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Optimization of the Hydraulic Operation of the Yopougon-Koweït Drinking Water Supply Network (Abidjan, Côte d'Ivoire)

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Abstract

The drinking water supply in the Yopougon-Koweït neighborhood of Abidjan (Côte d'Ivoire), is experiencing operational difficulties. This study aims to optimize the network's hydraulic operation. The data is based on the network plan and water consumption volumes. First, the operation of the distribution network was simulated using Epanet software, and then strategies for optimizing the network were proposed. Water requirements for Yopougon-Koweït are estimated at 6278 m^3/day in 2022 for a population of 48,293 and 9640 m^3/day in 2037 for an estimated population of 74,151. Two technical optimization solutions are proposed: The first is the construction of a 3854 m^3 storage reservoir at a cost of 2.44 billion CFA. The second is the installation of two pumps with flow rates of 100 l/s and 70 l/s, which would cost 207.58 million CFA. This study reveals the need for targeted technical interventions to ensure sustainable and equitable access to water.

Keywords

Drinking Water Network, Hydraulic Simulation, Optimization of a Drinking Water Network, Yopougon-Koweït

1. Introduction

Achieving equitable and universal access to safe drinking water has been identified as one of the major challenges of the current century [1]. Notwithstanding the progress achieved, a mere 2.1 billion individuals worldwide have access to safely managed drinking water services. However, according to [2], 703 million people still lack access to fundamental drinking water services. The United Nations (UN) has therefore committed itself, through Sustainable Development Goal 6 (SDG 6), to ensuring access to water and sanitation for all and to ensuring sustainable water resource management by 2030 [3].

In sub-Saharan Africa, approximately 30% of urban dwellers live in informal settlements [2]. This segment of the population living in informal settlements faces particular difficulties in accessing basic services, including drinking water [4].

In Côte d'Ivoire, access to drinking water remains insufficient. In rural areas, 76% of needs are covered by the National Village Water Supply Program (PNHV). In urban and semi-urban areas, approximately 75% of the population has access to water, with variations depending on location [5]. The Harmonized Household Living Conditions Survey (EHCVM) indicates that 29% of urban households do not have constant access to water in all seasons [6].

Furthermore, the city of Abidjan is not immune to problems related to access to drinking water [7] [8]. According to [9], neighborhoods in Abidjan suffer from disruptions to the public drinking water service, ranging from low pressure to water shortages, in both the north and south of the city. The Yopougon-Koweït neighborhood, the focus of this study, is one of the neighborhoods in Yopougon that is experiencing problems with its drinking water supply networks [10]. Recognizing the importance of access to water for the well-being of the population in peri-urban neighborhoods, the main objective of this study is to propose strategies for action to water stakeholders in order to ensure sustainable access to drinking water in the Yopougon-Koweït neighborhood, when formatting individual papers, 1) automatic compliance to electronic requirements that facilitate the concurrent or later production of electronic products, and 2) conformity of style throughout a journal paper. Margins, column widths, line spacing, and type styles are built-in; examples of the type styles are provided throughout this document and are identified in italic type, within parentheses, following the example. Some components, such as multi-leveled equations, graphics, and tables are not prescribed, although the various table text styles are provided. The formatter will need to create these components, incorporating the applicable criteria that follow.

2. Material and Methodes

2.1. Study Area

The Yopougon-Koweït neighborhood is located in southern Côte d'Ivoire, between longitudes 4˚3'0" and 4˚3'36" West and latitudes 5˚18'15" and 5˚19'20" North (**Figure 1**). It covers an area of 1.7 km^2 and has an estimated population of 46,932 [11]. Yopougon-Koweït is bordered to the north by the Toit Rouge neighborhood, to the south by the Ebrié lagoon, to the east by Santé, and to the west by Camp Militaire. It is subdivided into five sub-neighborhoods. Johannesburg neighborhood to the north, Ravin neighborhood to the northeast, Konan Ferrand and Sante extension neighborhoods to the southwest, and Sub-Koweït and Gouro neighborhoods to the southeast. Figure 1 shows the different neighborhoods of Abidjan and the Yopougon-Koweït neighborhood.

