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Reliability Analysis of a Gravity Adduction of Water Supply System: Case Study

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Abstract: The gravitational transfer of drinking water through gravity-fed supply pipes from a departure tank to a receiving tank often follows very complex and winding itineraries. The longitudinal profiles of these itineraries consist of a succession of singular points (top and bottom points). A common mistake made by inexperienced engineers is to ignore these specific features and focus only on the levels of the departure and receiving tanks. The problem becomes even more complex when the longitudinal profile forms a siphon, where the transferred water undergoes a significant drop to the lowest point before rising again to reach the receiving tank. This paper focuses on the study of a practical case of a siphon in a gravity-fed water supply system connecting two tanks over a distance of 15.25 km. By using a Geographic Information System (GIS), a Digital Elevation Model (DEM) was generated along the pipeline itinerary to highlight the terrain's complexity and the singular points of the pathway. A deterministic analysis was conducted to evaluate the service life of the siphon-shaped gravity-fed water supply system. This analysis revealed that uncertainties in the gravity adduction, particularly regarding the internal roughness of the pipeline, can directly impact operating pressures at singular points and, consequently, affect the system's lifetime. Additionally, a reliability-based analysis was performed, accounting for the random variability of roughness. The limit state function is governed by the normal operating conditions and failure criteria of the water supply system. The failure probabilities of the gravity adduction with respect to these limit state functions were computed using the classical Monte Carlo simulation method and then compared to the allowable failure probability for civil engineering structures.

Keywords: Gravity-fed water supply, Siphon, Deterministic analysis, Reliability analysis, Failure probability

Introduction

Gravity-fed water Transfer is extremely sensitive to topography, particularly in Kabylia region, where villages are perched on hilltops or mountains forming a segment of the mountain system. The transfer of water by gravity via supply pipes from one tank to another is subject to very Pressure drops**.** At these low points (siphon), there is extreme hydrostatic pressure, which puts a severe strain on the pipes. This is exacerbated by water hammer.

Usually, in design offices, the analysis and design of drinking water addictions are based on deterministic approaches, and the calculation parameters are considered by engineers as constant values. However, the literature has shown that, in general, variables such as the consumption rate, the Hazem Williams coefficient and the peak coefficient are considered to be random (Jung, 2010 ; Seifollahi, 2013 ; Basupi, 2015; Hwang, 2017). To this end, reliability theory is increasingly used to take account of the randomness and uncertainty inherent in these different parameters (Tori et al., 2012 ; Galaitsi et al.2016 ; Batsirai et al, 2018).

This scientific approach leads to the estimation of the probability of failure of these structures. Several methods are used to calculate the probability of failure of a drinking water supply network (Gheisi, 2016; Goulter, 2000; Pandey, 2020; Sirsant, 2023). The Monte Carlo method is still the most widely used because of its simplicity and effectiveness. To describe the variability of random parameters, the normal distribution and the betta distribution are the most commonly used to generate the probability low distributions (Jung, 2010; Basupi, 2015; Hwang 2017).

In this article, the hydraulic behaviour (pressure) of the Oued Aissi siphon is examined, which is an adduction pipe linking Larbaa Nath Irathen tank to Béni Douala tank over a length of 15.25 km. This pipeline, which began in 1946, served a project involving 100 villages and was supplied from the Souk El Djema dam (Ain El Hammam). This project was resumed in 1963. The pipe at siphon level, with a nominal pressure PN100 was swept away by the flood of April 1974, then repaired and put back into service. In view of the high nominal pressures and the vulnerability of the pipe due to the river crossing, this supply line was decommissioned at the end of 1976. Using a deterministic calculation of velocities and pressures, we will attempt to provide technical and hydraulic explanations for these repeated ruptures, which led the hydraulic department of Tizi Ouzou to abandon this siphon. In addition, the adopted reliability analysis allows the random variability of Hazen William's roughness coefficient to be taken into account. The results of the calculation of the probability of failure highlighted the sensitivity of the pressure and velocity criteria to the random variability of the roughness.

Presentation of the Gravity Supply

The Oued Aissi supply network starts from a tank with a capacity of 1000 m³ located in Aboudid (LNI) at level of 1035 m (Figure 1). The water will be conveyed to tank with a capacity of 1000 m³ located at Djouad (Beni Douala) at level of 880.27 m (Figure 1).

