engineering proceedings

MDPI

Proceeding Paper

Evaluating Pipe Burst Flooding Impacts in Urban Environments Using a Hazard-Vulnerability-Risk Approach †

Diego A. Paez * and Hailiang Shen

Computational Hydraulics Incorporated (CHI), Guelph, ON N1H 4E9, Canada; hailiang@chiwater.com
* Correspondence: da.paez270@gmail.com

† Presented at the 3rd International Joint Conference on Water Distribution Systems Analysis & Computing and Control for the Water Industry (WDSA/CCWI 2024), Ferrara, Italy, 1–4 July 2024.

Abstract: In this paper, a hazard-vulnerability-risk approach is implemented to assess the impacts of water main break flooding events in an urban setting. The hazard component is evaluated through a combination of estimated burst likelihoods for each water distribution pipe and a two-dimensional flooding model for the city's overland area. Vulnerability is assessed using the damage curves available in the literature for overland flooding. The output of risk is computed in the form of expected annual losses. The application of the proposed approach and the implemented simulation tools are illustrated through a real-life case study at an undisclosed location.

Keywords: pipe failures; urban flooding; risk assessment

check for updates

Citation: Paez, D.A.; Shen, H. Evaluating Pipe Burst Flooding Impacts in Urban Environments Using a Hazard-Vulnerability-Risk Approach. *Eng. Proc.* **2024**, *69*, 80. https://doi.org/10.3390/engproc2024069080

Academic Editors: Stefano Alvisi, Marco Franchini, Valentina Marsili and Filippo Mazzoni

Published: 6 September 2024

1. Introduction

Pipe bursts in water distribution systems are unpredictable events with low likelihood [1]. However, the impacts that these events can have are significant in both economic and social terms. One important effect is the potential flooding of areas adjacent to the pipe failure location. This flooding can result in damage or losses to buildings, streets, and other infrastructure.

Different examples of these events can be easily found in news outlets, as in Canada in 2023. First, a major water main broke in the city of Montreal on 28 July 2023, wherein a 900-millimeter (36-inch) pipe burst at 4 am, flooded the neighborhood, and buckled the road [2]. This event resulted in over 18 buildings being evacuated, more than 11,000 people being without access to power, a boil-water advisory being issued for over 75,000 people, damage to several cars, and a sinkhole in the road. An important water main break was also reported in Halifax on 10 April 2023, which resulted in flooded roads with the associated traffic disruption, damage to cars, the temporary closure of two university facilities, and low water delivery pressure for several residents, with 20–30 connections being completely disconnected [3]. On 6 April 2023, a 250-millimeter (10-inch) water main broke in Kelowna, flooding the lobby and parking basement of a 32-unit apartment building. Several cars were compromised, and the building's electrical system sustained damage that resulted in no power access for more than four days for the residents [4]. Finally, on 12 November 2023, a water main break in Hamilton resulted in road closures and a sinkhole, as well as damage to nearby front yards, backyards, and driveways due to flooding [5].

This paper presents a methodology by which to assess the risk of flooding by potential water main breaks, using PCSWMM to combine an EPANET model for the water distribution system and a two-dimensional (2D) SWMM model for the overland drainage system.

2. Methodology

Modeling the flooding produced by a burst pipe requires combining a model for the water distribution system to estimate the outflows from the system at the location of the burst (e.g., EPANET) and a model to simulate the overland flow of those flow rates along streets, yards, parks, etc. (e.g., EPASWMM). Moreover, if the drainage capability of the minor drainage system is to be included in the calculations, an integrated 1D–2D model of the dual drainage system is required. Therefore, the use of georeferenced models that allow linking the two models and postprocessing the results is needed. PCSWMM's current capabilities regarding the three end types, plus the availability of a Python environment, allowed for the implementation of the required tools for this purpose.

