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Understanding the discoloration risk as consequence of hydraulic transients

Entendendo o risco de descoloração como consequência de transientes hidráulicos

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Abstract

This paper presents an analysis of the challenges associated with discoloration risk management and the impact of hydraulic transients on water quality within distribution systems. Focusing on the Metropolitan Region of Curitiba, Paraná, Brazil, the study employs a comprehensive methodology that combines the Characteristic Method for simulating hydraulic transients and real-time monitoring of water quality parameters, such as turbidity and chlorine levels. A framework for managing discoloration risk is proposed, highlighting strategies for identifying potential causes, assessing risk severity, developing prevention and mitigation strategies, and implementing continuous improvement processes. The experimental section details the impact of hydraulic transient events on water quality, with significant findings indicating a direct correlation between flow dynamics and water quality degradation, particularly in terms of increased turbidity and decreased chlorine levels during pump deactivation. The study contributes valuable insights into effective water distribution system management, emphasizing the importance of advanced monitoring and risk management techniques to maintain high-quality water standards.

Keywords: Real system; Hydraulic transient; Discoloration; Drinking water; Risk management.

Resumo

Este artigo apresenta uma análise dos desafios associados ao gerenciamento do risco de descoloração e o impacto dos transientes hidráulicos na qualidade da água dentro dos sistemas de distribuição. Concentrando-se na Região Metropolitana de Curitiba, Paraná, Brasil, o estudo emprega uma metodologia abrangente que combina o Método das Características para simular transientes hidráulicos e o monitoramento em tempo real de parâmetros de qualidade da água, como os níveis de turbidez e cloro. É proposto um quadro para o gerenciamento do risco de alteração de qualidade da água, destacando estratégias para identificar causas potenciais, avaliar a severidade do risco, desenvolver estratégias de prevenção e mitigação e implementar processos de melhoria contínua. A seção experimental detalha o impacto dos eventos transientes hidráulicos na qualidade da água, com achados significativos indicando uma correlação direta entre a dinâmica do fluxo e a degradação da qualidade da água, particularmente em termos de aumento da turbidez e diminuição dos níveis de cloro durante a desativação das bombas. O estudo contribui com insights valiosos para o gerenciamento eficaz de sistemas de distribuição de água, enfatizando a importância de técnicas avançadas de monitoramento e gerenciamento de riscos para manter padrões elevados de qualidade da água.

Palavras-chave: Sistema real; Transiente hidráulico; Turbidez; Água potável; Gestão de riscos.

INTRODUCTION

Recent studies have underscored the profound effects of unsteady hydraulic conditions on water distribution systems (WDS), presenting dual facets of influence: firstly, on the physical integrity of the infrastructure, where they can cause direct ruptures through excessive pressure or indirectly exploit vulnerabilities such as corrosion, earth pressures, or construction faults (Chaudhry, 1979; Karney & McInnis, 1990; Lansey & Boulos, 2005; Karney, 2004); and secondly, on water quality parameters such as disinfectant residual, turbidity, and color. These changes in water quality arise from the re-suspension of sediments, scouring of biofilms, and tubercles from the pipe walls, coupled with increased mixing (Douterelo et al., 2016). This dynamic interplay has propelled the call for further experimental research to delve deeper into these interactions (Wood et al., 2005; Boulos et al., 2005; Armand et al., 2015; Karim et al., 2003; LeChevallier, 1999; Kirmeyer, 2001; Funk et al., 1999; Kim & Kim, 2017). However, discoloration as a direct consequence of hydraulic transients remains an area less explored, signaling a gap in our comprehensive understanding of WDS impacts (Braga & Filion, 2022, 2023), that will be addressed in this paper.

Hydraulic transients, set off by any disturbance in flow conditions such as pump start-ups or valve manipulations, can induce maximum system pressures, cavitation, and hydraulic vibrations. These events not only pose safety risks but also present operational challenges, highlighting the critical need for effective management and mitigation strategies to prevent equipment damage and ensure operational continuity (Wood et al., 2005; Boulos et al., 2005; Walski & Koelle, 2003; Funk et al., 1999).

Furthermore, the formation of biofilms within WDS represents a significant challenge in maintaining water quality. The resilience of biofilms, safeguarded by extracellular polymeric substances (EPS), greatly contributes to the degradation of water quality post-treatment. Factors such as disinfectant type, water age, and pipe materials play crucial roles in influencing biofilm structure and the diversity of microbial communities (Braga & Filion, 2022; Liu et al., 2016; Douterelo et al., 2016; Wang et al., 2014; Afonso et al., 2021; Flemming et al., 2016; Rumbaugh & Sauer, 2020).

