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Optimization of Drinking Water Network Management: Traditional and Innovative Approaches for Leak Detection and Management

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INTRODUCTION & AIM

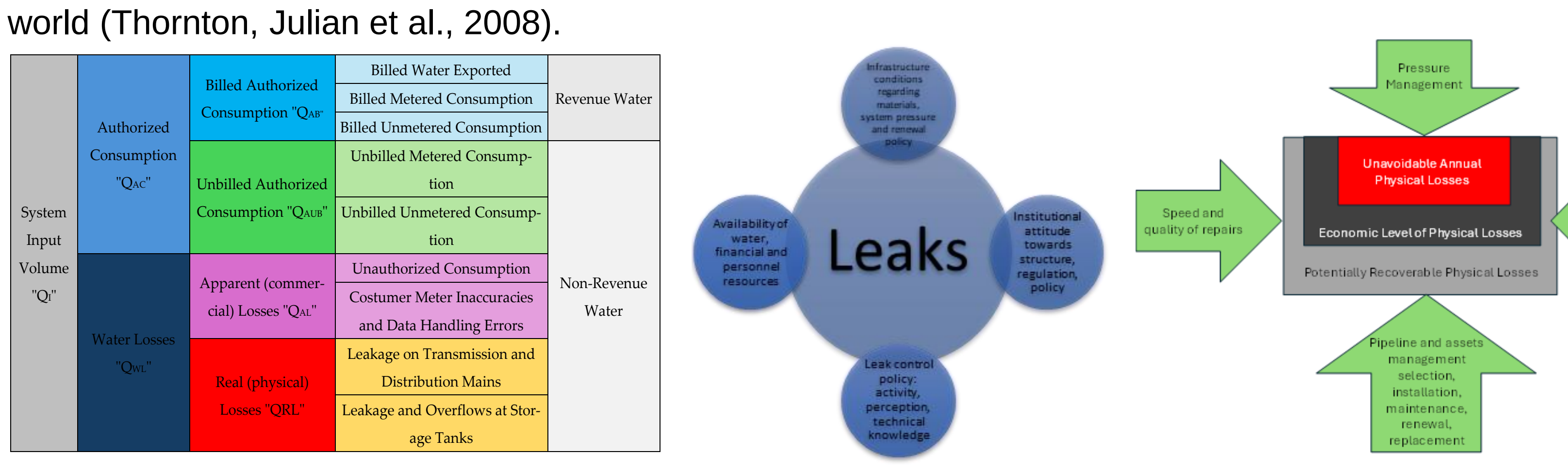
The study of leaks in potable water networks is crucial due to rates that can exceed 30%, resulting in significant losses and impacting finances, the environment, and water availability. Water management companies grapple with effectively managing these systems, especially in reducing leaks in aging infrastructure. Innovative technologies like mathematical modeling and computational simulation enhance leak detection and management. However, these methods often disregard system inertia, omitting variations in pressure regulating valve (PRV) operations over short periods.

Based on the references of institutional and governmental efforts carried out around the world (PI; KPI; IWA and AWWA leak control methods) and the SDGs of the UN 2030 Agenda, it is clear that reducing water losses is the main asset management objective of water companies around the world, since leaks represent the "health" of the asset and depend on both the deterioration of the pipe and the pressure conditions; a situation that became more noticeable in 2020 due to the global COVID-19 pandemic, which clearly showed the importance of the preparation and resilience of critical infrastructures to face extreme events, aggravated by the growing global demand for water and the impacts of climate change. In the aftermath of the pandemic, recovery initiatives witnessed an unprecedented allocation of resources towards drinking water infrastructures (DWIs), to make their management more efficient and sustainable by implementing digitalization in both water transmission (WTS) and distribution (WDN) systems (Giustolisi et al., 2024).

This article compares traditional methodologies with an alternative approach introducing an innovative rigid water column model. This model evaluates losses considering PRV adjustments over short periods, analyzing pressure variations and leakage flow patterns. By factoring in system inertia, it provides a more accurate assessment of leak volumes, improving water management efficiency, and offering a practical tool for engineers assessing leakage volumes in real networks. The importance of considering system inertia to properly simulate PRV operations in water distribution systems is emphasized.