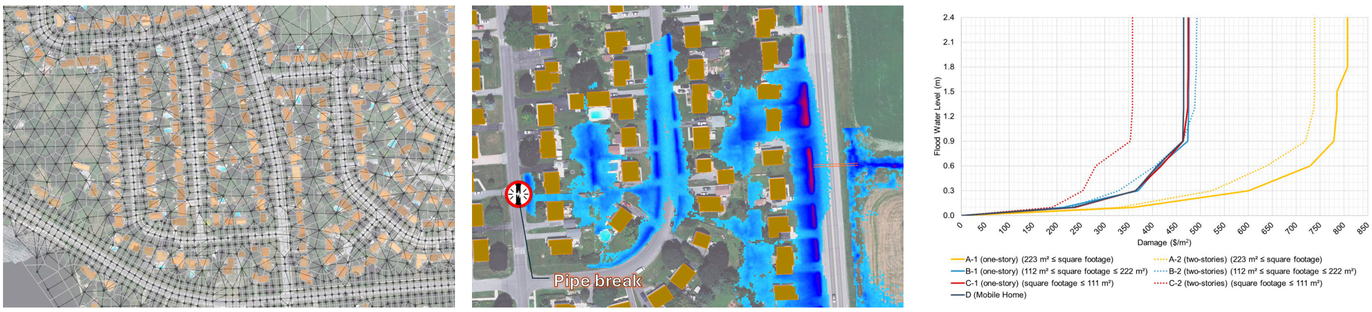
The methodology presented herein is divided into three main phases: (1) computation of hazards, (2) computation of vulnerability, and (3) computation of risk.

2.1. Computation of Hazards

The computation of hazards begins with the estimation of pipe failure probabilities for each pipe (also known as the annual rate of occurrence—ARO). This estimation depends on the available information. Simple models require few parameters for estimation, like pipe material, age, and/or diameter (e.g., in [1]). Complex models include additional parameters like operative pressure ranges, the type of soil, soil humidity, temperature variations, etc. (e.g., in [6]). For this project, the probability of failure of each pipe is treated as an input for the methodology.

The second step is the estimation of outflows from the broken pipe using the model presented in [7]. This assumes a 0.5° round crack at the midpoint of the pipe. Small-diameter pipes are assumed to be fully disconnected, while large-diameter pipes are not. The model in EPANET is adjusted with separate pipe entities, check valves, and a dummy pipe with a check valve connecting the midpoint to an emitter [8].

After computing the outflows for each possible pipe breakage event, overland flooding is modeled in a 2D drainage model using the SWMM5 engine. Different mesh types represent the elevation features of the study area, including hexagonal and adaptive meshes for flat areas and directional meshes for roads and ditches (see Figure 1a). The outflows are located in the 2D cell closest to the midpoint of the pipe. If the conveyance capacity of the sewer network is relevant, it can also be included in the model.



(**a**) (**b**) (**c**)

Figure 1. (**a**) Example of the 2D mesh used to represent an urban study area for flooding simulations. (**b**) Example of the simulated flood depth caused by a pipe break. (**c**) Example of the damage curves used for the study case [9].

2.2. Computation of Vulnerability

Damage curves correlate hazard levels (e.g., water depths) with the expected damage. Typically, damage is quantified in monetary units, such as the percentage asset value loss or economic loss per unit area.

Various flood-related damage curves exist, including those in FEMA's HAZUS software, which detail the economic loss percentages corresponding to water depths for diverse assets like residential and commercial buildings, roads, and crops. In Canada, the Federal Flood Damage Estimation Guidelines for Buildings and Infrastructure offer a framework for crafting local damage curves that covers structural damage, contents loss, business interruption, residential displacement, and more.

In this project, each polygon asset receives a damage curve of computed flood depths vs. percentage loss, loss per unit area, or total loss. By applying these curves to each asset type and the corresponding flood depth, we can compute the expected damages per asset and aggregate them to derive the single loss expectancy (SLE) value.

2.3. Computation of Risk

After computing the flood depths and estimated losses using damage curves for each pipe breakage scenario, various risk metrics are computed. The expected totalized damages (in SLE) per breakage event can visualize potential losses geographically. Incorporating breakage event probabilities highlights the high-risk areas. Additionally, the expected annual loss (ALE), calculated as the sum of single-event losses per water main multiplied by their occurrence probabilities, gives a system a wide measure of risk.

3. Case Study

This methodology was tested in a Canadian city at an undisclosed location. Data on water distribution, buildings, and elevations were estimated using publicly available or local utility-provided information. Pipe breakage ARO was calculated using a simple pipe availability equation [1]. A 2D model employing various mesh types was developed, and flood simulations were conducted using SWMM5 (Figure 1). The outflow duration from pipe breaks was assumed to be two hours, considering various operational factors such as community reports, crew dispatch, valve closures, and approvals from engineering teams.