Discoloration, predominantly resulting from the re-suspension of accumulated particles, is significantly influenced by biofilm dynamics. This includes pathways such as gravitational and non-gravitational sedimentation, corrosion-related releases, and biofilm-associated particle entrapment. The role of biofilms in shaping the microbial characterization of drinking water quality, along with the impacts of temperature and hydraulic regimes on biofilm accumulation and discoloration behavior, underscores the complexity of the issue (Boxall et al., 2001; Vreeburg & van den Boomen, 2002; Mays, 2000; Fish et al., 2022).

The interplay between hydraulic transients and biofilm dynamics, which affects nutrient availability, oxygen levels, and substrate conditions, can lead to biofilm detachment. This detachment releases microbial cells and particulate matter into the water, potentially degrading water quality. Such mobilization of biofilms and accumulated materials due to hydraulic transients highlights the intricate balance between physical forces and microbial ecology within WDS (Aisopou et al., 2012; Weston et al., 2015, 2019, 2021).

Moreover, pressure transients are a conduit for the intrusion of external contaminants into WDS, posing significant health risks. Maintaining the integrity of distribution pipes is paramount to averting such events, especially since low and negative pressures can exacerbate the risk of pollutant intrusion. The presence of harmful bacteria and pathogens in soil and water near water mains accentuates the necessity for diligent system management to mitigate intrusion risks (Lindley & Buchberger, 2002; Collins & Boxall, 2013; Karim et al., 2003; Fontanazza et al., 2015; Jones et al., 2018; Keramat et al., 2020).

The dominant emphasis on laboratory research highlights the critical necessity for additional exploration in actual environmental contexts to adequately tackle and lessen the difficulties that hydraulic transients present to water quality (Calero Preciado et al., 2021; Weston et al., 2021; Chen et al., 2020; Speight et al., 2019). Moreover, recent literature works demand an intensified investigation into the connection between hydraulic transients and water quality, with a specific focus on the dynamics within real systems. Such improved comprehension will facilitate the creation of more robust and secure water distribution networks.

In this context, the main objective of the paper is to assess how do hydraulic transients in real-world pipeline systems affect biofilm-associated turbidity levels, and what is the relationship between flow and pressure variations and turbidity modifications.

METHODS

The method encompasses a dual approach. Initially, it outlines a framework comprising a series of steps designed to mitigate the risk of water discoloration.

As part of the study, the main water pipeline system in the Metropolitan Region of Curitiba, Paraná, Brazil, serves as a focal point for investigation. Additionally, this research incorporates the development and application of models to simulate hydraulic transients within the water distribution network, employing the Characteristic Method (Agostinho, 2018). It includes an in-depth analysis of the system's behavior during transient events, focusing on how turbidity and chlorine levels fluctuate under varying hydraulic conditions. This is achieved by monitoring real-time data to grasp the immediate impact of these unsteady hydraulic states on water quality. Moreover, statistical techniques, such as regression analysis and the calculation of correlation coefficients, are utilized to establish and quantify the significant links between alterations in water quality and the occurrence of hydraulic transient events.

The experiment

The area under study belongs to the Water Supply System of Curitiba and the Metropolitan Region, named SAIC, represented by Figure 1. The current production and treatment system is around 10 m^3/s. After the treatment, the water is sent to around 50 existing reservation centers, being in all 377,650 m^3 reserved. There are currently 160 pressure zones serving 3.5 million people. In this study was selected one of the main important pipelines