METHOD

Water losses in distribution systems: In water distribution networks (WDN), the concept of non-revenue water (NRW) refers to water that is produced by the system but never reaches the final consumer, since it is lost along the distribution network, either through leaks (real and apparent), theft or illegal use (Adedeji et al., 2018). The water balance of water inputs and outputs of the system proposed by the International Water Association (IWA) is the most widely used worldwide (A. O. Lambert, 2001) and provides the basis for managing actions seeking to eliminate and/or reduce water losses (Thornton, Julian et al., 2008; Ziegler et al., 2010). Generally applying the following 4 key factors that influence the degree of leakage within a water company's pipe network (Farley, 2001); and implementing a loss control program based on a sustainable reduction of water losses by applying 4 basic management tools tested and proven in different parts of the world (Thornton, Julian et al., 2008).



System Input Volume "Q_I"	Authorized Consumption "Q_{AC}"	Billed Authorized Consumption "Q_{AB}"	Billed Water Exported	Revenue Water
			Billed Metered Consumption	
			Billed Unmetered Consumption	
		Unbilled Authorized Consumption "Q_{AUB}"	Unbilled Metered Consumption	Non-Revenue Water
			Unbilled Unmetered Consumption	
	Water Losses "Q_{WL}"	Apparent (commercial) Losses "Q_{AL}"	Unauthorized Consumption	
			Costumer Meter Inaccuracies and Data Handling Errors	
		Real (physical) Losses "QRL"	Leakage on Transmission and Distribution Mains	
			Leakage and Overflows at Storage Tanks	

Figure 1. Iwa Water Balance and Wáter Loss Control, adapted from (Farley, 2001, Thornton, Julian et al., 2008; Ziegler et al., 2010)

According to the figure 2 presented regarding the state of NRW worldwide (National Water Commission, 2020; Liemberger & Wyatt, 2019; OFWAT, 2023), this value is located between 4% (Singapore, Southeast Asia) and 83% (Armenia, South Caucasus Asia); with a world average value of 29.52%.