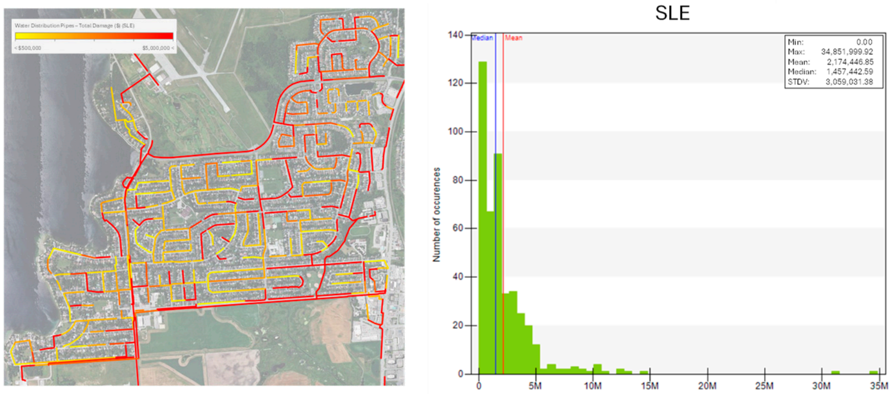
A total of 438 pipes were assessed”for ’Ipe breakages, resulting in 438 SWMM5 simulation runs and postprocessing. Only building damage was included, although other damage could be included if information is available. Damage curves from a similar location [9] were used after unifying them as single total-loss curves.

4. Results

The SLE for each pipe breakage event was computed. EPANET 2.2 and SWMM 5.2.4 were used for the hydraulic simulations. Scenario runtimes were less than 2 s and about 5 min for the EPANET and SWMM simulations, respectively. The estimated outflows ranged from ~20 L/s to 1560 L/s, with the high flows being concentrated in the large-diameter pipes (450–1200 mm) and low flows in pipes with the minimum allowable diameter (150 mm). However, the operative pressure of the pipes also correlated with the computed outflows, with some small/medium-diameter pipes having outflows on the high end of the range, and some medium-diameter pipes having low estimates for their outflows.

The computed SLEs exhibited a wide range per event, going from CAD 0 (mostly for pipes that produced flooding only along streets, near agricultural/green areas that were not characterized with damage curves, or that were near the shoreline) to ~CAD 10 M (for large or medium pipes producing flooding near highly vulnerable buildings, or in flat areas where several single-detached homes were partially affected). Finally, there were some outliers above CAD 10 M and reaching up to CAD 35 M for pipes near a school and luxury building, with very high exposed values. Figure 2 shows the spatial and statistical distributions of the SLE.

Finally, the computed ALE value for the study area was CAD 262,679/year. This value gives a first indication of the yearly amount worth investing in mitigating these risks, which should be compared with the estimated costs of such action.



(**a**) (**b**)

Figure 2. SLE results for the study case. (**a**) Spatial distribution of the SLE; (**b**) statistical distribution of the SLE.

5. Conclusions

The proposed methodology allows for the quantification of the flooding risk associated with water main bursts. The implementation of the methodology in PCSWMM is convenient as it allows for an easy transition between the part of the methodology that is completed in an EPANET project and the part of the methodology that is completed in a SWMM project.

Considering the different data availability for the estimations of the ARO for each pipe breakage event, as well as the different formats for the damage curves of exposed assets, it is important to maintain the methodology and versatility of the implemented tool to incorporate these different formats.

The ALE is a useful decision-making tool that can aid in deciding if a mitigation strategy is required, if mitigation is worth it, and if the strategy is better than other alternatives.

Author Contributions: Conceptualization, methodology, software, formal analysis, and writing—original draft preparation, D.A.P.; writing—review and editing, D.A.P. and H.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Computational Hydraulics Incorporated (CHI).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used and developed for this project are confidential and only summary results are available by request to the first author.

Conflicts of Interest: The research described in this paper was funded by Computational Hydraulics Incorporated (CHI), and the authors are employed by the company, which has a commercial interest in the PCSWMM software presented.

References

1. Cullinane, M.J.; Lansey, K.E.; Mays, L.W. Optimization-availability-based design of water-distribution networks. *J. Hydraul. Eng.* **1992**, *118*, 420–441. [CrossRef]
2. Global News Canada. Major Montreal Water-Main Break Causes Rushing Floods, Large Sinkhole. Available online: https://globalnews.ca/news/9863421/montreal-water-main-break-flooding-sinkhole/ (accessed on 22 March 2024).
3. Global News Canada. Water Main Break Disrupts Service, Floods Armdale Roundabout in Halifax. Available online: https://globalnews.ca/news/9612812/armdale-roundabout-halifax-flooded/ (accessed on 22 March 2024).
4. Global News Canada. 'Dark and Cold': Residents of Flooded Kelowna, B.C., