Investigation of sudden contaminant intrusion from a leakage point induced by transient flow

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ABSTRACT

The sudden intrusion of contamination in water distribution systems is a complex and stochastic phenomenon that requires efficient numerical models to estimate the mass of intruded pollutants and predict their fate. A negative pressure wave generated by a water hammer, when reaching vulnerable points such as leaks, causes the sudden suction of contaminants from the surroundings into the pipe. The subsequent positive pressure wave can partially force the contaminants back out through the leak. This study introduces an Eulerian–Lagrangian numerical solver developed in MATLAB, capable of systematically quantifying contaminant re-extrusion by considering the interaction of pressure wave oscillations. A comparison between the computed contamination intrusion volume and experimental data shows a mean normalized root mean square error (nRMSE) of 4.95%, confirming the accuracy of the hydraulic and leakage modeling. Contaminant transport under transient conditions was modeled using the Lagrangian approach, which yielded high accuracy with a maximum nRMSE of 5.5%. Results from a comprehensive sensitivity analysis, including 36 different scenarios, indicate that the relative pressure head along the pipeline is the most influential factor affecting the volume of contaminant intrusion. The highest contaminant ejection rates—up to about 68%—were observed near downstream valves, while the middle sections of the pipe exhibited the greatest contaminant suction and entrapment.These findings suggest that although contaminant ejection effects can be significant under certain conditions, they may generally be neglected for conservative analysis. Overall, the results provide an improved understanding of the dynamics of sudden contaminant intrusion, enhance the simulation of such events in water distribution systems, and ultimately support more effective management strategies for ensuring safe water supply.

KEYWORDS

Contaminant intrusion, Re-extrusion; Contaminant transport; Leak; Eulerian and Lagrangian approaches.

Introduction

Water is vital for human life, and the water distribution infrastructures are crucial to human health and well-being relating to material life, culture, society, politics, and economy. Therefore, the safety of the water distribution system (WDS) plays an important strategic

role in maintaining public health and industrial growth [1]. The three components of contaminant intrusion risk, as outlined by Lindley and Buchberger [2] and supported by research and evidence [3], are contaminant sources, driving forces (specifically low/negative pressure), and pathways. Boyd et al. [4, 5] provided the first experimental evidence of intrusion caused by transient negative pressure events. Jones et al. [6] conducted an experimental study aimed at quantifying intrusion volumes. The research explored the correlation between intrusion volumes and driving pressures. It also proposed a method to estimate these volumes by using the measured driving head over time. Their investigation did not consider the push-pull exchange of contaminants through the orifice and the re-extrusion phenomenon. Any volume that entered the pipe from the leak was considered a risk of contamination. Shao et al. (2020) studied how intrusion volumes vary with different conditions, such as flow velocities, internal and external pressures, and orifice diameters. They found that intrusion volume had a positive correlation with each of these factors [7]. The study by Keramat et al. (2020) focused on examining the intrusion of contaminants in elastic and viscoelastic pipes. Researchers discovered that contaminant intrusion in viscoelastic pipes was significantly lower than in elastic pipes, especially in long transmission lines with extended periods of negative pressure. To ensure simplicity and safety, the study did not include the push-pull mechanism of contaminants from leaks[8]. a comprehensive sensitivity analysis involving 36 scenarios will be conducted to elucidate the mechanisms of contaminant intrusion and re-extrusion at leakage points. Given the persistent difficulties associated with leak detection, this study focuses on how contaminants near leaks can enter and spread within aging urban pipe networks, particularly during nighttime pressure fluctuations.

Methodology

Water Hammer Equations

The following two customary mass and momentum conservation equations are employed for fluid transients in elastic pipes [9]:

$$\frac{\partial H}{\partial t}+\frac{a^2}{gA}\frac{\partial Q}{\partial x}=0 \tag{1}$$

$$\frac{\partial H}{\partial x}+\frac{1}{gA}\frac{\partial Q}{\partial t}+J=0 \tag{2}$$

where H is the pressure head, Q is the discharge, t is time, x is the distance along the pipe, a is the wave speed, g is the gravitational acceleration, A is the cross-section area of the fluid flow and J is the friction term.

Contaminant Ingress Model

This modified approach incorporates a correction coefficient aimed at enhancing the traditional orifice model. The corrected orifice equation can be represented as:

$$Q_{\mathrm{L}}=\eta C_d A_l\sqrt{2g\left|h_{\mathrm{L,out}}-(h_{\mathrm{L,in}}-Z_{\mathrm{L}})\right|}, \tag{5}$$

$$\eta=0.012\frac{k_1^{0.008}}{k_2^{2.422}k_3^{0.513}},$$

$$k_2=\frac{H_{\mathrm{res}}-h_{\mathrm{L,out}}}{H_a}\qquad k_1=\frac{u_0}{a}\times 100,\qquad k_3=\frac{d}{D}$$

where η is the orifice correction coefficient, C_d is the orifice coefficient, A_l is the leakage cross-sectional area, H_{L} is the piezometric head across the leak node, $h_{\mathrm{L,out}}$ is the pressure head outside the leakage, $h_{\mathrm{L,in}}$ is the pressure head inside pipe at the leak location, Z_{L} is the leak elevation, Q_{L} is the leak discharge, u_0 is the initial velocity of the fluid inside the pipe, H_{res} is the pressure head at the reservoir, H_a is the atmospheric pressure (10.33 m H_2O), d is the diameter of the leak hole.

Contaminant Transport Model

The mass transport equation can be simplified to a partial differential equation using the formulation proposed by Rossman and Boulos [10]:

$$\frac{\partial \phi}{\partial t}+u\frac{\partial \phi}{\partial x}=0 \tag{6}$$

where u is the fluid velocity and ϕ is the contaminant concentration. In this study, the suction of pollutants was simulated by combining Eulerian and Lagrangian methods. The Eulerian method was used to simulate the flow hydraulics, while the Lagrangian method was applied to model pollutant transport.

Verification

Figs 1 compare the laboratory results reported by Yu et al. (2016) with the calculated intrusion volumes using the Eulerian solver (MOC) [11]. The distribution of points along the 45-degree line, along with a favorable coefficient of determination (R^2 = 0.9718) for the Eulerian solver indicates a strong correlation between the laboratory and calculated intrusion volumes.

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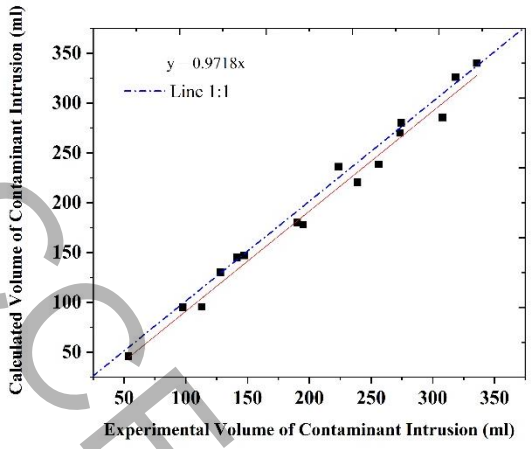

Fig.1. Comparison of the laboratory and calculated volumes of intrusion by the Eulerian solver (MOC).

Case Studies and Discussion

Through a comprehensive sensitivity analysis encompassing 36 distinct scenarios, the research focuses on understanding the re-extrusion of contaminants from leakage locations. This study examined two distinct pipeline configurations to model urban and suburban water transmission systems. For Test-1, representing urban pipelines, the parameters were set as follows: L = 280 m, D = 50.6 mm, and hvalve =14 m. In contrast, Test-2 simulated suburban water transmission systems with parameters: L = 2300 m, D = 600 mm, and hvalve = 40 m.

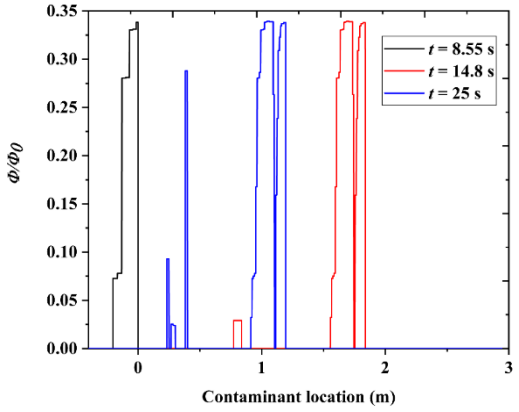

Fig.2. Formation and migration of the contaminant, Test-2, (u_0 = 1.5 m/s , x_l/L=0.66, δ = 0.01).

Conclusions

This study provides a comprehensive understanding of sudden pollutant suction and re-entry due to transient flow by systematically quantifying contaminant re-entry through sensitivity analysis of 36 distinct scenarios. Simulations combined Eulerian (flow hydraulics) and Lagrangian (pollutant transport) methods, with model errors below 5% when validated against experimental data. Key findings include: Pipeline configuration (relative position of valves, pumps, and leaks) significantly affects sudden suction and re-entry behavior.Contaminant re-entry was small (≈8% of total inflow) in 75% of tests, but became significant in specific conditions (last third of the pipe) and must be considered in design and network management. Sensitivity analysis: Relative pressure is the most influential factor (avg. 43.1% change in relative pollutant mass slope), followed by leak diameter (negative effect, slope -0.97%), and leak location (least effect, slope -0.25%). Leak location: Mid-pipe leaks trap the most pollutants, while leaks near the downstream valve can re-release up to 68% of contaminants. Re-extrusion dynamics: Strong correlation between higher re-entry and increased upstream pollutant advance for leaks near the downstream valve, consistent with the physical model configuration.

References

[1] V. Kanakoudis, S. Tsitsifli, Potable water security assessment—A review on monitoring, modelling and optimization techniques, applied to water distribution networks, Desalin. Water Treat, 99 (2017) 18-26.
[2] T.R. Lindley, S.G. Buchberger, Assessing intrusion susceptibility in distribution systems, Journal-American Water Works Association, 94(6) (2002) 66-79.
[3] S. Fox, W. Shepherd, R. Collins, J. Boxall, Experimental quantification of contaminant ingress into a buried leaking pipe during transient events, Journal of Hydraulic Engineering, 142(1) (2016) 04015036.
[4] G.R. Boyd, H. Wang, M.D. Britton, D.C. Howie, D.J. Wood, J.E. Funk, M.J. Friedman, Intrusion within a simulated water distribution system due to hydraulic transients. I: Description of test rig and chemical tracer method, Journal of Environmental Engineering, 130(7) (2004) 774-777.
[5] G.R. Boyd, H. Wang, M.D. Britton, D.C. Howie, D.J. Wood, J.E. Funk, M.J. Friedman, Intrusion within a simulated water distribution system due to hydraulic transients. II: Volumetric method and comparison of results, Journal of environmental engineering, 130(7) (2004) 778-783.
[6] S. Jones, W. Shepherd, R. Collins, J. Boxall, Experimental quantification of intrusion volumes due to transients in drinking water distribution systems, Journal of Pipeline Systems Engineering and Practice, 10(1) (2019) 04018026.
[7] Y. Shao, S. Chu, C. Dang, T. Yu, Effects of leakage points on intrusion volume in a simulated water distribution system, Water Supply, 20(1) (2020) 251-258.
[8] A. Keramat, M. Payesteh, B. Brunone, S. Meniconi, Interdependence of flow and pipe characteristics in transient induced contamination intrusion: numerical analysis, Journal of Hydroinformatics, 22(3) (2020) 473-490.

ACCEPTED MANUSCRIPT

[9] M.H. Chaudhry, M.H. Chaudhry, Transient-flow equations, Applied hydraulic transients, (2014) 35-64.
[10] L.A. Rossman, P.F. Boulos, Numerical methods for modeling water quality in distribution systems: A comparison, Journal of Water Resources planning and management, 122(2) (1996) 137-146.
[11] Y.T. Yu TingChao, J.H. Jin HanFeng, Z.T. Zhang TuQiao, S.Y. Shao Yu, W.X. Wu Xiao, Experimental observation on factors affecting intrusion volumes during low or negative pressure events, (2016).

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