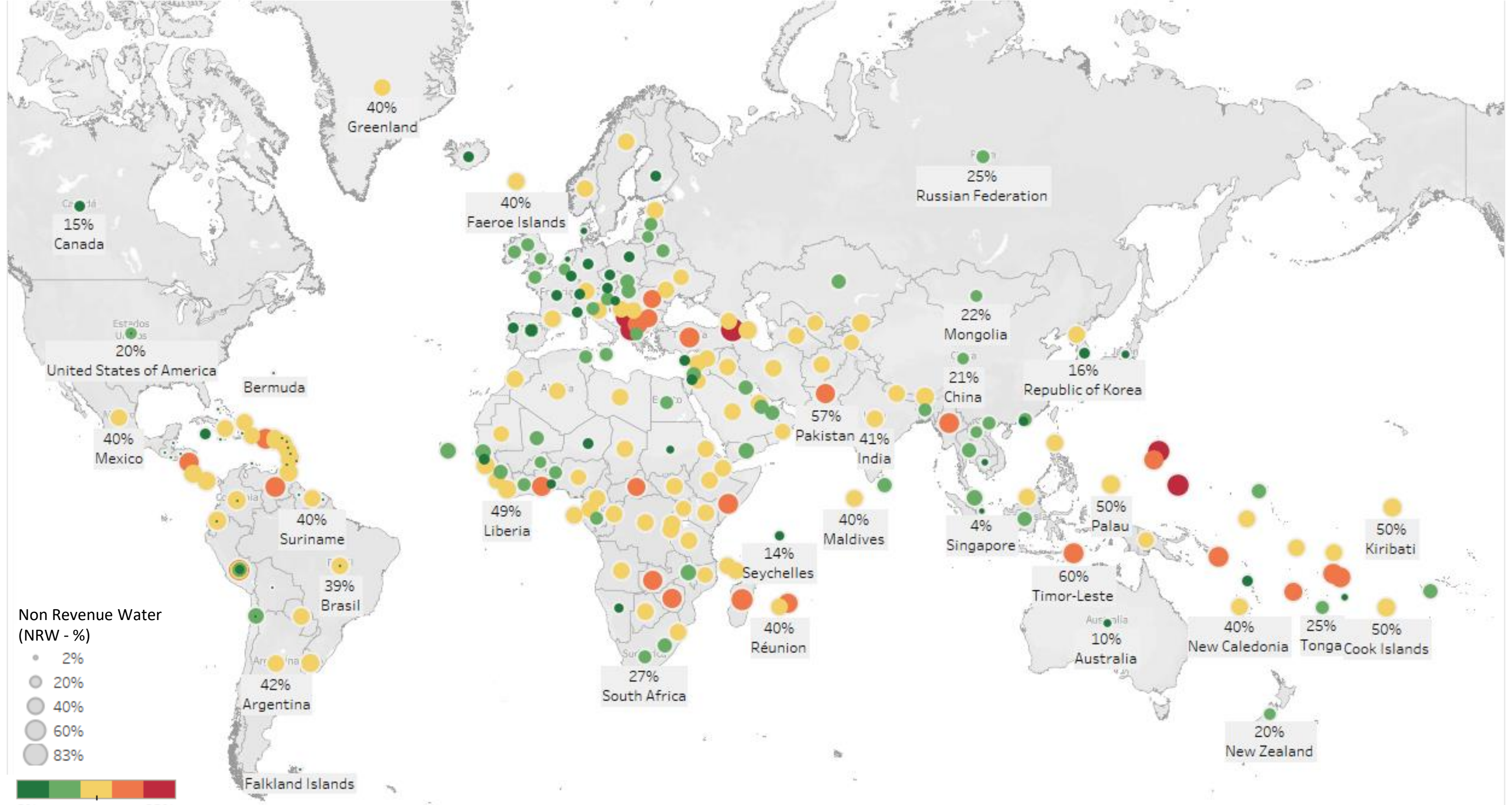


Figure 2, Global quantification map of the non-revenue water (NRW) problem, prepared from the global report compiled from different sources in 2018 by (Liemberger & Wyatt, 2019).

- **Emitter coefficient method or N1 power equation:** High sensitivity of the leak to pressure (Ziegler et al., 2010), initially using the orifice equation based on Torriceli's Theorem (Van Zyl & Clayton, 2007) according to the following Equation (1). Since 1881, a power equation called the power leakage equation or emitter coefficient equation (A. Lambert, 2001) has been adopted which is applicable to pipeline leakage analysis, and which can be written in a more general form as shown in Equation (2) (Tanyanyiwa & van Zyl, 2022). Where the emitter exponent α can be considerably greater than 0.5, however the normal range of the same is between 0.36 and 2.95, with a median of 1.15 (Ávila & Saldarriaga, 2004; Tan-yanyiwa & van Zyl, 2022; Van Zyl & Clayton, 2007)

$$Q_{orifice} = C_d A\sqrt{2gh} \quad (1) \qquad Q_{leakage} = Ch^{\alpha} \ (2)$$

- **Fixed and Variable Area Discharge (FAVAD) Method:** May 1994, leakage does not vary linearly with pressure Creating the FAVAD method, equation consisting of two terms: a flow term in which the area does not expand as a function of pressure and a flow term that takes into account the change in area as a function of pressure. The FAWAD equation was derived by first defining the relationship between area and pressure as linear, as shown in the following equation (Malde & Van Zyl, 2015).

$$A = A_0 + mh \ \ (3) \qquad Q_{leakage\_FAVAD} = C_d\sqrt{2g}\,(A_0 h^{0,5} + mh^{1,5}) \ \ (4) \qquad \frac{Q_{f1}}{Q_{f0}} = \left(\frac{p_1}{p_0}\right)^{N1} \ \ (5)$$

RESULTS & DISCUSSION

- **Software-based methods:** steady state, extended period (EPS); handle data time windows of 5-15 minutes and models with simulation time windows of 1 hour

