Article de recherche

Rev. Cong. Sci. Technol., Vol. 04, No. 03, pp.554-561 (2025)

OPEN ACCESS

Revue Congolaise des Sciences & Technologies

ISSN: 2959-202X (Online); 2960-2629 (Print)

https://www.csnrdc.net/

REVUE CONGOLAISE DES SCIENCES ET TECHNOLOGIES

# Optimisation du système de distribution d'eau potable grâce à une approche de modulation de pression : cas du secteur de Ngaliema (Kinshasa, RDC)

**[Optimimising drinking water distribution systems through pressure modulation approach : Acase study of the Ngaliema sector (Kinshasa , RDC)]**

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**Résumé**

La gestion efficace des réseaux d'approvisionnement en eau reste un défi important pour les pays en développement, afin de garantir l'approvisionnement en eau à une grande partie de la population et de préserver l'eau et l'énergie. Le présent travail vise à optimiser la pression de l'eau en utilisant une méthode de régulation de pression dans le réseau de distribution d'eau potable de la ville de Kinshasa, une ville confrontée à d'importants défis en matière d'approvisionnement en eau en raison d'un niveau de gestion insuffisant. L'étude se concentre sur l'utilisation d'un modèle hydraulique pour optimiser la pression, à l'aide d'une campagne de mesure sur le terrain pour collecter les paramètres hydrauliques essentiels. Ces paramètres ont ensuite été utilisés pour le calage et la validation du modèle, ce qui a permis d'obtenir un coefficient de corrélation élevé (r = 0,99) décrivant avec précision le comportement hydraulique du réseau. Par la suite, quatre scénarios de distribution distincts ont été évalués à l'aide du modèle calibré. Le scénario le plus ambitieux, qui prend en compte plusieurs zones de pression, une population croissante et des exigences en matière de protection contre les incendies, a donné des résultats favorables, avec des vitesses d'écoulement allant de 0,5 m/s à 2 m/s et des niveaux de pression compris entre 2 et 6 bars. Cette approche illustre une stratégie de modulation de pression basée sur les données et la modélisation, offrant une méthodologie précieuse pour améliorer la performance et la fiabilité du système d'approvisionnement en eau à Kinshasa et dans des contextes urbains similaires.

**Mots-clés** : Calage, Kinshasa, Desserte en eau potable, Modélisation, Modulation de pression.

**Abstract**

Efficient management of water supply networks is still an important challenge for developing countries, to guarantee water supply for a large part of the population, and preserve water and energy. The present work aims to explore optimal operational strategies for Kinshasa's drinking water distribution system, a city facing significant water supply challenges due to an insufficient level of management. The study focuses on developing a hydraulic model for pressure monitoring, initiated by a comprehensive field measurement campaign to collect essential hydraulic parameters. These parameters were then used for the calibration and validation of the model, achieving a high correlation coefficient (r = 0.99) that accurately describes the hydraulic behaviour of the network. Subsequently, four distinct distribution scenarios were evaluated using the calibrated model. The most challenging scenario considering multiple pressure zones, an increasing population, and fire protection requirements produced favourable results, with flow velocities ranging from 0.5 m/s to 2 m/s and pressure levels between 2 and 6 bars. This approach exemplifies a data-driven and modelling-based strategy for pressure modulation, offering a valuable methodology for enhancing the performance and reliability of the water supply system in Kinshasa and similar urban contexts.

**Keywords**: Calibration, Kinshasa, Drinking water supply, Modelling, Pressure modulation.

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https://orcid.org/0009-0001-1397-1995; Reçu le 07/07/2025; Révisé le 23/07/2025 ; Accepté le 20/08/2025

