each zone has its raised water tank, from which gravity-fed water is provided through an organized system of pipes and connectors. The pipes range in size from 75 mm diameter pipes used to disseminate water to homes to 600 mm diameter pipes used to convey water from capacity tanks. Figure 1a shows Cross River State on the map of Nigeria, while Fig. 1b shows Calabar metropolis.

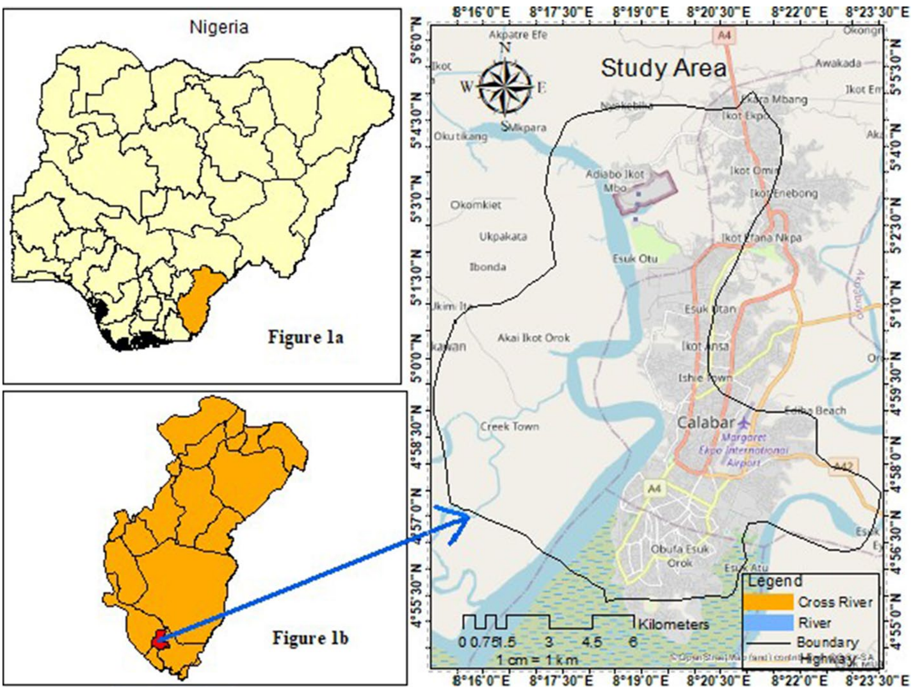


Fig. 1 Map of Nigeria showing cross-river state. Figure 1b: Map of Calabar Metropolis

2.2 Data collection

To perform an extended period simulation, data such as the population of the various zones, general layout map, nodal elevations, nodal demand, and time pattern of demand consumption are required. Population statistics were obtained from the National Population Commission (NPC) and the Cross River State Water Board Limited (CRSWBL, 2021). Unlike the research carried out by Agunwamba et al. (2018), time demand patterns were introduced into the population demand to effectively model extended period demands of the water supply system (WSS). Other parameters such as fire demand, losses due to bends, and unaccounted-for-water (UFW. i.e., water that leaves the system without being accounted for. E.g., leakages) from the system were all estimated and applied in the analysis of the water supply system. The per capita demand per household and the estimation of the number of individuals per household of the four distribution zones were likewise evaluated to acquire the per capita usage for every conveyance zone. The demand at a given node was generated by multiplying the per capita usage by the number of buildings that are supplied by each node and the usual consumers per home was then converted totally to LPS for uniformity in the simulation study. The buildings were assigned to nodes using Thiessen's polygon approach with which an estimated average of buildings around every node was considered. The simulation was run for every distribution zone, as each zone's elevated water tanks (EWTs) supplied the household in that zone.

2.3 Overview of hydraulic simulators (WaterCAD and EPANET)

EPANET simulation package is a computer program that mimics pressure-driven and water quality conduct in compressed pipe networks over short and extensive intervals. The US Environmental Protection Agency (USEPA) created EPANET as an open-organized, public-space pressure-driven water quality model that is used all over the globe (Rossman, 2000). EPANET has turned into a well-known instrument for assessing both complicated and fundamental water distribution networks in both advanced and non-industrial nations. Experts and analysts have involved EPANET's simulation capacities in the plan, operation, and improvement of various water network conveyance frameworks (Adeniran & Oyelowo, 2013). The two parts of the EPANET PC model utilized for water distribution network investigation are the data source file and the EPANET program. The information document characterizes the line (pipe) system elements, nodes (pipe ends), and control parts (like siphons and valves). For pressures at nodes and flow rates in pipes, the PC program applies nonlinear energy conditions and linear mass conditions (Anisha et al., 2016). WaterCAD is a product instrument for demonstrating water distribution networks created by Bentley Systems Inc. that runs on Windows. WaterCAD aided design utilizes gradient techniques to tackle frameworks of conditions that portray both heads and discharge in pipe networks (Todini & Pilati, 1987). The gradient approach uses a matrix formulation to solve network problems in line with today's computer capabilities. Individual energy equations are supplied for each node in the formulation enabling a simultaneous solution of both nodal heads and individual line (pipes) flows (Agunwamba, 2000).

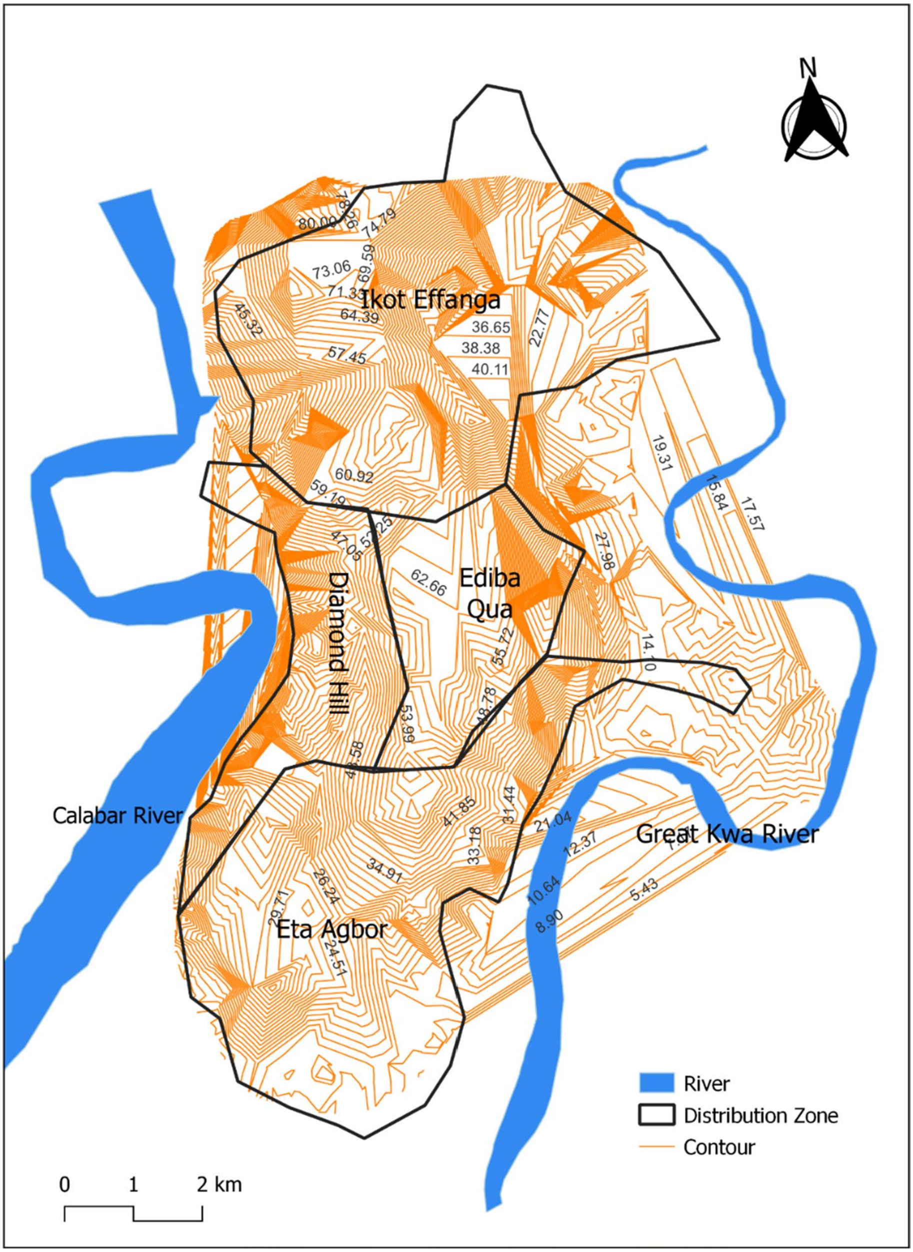


Fig. 2 Topography of Calabar metropolis and the four distribution zones. (*Source*: Authors)

2.4 Model construction and definition of attributes

As part of the EPANET software model (skeletonization, Fig. 2), each of the elevated water tank (EWT) map zones was individually loaded into the software and used to simulate the existing pipe-borne water network, as well as the tank locations, the pipes, and the nodes (nodes), in a geometric network topology. The skeletonized WSS of Diamond Hill zone comprises 392 pipes with diameters going from 75 to 600 mm, 329 nodes, and 1 tank. The subsequent zone (Ediba Qua) comprises 283 pipes with diameters also going from 75 to 600 mm, 257 nodes, and 1 tank. The next distribution zone (Eta Agbor) which incidentally is the biggest zone comprises 675 pipes with diameters going from 75 to 600 mm, 568 nodes, and 1 tank. The last distribution zone (Ikot Effanga) comprises 324 pipes with diameters going from 75 to 600 mm, 290 nodes, and 1 tank. The plan of these components (pipes, nodes, tanks, etc.) in the virtual environment follows the connection of pipes and nodes by utilizing the tool palette accessible in the computer (PC) model. The result of these models is intended to calculate pressures in the framework, velocities, head losses/energy dissipated, pipe flow rates, reservoir level, influxes, surges, and water-driven grade with varying time demand patterns as the major determinant (Agunwamba, 2000). Figures 3a, b and 4a, b show the map of the different zones (Diamond Hill, Ediba Qua, Eta-Agbor and Ikot Effanga) before simulation at the different time patterns.