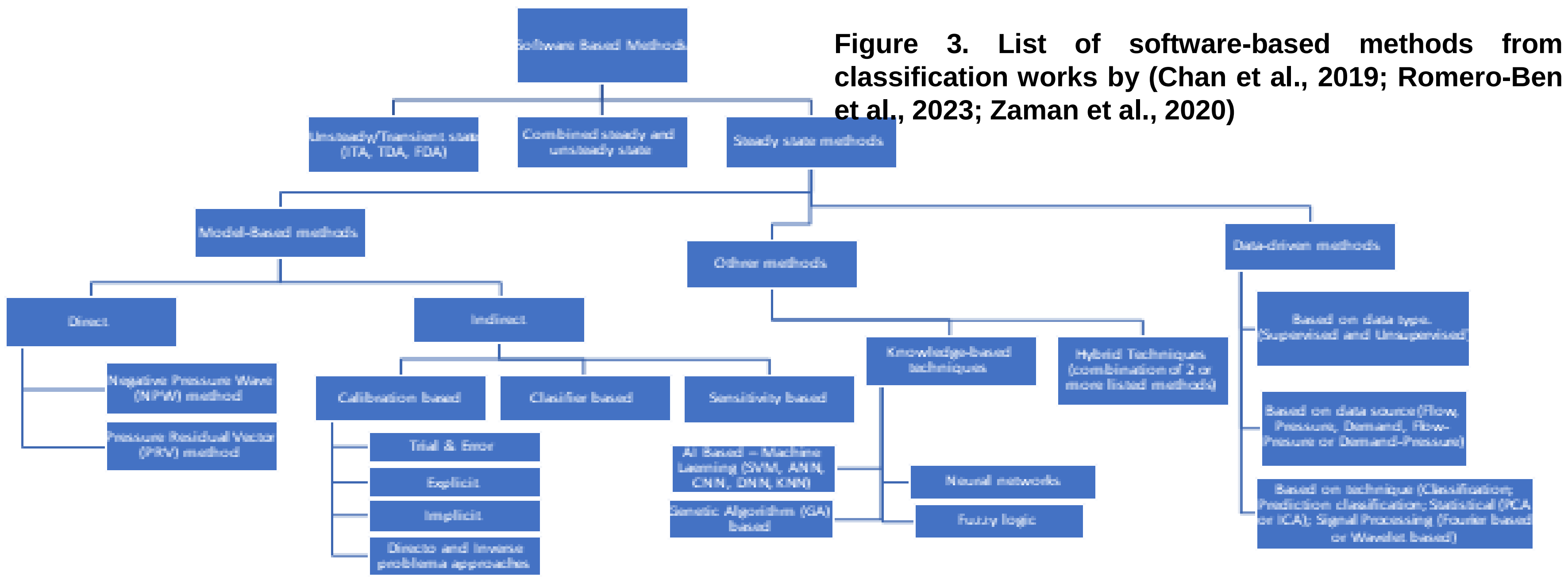


Figure 3. List of software-based methods from classification works by (Chan et al., 2019; Romero-Ben et al., 2023; Zaman et al., 2020)

- **The Rigid Water Column method:** Water losses in WDN are normally analyzed by means of extended period simulations, using the gradient method for their numerical resolution, assuming that the opening-closing maneuvers (operation) of the regulating valves occur during an extended period of time, leaving aside the inertia of the system. A rigid water column (RWC) model can be applied to analyze water leaks in single and/or parallel pipes to take into account the adjustments of the regulating valves in shorter periods of time, thus providing greater precision when evaluating water losses in these periods due to the transient phenomena implicit in them that generate pressure variations and therefore leaks that, for leaks of all types, especially bottom leaks, can represent an excess of controllable leakage by applying good operating practices. The mathematical model used to assess leakage in a simple pipe uses the water balance expressed as follows:

$$Q_{inyected} = Q_{measured} + Q_{leak} (6) \ \Rightarrow \ \begin{array}{l} Q_{measured} = C_m \times \overline{Q_m} \ (7) \\ Q_{leakage} = Kh^{0,5} \ (8) \end{array}$$

Where Cm = the Qm modulation coefficient; Qm = the average Qm; K= emitter coefficient, h = pressure atevaluate node

Applying continuity and momentum equations obtain equation (9) that simulates water behaviour based on the RWCM (Coronado-Hernández et al. 2018); and by replacing the terms and solving (9) the equation is obtained in relation to time:

$$Z_1 = Z_2 + \frac{P_2}{\gamma_W} + \frac{4L}{g\pi d_0^2}\frac{dQ_{iny}}{dt} + \frac{8fLQ_{iny}|Q_{iny}|}{g\pi^2 d_0^5} + R_v Q_{iny}|Q_{iny}| + \frac{8\sum K_m\, Q_{iny}|Q_{iny}|}{g\pi^2 d_0^4} \ (9)$$

$$\frac{dQ_{iny}}{d_t} = \frac{\left(Z_1 - Z_2 - \frac{P_2}{\gamma_W}\right) g\pi d_0^2}{4L} - \frac{2fQ_{iny}|Q_{iny}|}{\pi d_0^3} - \frac{R_v Q_{iny}|Q_{iny}|g\pi d_0^2}{4L} - \frac{2\sum K_m\, Q_{iny}|Q_{iny}|}{\pi L d_0^2} \ (10)$$