DOI: https://doi.org/10.59228/rcst.025.v4.i3.182

# 1. Introduction

Safe drinking water is essential to ensure human well-being, and the issue of water scarcity is a frequent issue that is widely discussed in various countries around the world. The poor management of water resources both in terms of resources and in terms of drinking water distribution is considered one of the main constraints to sustainable economic and social development in many regions of the world (Malla et al., 2019). Developing countries are experiencing several problems according to water supply such as the absence of balance tanks and water control devices for pressures and flow rates recording, which make difficult to regulate the pressure and distribute the water flows correctly over various parts of the distribution network; the under sizing of secondary and tertiary networks; the illegal water use from the distribution network and special connections and the rupture of pipes following the deterioration of the pipes. These problems related to water supply are accentuated by population growth in the developing country (Kettab et al., 2008). Sustainable access to drinking water must be considered from the perspective of a service because it requires the maintenance and renewal of pipes according to a well-ordered schedule by monitoring hydraulic parameters such as pressure and flow, a first approach consists of making a hydraulic calibration via a field measurement campaign and secondly by gradually inserting the instantaneous monitoring devices of these parameters. Planning for the provision of a sustainable drinking water service requires knowledge of the costs of the systems it consists of for care and maintenance. Several developing countries fail to invest in the maintenance and maintenance of the water distribution network (Pezon & Bassono, 2012). While there has been a progress in increasing access to water, this improvement has not been matched by the development of adequate sanitation services. As a result, water pollution has increased, treatment costs have risen, and management challenges have emerged, including erosion, flooding, and declining water quality (Bishoge, 2021).

The Democratic Republic of Congo possesses sufficient resources to provide drinking water not only throughout the country but also to neighboring regions. The daily demand for drinking water in the city of Kinshasa is estimated at 1,500,000 m³/day (REGIDESO, 2022). Despite the investments made in recent years in the expansion of water production capacity, the distribution network is facing water shortages and low-pressure problems in several districts. Water production capacity has increased from 513,000 m³/day in 2010 to 676,000 m³/day in 2023 with the construction of the Lemba-Imbu (35,000 m³/day) and Binza-ozone (110,000 m³/day) drinking water treatment plants (REGIDESO et al., 2010). Despite the sectorization of the Kinshasa network, which has enabled monitoring of incoming and lost water volumes to enhance network performance, the implementation of sector meters has primarily highlighted existing shortcomings. Addressing these issues requires the development of a digital model of the water supply network, which can be calibrated using in situ measurements of pressures and flows (Shen & McBean, 2012). The primary objective of this study is to develop a comprehensive hydraulic model of the drinking water distribution network in Kinshasa. This model aims to analyse and optimise the network's performance, ensuring a reliable and sustainable supply of drinking water to meet the growing demands of the population in both the short and long term. By incorporating various hydraulic parameters and scenarios, the model will facilitate informed decision-making for effective water resource management and infrastructure development.

# 2. Material and methods

## 2.1. *Material*

### 2.1.1. *Study area*

The municipality of Ngaliema is located in the city-province of Kinshasa in the Democratic Republic of Congo, in the LUKUNGA district, it is one of 24 communes in the city-province of Kinshasa. It is bounded to the north by the River Congo and the commune of Gombe, to the north-east by the commune of Kintambo, to the east by the communes of Bandalugwa and Selembao, and to the west and south by the commune of Mont-Ngafula. Administratively, the commune of Ngaliema is one of the largest in the city of Kinshasa, covering an area of 62.64 km2 and comprising 21 districts. The municipality of Ngaliema is supplied with drinking water by the Binza-Ozone drinking water treatment plant, extracting water from the Congo River.

The water distribution network of the Binza-ozone plant has three pressure zones with pumps in parallel, the first is the low pressure zone which is equipped with six pumps with a flow rate of 325 m³/h each and a head of 30 mwc, the second is the medium pressure which is composed of two pumps with a flow rate of 750 m³/h and a head of 75 mwc and the third is the zone of three pumps with a flow rate of 600 m³/h and a head of 125 mwc. The distribution network is of a mixed type with significant differences in level between the pressure zones. Figure 1 shows the three pressure zones in the study area.

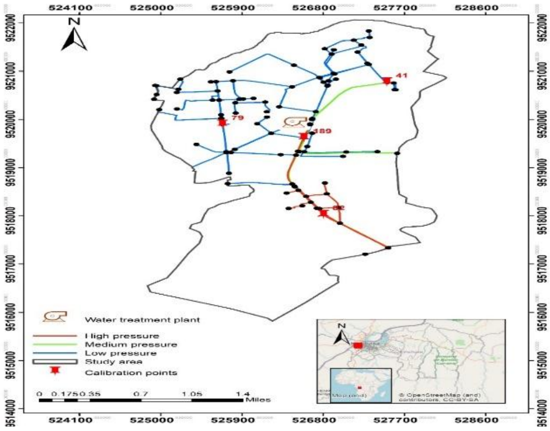



*Figure 1. Distribution network in the REGIDESO/NGALIEMA sector.*

From a morphological point of view, the topography of the Ngaliema municipality (figure 2) is characterized by the presence of several hills. Elevations range between 245 m in the north to 445 m in the south. This varied topography significantly impacts the pressure dynamics within the water supply system, particularly since water is being pumped to overcome gravitational forces. In a pumped water supply system, the elevation differences necessitate careful management of pressure to ensure efficient delivery. Water is typically pumped from lower elevations to higher ones, and as it ascends, the pressure must be sufficiently high to overcome both gravitational pull and friction losses in the piping network. In the southern regions of Ngaliema, where elevations reach up to 445 meters, pumping stations must generate substantial pressure to deliver water effectively to these higher areas. This can lead to increased energy consumption and operational costs.

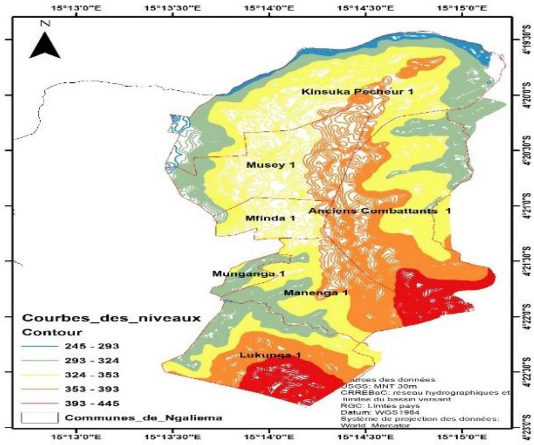
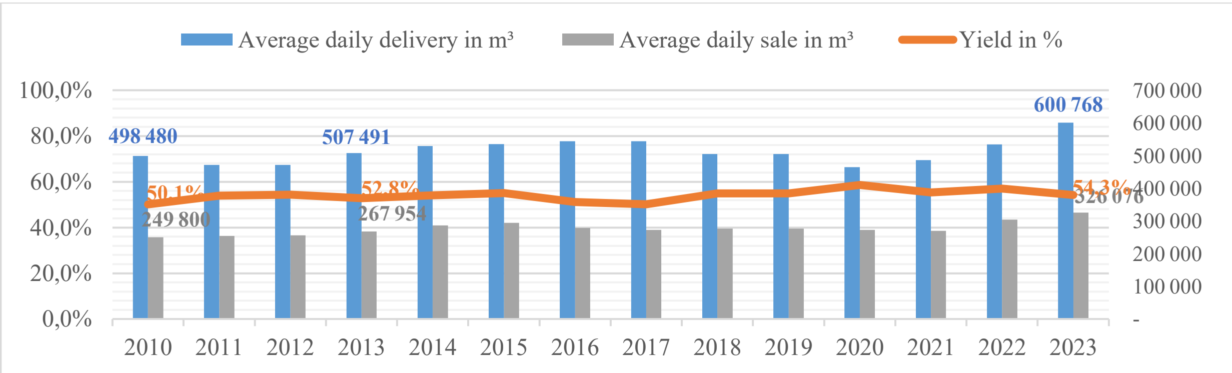



*Figure 2. Elevations of study area*

*2.1.2. Water demand data*

The demographical data used in this study were provided by the Ngaliema municipality. The population of the Ngaliema municipality has been estimated at 206 466 inhabitants in 2022 for the districts including the Ngaliema sector alone.

The municipality of Ngaliema is one of several municipalities of Kinshasa city. The last one is characterized by water shortage problems and low pressure in several districts despite the increase in water production capacity in recent years through the construction of several water treatment plants. Figure 3 shows trends in the delivery, sale and yield of water to the distribution network in the city of Kinshasa




Annual water production capacity: 513,000 m³/d, with commissioning of the 3rd phase of the N'djili plant (110,000 m³/d)

Annual production capacity: 531,000 m³/d, with commissioning of the 2nd phase of the Lukaya plant (18,000 m³/d)

Annual water production capacity: 676,000 m³/d, with the commissioning of the 1st phase of the Binza-ozone plant (110,000 m³/d) and the Lemba-Imbu plant (35,000 m³/d).

*Figure 3. Kinshasa network yield trend*

Referring to figure 3., the water production capacity has increased from 513,000 m3/d in 2010 to 676,000 m3/d in 2023 with the start-up of the Lemba-Imbu (35,000 m3/d) and Binza-ozone (110,000 m3/d) plants, In spite of these investments, the network efficiency is around 50% with a water loss of 274,692 m3/d currently because the distribution network is characterized by the absence of balance tanks and the pressure and flow control devices, which make it difficult to regulate pressure and distribute flows correctly over various parts of the distribution network

*2.1.3. Data*

Water demand (needs of schools, hospitals, official offices, shops and households) was collected at REGIDESO and the municipality of Ngaliema. Data for Pipe characterization was provided by the operations department of REGIDESO Company. These data play an important role in pipe sizing and model calibration. The hydraulic network in the REGIDESO/NGALIEMA sector is composed by steel, PVC (%) and HDPE pipes (%).