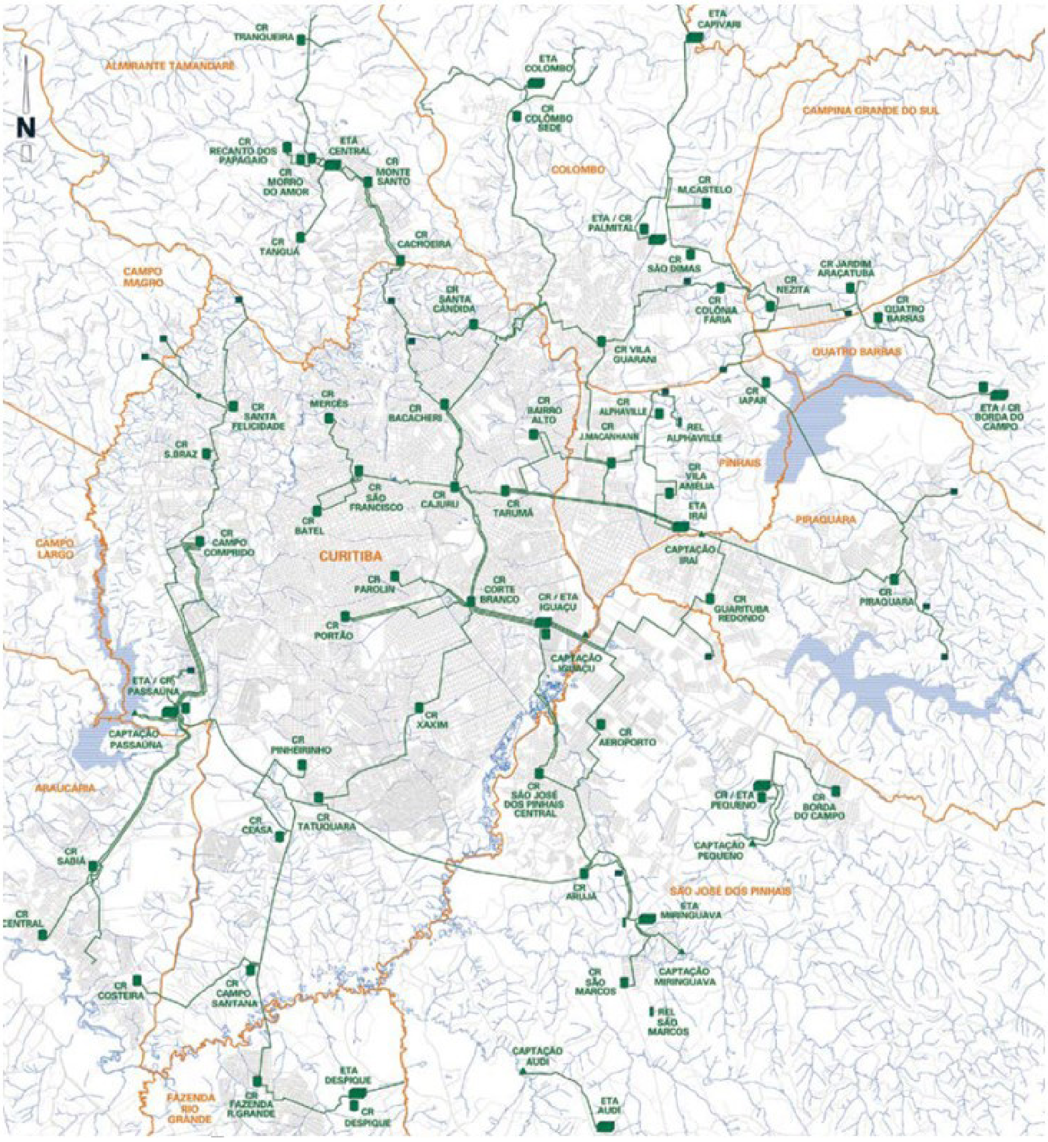

Figure 1. Main distribution system of Metropolitan Region of Curitiba.
Source: Companhia de Saneamento do Paraná (2013).

of the SAIC system (Agostinho, 2018) that are responsible for treated water transportation by Iguacu Water Treatment Plant (WTP) to Corte Branco Tank.

The Iguacu WTP is a conventional treatment plant with flocculation, decantation, filtration, fluoride application and chlorine disinfection. After treatment the water is stored in the Iguacu Tank and pumped to Corte Branco Tank, through three pipelines in parallel, with a length of approximately 3.4 km, two cast iron, 800 mm in diameter each and one steel, 1,100 mm. The average flow is 2,700 L/s. The pipeline counts with air valves and one open surge tank on the 1,100 mm pipeline. The estimated total volume within the pipelines is approximately 6,650 liters. The pumps are composed of three 03 sets of turbine-type vertical axis and 03 sets of the bipartite horizontal axis, with 600 hp of power each. Figure 2 shows The Iguacu Water Treatment Plant, the surge tank and the pump station.

Figure 3 represents elements of a pipeline section that was replaced, where it is possible to observe biofilm and encrustations that has been associated to the impact from hydraulic conditions of the system.

Four water quality measurement campaigns were realized during hydraulic transient events in order to obtain the relationship between the physicals and quality results. The samples were used to measure the turbidity and chlorine. Both parameters were analyzed using electronic Hach sensors: (i) Turbidity - model 2100 Q (range 0 – 1000 NTU; Accuracy ± 2% of reading plus stray light); (ii) Chlorine - model DR 900 for Chlorine (Photometric Accuracy ± 0.03 Abs and Measuring Range 0.02 to 2.00 mg/L Cl2).