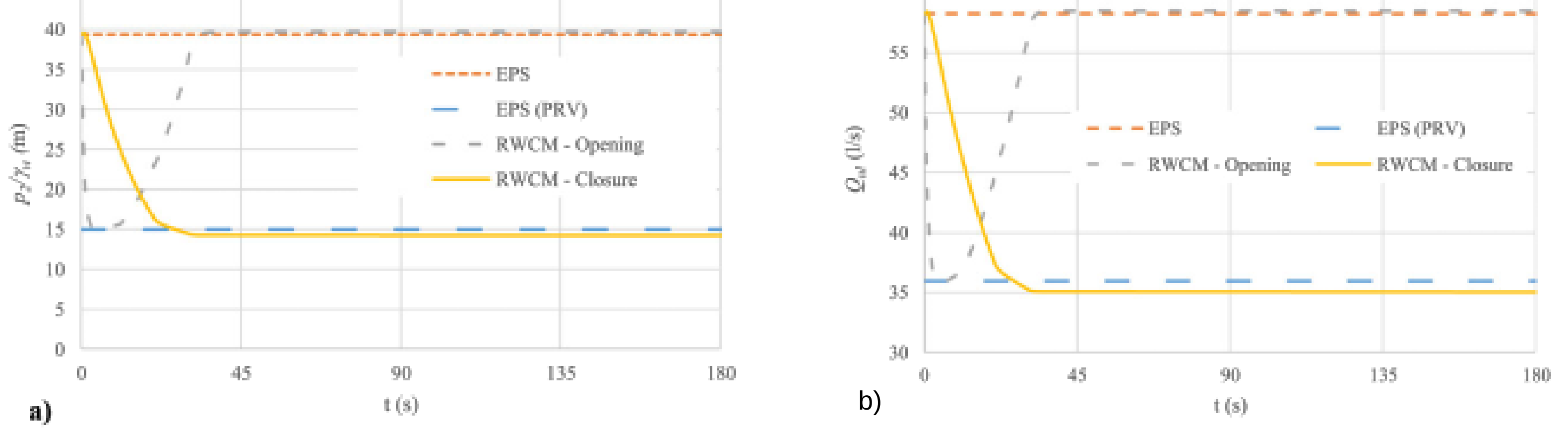


Figure 4. Comparison between EPS, EPS-PRV, RWCM-opening, and RWCM-Closure models: (a) Pressure head; (b) Physical leakages (Qul),

CONCLUSION

In current software-based methods, leakage calculation relies on steady-state and/or Extended Period Simulations (EPS), typically using a long analysis window (on average, 1 hour). However, this approach neglects the inertial effects of rapid valve regulation maneuvers that occur over short time intervals. This means that actual water losses occurring during these instantaneous phenomena are not estimated, as they fall outside the typical range analyzed by EPS models, which generally use average values for pressure, leakage coefficient, and exponent, without accounting for intermediate valve seat positions or the instantaneous inertial effects on pressure and flow rate. By accurately simulating these phenomena using methods such as the Rigid Water Column (RWC) and calculating them based on valve opening and closing times, actuator positions, and their transient effects on downstream pressures and flows, the results could serve as valuable decision-making tools for utilities in operational and leak management. The numerical resolution of the RWC algebraic-differential system provides a satisfactory solution to the water-leakage flow problem because it satisfies the condition that leakage flow increases with pressure, occurring in pulses over both short and long time periods. This approach can be applied to more complex water systems, confirming that system inertia has a substantial influence on leakage flow, producing significantly different results compared to EPS. During opening and closure maneuvers, discrepancies of 4.0% to 25.7% and 23.4% to 37.1% have been found in case studies relative to EPS. The proposed model can be implemented in digital twin approaches, enhancing the sustainability management of water systems.

FUTURE WORK / REFERENCES

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