To predict everyday water usage via EPANET, pressures and flows at every node and pipe were assessed and monitored in turn, respectively. The attribute information of the nodes, pipes, and EWTs (Table 1) was inputted into the simulation program. The ground elevation of these parts which decides the pressure and flow rate of water to houses was

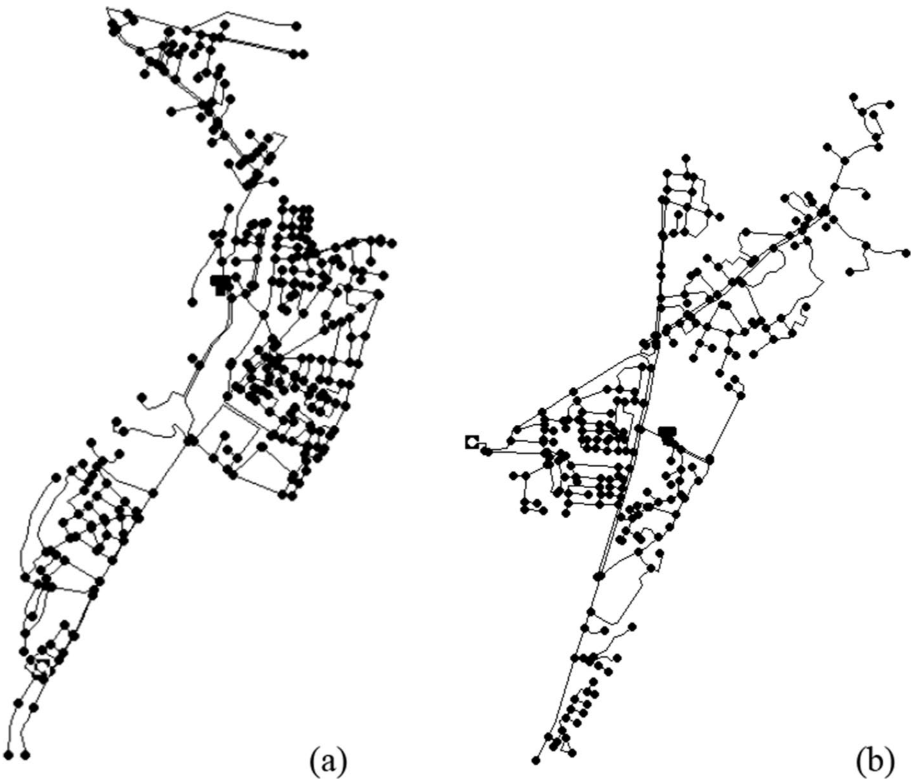


Fig. 3 **a**, **b**: Diamond Hill and Ediba Qua WSS on EPANET software

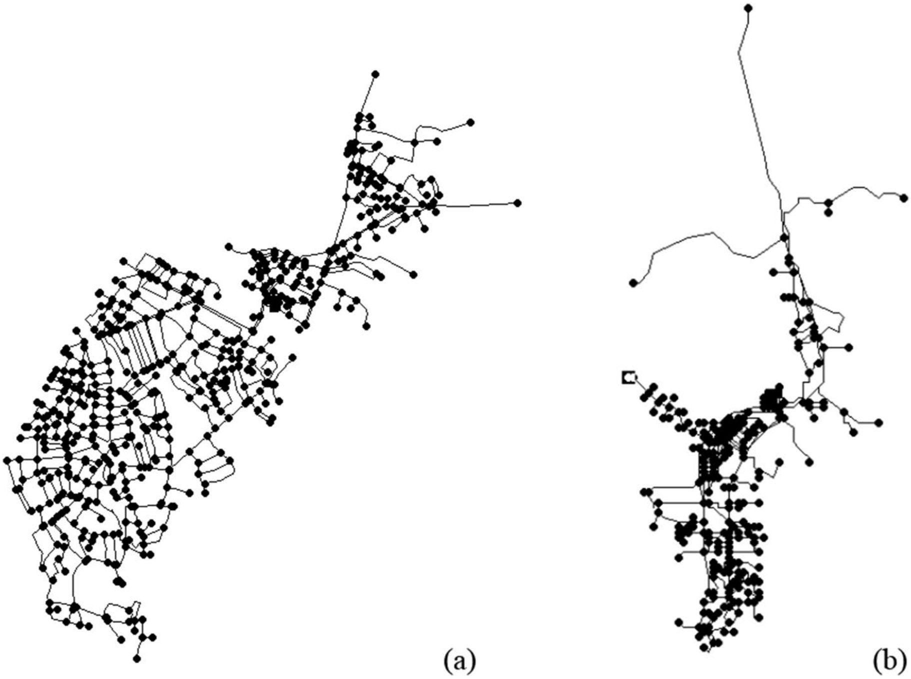


Fig. 4 **a**, **b**: Eta-Agbor and Ikot Effanga WSS on EPANET software

Table 1 Nodal and pipe attribute data within the network (WSS)

Feature	Input	Attribute
PIPE	Pipe ID	Px
	Length (m)	Auto-generated for every pipe
	Diameter (mm)	75, 110, 160, 200, 225, 350, 500, 600
	Roughness	140
NODE	Node ID	Jx
	Elevation (AMSL)	Node specific
	Base Demand (LPD, Per Household)	Varies
	Demand Pattern	Pattern 1 (Pa 1)

likewise inputted, particularly as CRSWBL utilizes a gravity-fed conveyance framework as indicated by Harding (2008).

2.5 Extended period pattern and design criteria

The 24 h pattern was obtained from fieldwork done by the Cross River State Water Board Limited (CRSWBL) and was adopted for this study. It was assessed by measuring demand for 24 h at 20 different locations in Calabar. The observed water demand was maximum in the early mornings and late evenings, thus the average for each hourly interval was determined and utilized. This concept also played a role in the extended period simulation (EPS) of both pressure and flow rate at different times of day (6:00 am, 12:00 pm, 6:00 pm, and 12:00 am). Figure 5a, b shows the daily consumption pattern and per capita demand for various zones.

The least residual pressure for pipe network systems changes from one water organization to another and between locations, according to Ayanshola and Sule (2006). However, a system pressure of 25 m minimum and 70 m maximum should suffice (Bhardwaj, 2001). The American Water Works Association (1940) states that there is a 15 m threshold and a 70 m maximum. Any pressure less than the 15 m threshold is deemed inadequate and may imply severe water loss at the node. Similarly, hydraulic shock may occur when the pressure surpasses 70 m, hence, may result in damage to the water mains (Wire, 2015). It is also allowed to have a minimum flow rate of at least 0.15 L per second (Bhardwaj, 2001). A flow rate less than the minimum would cause water flow issues at the customer's stop tap.

3 Results and discussion

The simulation results indicate the fluctuations in pressure, velocity, and water demands caused by the extended period demand patterns at each of the four water supply zones concerned. Both simulators were used to analyze the system for all the zones concerned. The consumption pattern of Calabar Metropolis exhibits double maxima at 6:00 h and 18:00 h situated twelve hours apart. The amount of water consumed at 6:00 h accounts for 25% of the total daily demand, while the amount consumed at 18:00 h accounts for 12.5% of the total daily consumption which is half of the demand at 6:00 h. More than half of the daily water consumption, precisely 58.6% is exerted within a five-hour window starting from 5:00 h to 9:00 h. This period is characterized by numerous household activities that exert intense water demand such as bathing, toilet flushing, cooking, laundry, house cleaning, and washing cars. Most of these activities are repetitive daily and consume lots of water. In the same vein, 20% of the total daily demand occurs in the evening period between 17:00 h

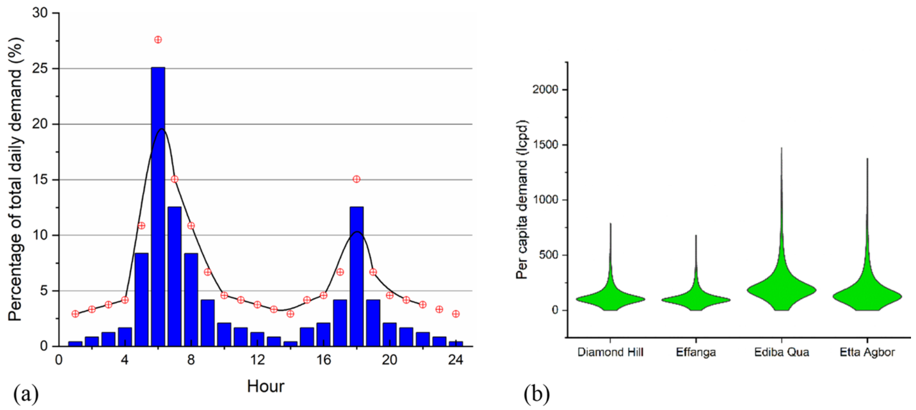


Fig. 5 **a** Daily consumption pattern, **b** per capita demand for various zones

and 19:00 h for almost the same reasons adduced for the morning peak. The other 22% are almost evenly distributed among the remaining hours of the day.