In the first campaign the pipelines were with no flow for about 3 hours. The test consisted in turn on the pumps following the operational routine, turning on one by one. Then, a time was wait and after that, all of them were turned off together. In the second one the pipelines were operating. The test consisted in turn off all pumps. Then turn on one by one and then turn off all of them. Table 1 summarizes the experimental transient maneuver for this research.

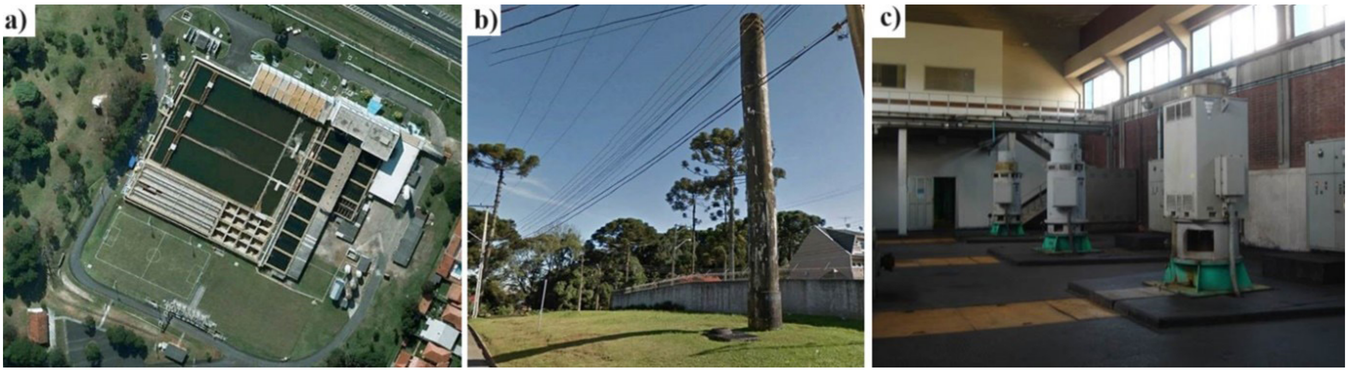

Figure 2. (a) Iguaçu WTP; (b) Surge Tank; (c) Pump station.

Figure 3. Detachment material in pipeline.

Table 1. Procedure of each campaign.

CAMPAIGN	PROCEDURE	CONDITIONS
1ª	Operational Procedure: Start – Shut down	10 minutes between starts. Start: pump OFF
2ª	Shut down – Start – Shut down – Start	4 minutes between starts. Start: pump ON
3ª	Shut down – Start – Shut down	4 minutes between starts. Start: pump ON
4ª	Shut down – Start – Shut down	4 minutes between starts. Start: pump ON

The samples were collected in the end of the pipeline each five minutes in the first test and two minutes in the second one.

Computational model

The development of the computational model for simulating the effects of hydraulic transients on water quality was refined using real-time monitoring data, including pressure, flow rates, and reservoir levels. These measurements were instrumental in calibrating the model's pipeline characteristics, specifically the Hazen-Williams roughness coefficient and the operational points of pump curves, ensuring that the simulation accurately reflected the physical behavior of the water distribution system. The calibration process is based on a Geographic Information System (GIS) database of the existing network infrastructure, incorporating detailed information on pipe materials, diameters, lengths, and the topography of the serviced areas to accurately represent the system's layout and environmental context. The calibration and validation of the model were achieved through an iterative process, aligning the model outputs with observed data to refine the simulation parameters, as presented by Agostinho (2018).

DISCOLORATION RISK

Discoloration risk management is a process of identifying, assessing, and mitigating the potential risks associated with the