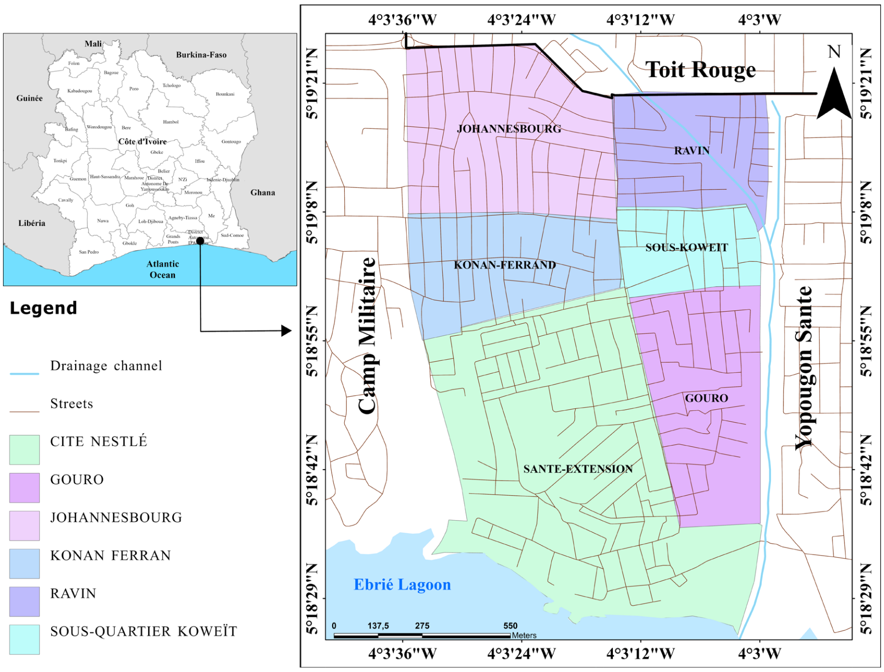


Figure 1. Presentation of the study area.

Yopougon-Koweït has an equatorial climate, marked by four distinct seasons: two rainy seasons (March to July, with a peak in June, and October to November) and two dry seasons (August to September and December to February) (Figure 2). The climate is generally humid, with average monthly temperatures ranging from 24.2˚C in August, the coolest month, to 27.4˚C in March, the hottest month [12].

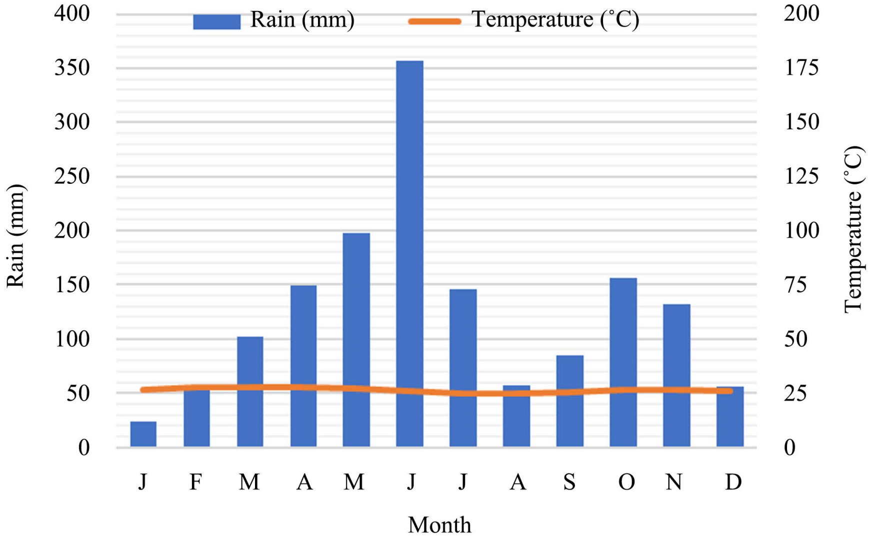


Figure 2. Ombrothermic diagram at the Adiopodoume station.

2.2. Data and Tools

The data used in this study consists of demographic data [11] and AEP data for the years 2010, 2015, and 2022. This includes the number of subscribers, annual water consumption volumes, and a layout plan of the network showing its characteristics (pipe diameters and lengths). A differential GPS, a portable flow meter (Sewerin), and pressure sensors (Cello 4s) were used to collect the natural terrain elevations, distribution flows, and network pressures, respectively. The network was modeled using EPANET software. This simulation of the network's operation involved the use of Mensura 12 software to link the elevations of the natural terrain to the network nodes and EpaCAD software to convert DXF files to INP format.

2.3. Methodological Approach

- ✓ **Population estimate**

The population of Yopougon-Koweït was estimated based on geometric population growth. The method used was trend extrapolation (Equation (1)). The years concerned are 2022, 2027, 2032, and 2037.

$$P_n = P_0\left(1+\Phi\right)^n \tag{1}$$

With:

P_0: Population in the initial year

P_n: Population in the year considered as the deadline

Φ: Growth rate

n: Deadline

- ✓ **Average daily demand**

The average daily requirement (m^3/day) or average daily consumption is the amount of water consumed by all active subscribers over a 24-hour period. In this study, requirements will be estimated using a specific consumption rate of 100 l/day/resident according to [13] [14]. It is calculated using Equation (2) [15]:

$$Q_{a.d} = \frac{Cs \times N}{1000} \tag{2}$$

With:

$Q_{a.d}$: Average daily demand

Sc: Specific consumption

N: Population

- ✓ **Assessment of the increased average daily demand**

The average daily increase is calculated based on drinking water requirements, taking into account leaks in the network and waste. To do this, an increase is applied according to Equation (3) [15]:

$$Q_{a.d.Surp} = \left(1+\alpha\right) * Q_{a.d} \tag{3}$$

With:

$Q_{a.d.Surp}$: Surplus average demand

α : Surplus coefficient expressing water losses.

Estimated water losses vary from 15% to 50%. In this study, a water loss coefficient of 30% is used in relation to age and network maintenance rate, as recommended [16].

✓ **Average hourly demand and peak hourly flow**

The average hourly requirement is given by Nesrine's Equation (4) [17]:

$$Q_{moy.h} = \frac{Q_{max.d}}{24} \tag{4}$$

With:

$Q_{a.h}$: average hourly flow en m³/h

$Q_{max.d}$: maximum daily flow en m³/day

The peak hourly flow corresponds to the consumption flow rate during the hour of maximum network demand. It is given by Nesrine's Equation (5) [17]:

$$Q_p = Q_{max.h} = K_{max.h} * Q_{a.h} \tag{5}$$

With:

$Q_{max.h}$: Maximum hourly flow

$Q_{a.h}$: Average hourly flow

$K_{max.h}$: Maximum hourly irregularity coefficient, which can be broken down into two other coefficients that depend on the characteristics of the urban area, namely α_{max} and β_{max}.

The maximum hourly irregularity coefficient is determined using Equation (6) [17]:

$$K_{max.h} = \alpha_{max} * \beta_{max} \tag{6}$$

With:

α_{max} : Coefficient taking into account the level of comfort and amenities. It varies between 1.2 and 1.4.

β_{max} : Coefficient based on the size of the urban area (**Table 1**).

Table 1. Values of $\beta_{\max}$ as a function of the number of redents.

Number of residents * 1000	1	1.5	2.5	4	6	10	20	30	100	300	1000
$\beta_{\max}$	2	1.8	1.6	1.5	1.4	1.3	1.2	1.15	1.1	1.03	1

2.3.1. Simulation of the Operation of the Yopougon-Koweït Water Supply Network

✓ **Model design**

The physical characteristics of the pipes (diameters, lengths) extracted from the site plan in shapefile format in ArcGIS were integrated via conversion to DXF. A topographic survey of elevations using differential GPS enabled the generation of a Digital Terrain Model by interpolation. This made it possible to superimpose the network imported in DXF and assign elevation coordinates to the nodes using Mensura 12 software. EpaCAD software was used to convert the DXF file to INP format compatible with EPANET. The final configuration in EPANET consisted of materializing the structures (reservoirs, pumps) and specifying the simulation parameters.

- ✓ **Model calibration**

Calibration is a step without which a model is meaningless. Its purpose is to ensure that the model is representative and can be used to understand and predict the behavior of the network outside of normal operating conditions. Calibration is the final step in modeling a drinking water network [18]. This step aims to adjust the model's pressure parameters so that the model's results are as close as possible to reality. In this study, calibration consisted of installing six (06) sensors over a period of 24 hours at a rate of one sensor per sub-neighborhood. At the end of this stage, pressure calibration was performed. This involved integrating the data recorded (pressure and flow rates) at the sensors into the model to achieve a perfect match between the pressure data simulated by the model and that recorded in the field. The results are considered satisfactory for a correlation coefficient close to 1 and an RMSE of less than 10 [7].

2.3.2. Sizing of Water Supply Structures

- ✓ **Pump sizing**

The sizing of hydraulic pumps involves the total manometric height (TMH) (Equation (7)), which takes into account the geometric height (Equation (8)) and pressure losses (Equation (9)):

$$\text{TMH} = H_{geo} + \Delta H + \frac{\Delta P}{\varpi} \tag{7}$$

Avec:

H_{geo} : Geometric height;

ΔH : Pressure drop in the supply pipe;

ΔP : Pressure variation between suction and discharge point (bar);

ϖ : ρg .

$$H_{geo} + \frac{P}{\rho g} + \frac{V^2}{2g} = C^{te} \tag{8}$$

$$\Delta H = \lambda \frac{L}{D} * \frac{V^2}{2g} \tag{9}$$

With:

λ : Pressure drop coefficient;

V : Flow velocity (m/s);

D : Pipe diameter (m);

L : Length (m);

p : pressure (bar);

g : gravity ($\text{m}\cdot\text{s}^{-2}$).

- ✓ **Determination of the hydraulic power of pumps**

Hydraulic power represents the energy transferred to the pumped fluid to increase its velocity and pressure in the RePEP. It is calculated using Equation (10) [19]:

$$P = \frac{\rho * g * Q * \text{HMT}}{\eta} \tag{10}$$

With:

ρ : Fluid density (kg/m^3);

g : gravity (environ 9.81 m/s^2);

Q : Flow (m^3/s);

η : Pump efficiency (on prend 80%);

HMT: Total Manometric Height (m).

- ✓ **Reservoir sizing**

In this study, the storage tank capacity is sized to hold 30% of the total daily demand, which is within the recommended range of 25% to 50% for large communities. Indeed, due to the lack of reliable statistics on supply systems in West Africa, [20] recommends using 30% of the daily peak flow rate for tank sizing.

- ✓ **Determination of the elevation of the foundation slab**

The base elevation refers to the minimum piezometric elevation required at the head of the network to guarantee flow rates and operating pressures at the various nodes [21]. It is determined by the Equations (11) and (12):

$$C_{minclear} = Max\left(H^{i}_{imp}\right) \tag{11}$$

With:

$$H^{i}_{imp} = Z^{i}_{aval} + \sum_{i}^{TR} pdc + P^{i}_{minimal\ service} \tag{12}$$

H^{i}_{imp} : Initial height imposed (m);

Z^{i}_{aval} : Initial downstream slope (m);

pdc : Pressure drop (m);

$P^{i}_{minimal\ service}$: Minimum operating pressure.

The minimum operating pressure is calculated using the Equation (13):

$$P^{i}_{minimal\ service} = H^{i}_{aval} - Z^{i}_{aval} \tag{13}$$

With Equation (14):

$$H^{i}_{aval} = H_{TR} - \sum_{i}^{TR} pdc \tag{14}$$

- ✓ **Reservoir sizing**

The dimensioned tank is cylindrical in shape. Its diameter is calculated by setting an arbitrary height for the tank. This is given by Equation (15) as follows [22]:

$$D_{ins} = \sqrt{\frac{4 * V}{\pi * h}} \tag{15}$$

D_{ins}: Inside diameter (m);

V: volume (m^3);

h: arbitrary reservoir height (m).

- ➢ **Determination of the outer diameter**

$$D_{out} = D_{ins} + 2 * e_{v} \tag{16}$$

e_v : veil thickness (30 cm).

- ✓ **Optimization of the distribution network**

Optimizing the drinking water network will make it possible to adjust pressure and flow velocity to ensure a sustainable supply for the residents of Yopougon-Koweït. The parameters have been set to maintain: 1) pressure between 1 and 6 bars and 2) flow velocity between 0.5 and 1.5 m/s, in accordance with the standards authorized for an optimal network.

3. Results

3.1. Water Demands in the Yopougon-Koweït Neighborhood

The daily water demands of the population of Yopougon-Koweït are estimated at 4829 m^3/day for a population of 48,293 residents in 2022. These demands will be 9640 m^3/day by 2037, representing an anticipated satisfaction rate of 80%. An increase in this demand gives 6278 m^3/day in 2022 and 9640 m^3/day in 2037. The water consumption rate of subscribers is estimated at 2407 m^3/day in 2022, representing a water demand satisfaction rate of 38%. This satisfaction rate will fall to 25% in 2037, a decline of 13%. Average daily production is set at 2407 m^3 (Table 2).

Table 2. Drinking water demand.

Years	2022	2027	2032	2037
Population	48,293	55,714	64,274	74,151
$Q_{a.d}$ (m^3/day)	4829	5571	6427	7415
$Q_{a.d.Surp}$ (m^3/day)	6278	7243	8356	9640
$Q_{a.h}$ (m^3/h)	262	302	348	402
Q_p (m^3/h)	387	444	509	584
Q_p (l/s)	107	123	142	162
Satisfaction rate (%)	38	33	29	25
Expected satisfaction rate (%)	60	80	80	80

3.2. Hydraulic Model Performance

The calibration of the hydraulic model indicates that the correlation coefficient between the observed and simulated values is 0.97, while the root mean square error (RMSE) is 8.17 (Table 3).

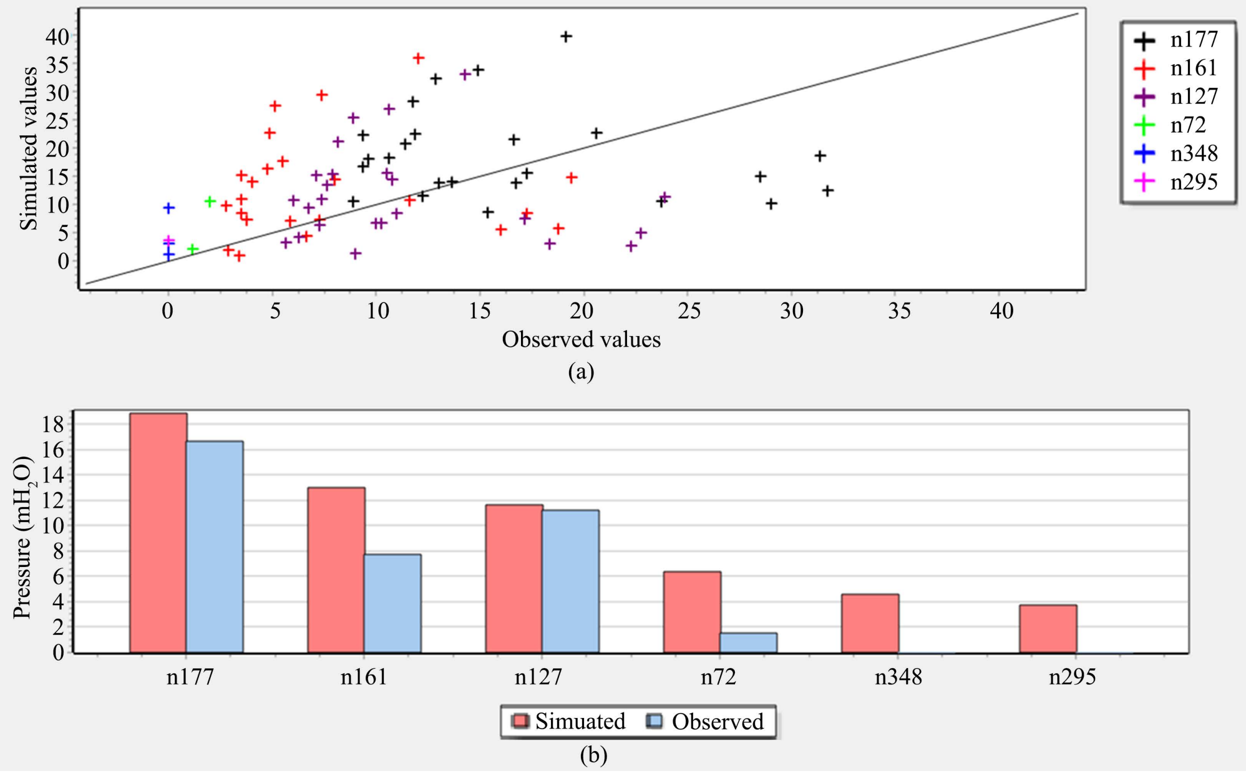
Table 3. Correlation report between simulated and observed pressures.

Nodes	Numbers of observations	Observed Values	Simulated Values	Error	RMSE
n177	24	16.65	18.85	9.631	11.76
n161	23	7.72	12.95	8.966	11.382
n127	24	11.23	11.65	8.451	10.349

Continued

n72	2	1.56	6.38	4.815	6.079
n348	3	0	4.55	4.551	5.761
n295	1	0	3.7	3.703	3.703
	Mean	9.68	6.19	6.69	8.17
		Correlation Coefficient 0.97			

Figure 3(a) confirms the strong linear correlation (r = 0.97) between simulated and observed values. The vast majority of points are aligned along the first bisector. Furthermore, a comparison between simulated and observed data indicates overall agreement between them (**Figure 3(b)**).



(a)

(b)

Figure 3. Comparison of values. (a) Comparison of simulated and observed values; (b) Linear correlation between simulated and observed values.

3.3. Characteristics of Water Supply Structures

3.3.1. Size of Pumps

The pumps (P1 and P2) have been sized with total manometric heights (HMT) of 68 m each. They will be positioned at the various entrances to the RePEP in the Yopougon-Koweït neighborhood (P1 "military camp" and P2 "Koweït pharmacy"). They will deliver 100 l/s and 70 l/s respectively. Pump (P1) will use 83,017 W of power compared to 58,112 W for pump (P2) to propel water into the RePEP (**Table 4**).

Table 4. Characteristics of sized pumps.

	TMH (m)	Q (l/s)	P(W)
Pump 1	68	100	83,017
Pump 2	68	70	58,112

3.3.2. Size of Water Reservoir

The reservoir in the Yopougon-Koweït neighborhood has been designed with a capacity of 3854 m^3. The inner and outer diameters are 26 m and 27 m, respectively. The depth of the foundation slab is estimated at 43 m (**Table 5**).

Table 5. Water reservoir size.

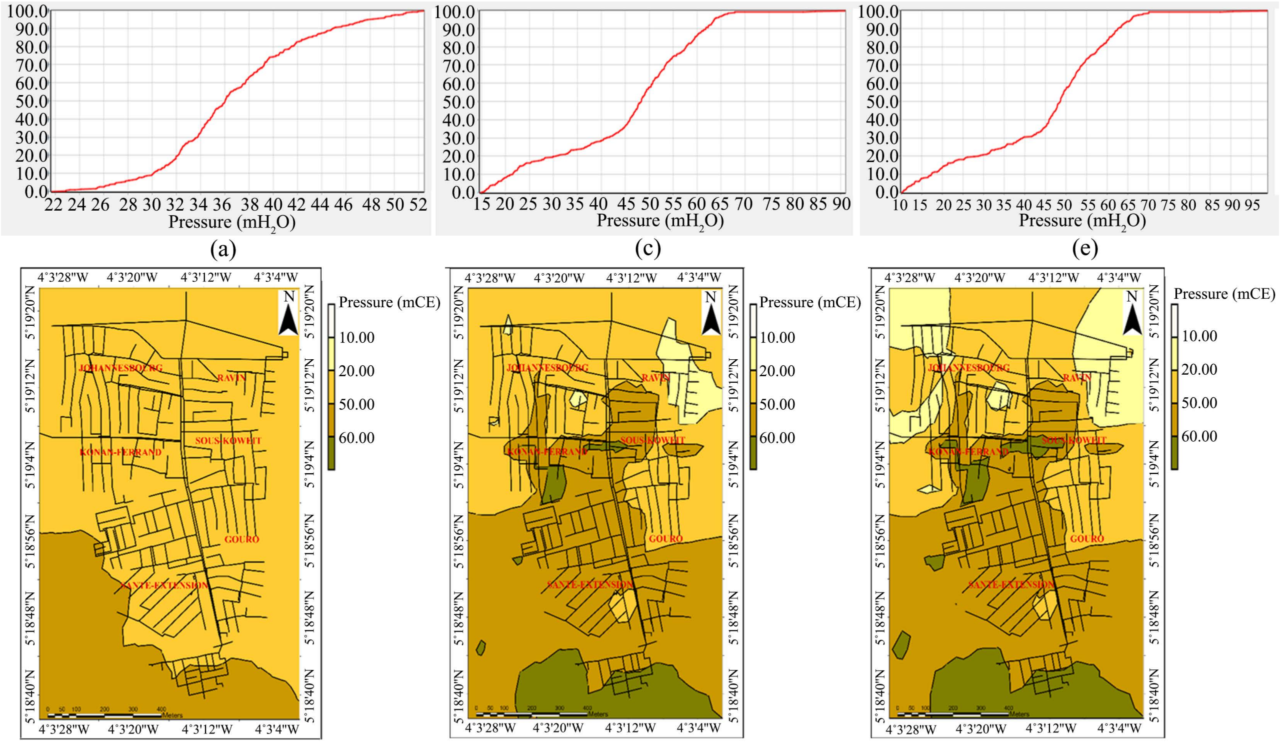
Characteristics	V reservoir (m^3)	Dins (m)	Dout (m)	Cclear (m)
Values	3854	26	27	43

3.4. Analysis of Optimized Network Operation

Pressure variations in the network

✓ **Variation at 3 a.m., 8 a.m., and 5 p.m. (pump option)**

All pipes (100%) in the RePEP will have good pressure at 3 a.m. This pressure will be between 22 and 52 mWC (meter of water column) for all six sub-neighborhoods (**Figure 4(a)** and **Figure 4(b)**).



(a) (c) (e)

(b) (d) (f)

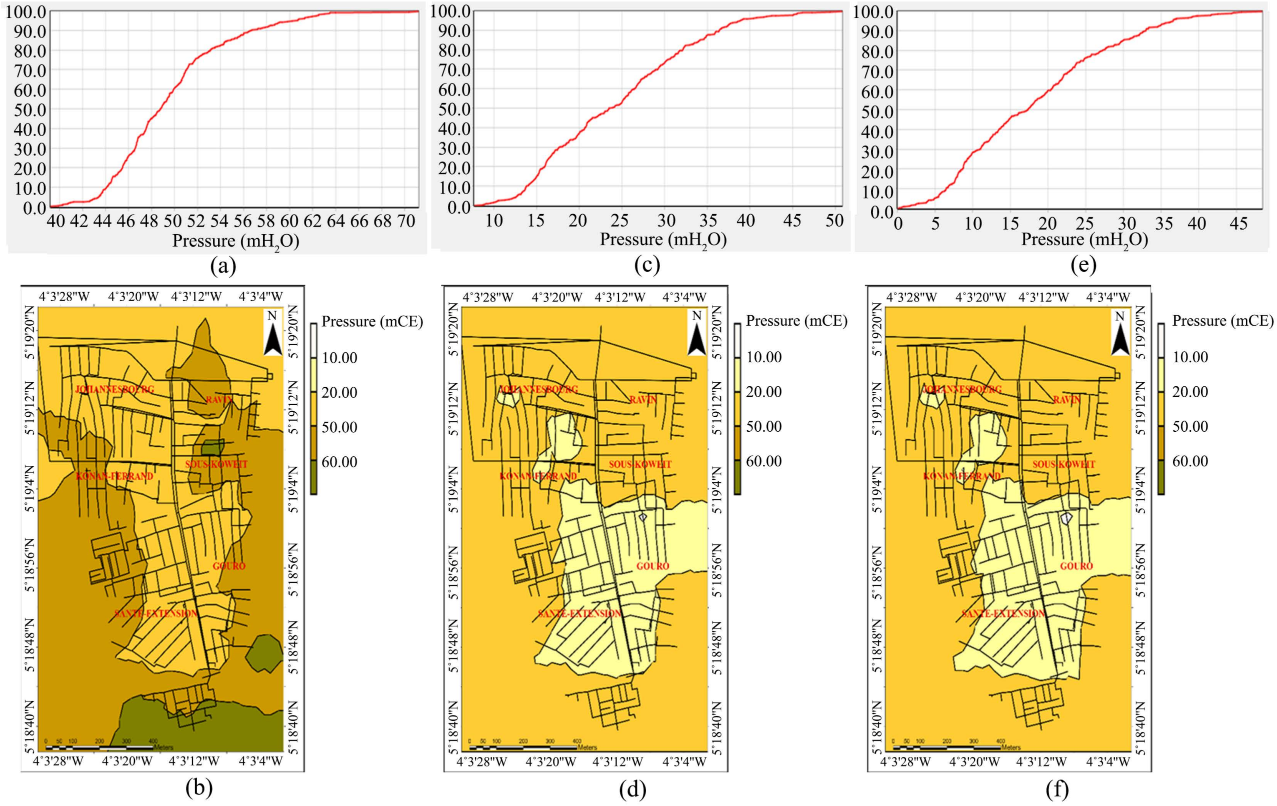
Figure 4. Pressure variation on the Yopougon-Koweït RePEP (pump option). (a) Pressure variation on the RePEP at 3 a.m.; (b) Pressure distribution at 3 a.m.; (c) Pressure variation on the RePEP at 8 a.m.; (d) Pressure distribution at 8 am.; (e) Pressure variation on the RePEP at 5 p.m.; (f) Pressure distribution at 5 p.m.

At 8 a.m., pressure variations in the pipes will peak at 63 mWC. The majority of pipes (88%) will have good pressure (15 and 60 mWC). Only 12% of pipes will have pressure above 60 mWC. The majority of neighborhoods (Johannesburg, Ravin, Gouro, Sante Extension, Sub-Koweït, and Konan Ferrand) will have good pressure. However, a small portion (2% of pipes) of the Santé Extension (Sikasso) and Konan Ferrand neighborhoods will have estimated pressure of 62 mWC (**Figure 4(c)** and **Figure 4(d)**).

At 5 p.m., most pipes (82%) will have good pressure between 10 and 60 mWC. However, 18% of RePEP pipes will have pressure above 60 mWC. The Johannesburg, Ravin, and Gouro neighborhoods will have good pressure. However, the Konan Ferrand neighborhoods and certain areas of the Sante Extension and Sub-Koweït neighborhoods will have estimated pressure of 68 mWC (**Figure 4(e)** and **Figure 4(f)**).

✓ **Variation at 3 a.m., 8 a.m., and 5 p.m. (reservoir option)**

Almost all of the pipes (95%) in the RePEP will have a pressure between 39 and 60 mWC at 3 a.m. Only 5% of the pipes will have a pressure between 60 and 64 mWC. All sub-neighborhoods of Yopougon-Kowët will have good pressure. However, part of the Sub-Koweït sub-neighborhood will have high pressure above 60 mWC (**Figure 5(a)** and **Figure 5(b)**).



(a) (c) (e)

(b) (d) (f)

Figure 5. Pressure variation on the Yopougon-Koweït RePEP (reservoir option). (a) Pressure variation on the RePEP at 3 a.m.; (b) Pressure distribution at 3 a.m.; (c) Pressure variation on the RePEP at 8 a.m.; (d) Pressure distribution at 8 am.; (e) Pressure variation on the RePEP at 5 p.m.; (f) Pressure distribution at 5 p.m.

At 8 a.m., the pressure variation in the pipes will peak at 41 mWC. The majority of pipes (99%) will have good pressure (33 and 56.5 mWC). Only 1% of pipes will have pressure below 10 mWC. The neighborhoods of Yopougon-Koweït will have good pressure. However, a small part of the Sub-Koweït sub-neighborhood will have low pressure below 10 mWC (**Figure 5(c)** and **Figure 5(d)**). Almost all pipes (98%) will have pressure between 10 and 45 mWC. However, 2% of pipes will have pressure below 10 mWC.

At 5 p.m., almost all pipes (98%) will have a pressure between 10 and 45 mWC. However, 2% of pipes will have a pressure below 10 mWC. All Yopougon-Koweït will have good pressure. However, a small part of sub-Koweït will have low pressure (**Figure 5(e)** and **Figure 5(f)**). The variation in pipe velocities will reveal that, on average, 72% of pipes will have a velocity between 0 and 0.5 m/s, 12% will have a velocity of zero, and 16% will have a velocity greater than 1.5 m/s.

4. Discussion

The water demand for the Yopougon-Koweït neighborhood is estimated at 6278 m^3/day in 2022 and 9640 m^3/day in 2037 for populations estimated at 48,293 and 74,151 residents, respectively. However, daily production in 2022 will be 2407 m^3, meaning that only 38% of demand will be met. This low satisfaction rate could be explained by a lack of water production infrastructure. This situation means that it will not be possible to meet the growing demand from the population. The satisfaction rate will fall by 13% in 2037, with average daily production set at 2407 m^3. To meet the area's water demands, two options have been selected: the installation of pumps [23] and the construction of a reservoir [24].

The first option consists of installing two pumps at the sector meters of the military camp (P1) and the Koweït pharmacy (P2). These pumps will have a TMH of 68 m each and respective flow rates of 100 L/s and 70 L/s. These results are consistent with those obtained by the Japan International Cooperation Agency (JICA) in 2016 and the Senegalese Water Agency (SDE) in 2018. Indeed, these studies reveal the use of booster pumps to supply drinking water to the most disadvantaged areas.

The second option involves installing a water reservoir with an estimated capacity of 3854 m^3. The inside and outer diameters of the reservoir will be 26 m and 27 m, respectively. The height of the foundation slab will be 43 m. Simulation of the optimized network's operation (during peak hours) with two pumps shows that the RePEP in the Yopougon-Koweït neighborhood is operating under generally satisfactory conditions. In fact, 82% (at 5 p.m.) and 88% (at 8 a.m.) of the pipes have pressures that comply with the standard (10 mWC to 60 mWC) [20]. Only 12% to 18% of pipes have pressures above 60 mWC. These high pressures were observed during peak hours. According to [25], pressures at nodes above 60 mWC are attributable to the uneven terrain. In addition, analysis of flow velocities during peak hours reveals that the RePEP is functioning well. In fact, only 10% of pipes in the Yopougon-Koweït sub-neighborhood have velocities close to zero.

And 15% of pipes have velocities greater than 1.5 m/s. According to [26], for proper hydraulic functioning, velocities must be between 0.5 m/s and 1.5 m/s in a water distribution network. This ensures a good water supply to consumers. Conversely, simulation of the network's operation, optimized by the installation of a water storage reservoir, demonstrates the optimal functioning of the Yopougon-Koweït RePEP. The majority of pipes (99%) have pressures between 10 mWC and 56.5 mWC. According to [27], the integration of storage tanks into distribution network models promotes good pressures on the RePEP. The pipes have generally satisfactory velocities, with only 15% showing zero velocities. Optimizing the network by building a reservoir is therefore more effective than installing pumps. In fact, all pipes have pressures that do not exceed 60 mWC in the case of the reservoir. Whereas, on average, 15% of pipes have pressures that exceed the maximum pressure required in a RePEP (60 mWC) for the pump option. However, these high pressures can be corrected by installing pressure regulators [28]. These results are consistent with those obtained by Mays (2000). Elevated tanks allow for constant pressure regulation in the network. Pump systems, on the other hand, are subject to load variations [29]. These results are consistent with the recommendations of [30], who identifies elevated storage tanks as the most reliable and effective method for ensuring pressure stability. In addition, the cost of constructing the water storage reservoir amounts to 2,444,114,000 CFA. The cost of installing the two booster pumps on the distribution system is 207,580,000 CFA francs. According to studies by [31], although the reservoir is more expensive to build, it is the optimal solution in the long term. Indeed, the reservoir offers several technical and economic advantages, including durability (30 - 50 years), hydraulic stability, and low operating costs. In contrast, the booster pump, although flexible, has high energy costs and is vulnerable to breakdowns [32].

5. Conclusion

The network optimization strategy to correct hydraulic defects indicates a significant gap between supply and demand. The satisfaction rate is estimated at 38% in 2022. This rate is likely to fall to 25% by 2037 if no corrective measures are taken. To address this deficit, two technical approaches have been proposed. These are the installation of two booster pumps and the construction of a water storage reservoir. Hydraulic simulation shows that the reservoir option offers significantly better performance. In fact, 99% of pipes have optimal pressures between 10 mWC and 56.5 mWC, compared to only 85% on average in the case of pumps. In addition, the reservoir significantly reduces the risk of suppression (0% compared to 15% for pumps). It also ensures greater network stability. Despite the high investment costs, the reservoir proves to be more economical in the long term thanks to its durability, resilience to technical failures, and low operating costs. In contrast, pumps incur significant energy costs and require increased maintenance. Thus, although pumps are a temporary solution, the construction of a reservoir appears to be the most viable strategy for meeting the drinking water needs of the populations of the Yopougon-Koweït neighborhood.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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