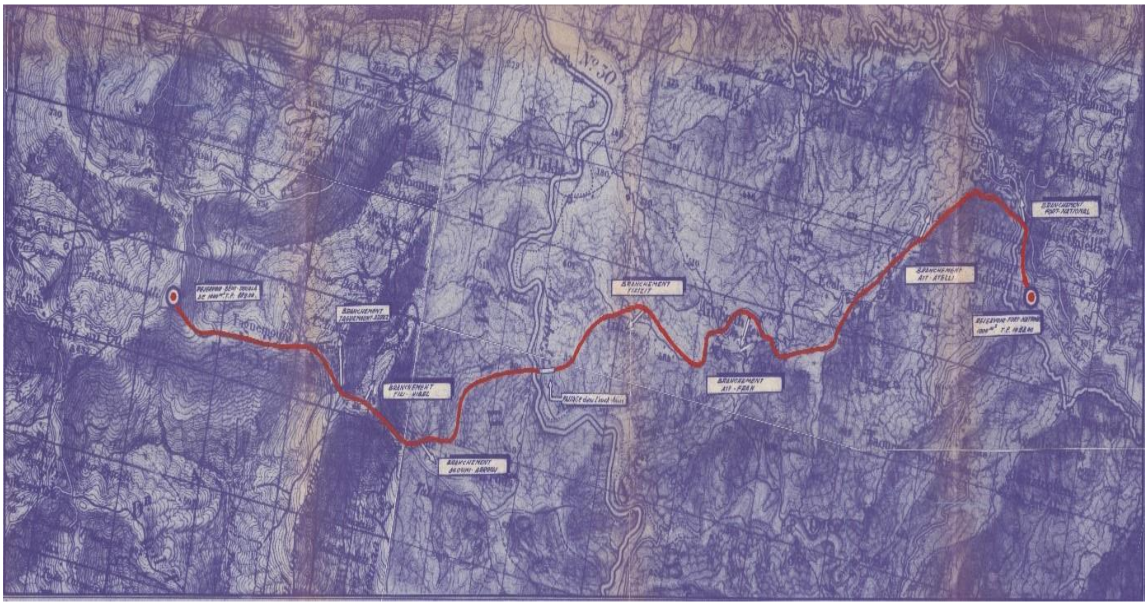

Figure 1. Sketch of the route of the gravity-fed water supply, overlaid on a topographic map

The steel supply pipe is made up of 64 sections. The corresponding lengths and altitudes are taken from the longitudinal profile of the network (Figure 2). Several tapping points are successively made along this pipe to supply 7 villages. The flow rate through the network varies according to the different tapping points (Table 1). Figures 1 illustrate the route sketch and longitudinal profile of this pipeline, respectively. This figure highlights the topographical configuration of the project, which is referred to as a siphon. If the difference in altitude between the departure tank and the receiving tank is only 154.73 m, the water must undergo a fall of 871.62 m before it can rise to the receiving tank.

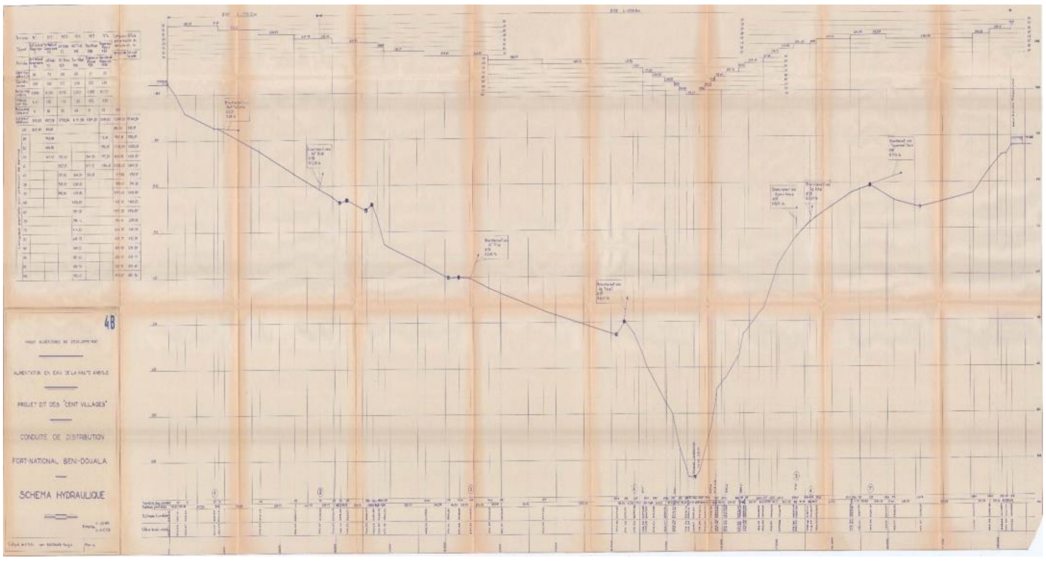

Figure 2. Longitudinal profile of the gravity pipeline

Table 1. Flow transiting by the addiction pipe

Pipeline section	1,00	2,00	3,00	4,00	5,00	6,00
Departure	LNI tank	LNI Tizi N'Smlal	Ait Atelli	Ait Ferah	Tizi Hibel	Taguemount Azouz
Arrival	LNI Tizi N'Smlal	Ait Atelli	Ait Ferah	Tizi Hibel	Taguemount Azouz	BD tank
Transited flow (l/s)	99,00	71,00	68,32	64,54	61,13	52,07
Tapping flow (l/s)	28,00	2,68	3,78	3,41	9,06	-

Digital Terrain Model (DTM)

To generate a Digital Terrain Model along the pipeline route (Larbaa Nath Irathen - Beni douala), a semi of 1406 points was carried out on the staff map (Oued Aissi-Takhoukht-Mechtras) at a scale of 1:25,000 (Figure 3), using GIS (Geographic Information System).