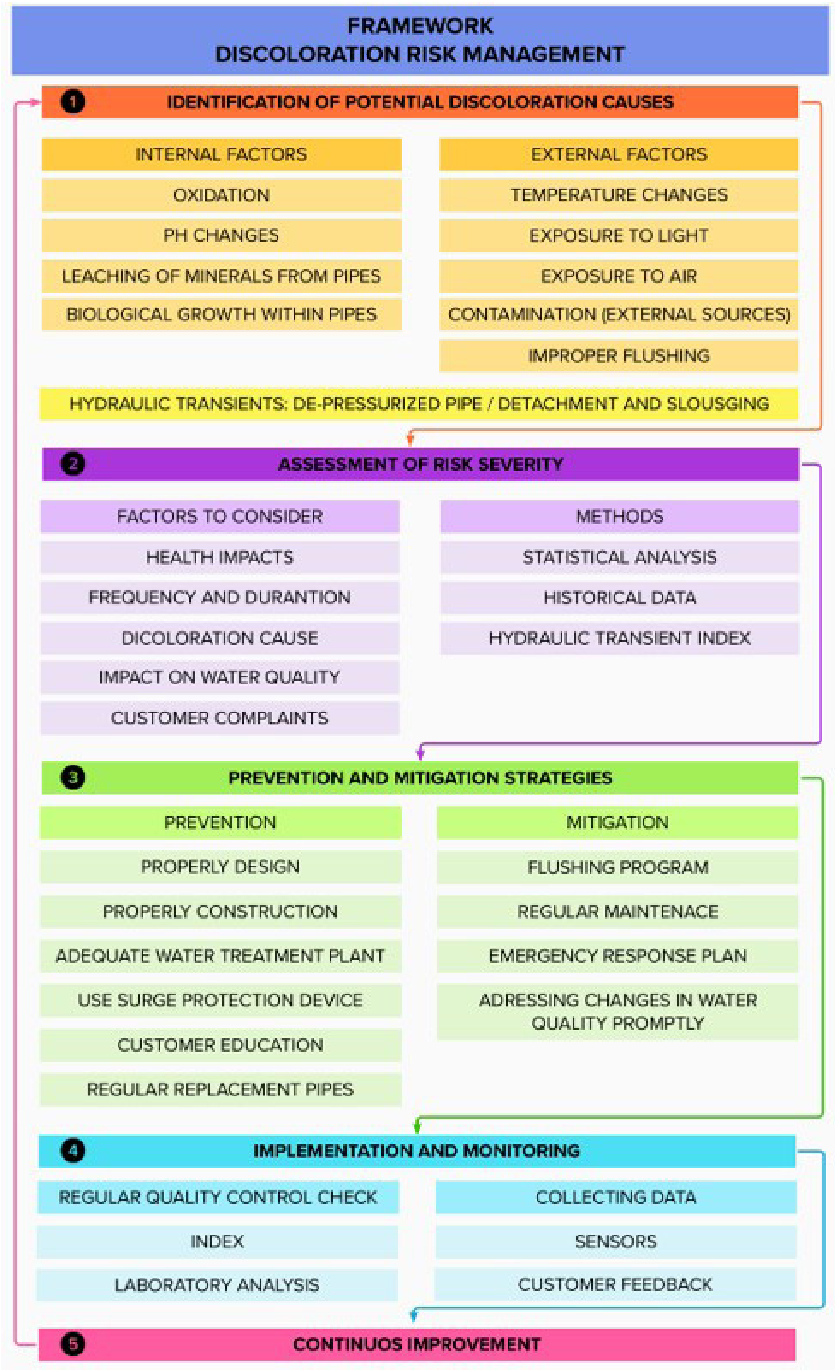

Figure 4. Framework: Discoloration Risk Management.
Source: Author (2023) based on World Health Organization (2011); U.S. Environmental Protection Agency (2013); American Water Works Association (2010); Armand et al. (2015).

discoloration of water. Armand et al. (2017) study on discoloration risk management in water systems identifies several key factors contributing to water discoloration, including the significant role of trunk mains, flushing, and pipe bursts, which account for about 35% of events. It highlights the importance of managing high-velocity flows in mains, the risks associated with low-flow conditions, and the detrimental effects of high-water age in pipes operating in sedimentation zones, particularly at dead-ends. Additionally, the study points out that over a third of discoloration events are linked to the structure of District Metered Areas (DMAs), suggesting a need for careful design and control measures to minimize the risk of discoloration by addressing specific hydraulic conditions and network configurations.

Based on the literature, is proposed a framework, presented in Figure 4 describes steps to manage the discoloration risk. a) Identification of potential discoloration causes; b) Assessment of risk severity; c) Development of prevention and mitigation strategies; d) Implementation and monitoring; e) Continuous improvement: Regularly review and update your framework, incorporating lessons learned and new information to improve its effectiveness over time.

Identifying the causes of discoloration in water distribution systems involves several key methods (World Health Organization, 2011; U.S. Environmental Protection Agency, 2013; American Water Works Association, 2010): water testing to detect contaminants, visual inspections for obvious signs of discoloration sources like corroded pipes or algae, monitoring flow and pressure for blockages or restrictions, and reviewing the system's history to understand past issues and maintenance. These approaches help pinpoint the origins of water discoloration effectively.