The pressure data used was measured in situ for four nodes. These nodes measurements were then used to calibrate the REGIDESO/NGALIEMA sector network model. Concerning the flow calibration process consisted of taking the hourly demand modulation data in each pressure zone, this data was assigned to each node in the network as coefficients of demand variation.

***2.2. Methods***

The figure 4 shows the methodological approach used in this study, from calculating water demand to optimize the network

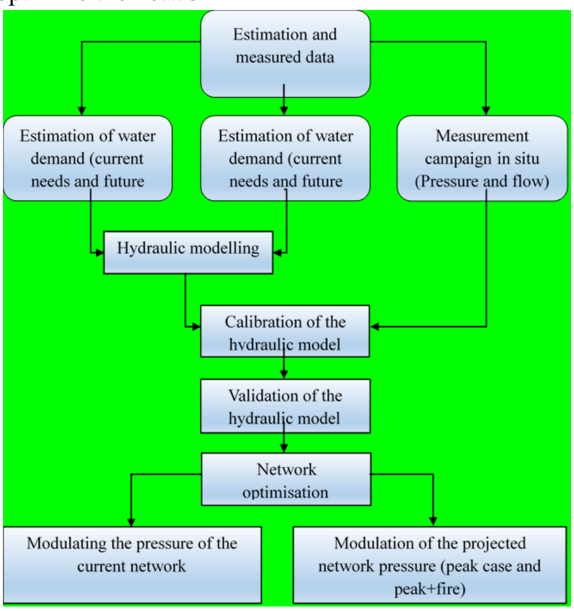



*Figure 1. Conceptual Methodology Diagram*

As shown in the flow chart above, the methodology used in this study is based on a digital model which consists of modelling and simulating the network using hydraulic modeling software. First of all, the water demand of the study area had to be determined. Water requirements are not constant but vary over time, and flows are determined according to daily and hourly variations (Touhami & Mekerta, 2017). For the design of the project, the following values were important to have the water demand of the area:

a. The actual daily demand (D1)

The current daily demand is the average water demand for the area per day at the time the project is inaugurated. It is calculated using equation (1) below.

$$D_1 = actual\ population \times allocation \quad (1)$$

b. The future daily demand (D2)

The future daily demand is the average water requirement for the area after a period equal to the project horizon (useful life). Equation (2) presents its formula.

$$D_2 = future\ population \times allocation \quad (2)$$

The study area is a domestic type area, which made it possible to use the compound formula of interest (3) for the future water demand Pn,

$$P_n = P_0(1+i)^n \quad (3)$$

With $P_0$ = current population, the population growth rate of the city of Kinshasa i = 3.5% and the number of years n = 25 years.

c. The maximum daily flow rate (Fd)

The maximum daily flow rate is the peak day flow rate expressed in m3/d. It is calculated as follows

$$F_d = D \times K_{dp} \quad (4)$$

With Kdp: the daily peak load factor, which varies between 1.3 and 1.6

d. Average hourly flow rate (Fh) in $m^3/h$

The average hourly flow is given by the following formula:

$$F_h = \frac{F_d}{24} \quad (5)$$

In order to distribute demand over the entire study area, the Thiessen polygon method was used with Geographic Information System software (Tufa & Abate, 2022). Once the water demand had been determined, a measurement campaign was essential, regarding the fact that the distribution network does not contain any devices for monitoring hydraulic data (pressure and flow rate). It was therefore necessary to place the measurement devices in the field in order to collect pressure and flow rate data for 24 hours, which was later used to calibrate the distribution network in the study area. After calculating the water demand and carrying out the measurement campaign, we used a number of software packages to model the network. The network was mapped using GIS software, and the network was modelled using Epanet hydraulic simulation software and calibrated/validated to calculate hydraulic parameters for various scenarios.

As part of this work, the network was calibrated using the parameters needed to give a true representation of reality. These parameters are pressure and flow rate. There are values measured in the field and those calculated by the software. By adjusting the roughness of the pipes, the two values (measured and simulated) can be matched or brought as close as possible to give a much more realistic representation (Kadhim et al., 2021). The performance or validity of the calibration results on the Epanet model is evaluated using two statistical parameters: mean square error and correlation (Pordal et al., 2023). Figure 1 above illustrates the four in-situ measurement points that were used to calibrate the hydraulic model.

The performance or validity of the alibration results on Epanet model is assessed using two statistical parameters: the mean square error and the correlation (Pordal et al., 2023). Lastly, it was necessary to optimise the network so that it could function properly now and, in the future, while complying with the pressure and speed standards for a drinking water distribution network.

# 3. Results and discussion

## *3.1. Simulations of the water distribution network*

This section presents the results of estimating the characteristics of the networks, in particular the current and future water requirements of the nodes, the design flow rates for the pipes, and the simulations obtained after calibrating the hydraulic model of the distribution network.

### *3.1.1. Estimation of current and future water requirements*

Table I shows the discharge values for the water supply in the present situation of the study (2022) and also for the projections in the future (2046).

*Table I. Flows of sizing network*

| Year | Daily peak coefficient $Dp_c$ | Maximum daily discharge $Q_j$ | Average hourly discharge $q_h$ |
|---|---|---|---|
| | | ($m^3$/jour) | ($m^3$/h) |
| Actual (2022) | 1,5 | 42 883,08 | 1 786,79 |
| Future (2046) | 1,5 | 95 909,73 | 3 996,24 |

Table I shows the results of the current and long-term design flows. As we can see, in 25 years the flow will double, hence the need to model for the future year (2046) without compromising the operation of the network at the current horizon, which complies with speed and pressure standards.

### *3.1.2. Network calibration*

By calibrating the network, we were able to represent the actual situation of the network. The profiles before calibration (figure 5) and after calibration (figure 6) show approximately the state of the existing network.

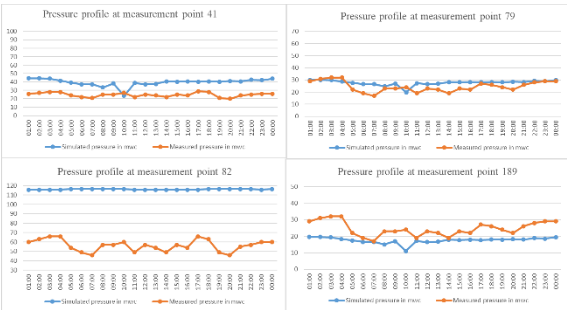



*Figure 5. Pressure profiles before calibration*

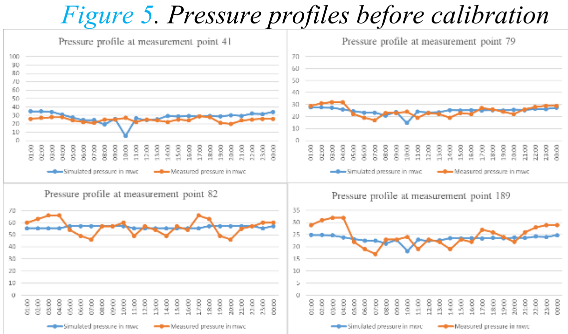



*Figure 6. Pressure profiles after calibration*

Figures 5 and 6 show that there is a difference between the simulated values and the values measured in the field. This difference is due mainly to the estimation of the hydraulic calculation parameters, some pipes are obsolete, which means that the two values are different. To approach these two values, the roughness values have to be adjusted, which involves changing the pressure drops. The aim is to have a correlation coefficient close to 1.

*3.1.3. Validation and assessment of model performance*

Table II shows the results of the performance evaluation of the hydraulic model of the water distribution network after manual calibration with the EPANET software. The values of the mean square error and the correlation coefficient show a strong correlation between the observed and simulated values.

*Table II. Model validation*

| Measurement points | Number of observed | Average observed P (mwc) | Before | | After | |
|---|---|---|---|---|---|---|
| | | | Simulated average P (mwc) | MSE | Simulated average P (mwc) | MSE |
| 41 | 24 | 24,8 | 39,6 | 15,5 | 27,9 | 7,0 |
| 79 | 24 | 24,6 | 27,7 | 4,8 | 24,7 | 3,8 |
| 82 | 24 | 56,4 | 116,0 | 59,9 | 56,3 | 6,4 |
| 189 | 24 | 24,6 | 17,5 | 8,0 | 23,3 | 4,0 |
| Network | 96 | 32,6 | 50,2 | 31,3 | 33,0 | 5,5 |
| | | | | | | **r= 0.991** |

***3.2. Optimization of the distribution network and assessment of scenarios***

Once the model had been designed and calibrated, several network optimization scenarios were carried out, i.e. reinforcement of the current and projected network (after calibration), as well as its optimization. Figures 7 shows the pressure scenarios, i.e. the current network, the future network without control devices, the future network in the event of a peak and the projected network in the event of a peak + fire(with control devices).

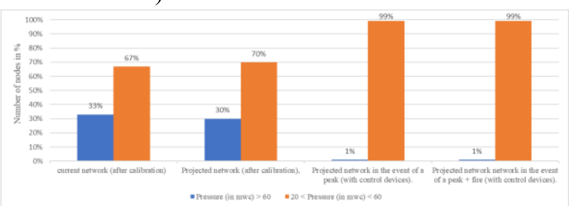



*Figure 7. Distribution System Pressure repartition*

Figures 7 shows the results of pressures and for the 4 scenarios studied. The current and future scenarios without the control devices have respectively 33% and 30% of the nodes with very high pressures (> 60 mwc). The speeds in the pipes are satisfactory for all scenarios.

## 4. Conclusion

The calibration process was essential for identifying the optimal values for the pipes, enabling the effective reinforcement of the water supply network. After calibration, it was observed that several pipes exhibited flow velocities that did not comply with the acceptable standards for proper network operation, which range from 0.5 m/s to 1.5 m/s. Low velocities (less than 0.5 m/s) increase the risk of microbial penetration in the event of a leak, potentially leading to waterborne diseases among consumers. Conversely, high velocities (greater than 1.5 m/s) heighten the likelihood of pipe breaks and ruptures. Once the network had been calibrated, the focus shifted to optimisation process. Several scenarios were proposed to better understand the challenges of the distribution network in the REGIDESO/Ngaliema sector and to select an effective network configuration that ensures a reliable supply of drinking water in both the short and long term. Hydraulic simulations were conducted to explore optimal operational strategies for the distribution network, examining four scenarios after the calibration process.

The first two scenarios involved reinforcing the existing network for current and future demands; however, these scenarios did not adequately address the water supply issues. The configuration of the existing distribution network lacks pressure regulators, leading to excessive pressures due to topographical variations with elevation differences of up to 200 meters. This situation underscores the necessity for installing regulating devices (both flow and pressure).

In contrast, the latter two scenarios accounted for pressure regulation by incorporating these devices into the network. These scenarios simulated network performance during peak demand and both peak demand with fire flow scenario. The results from these scenarios were satisfactory in terms of maintaining acceptable velocity and pressure levels, as they considered the unique configuration of Kinshasa's distribution network, which features multiple pressure zones and significant altitude variations.

To minimise leaks and enhance effective monitoring of the network, it is recommended to carefully select locations for measuring devices such as flow meters and pressure gauges. This will facilitate improved oversight of the Kinshasa network. Additionally, creating a comprehensive map of the network based on operational data and progressive calibration will aid in identifying vulnerabilities. Implementing a pipe renewal program and establishing balance and head tanks will further support effective pressure regulation and flow distribution across various segments of the distribution network. In conclusion, this study highlights the importance of optimising the water supply network in Ngaliema through calibration and the strategic implementation of pressure regulation devices. By addressing these challenges, the network can achieve a reliable and safe supply of drinking water, ultimately improving public health outcomes and service delivery in the region.

## Acknowledgements

This work was carried out with the support of REGIDESO S.A, Regional School of Water (ERE) & Congo Basin Water Resource Research Center (CRREBaC) of the University of Kinshasa (UNIKIN), whom we thank for providing the necessary resources.

## Funding

The authors declare that they received no funding and that this had no influence on the results presented.

## Conflict of interest

The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper. On behalf of all authors, the corresponding author states that there is no conflict of interest.

## Ethical considerations

The authors guarantee the accuracy of the results presented, whether positive or negative, and assure that the raw data will be made available upon request.

## Contributions of authors

A.M.P, A.A., and T.M.R: Conception and design of study

A.M.P., A.A., T.M.R., K.D., and N.N.L.: acquisition of data

A.M.P., A.A., T.M.R., K.D., and N.N.L: analysis and/or interpretation of data was done by

by A.M.P., A.A., T.M.R., K.D., and N.N.L: drafting the manuscript

A.M.P., A.A., T.M.R., K.D., and N.N.L: revising the manuscript critically for important intellectual content

A.M.P., A.A., T.M.R., K.D., and N.N.L: approval of the version of the manuscript. All authors have read and agreed to the published version of the

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