3.1 Pressure and demand variations of the extended period simulation in the various zones

3.1.1 Diamond hill zone

The system had fluid pressure lower than 15 m at 33 nodes in the morning (6:00 am), accounting for 10% of the nodes operating below the design requirements specified for nodes. The remaining 295 nodes were within permissible limits. When the minimum pressure criteria (MPC) for nodal demands such as in taps, showers, field watering are not met, energy usage, leakages, and the occurrence of pipe breaks may all be decreased (Ghorbanian et al., 2015). When pressures fall below the established standards, however, systems become more prone to mild-pressure malfunction, which can be hydraulic (e.g., the failure to produce the proper flow) or safety-related (e.g., risks from a transient event). Designers should have an exhaustive comprehension of the repercussions and compromises. Simultaneously, the flow was within serviceable limit values, aside from 15 pipes (4%) spread around the zone. By early afternoon, water pressures in this zone were within the given guidelines as just 14 nodes (4%) had low pressures around similar range at dawn. The flow rate fell significantly with only pipelines having a diameter larger than 200 mm demonstrating substantial flow rates. The evaluation found that at sunset (6:00 pm), the pressure was low with 17 nodes (5%) indicating low pressures while 121 pipes (31%) had flow rates short of 0.15 LPS. The water flow rate was much greater and enough for appropriate supply between the morning and night hours when water usage is at its highest. The failure of the system to satisfy MPC for some nodes within the network at 6:00 h can be attributed to the high demand exerted on the system at that time of the day. The situation is further complicated by pipe leakage along the network and property at high elevations since the system is gravity driven. Because the area is fed by gravity, properties at higher altitudes are the most common causes of low pressures. However, Pumps may be required to transport water to underserved regions in the mornings (6:00 a.m.) and at night (6:00 pm), when the water demand is greatest. The pressure and flow variations are shown in Fig. 6a, b. ANOVA was

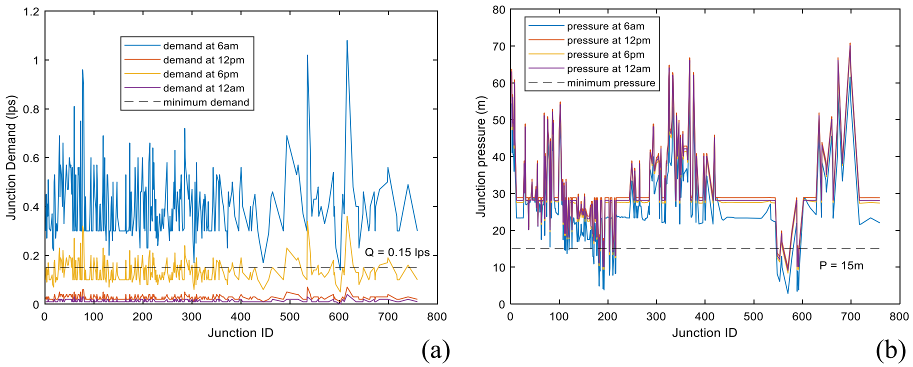


Fig. 6 **a** Extended period variation of nodal demand at different time patterns in Diamond Hill Zone. **b** Extended period variation of nodal pressure at different time patterns in Diamond Hill Zone

performed to ascertain if there is any significant difference between the values of pressure, demand, and velocity for selected periods. The periods considered are 6 am, 12 pm, 6 pm and 12 a.m. for diamond hill zone. There was a significant difference between the values of pressure as the period of the simulation was extended ($p = 0.00$; F (17.7) > F_{cr} (2.61). However, since there was a level of difference, turkey's post hoc multiple comparison test was adopted to ascertain where the difference lies (Nnaji et al., 2019). The comparison between pressures at 6am and 12pm ($P = 0.001$), 6 am and 6 pm ($p = 0.001$), and 6am and 12 am ($p = 0.001$) are the contributors to the difference noted in the test. Unlike pressure, no statistically significant difference was noticed in demand and velocity.

Figure 6a, b shows the extended period variation of nodal demand and nodal pressure at different time patterns in Diamond Hill Zone respectively. The extended period spatial distribution of predicted hydraulic parameters for the Diamond Hill Zone is depicted in Fig. 7a–h.

3.2 Ikot Effanga zone

The pressure and flow variations of Ikot Effanga zone are shown in Fig. 8a, b. At dawn (6:00 am), the WSS recorded pressures less than the threshold in about 105 of the nodes which represents 36.33% of the total nodes in that area likely due to higher nodal elevations and pipe roughness (Goziya et al., 2020). For a WSS to function and for water to be delivered to all consumers' taps, a minimum amount of pressure is required. On this note, water operators must ensure to maintain an operating pressure equal to the minimum or above to meet water demand, especially when considering topological factors (e.g., altitude changes inside cities) (Nikalaos et al., 2020). Flow rate at the early hours of the day is depicted to be below 0.15 L in 10 pipes and higher rates were noticed from the major conduit of the EWT in that zone. Low flow rates could likewise be ascribed to low pressure which was seen on account of this system at damn. Pressure around early afternoon had comparative qualities to what was obtained at dawn. However, a slight discrepancy was noticed with about 102 nodes having pressures not exactly as stipulated. Around early afternoon, the flow almost tumbled to zero as anticipated. Here, just 75 pipes (23.29%) had adequate flows while 249 were lacking in the expected rate of 0.15 LPS. By nightfall (6:00 pm), pressure improved, with 186 nodes exceeding the allowable limit and 177 pipes having flows over 0.15 LPS. This is evident that an increase in pressure can also influence the increase in flow rate. Changes in water flow can cause sediments in the distribution system to resuspend, thus resulting in the deterioration of the drinking water's aesthetic attributes (Markku et al., 2006). Ikot Effanga has the city's highest elevation. This might imply why there was low pressure over 100 nodes all through the simulation periods of the day. These regions with their high heights and low-pressure rates are generally inclined to endure discontinuity in water supply, in this way diminishing their general admittance to pipe-borne water. ANOVA was performed for an extended period simulation of hydraulic parameters in the Ikot Effanga Zone. There was no significant variation between the values of pressure throughout the selected extended period of simulation ($p = 0.76$). But for demand and velocity, there were significant variations in the extended period selected with p values of 0.00, respectively. Upon these differences noticed, a further test was conducted to reveal the source of the difference. All the periods (6 am, 12 pm, 6 am, 12 am) varied, significantly contributed to the difference ($p = 0.001$). Figure 8a, b shows the extended period variation of nodal demand and nodal pressure at different time patterns in Ikot Effanga

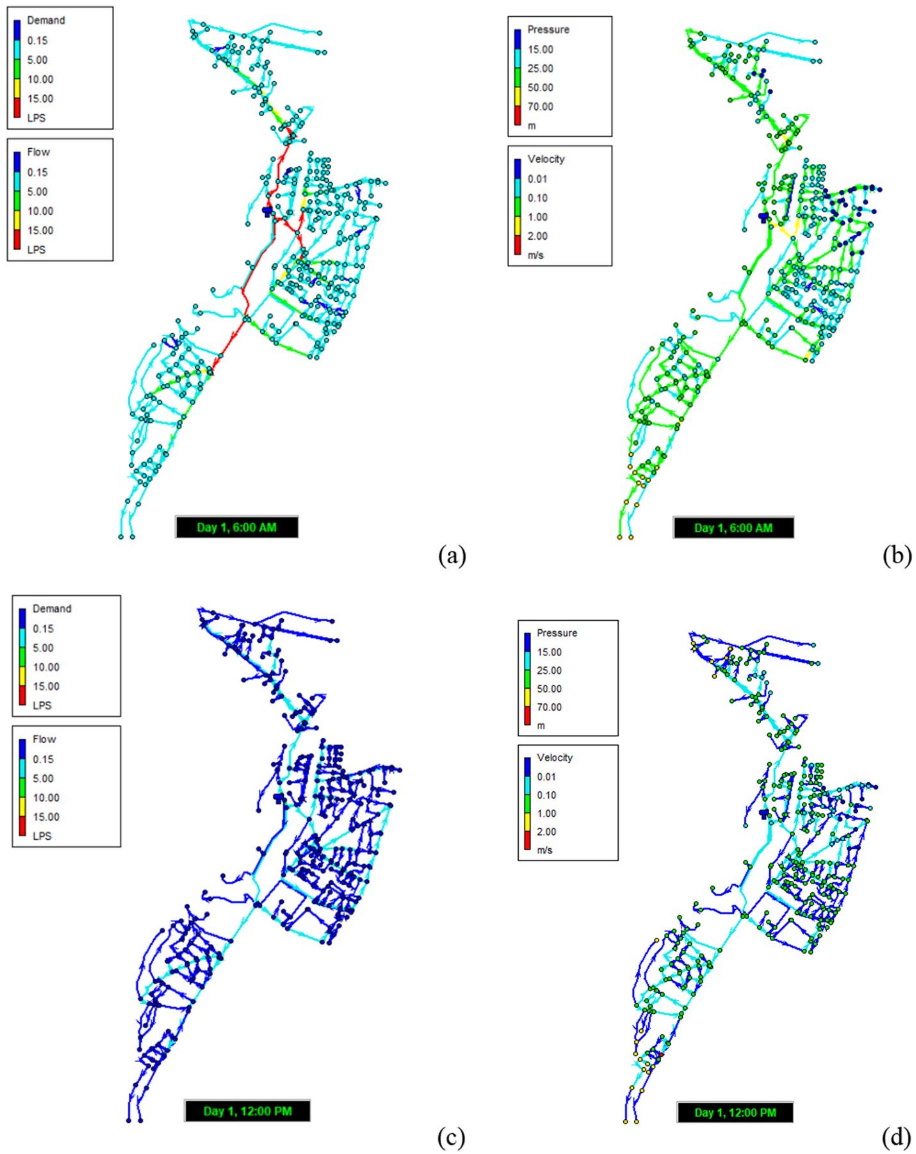


Fig. 7 **a**–**h** : Extended period spatial distribution of predicted hydraulic parameters for Diamond Hill Zone