To prevent and mitigate discoloration in water distribution systems, strategies include: designing systems with proper slopes, pressure zones, and using corrosion-resistant materials (American Water Works Association, 2017; Walski & Koelle, 2003; Jung et al., 2011), proper water treatment and disinfection to prevent chemical reactions causing discoloration (Health Canada, 2012; U.S. Environmental Protection Agency, 2015), regular flushing to remove sediments (van Bel et al., 2019; Pourcel & Duchesne, 2020; Calero Preciado et al., 2021; Zeidan & Ostfeld, 2022), using corrosion inhibitors (World Health Organization, 2011), maintaining the system by repairing or replacing damaged pipes, and educating consumers on minimizing discoloration effects. These combined efforts aim to ensure water quality and system integrity.

A specific risk associated with discoloration is hydraulic transients, dynamic changes in water pressure and flow with potential to damage infrastructure and disrupt supply. Quantifying the severity of these events through various metrics enables better understanding, prediction, and mitigation of their impacts, ensuring the reliability and safety of water distribution systems. Understanding and utilizing these metrics is essential for ensuring the reliable operation of water supply systems and protecting against the damaging effects of hydraulic transients. Some index was summarized in Agostinho et al. (2018), as shown in Table 2, part A.

RESULTS

Upon conducting a simulation of the hydraulic transient resulting from a 600-second pump shutdown using the HAMMER software, the outcomes depicted in Figure 5 were observed. This simulation facilitated the computation of the indicators outlined in Table 2, part A, for this specific scenario. The calculated indicators are comprehensively presented in Table 2, part B.

Figure 6 represents the measured parameters for the realized campaigns, with flow, pressure, turbidity, and chlorine.

The data from these campaigns reveal a significant link between flow dynamics and water quality indicators, underscoring their mutual influence. During the initial phase of the first campaign, with pipeline pumps inactive for three hours, we observed a marked deterioration in water quality. Residual chlorine was completely absent, and turbidity peaked around 3.5 NTU. This suggests that water stagnation, coupled with interactions with the pipe walls, has a pronounced impact on water quality. Hydraulic transients, especially those stemming from pump deactivations, were critical periods where turbidity escalated sharply, soaring from 0.5 to 1.1 NTU.

In the subsequent campaign, the transient caused by pump deactivation was again a pivotal moment, as evidenced by the spike in turbidity values, which surged from 1.0 to 2.2 NTU initially and from 1 to 1.6 NTU subsequently.

The third investigation followed a similar trend, where activating the pumps was associated with a significant rise in turbidity, escalating from 1.0 to 2.2 NTU. In contrast, when the pumps were turned off, there was an increase in turbidity from 0.8 to 1.6 NTU and then from 0.9 to 1.8 NTU in another instance. These occurrences were also marked by a slight reduction in the chlorine index, which decreased concurrently with the increases in turbidity. The fourth study focused solely on a single transient event caused by a pump shutdown.

The correlation graphs from the fourth campaign are depicted in Figure 7, illustrating the dynamics of this specific event. The graphs from all results are presented in Supplementary Material.

In this analysis, the optimal correlation between physical parameters and water quality metrics was observed with a time lag of approximately six minutes. The relationship between flow and pressure dynamics and turbidity demonstrated a correlation coefficient of about 0.7. Notably, when pumps were deactivated, turbidity levels rose sharply from 1.0 to 2.4 NTU, accompanied by a marginal decrease in the chlorine index as turbidity levels increased.

Although graphical analyses were unable to definitively identify the sources of material mobilization within the pipeline system, they did uncover several key findings: a) variations in turbidity reaching up to 1.4 NTU; b) a noticeable deterioration in

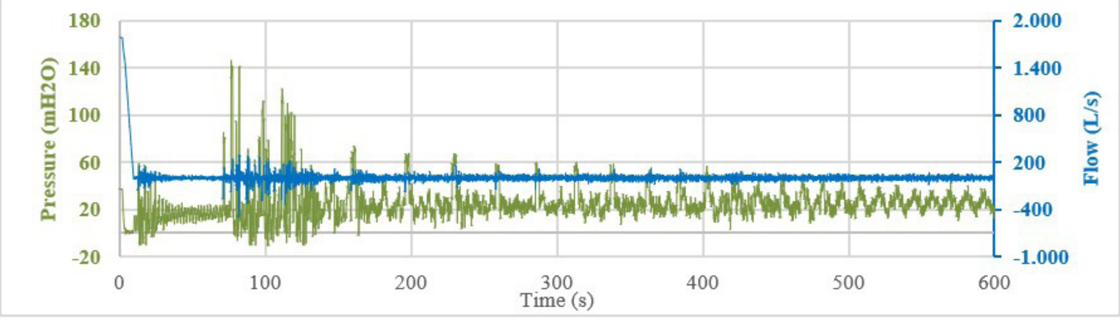

Figure 5. Pressure and Flow during a hydraulic transient event.