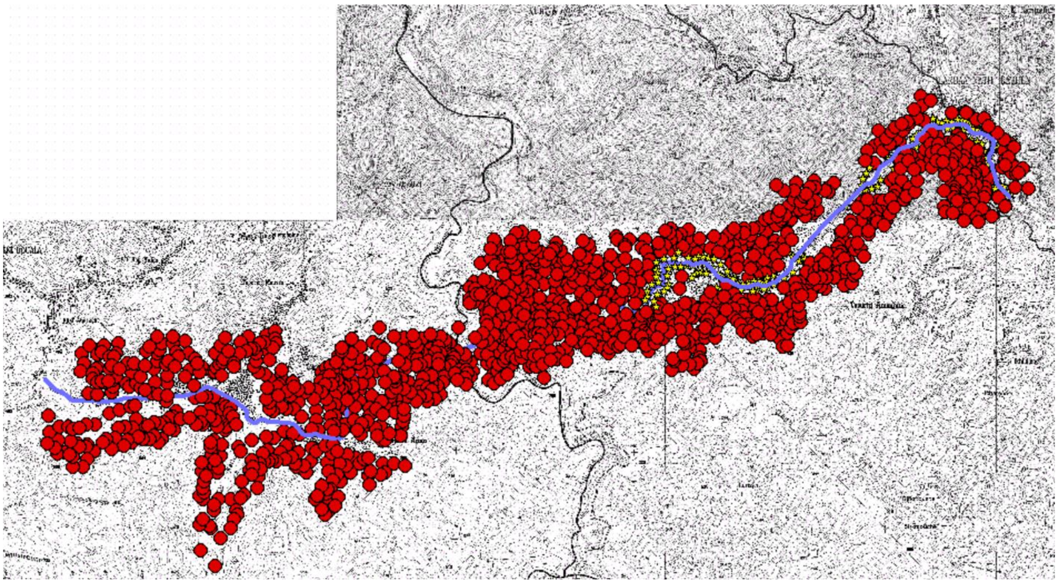

Figure 3. Topographic survey.

To give meaning to this graphical representation and show the difference in altitude between the various sampled points, a thematic map is created (Figure 4). We observe that the altitude ranges from 200 m to 950 m.

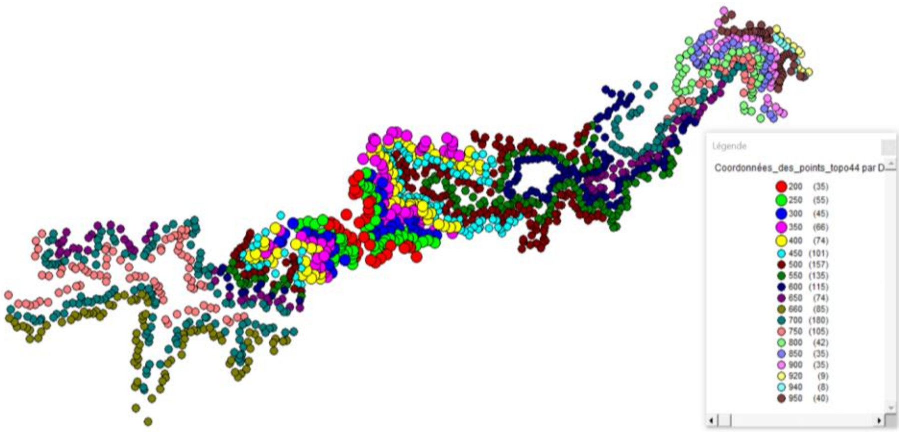

Figure 4. Analyse thématique des altitudes.

For each surveyed point, the X, Y, and Z coordinates were recorded in an Excel file and then imported into Surfer software to generate the DTM along the route of the Oued Aissi gravity pipeline (Figure 5). This DTM provides an accurate and detailed representation of the siphon, clearly highlighting the significant elevation differences between the departure tank and the receiving tank. Thus, it serves as a relevant tool for understanding terrain complexity, optimizing route analysis, and supporting decision-making related to the installation or maintenance of the hydraulic network.

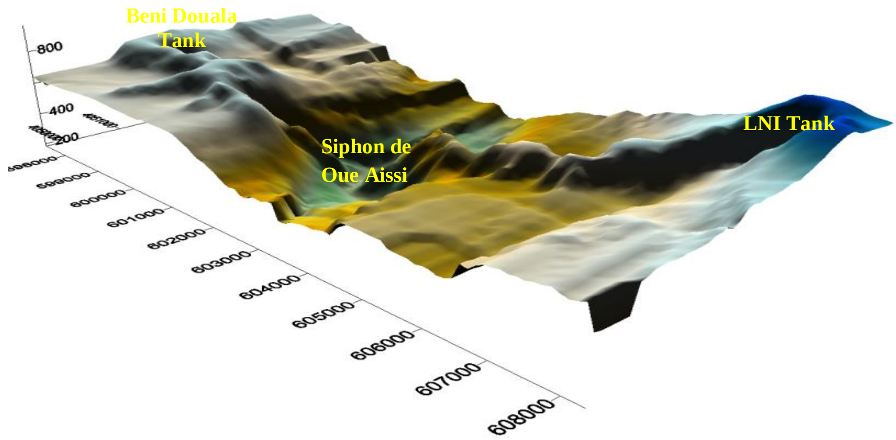

Figure 5. Digital Terrain Model along the pipeline route (Larbaa Nath Irathen - Beni douala).

Hydraulic Calculation of Gravity Supply Network

The purpose of the hydraulic calculation of the gravity supply network pipe is to determine the flow velocity V(m/s) and piezometric level Hi (m) in the various sections of the pipe. Two standard diameters are adopted, DN300 and DN250. The flow velocity V(m/s) in the pipeline is determined using the continuity equation:

$$V = \frac{4\,Q}{\pi\,DN^2} \tag{1}$$

To ensure the proper functioning of the network, the piezometric level (or Hydraulic head) H^i at node (i) must satisfy the following condition:

$$H_{min\,adm} < H^i \leq H_{max\,adm} \tag{2}$$

Where:

$$H^i = H^{i-1} - \Delta H \tag{3}$$

ΔH: Total head losses (linear and singular), given by:

$$\Delta H = 1.15\; j\; L \tag{4}$$

Where L is the length of the pipeline and j is the unit head loss, given by the Hazen-Williams formula:

$$j = 1.218 * 10^{10} \frac{Q^{1.852}}{chw^{1.852} * DN^{4.871}} \tag{5}$$

chw designate the Hazen-Williams roughness coefficient, equal to 136 for a new pipe and 95 for an old pipe. The minimum admissible service head is verified to ensure that water can enter the tank. It is given by:

$$H^{i}_{minadm} = NTE^{i} + 10 \tag{6}$$

Where 10 m represents the minimum service pressure and (NTE) the Natural Terrain Elevation. The maximum admissible head at a node (i) of the pipeline is obtained using the following equation:

$$H^{i}_{maxadm} = NTE^{i} + PN \tag{7}$$

Where PN is the nominal pressure of the pipe, in meters, selected from the catalogue based on the maximum pressures (P_{max}) and minimum pressures (P_{min}). The maximum and minimum pressure at any node (i) of the pipelinein according to water hammer are given by the following equations:

$$P^{i}_{max}=H^{i}_{geo}+B \tag{8}$$
$$P^{i}_{min}=H^{i}_{geo}-B \tag{9}$$

Where, Hgeo and B designate respectively the geometric height of the node (i) and the water hammer pressure at the same node (i). This water hammer is given by the following equation:

$$B = a\frac{V}{g} \tag{10}$$

a: Celerity of the water hammer wave, given by Allievi

$$a = \frac{9900}{\sqrt{48{,}90+K\frac{DN}{e}}} \tag{11}$$

Where K and e designate respectively the coefficient depending on the pipe material (steel, K = 0.50), and the pipe wall thickness [m]. The calculation results show that for the various sections the velocities are between (V_{min}=0.5 m/s) and (V_{max}=1.5 m/s), in accordance with the condition required by the regulations (Figure 6).

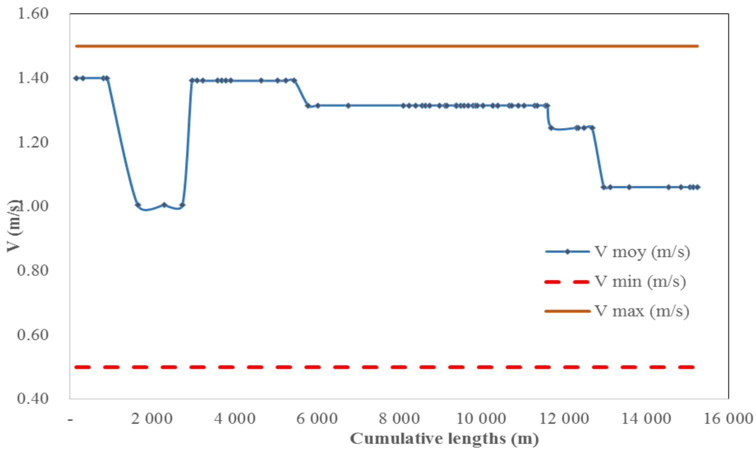

Figure 6. Velocity calculation results

For the pressures, Oued Aissi gravity feed network was modelled for both the commissioning phase (chw=136) and over 30 year (chw=95). The calculation results of the piezometric levels are shown in Figures 7 and 8. It can be seen that at commissioning, the piezometric line (H^{i}) is within the maximum and minimum allowable pressure range across all section. This deterministic analysis of velocities and pressures indicates that Oued

Aissi gravity feed network is properly designed at the time of commissioning, in accordance with hydraulic regulations. It should also be pointed out that the pressures at the Siphon are very high. To this end, we have adopted pipes of PN90 and PN100. Over a 30-year period (Chw=95), the results show that the piezometric level falls below the minimum admissible pressure at the last three nodes (63, 64 and 65). This, of course, leads to network malfunction, as the water will not reach the receiving tank. This means that the network is not properly dimensioned with regard to the hydraulic conditions required by the regulations. These nodes must therefore be points of attention for the infrastructure manager.

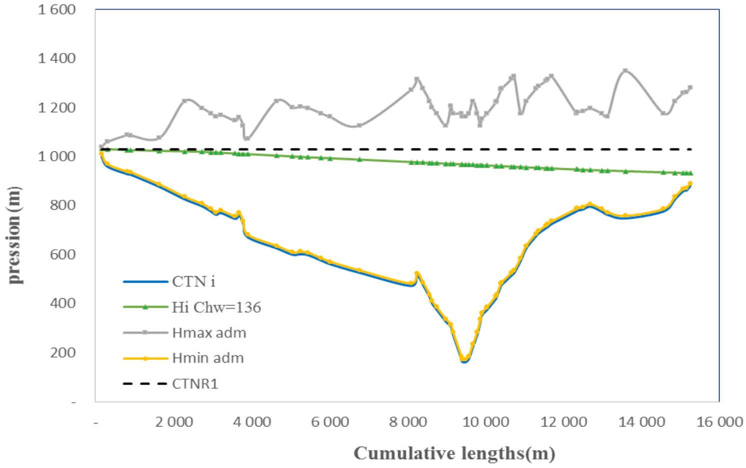

Figure 7. Piezometric line position at commissioning.

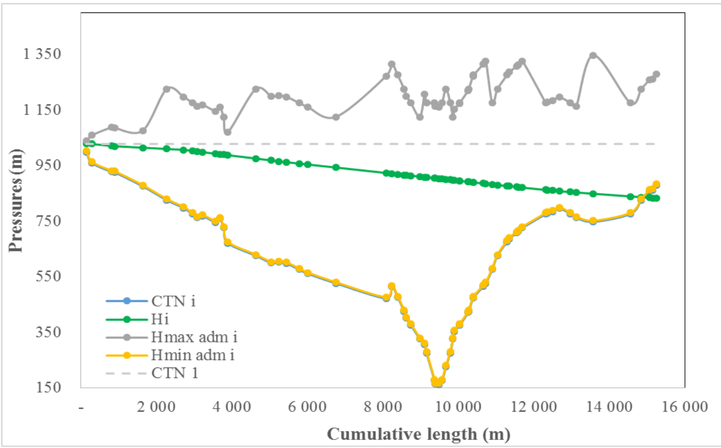

Figure 8. Piezometric line position over 30 years.

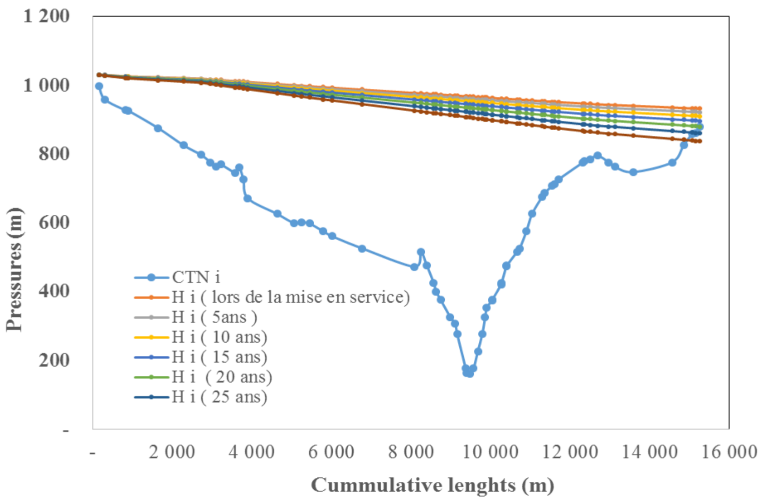

Figure 9. Evolution of piezometric levels.