Zone respectively. The extended period spatial distribution of predicted hydraulic parameters for the Ikot Effanga Zone is depicted in Fig. 9a–h.

3.3 Ediba Qua zone

The pressure and flow variations of Ediba Qua zone are shown in Fig. 10a, b. At precisely 6:00 a.m., the pressure fell below the 15 m threshold at 53 nodes likely due

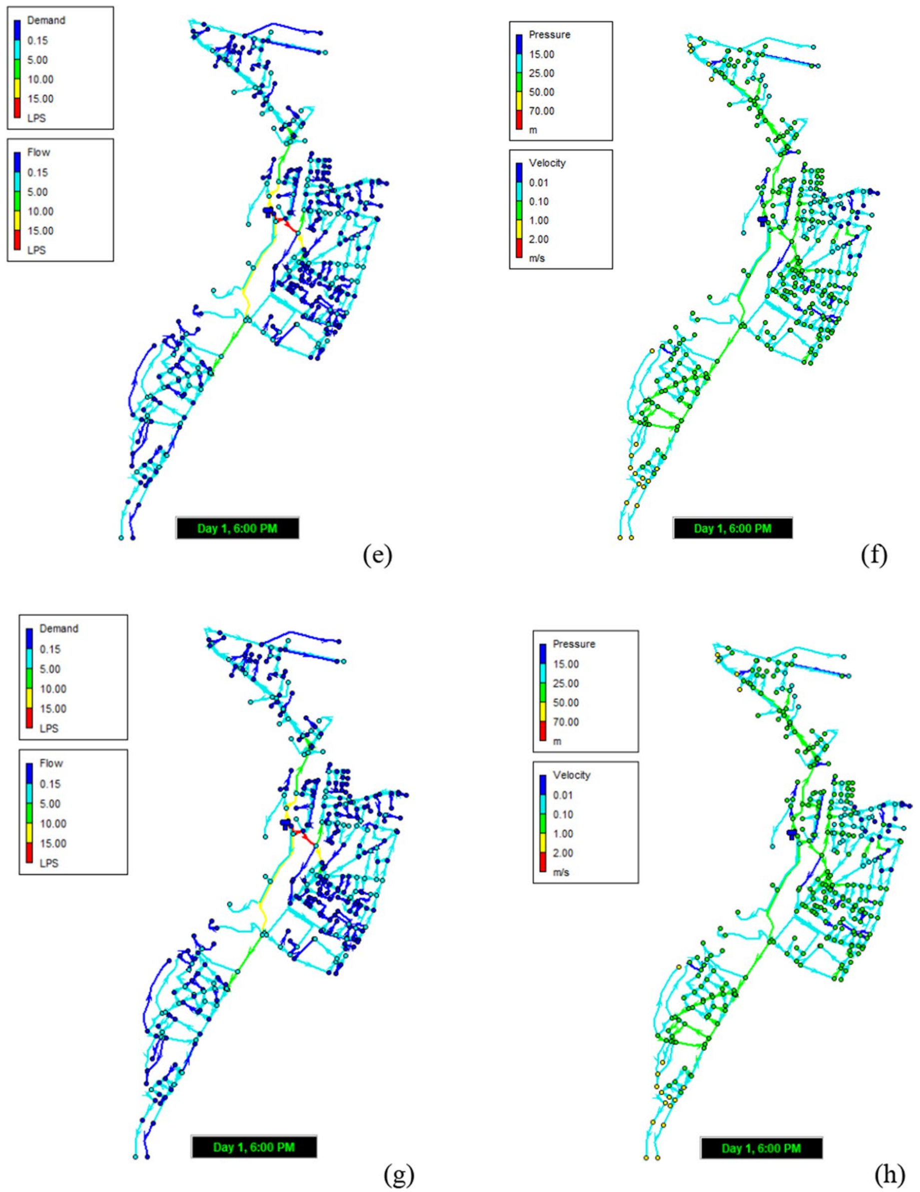


Fig. 7 (continued)

to low draw-out from the system (Ayanshola & Sule, 2006). No node exhibited pressures higher than the 70 m standard. In contrast, 109 pipes are said to have flow rates below the allowable limit of 0.15 LPS. Furthermore, the flow of water through the pipes seems to be more when the diameter of the pipes is small across the EWT region northwards. When low flow rates are noticed in a WSS, it means that the diameter of the pipes used is too large or that the pipe roughness is high (Nyende-Byakika, 2018).

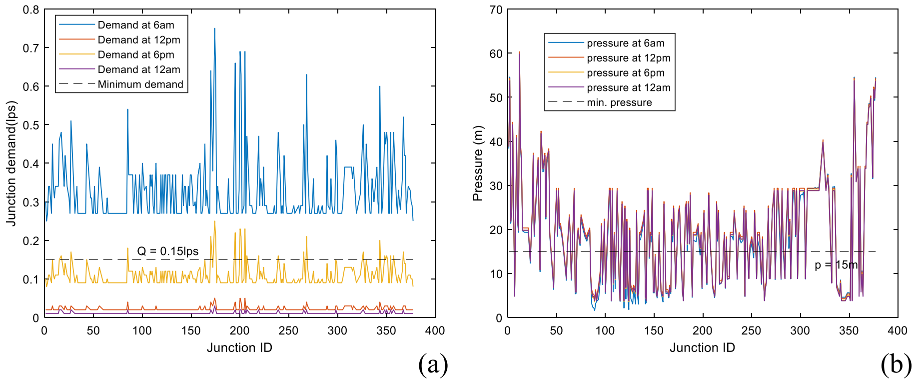


Fig. 8 **a** Extended period variation of nodal demand at different time patterns in Ikot Effanga Zone. **b** Extended period variation of nodal pressure at different time patterns in Ikot Effanga Zone

However, for this system, the noticeable increase in flow rate further buttresses the fact that the pipe diameter used at EWT northward is small. In this vein, it is critical to choose the right pipe size to produce the highest pressures and flows while avoiding both under- and oversizing, which raises both capital and operating expenses. Pressure around early afternoon was quite adequate having only 27 nodes short of the acceptable pressure limit with no node having pressures higher than 70 m indicating few regions with no reason for very low and exceptionally high-pressure worries respectively while the flow rate diminished substantially for most parts of the zone. Here, low draw-out was also responsible for the decline in flow rate. The assessment likewise showed that, at sunset (6:00 pm), the pressure in system significantly improved based on what was derived at the early hours of the day, nonetheless, at this moment, the flow rate improved likewise. However, about 63% of 283 pipes in the zone had flows under 0.15 LPS which could be because of the all in all low demands at that time of the day. The consequence of having pressures over the standard is that the water could obliterate the installations by causing successive breakage of pipes and nodes (Mesalie et al., 2021). Minimized pressure has been shown to benefit the WSS's economic life, as water losses due to leaks and breaks are reduced, and equipment (pipes, etc.) is burdened less owing to pressure variations within 24 h (Patelis et al., 2020). The Ediba Qua EWT was seen to be situated at a ground level moderately higher than different regions inside the zone, this necessitated the reduction of low pressures inside the zone yet nodes with apparently lower pressures were brought about by pipe leakages and bursts from the mains. The ANOVA conducted on the hydraulic parameters of Ediba Qua Zone showed that there was a significant difference between the extended period for demand and velocity hence a forward test was conducted. Tukey's post hoc test period reveals that all the periods considered had values of demand significantly different from one another with a *p* value of 0.001. A similar trend was noticed in the velocity of the zone. However, the velocity between 12 pm and 12 am were insignificant with a *p* value of 0.899. Figure 10a, b shows the extended period variation of nodal demand and nodal pressure at different time patterns in Ediba Qua Zone respectively. The extended period spatial distribution of predicted hydraulic parameters for Ediba Qua Zone is depicted in Fig. 11a–h.

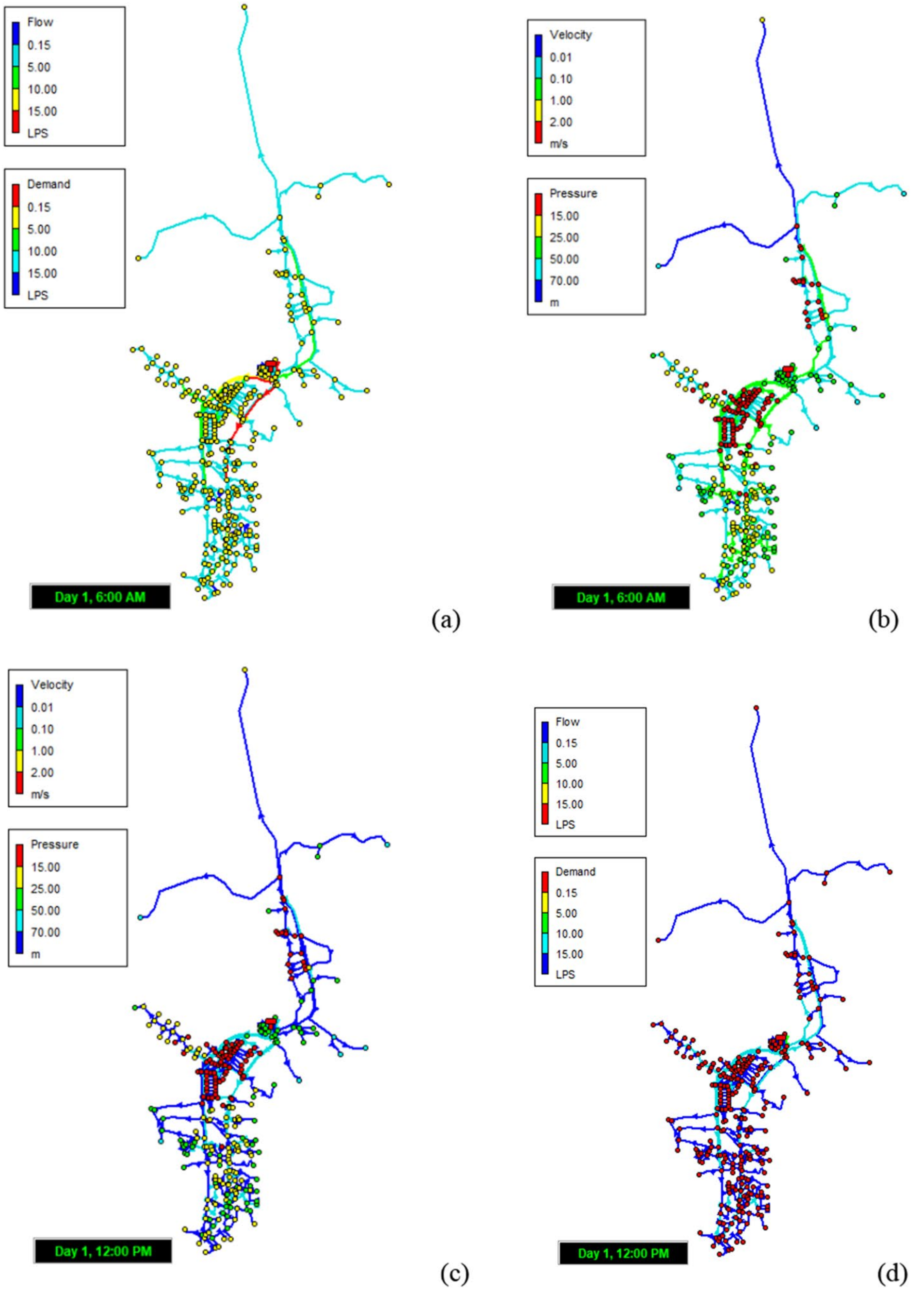


Fig. 9 **a**–**h**: Spatial distribution of predicted hydraulic parameters for Ikot Effanga Zone

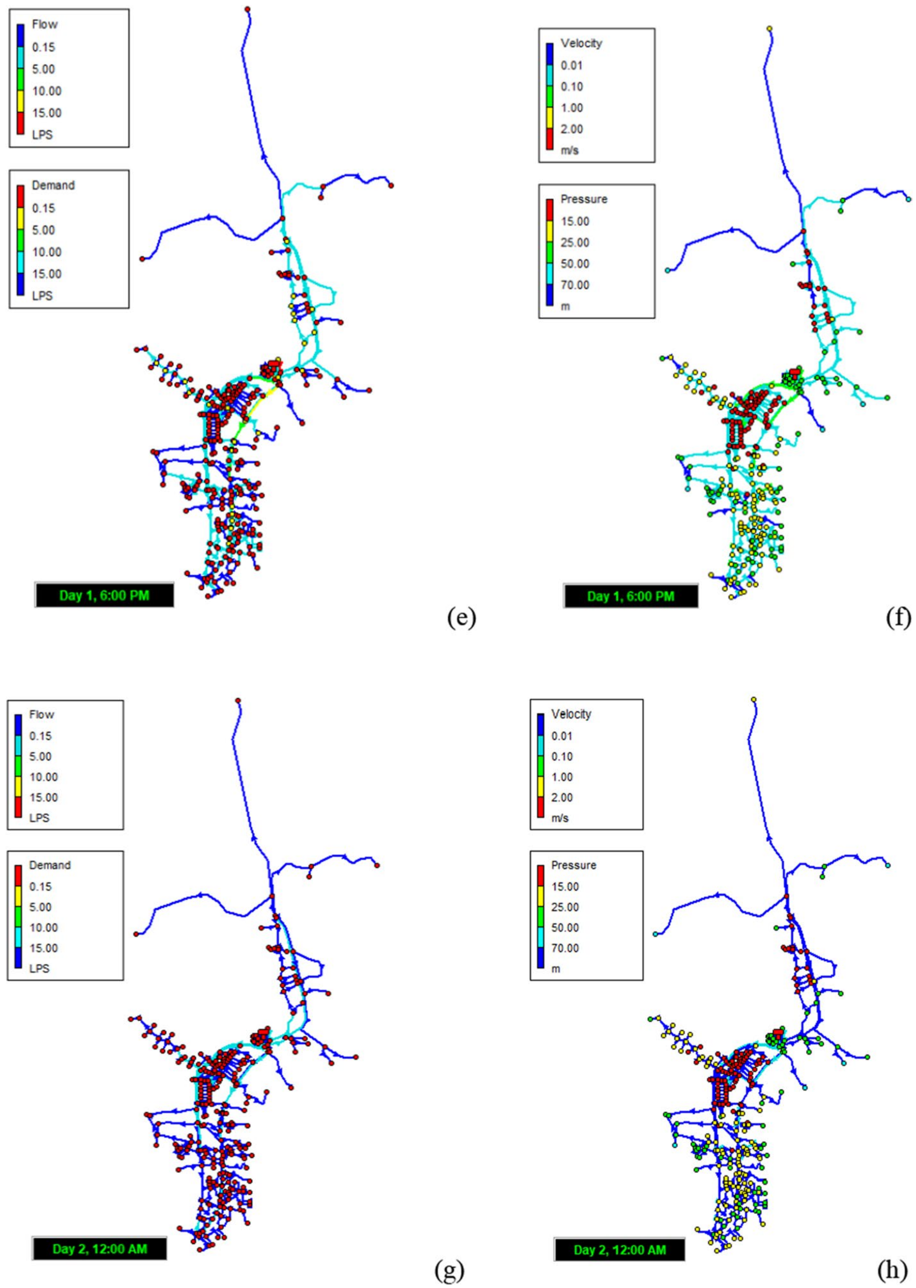


Fig. 9 (continued)

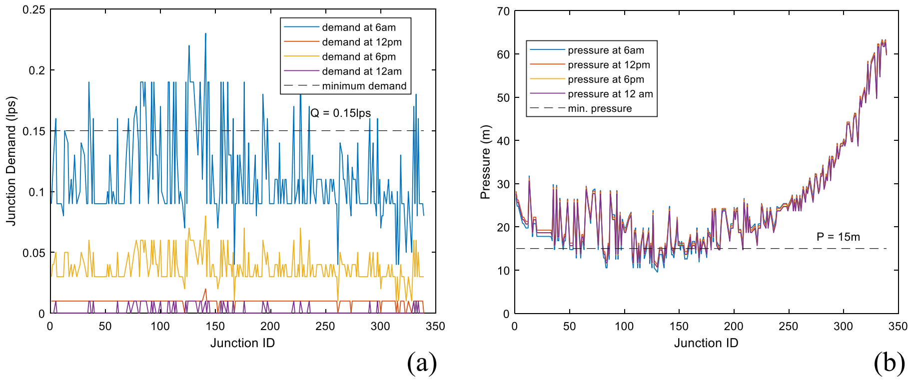


Fig. 10 **a** Extended period variation of nodal demand at different time patterns in Ediba Qua Zone. **b** Extended period variation of nodal pressure at different time patterns in Ediba Qua Zone

3.4 Etta Agbor zone

The pressure and flow variations of Etta Agbor zone are shown in Fig. 12a, b. The simulation revealed that there was generally no low water pressure detected at 6 a.m. However, 8 nodes showed pressures more than 70 m bar. These high pressures could often cause severe pipe bursts and water hammers thus making appurtenances and pipe installations fizzle. The flow rate assessment as of now likewise showed fluctuation inside the zone for most of the system (i.e., 348 of the 568 pipes) to be below 0.15 LPS. By early afternoon, pressures for all nodes were over the 15 m specified and flow rates were lower than 0.15 LPS aside from 45 pipes. At sunset (6:00 pm), no huge contrast with pressure values was recorded by early afternoon. No node had pressures short of the minimum allowable limit, while 221 nodes were above the 50 m clustered around the EWT of that region. Abnormal pressures were present in 7 nodes. The ANOVA result revealed no statistically significant difference between pressure levels that were varied for the selected extended period simulation ($p = 0.89$) (Fig. 3), but demand and velocity recorded significant variations with p values of 0.00 ($p = 0.00$). A further test was conducted on demand and velocity parameters. Of all the periods that varied against one another, only the values of 12 pm and 12 am showed insignificant variation. Thus, the other extended period contributed to the variations with a p value of 0.001 ($p = 0.001$). A similar trend was also noticed in velocity where velocities at 12 pm and 12 am showed insignificant variation with a p value of 0.89 ($p = 0.89$). Figure 12a, b shows the extended period variation of nodal demand at different time patterns in Etta Agbor Zone respectively. The extended period spatial distribution of predicted hydraulic parameters for Etta Agbor Zone is depicted in Fig. 13a–h.

3.5 Velocity variations of the extended period simulation in the various zones

For Diamond Hill zone, toward the beginning of the day (6:00 am), water velocity was lower than 0.1 m/s at 153 pipes. However, the other conduits were operating within acceptable parameters. By noon, water velocity was for the most part below the given threshold. The analysis shows that at sunset (6:00 pm), velocity within the system was down with just 82 nodes displaying velocities higher than 0.1 m/s. The velocity was considerably higher

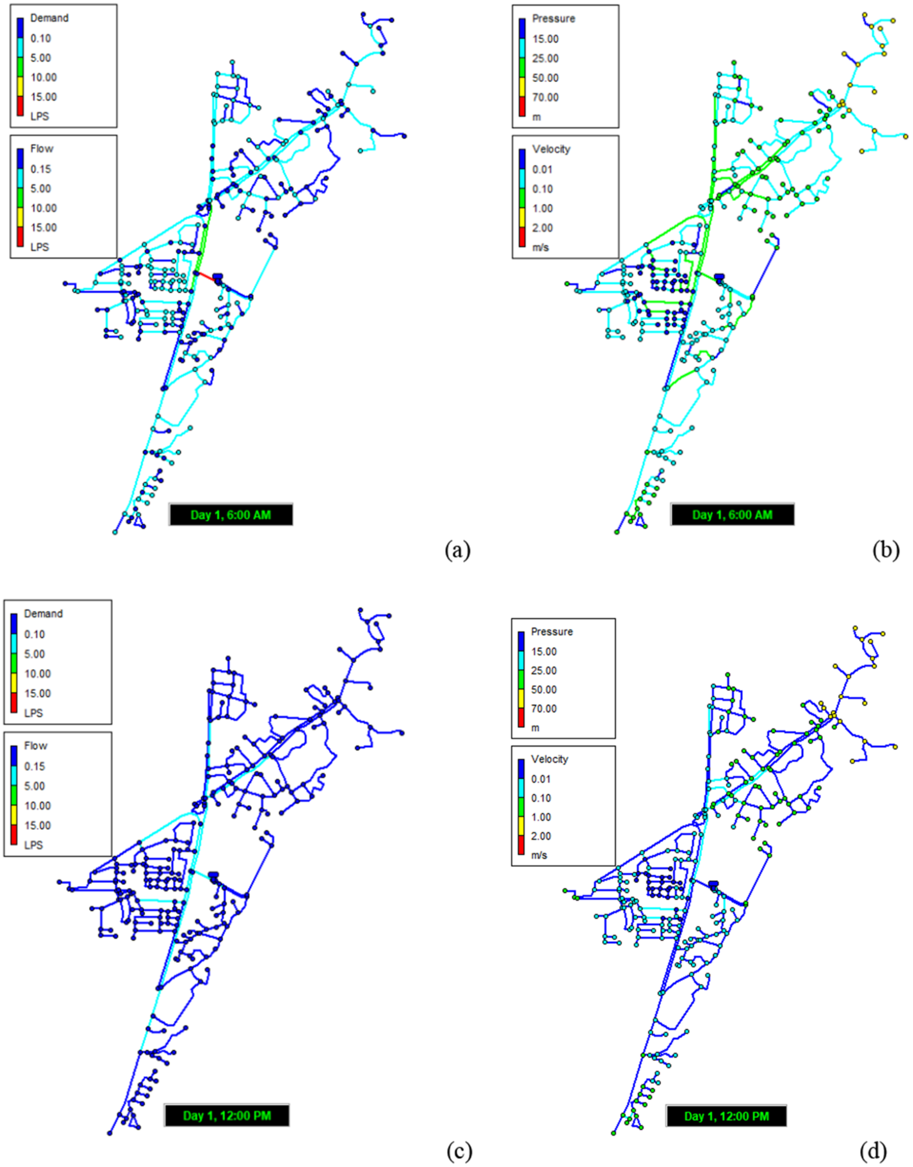


Fig. 11 **a**–**h**: Spatial distribution of predicted hydraulic parameters for Ediba Qua Zone

and adequate for adequate supplies over the morning and night hours when water utilization was at its peak. These pipes with low velocities are located where demand is low while utilizing oversized pipes ranging from 160 to 350 mm for distribution. Low velocities within these areas cause contamination and alteration of water quality. Figure 14a shows the velocity variations of the extended period simulation of Diamond hill zone.

At 6 am, velocity was less than 0.1 m/s in 183 pipes and 139 other pipes had velocities higher than the 0.1 m/s threshold. Velocity at noon fell below the stipulated range which

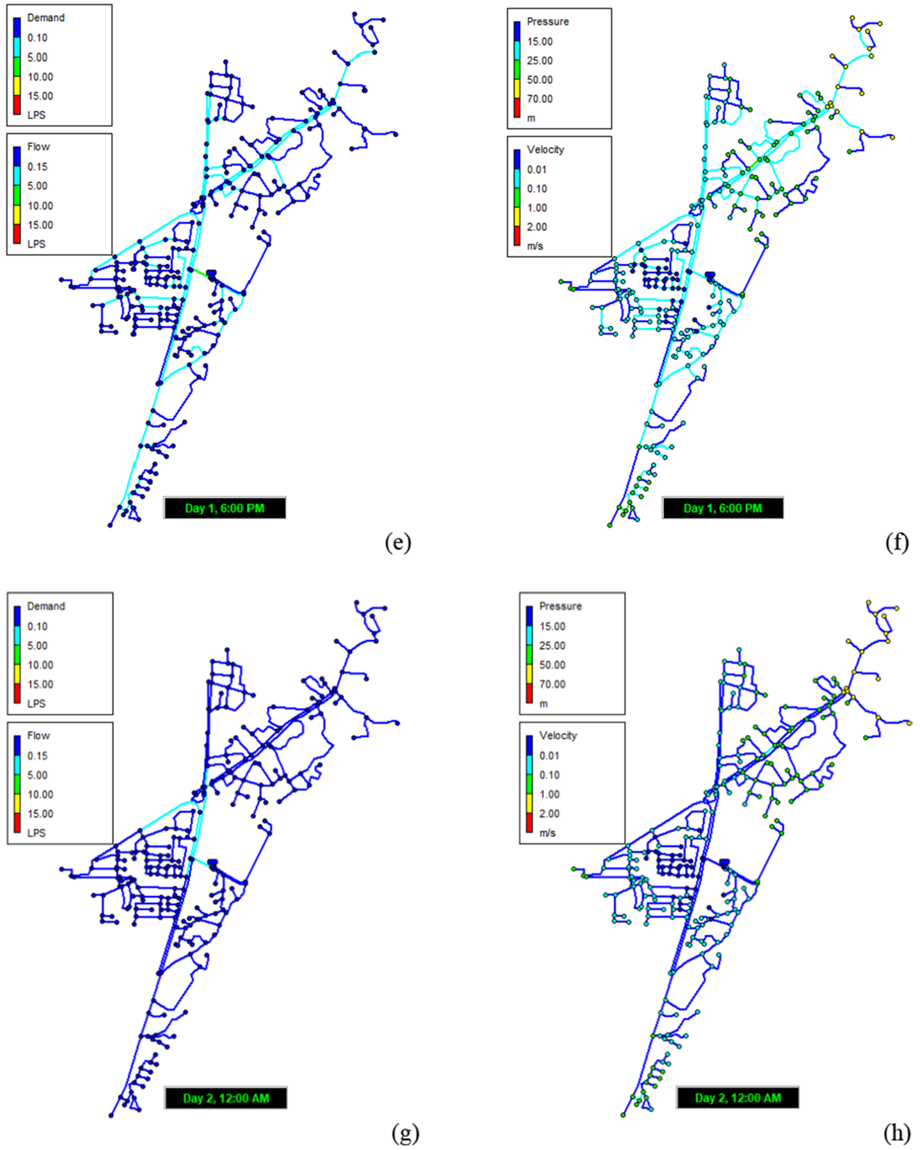


Fig. 11 (continued)

is primarily caused by low demands during the period. By sunset (6:00 pm), velocity had risen, with 38 links exceeding the permitted limit. The delivery would be most sufficient in the mornings and evenings when demand is highest. Ikot Effanga has the highest elevation in the city, with parts near the EWT. This might explain why low velocities were making the area prone to suffer intermittency in water supply and quality. Figure 14b shows the velocity variations of the extended period simulation of Ikot Effanga zone.

At precisely 6:00 am, velocity fell under the 0.1 m/s bar at 224 links. No link exhibited velocities higher than the 2 m/s standard but an are depicted higher velocities which

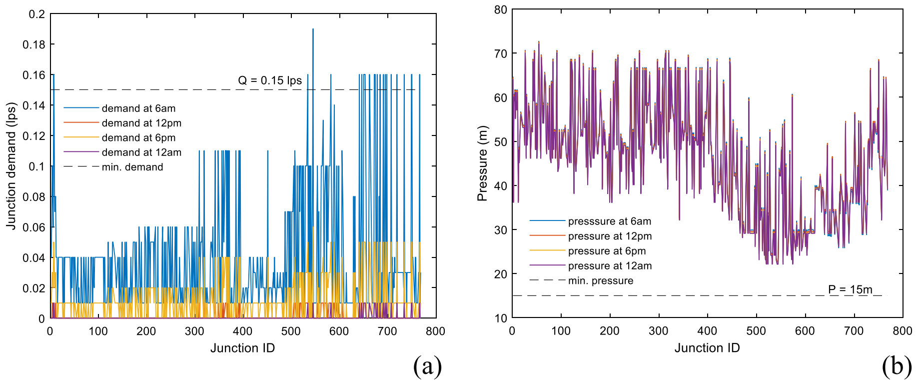


Fig. 12 **a** Extended period variation of nodal demand at different time patterns in Etta Agbor Zone. **b** Extended period variation of nodal pressure at different time patterns in Etta Abgor Zone

were due to increased commercial activities with higher demand at that nodal point. This is because most pipes are projected to serve much higher populations making them oversized for present uses. Velocity at noon was very insufficient all links were below the accepted range. The analysis likewise showed that at sunset (6:00 pm), velocity marginally increased based on what was observed per day, although as much as 90% still had velocities under 0.1 m/s which would be a consequence of by and large low demands at that time of the day. The result of having velocities lower than anticipated is a decrease in the chances of accessing potable water from the system. Figure 15a shows the speed varieties of the drawn-out period reenactment of Ediba Qua zone.

The study showed low velocities in nearly all regions during the early morning hours (6:00 am), when water usage is expected to be high. About 32 pipes exhibited velocities more than the 0.1 m/s bar. These low velocities tend to cause intense pipe water quality distortion and accumulation of contaminants along the pipe walls. Studies suggest the height of the EWTs be increased adequately to aid intense gravity distribution with higher velocities throughout the area or rather introduce booster pumps to drive water faster. By noon, all links' pressures were below the 0.1 m/s limit. There was no significant difference between pressure readings recorded at midday and those obtained in the evening (6:00 pm). Six links had speeds that were above the norm. The low velocities depicted in the early timeframe would most likely imply a lack of water supplies for residents. Figure 15b shows the velocity variations of the extended period simulation of Etta Agbor zone.

3.6 System violations of hydraulic parameters for all the zones

The percentages of system violations for all the hydraulic parameters considered are presented in Table 2. The most critical period of the demand pattern of the system's water consumption (6 am) which accounts for 25% of the demand pattern was used to obtain the violation of the system. In Diamond hill zone, about 4% of the system's pressure violated the minimum pressure (< 15 m) of the system while less than 1% of the system's pressure was above the maximum (70 m) adopted for this system. This is an indication that the system needs a little moderation to improve pressure efficiency. To correct such anomalies, control devices are usually installed to alter the pressure in WSSs (i.e., pressure control valves, pressure-reducing valves, and variable speed

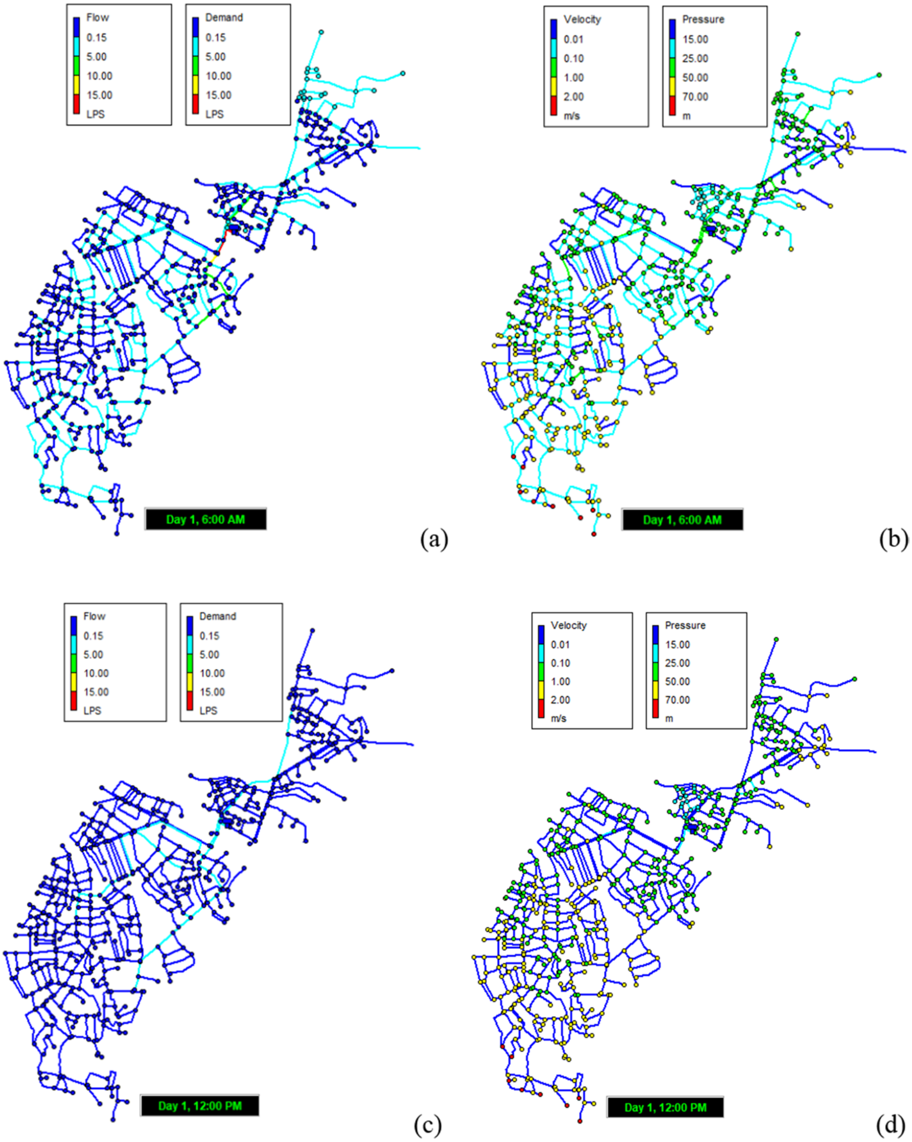


Fig. 13 **a**–**h**: Spatial distribution of predicted hydraulic parameters for Etta Agbor Zone

pumps) (Dai, 2021). This can lead to a more reliable operation of the WSS. But in general, the pressure criteria of the WSS are fair. The flow rate of the WSS is 95% above the 0.15 LPS mark adopted for the system while 4% of the flow rate is less than the adopted. The area with high flow rates can be attributed to high nodal demand (Adesogan et al., 2021). The velocity of the system at a critical point is 40% below the minimum (0.1 m/s) limit while no pipe experienced velocity above the maximum (2.0 m/s) adopted. When a system's velocity is low, deposition may occur (Castorina & Jegatheesan, 2002). Low velocity in a water supply system can lead to changes in water quality

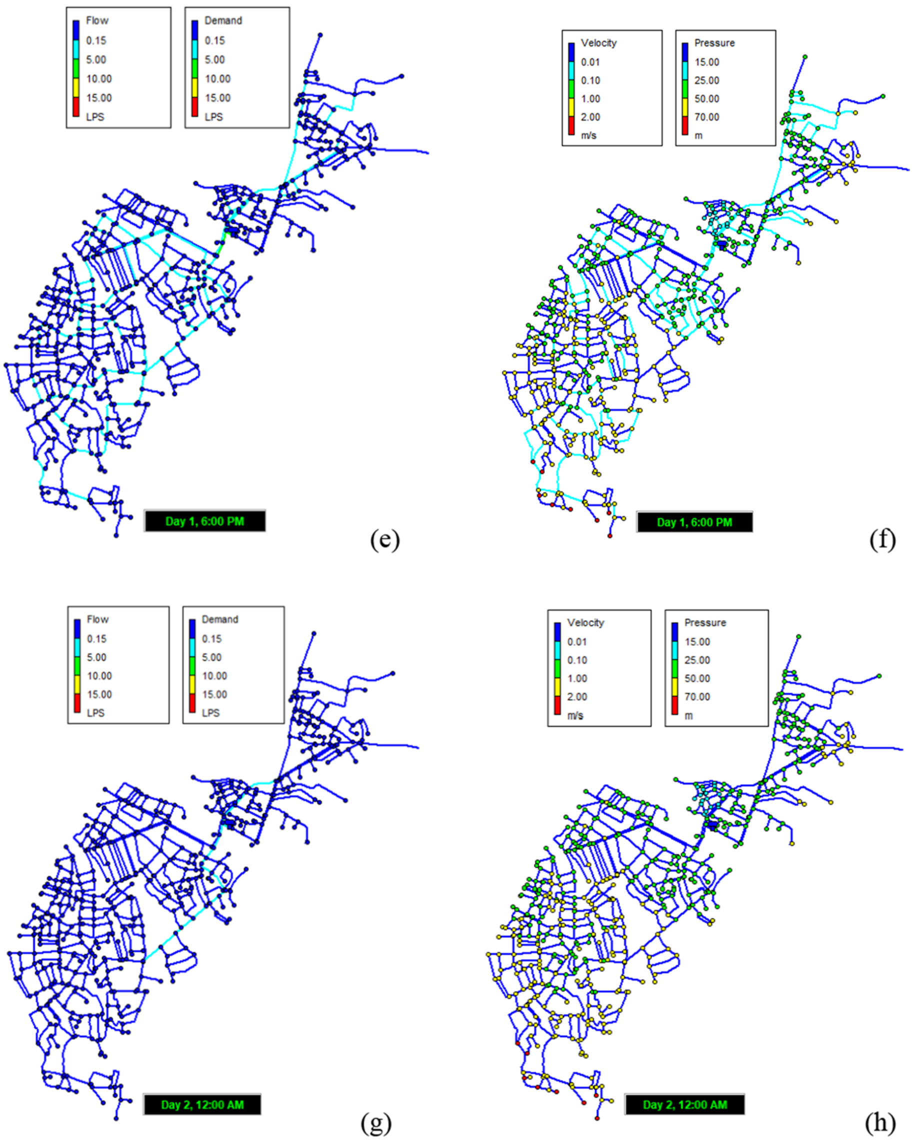


Fig. 13 (continued)

(Hossein et al., 2013). According to Nyende-Byakika (2018), when there are low velocities in a WSS, the diameter of the pipes in the affected areas should be systematically cascaded following the principle of mass conservation to increase the flow velocity.

In Ikot Effanga zone, 34% of the system's pressure violated the minimum pressure criterion for the WSS while 0% violated the maximum. As with Ikot Effanga zone, the low pressure can be attributed to the high nodal elevation of the terrain. The flow rate of the WSS is 97% above the 0.15 LPS limit adopted for the system while 3% of the flow rate fell below the adopted. The velocity of the system in Ikot Effanga zone has 53%

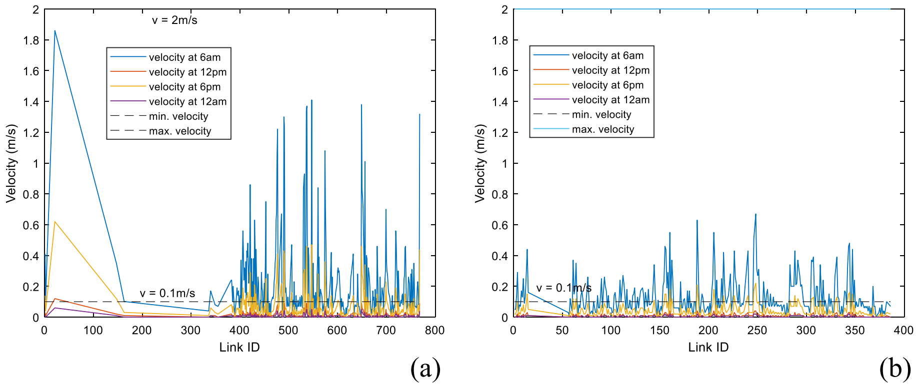


Fig. 14 **a** Velocity variations of the extended period simulation of Diamond hill zone. **b** Velocity variations of the extended period simulation of Ikot Effanga zone

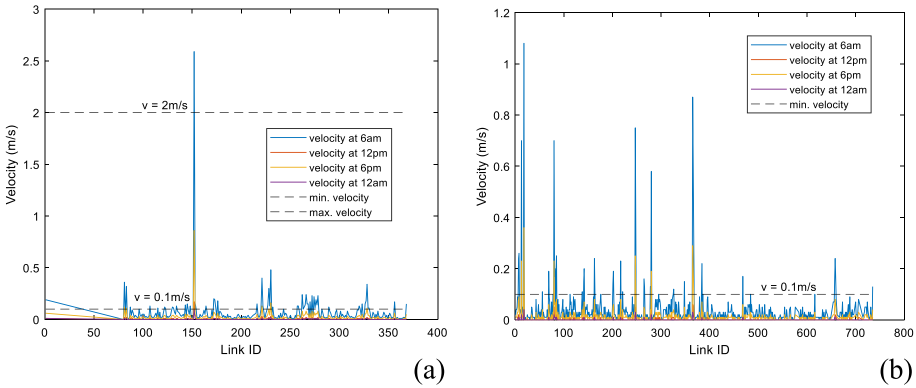


Fig. 15 **a** Velocity variations of the extended period simulation of Ediba Qua zone. **b** Velocity variations of the extended period simulation of Etta Agbor zone

Table 2 Summary of percentage violation of hydraulic parameters for all the zones

Zone	Percentage violation of Hydraulic Parameters (%)					
	Pressure (< 15 m)	Pressure (> 70 m)	Flow rate (< 0.15 LSP)	Flow rate (≥ 0.15 LSP)	Velocity (< 0.1 m/s)	Velocity (> 2.0 m/s)
Etta Agbor	0	2	7	93	100	0
Ikot Effanga	34	0	3	97	53	0
Diamond Hill	4	0.3	4	95	40	0
Ediba Qua	5	0	3	97	98	0

less than the minimum (0.1 m/s) velocity while non exceeded the maximum of 2 m/s velocities.

In the case of Ediba Qua zone, pressure below the minimum adopted pressure of the WSS is 5% while 0% was above the pressure adopted as minimum pressure for the system. The system recorded 3% of the flow rate as less than the 0.15 LPS mark adopted as the minimum flow rate and 97% above the 0.15 LPS mark. This scenario is similar to what was experienced in Ikot Effanga zone. The zone has 98% of its velocity below the minimum (0.1 m/s) limit adopted while non exceeded that of the maximum (2 m/s) limit adopted for the system. Low flow velocities promote siltation, deposit buildup, and low shear in pipes, pipelines with water velocities below 0.1 m/s are vulnerable to damage (Abdelbaki et al., 2017).

Etta Agbor zone had none of its pressure violating the minimum (15 m) limit adopted for the system while 2% of the pressure exceeded the 70 m maximum limit adopted likewise. The pressure of the system during critical demand periods is said to be adequate for effective water supply. 7% of the flow rate fell below the 0.15 LPS mark adopted for the system, while 93% went above 0.15 LPS. The velocity of the system at the critical demand period is very poor with 100% of the velocity below the 0.1 m/s minimum mark adopted for the system.

Analysis of variance (ANOVA) was adopted to statistically compare the results of EPANET and WaterCAD. The result showed no significant difference between the values predicted using both simulators (Table 3). However, when a comparison was done between predicted values of the extended period (6am, 12pm, 6pm, and 12am), there were differences resulting from the time patterns.

4 Conclusion

EPANET and WaterCAD computer packages were utilized in carrying out a real-time extended-period analysis of pressure-driven performance inside a compressed pipe network in Calabar city. The city was segmented into four zones specifically Diamond hill, Ediba Qua, Etta Agbor, and Ikot Effanga zones. The findings revealed that locations with low water pressure have high elevations. In a gravity-fed reticulation system, zones with such levels will probably encounter water supply irregularity and discontinuity. Besides, locations susceptible to pipe network infrastructure damage brought about by high-pressure water hammers were detected. The extended period simulation gave an in-depth understanding of the pressure and flow activity of the WSS inside the city. The overview from the results in similar manner demonstrated that there were a huge number of pipes with flow rates lower than 0.15 LPS threshold at midday in everything component of the circulation zones. A few pipes in the system were insufficient, resulting to exceptionally low velocities at a few spots in the system where nodal demands were notably low too. This is responsible for the extreme pipe water quality drop and clogs in the WSS, subsequently, lowering the overall framework functionality. It was discovered that the water distribution structure in Calabar city required upgrading for a more effective performance.

Table 3 Summary of ANOVA result for EPANET and WaterCAD simulators

Parameters	$F_{critical}$	p value	F	Conclusion
Pressure	3.86	0.98	0.00	The difference in pressure prediction between EPANET and WaterCAD is not statistically significant.
Demand	3.86	0.87	0.03	The difference in demand prediction between EPANET and WaterCAD is not statistically significant.
Headloss	3.89	0.54	0.39	The difference in headloss prediction between EPANET and waterCAD is not statistically significant.
Velocity	3.85	0.99	0.00	The difference in velocity prediction between EPANET and waterCAD is not statistically significant.

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Author contributions CCN conceptualized, designed, supervised the research and took part in manuscript drafting, ORE undertook further analyses and took part in manuscript drafting and revisions. CN undertook field study and computer simulations.

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Data availability All the data that are relevant in this study are included in the paper.

Declarations

Conflict of interest The writers are not affiliated with or involved with any organization or institution that has a financial or non-financial interest in the topic or materials mentioned in this article.

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