Table 2. Metrics to quantify transient pressures severity.

a					b
Risk	**Index**	**Author**	**Code**	**Definitions of variables**	**Case study**
Risk assessment associated with negative pressure	Intrusion potential	Friedman et al. (2004)	C1	Number of junctions with pressure < 0 mH2O	92
		Friedman et al. (2004) adapted	C2	% of junctions with pres.< 0 mH2O	97.9%
	Cavitation		C3	Number of junctions with vacuum pressure	85
			C4	Total time cavitation	69s
	Severity of cavity index	Martin (1983)	C5	$S = \frac{T_{SC}a}{2L}$ S=severity of cavity index; a=celerity; TSC=duration when cavity occurs; L=length	9.3
	Surge Damage potential factor (SPDF)	Jung & Karney (2011) adapted.	C6	$SPDF^{-} = \frac{\int_{ieN_{node}} H_i dt}{\text{junctions}}$ Hi = pressure < Hmin (allowable pressure)	-443.08
Risk assessment associated with positive pressure			C7	$SPDF^{+} = \frac{\int_{ieN_{\text{node}}} H_i dt}{\text{junctions}}$ Hi = pressure > Hmax (allowable pressure)	2.88
Risk assessment associated with negative and positive pressure			C8	$SPDF = \frac{\int_{ieN_{\text{node}}} H_i dt}{\text{junctions}}$ Hi > Hmax or <Hmin	-440.19
	Δ pressure	Jung & Karney (2006) adapted	C9	ΔP = Hmax - Hmin	281
	Hmax		C10	Minimum Pressure	-10
	Hmin		C11	Maximum Pressure	271
	Positive and negative transient risk index	Radulj (2009) adapted	C12	$TRI^{+} = \frac{\int_0^{T} {}^{+}P_{\max} dt}{\text{junctions}}$	99.82
			C13	$TRI^{-} = \frac{\int_0^{T} {}^{-}P_{\max} dt}{\text{junctions}}$	-9.52
Risk assessment associated with rapid change of pressure	Damage index	Shinozuka & Dong (2005)	C14	$D = \frac{H_2 - H_1}{t_2 - t_1}$ D = damage index; H2 and H1 = pressure heads at a node at time t1 and t2, respectively	-86.8

Source: Agostinho et al. (2018).

water quality following the abrupt cessation of pump operations; c) water quality changes associated with gradual increases in flow; and d) the significant impact of minor transients on overall water quality.

In Brazil, the oversight of water quality for human consumption and the standards for potability are outlined in Annex XX of the Consolidation Ordinance No. 5, issued by the Ministry of Health (Brasil, 2017). This ordinance sets forth that the turbidity limit for water to be considered potable must not exceed 5 NTU. Although monitoring campaigns have not reported any exceedances of this reference value, it's vital to acknowledge the proximity of some water mains to the treatment system. Moreover, the fact that some network points pass through more than five mains, in addition to the distribution network, suggests a potential risk for cumulative degradation of water quality.

These findings underscore the complex interplay between operational practices, such as the activation and deactivation of pumps, and the parameters defining water quality. This emphasizes the critical importance of meticulous management of hydraulic conditions to uphold water quality standards.