To analyse the lifetime of Oued Aissi gravity feed network, we considered a linear evolution of the Chw coefficient. The results of the piezometric levels evolution as a function of time (figure 9) show that the piezometric line decreases with time and therefore with the Hazen-Williams coefficient, falling below the CTN at around 20 years of service.

To obtain the exact year of the network failure, we superimposed the evolution over time of the piezometric level of the network with the natural ground level, as shown in figure 10. The results show that after 19 years of service, the initial design flow (99 l/s) cannot be insured. This would lead to a flow deficit and therefore a reduction in the supply. Under these conditions, after simulating the situation for 30 years, it turns out that the pipe could only provide 90 l/s.

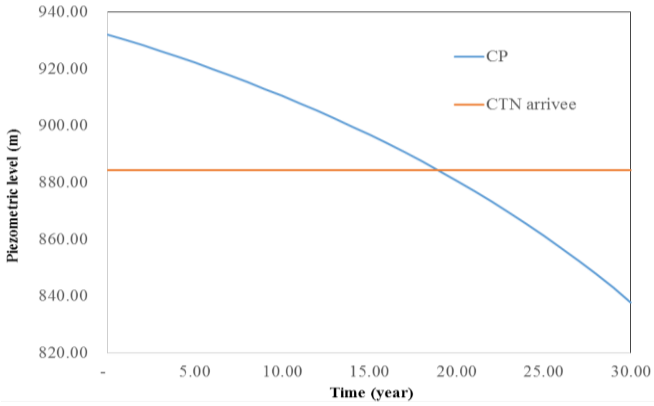

Figure 10. Analyse of the lifetime of Oued Aissi gravity feed network

The gravity supply network is analyzed under the condition of an instantaneous valve closure. For this purpose, the overpressures and underpressures induced by the water hammer (B) at each node were calculated according to relation 10. The results of these calculations are presented in Figure 11. It is observed that when the valve closes instantaneously, the overpressures exceed the permissible limits at several nodes (37, 59, and 61), which may damage the pipes and lead to leaks as well as weakened joints and connections. Particular attention should be paid to these nodes, especially in the vicinity of siphons.

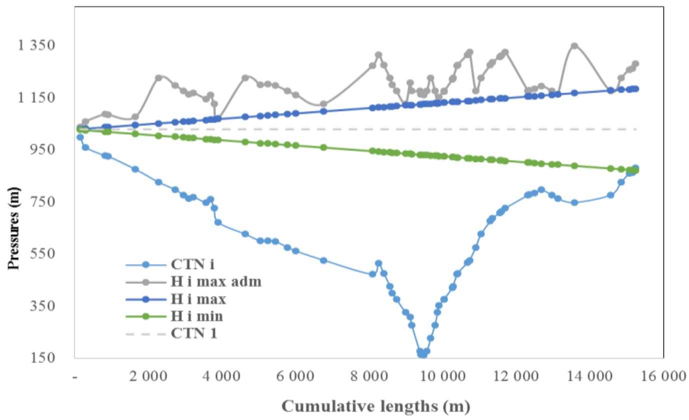

Figure 11: Pressures acting at instantaneous closure of the valve.

Finally, for a better analysis of the gravity feed failure, we propose a reliability study, taking into account the uncertain aspect of pipe roughness, throught the Hazen Williams coefficient (Chw).

Failure Mode and Limit State Function

In reliability theory, the failure of a system is defined by the general form of a limit state function G(X) (Lemaire, 2005), which defines its behaviour, as follows:

$$G(X) = R(X) - S(X) \tag{12}$$

Where X is the vector of random variables xi. The basic principle of structural design is that the ultimate resistance R(X) must be greater than the live load S(X) (Lemaire, 2005). The probabilistic approach consists of calculating the probability of the limit state criterion being exceeded, called probability of failure P_f, which is compared with a permissible probability of failure, which is is equal to 10^{-3} for civil engineering structures (Bouzelha et al, 2024):

$$P_f = P(G(X) \leq 0) \leq P_f^{adm} \tag{13}$$

In this study, the limit state function G(X) is defined by the failure of the water supply network in service, resulting from the ageing of the pipes. This ageing is mainly due to the increase in the roughness of the internal walls, which leads to a significant rise in head losses. The criterion for justifying this limit state is to check that the piezometric head H(X), taking into account the head losses, is greater than the minimum admissible head; previously defined:

$$G = H(X) - H_{min\ adm}(X) \tag{14}$$

Evolution of the Failure Probability

The failure probability P_f is given by the integral of the probability density function, as follows:

$$P_f = \int_{D_f} f_X(x_1, x_2, \ldots\ldots, x_1) dx_1, dx_2, \ldots\ldots, dx_n \tag{15}$$

The analytical evaluation of this integral is difficult and requires advanced mathematical skills. Several numerical approaches are proposed in the literature (Lemaire, 2005) such as the Monte Carlo simulation method and the First-Order Reliability Method (FORM), and the Second-Order Reliability Method (SORM). In this study, the calculation of the failure probability P_f is conducted with the classical Monte Carlo method. The principle of this method is based on generating a large number of random samples, denoted N_t, according to their joint probability distribution. For each sample, the response of the limit state function is evaluated (Figure 10). A failure indicator I_{di} is then introduced to identify the failure condition of the system based on the limit state function G(X), such that:

$$I_{di} = \begin{cases} 1 & \text{if } \; G(x) \leq 0 \\ 0 & \text{if } \; G(x) > 0 \end{cases} \tag{16}$$

The failure probability Pf is evaluated, for the predefined failure mode, by the following relationship.

$$P_f = \frac{\sum_{i=1}^{N_t} I_{di}}{N_t} \tag{17}$$

Random Variables and Distribution Laws

The behaviour of the water supply network is affected by numerous uncertainties linked to the geometry of the pipes, the characteristics of the materials and the hydraulic characteristics. The main source of uncertainty retained in our case study is the roughness of the pipes which wears away over time, thus affecting pressure losses and, above all, pressures in the network. This roughness is expressed by the Hazen-Williams coefficient. This random variable is generated using the normal distribution in accordance with the literature (Seifollahi et al, 2013; Xu et al. 1999). The probability density function of the normal distribution is given by expression (18) and illustrated in Figure 10 for different values of C_v

.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \tag{18}$$

x is the random variable, μ is the mean of the distribution, and σ the standard deviation.

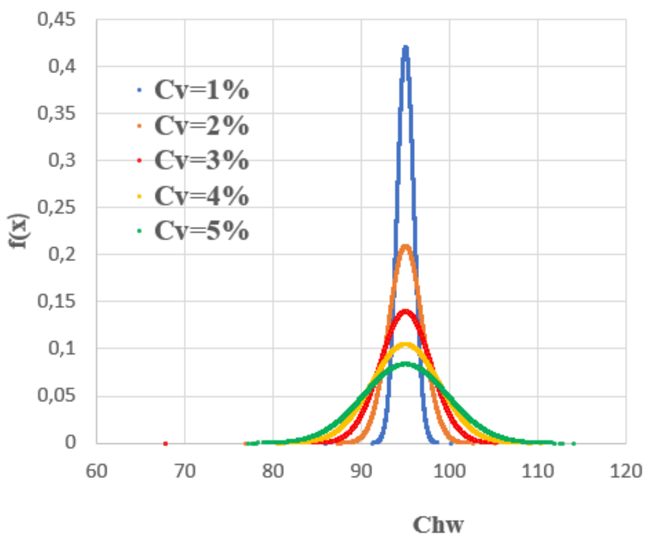

Figure 10. Density function of the normal distribution.

Results and Discussion

The probability of failure P_f is obtained using Monte Carlo simulations. The number of the number of samples (N_t) is fixed at 30 000.00, after a convergence test (Figure11).

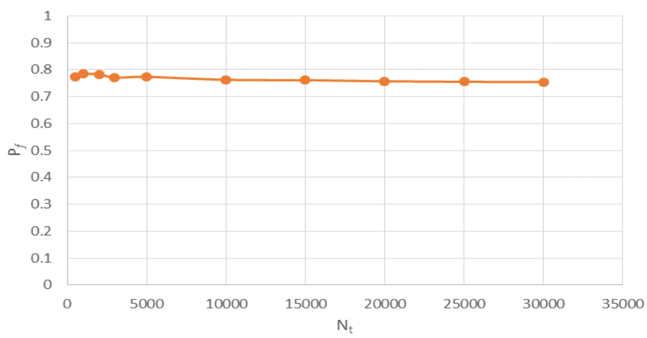

Figure 11. Variation of the failure probability as function of the number of draws.

The evolution of the probability of failure P_f as a function of time, for different coefficients of variation ranging from 1% to 5%, is illustrated in Figure 12. We note the sensitivity of the pressure criterion to the random variability of the pipe roughness.

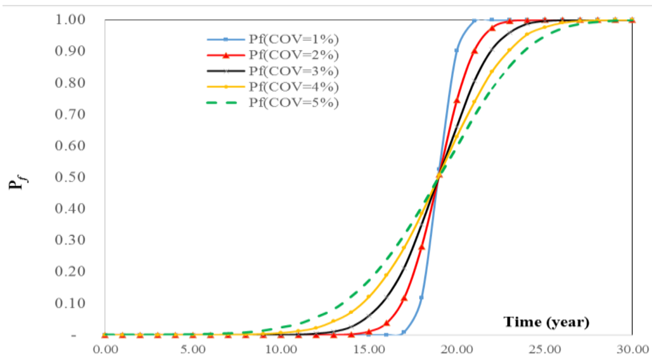

Figure 12. Probability of failure as a function of coefficient of variation.