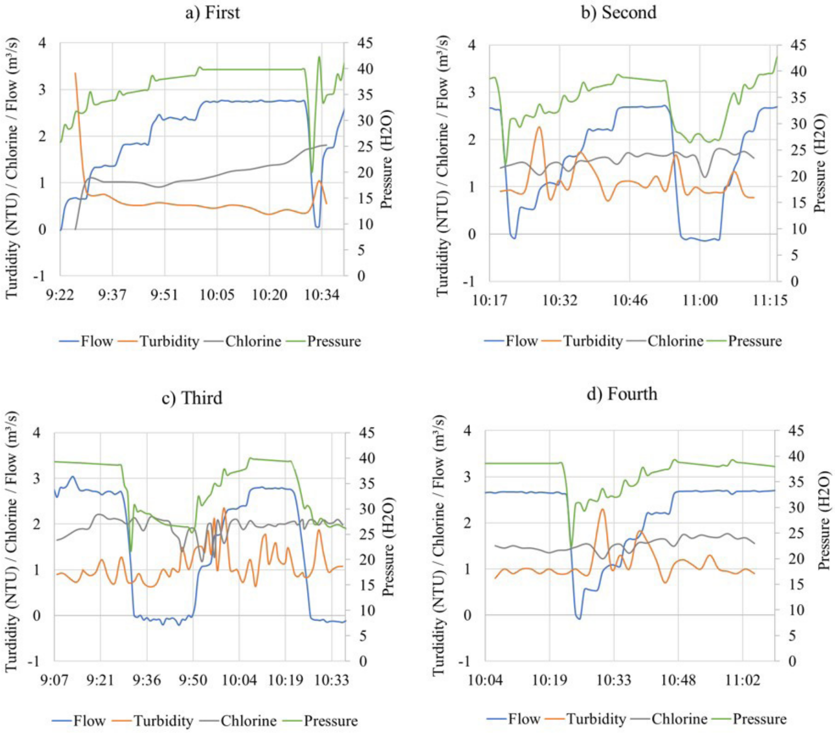

Figure 6. Field experiments: measured parameters.

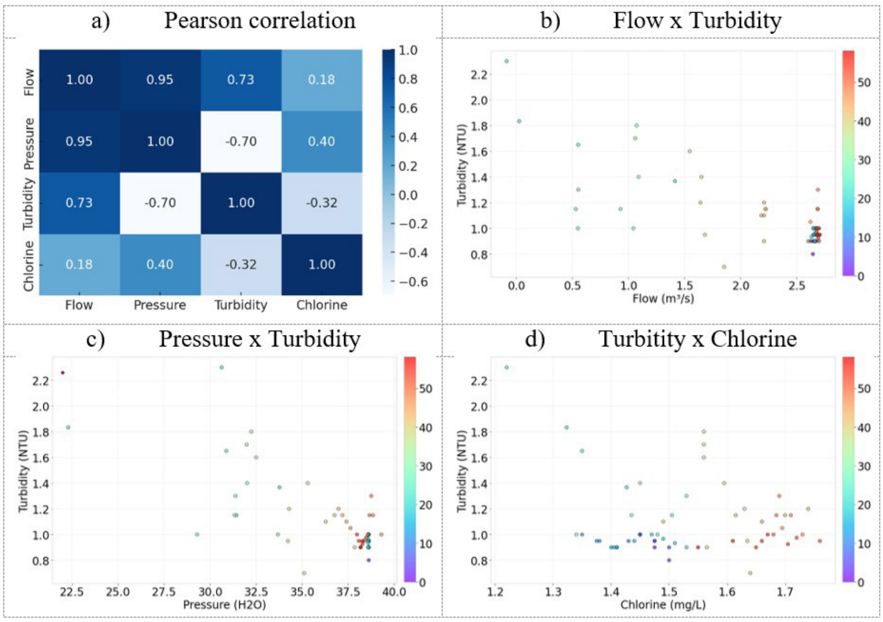

Figure 7. Fouth campaign results.

CONCLUSION

The study elucidates the intricate relationship between hydraulic transients and the quality of water within urban distribution networks, shedding light on the nuances of discoloration risk management. Through meticulous analysis of both empirical data and simulations, it underscores the indispensable role of advanced monitoring and operational strategies in mitigating the negative repercussions on water quality. This research advocates for a strategic shift towards a more proactive and integrated management approach within water distribution systems. By marrying cutting-edge hydraulic modeling with the precision of real-time analytics, the paper sets a new benchmark for safeguarding water quality. It not only augments our understanding of the dynamic interplay between operational practices and water quality parameters but also paves the way for pioneering advancements in the domain of water quality assurance. This contribution is pivotal for the evolution of water distribution practices, ensuring both the safety and the integrity of water supplies for future generations.

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Authors contributions

Mariele de Souza Parra Agostinho: Literature review, field trials: methodology and interpretation of results.

Cristovão Vicente Scapulatempo Fernandes: Guidance throughout the study, review, conclusion, and introduction.

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SUPPLEMENTARY MATERIAL

Supplementary material accompanies this paper.

Figure A. First campaign results.

Figure B. Second campaign results.

Figure C. Third campaign results.

Figure D. Fourth campaign results.

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