It is observed that the failure probability is zero during the first ten years of service. Between ten and thirteen years, P_f remains below the admissible probability (P_f^{adm}=10^{-3}). After thirteen years, the failure probability increases with time, as the network continues to age. The admissible probability is reached between 13 and 16 years, depending on the coefficient of variation C_v. In other words, the risk of network failure is likely to occur earlier than predicted by deterministic calculations (19 years), due to uncertainties related to roughness.

Conclusion

The combined analysis of the Digital Terrain Model (DTM) and the deterministic and probabilistic approaches applied to the Oued Aissi gravity-fed water supply network has led to several key practical insights essential for ensuring the long-term sustainability of the system. These include the importance of the DTM in the design and analysis of the pipeline route, as well as the limitations of the deterministic approach, which does not take into account the random variability of certain key parameters, particularly pipe roughness. In addition, several causes of failure or malfunction have been identified, such as:

- *Pipeline aging*, resulting in a gradual increase in internal roughness, leads to significant head losses and a drop in piezometric pressure. Over time, the pressure falls below the admissible value at the last three nodes, preventing water from reaching the receiving tank.
- *Insufficient flow*, observed from the 19^{th} year of operation, when the design flow rate of 99 l/s can no longer be maintained, leading to a supply deficit.
- *Random variability of roughness*, highlighted by the probabilistic analysis, anticipates failures between 13 and 16 years, which are not predicted by the deterministic approach.

These findings underscore the need for an adaptive network management, incorporating monitoring, preventive maintenance, and progressive redimensioning to ensure the long-term reliability of the service.

Scientific Ethics Declaration

*The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

*The authors declare that they have no conflicts of interest

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References

Basupi, I., & Kapelan, Z. (2015). Flexible water distribution system design under uncertainty. *Journal of Water Resources Planning and Management*, *141*(4), 786–797.

Batsirai, M., Suhrcke, M., & Hunter, P. R. (2018). Reliability of water supplies in low and middle-income countries: A structured review of definitions and assessment criteria. *Journal of Water, Sanitation and Hygiene for Development*, *8*(2), 142–164.

Bonnin, J. (1986). *Hydraulique urbaine appliquée aux agglomérations de petite et moyenne importance*. Eyrolles.

Bouzelha, K., Hammoum, H., Aliche, A., Aoues, Y., & Amiri, O. (2024). Contribution to calibration of partial safety factors for RC water tank design. *Structural Engineering International*, *34*(3), 404-413.

Galaitsi, S. E., Russell, R., Bishara, A., Durant, J. L., Bogle, J., & Huber-Lee, A. (2016). Intermittent domestic water supply: A critical review and analysis of causal-consequential pathways. *Water*, *8*(7), 274.

Gheisi, A., Forsyth, M., & Naser, G. (2016). Water distribution systems reliability: A review of research literature. *Journal of Water Resources Planning and Management*, *142*(11).

Goulter, I., Walski, T. M., Mays, L. W., Sakarya, A. B. A., Bouchart, F., & Tung, Y. K. (2000). Reliability analysis for design. In L. W. Mays (Ed.), *Water distribution systems handbook*. McGraw-Hill.

Hammoum, H., & Bouzida, R. (2010). *Pratique des Systèmes d'information Géographiques (SIG): Application sous Mapinfo*. Pages Bleues.

Hwang, H., Lansey, K., & Jung, D. (2018). Accuracy of first-order second-moment approximation for uncertainty analysis of water distribution systems. *Journal of Water Resources Planning and Management*, *144*(2), 04017088.

Jung, D., Chung, G., & Kim, J. H. (2010). Optimal design of water distribution systems considering uncertainties in demands and roughness coefficients. In *Water Distribution Systems Analysis 2010* (pp. 1390-1399).

Lemaire, M., Chateauneuf, A., & Mitteau, J. (2005). *Fiabilité des structures*. Lavoisier.

Pandey, P., Dongre, S., & Gupta, R. (2020). Probabilistic and fuzzy approaches for uncertainty consideration in water distribution networks: A review. *Water Supply*, *20*(1), 13–27.

Seifollahi-Aghmiuni, S., Bozorg Haddad, O., & Mariño, M. A. (2013). Water distribution network risk analysis under simultaneous consumption and roughness uncertainties. *Water Resources Management*, *27*(7), 2595–2610.

Sirsant, S., Hamouda, M. A., & Shaaban, M. F. (2023). Advances in assessing the reliability of water distribution networks: A bibliometric analysis and scoping review. *Water*, *15*(5), 986.

Torii, A. J., & Lopez, R. H. (2012). Reliability analysis of water distribution networks using the adaptive response surface approach. *Journal of Hydraulic Engineering*, *138*(3), 227–236.

Xu, C., & Goulter, I. C. (1999). Reliability-based optimal design of water distribution networks. *Journal of Water Resources Planning and Management*, *125*(6), 352–362.

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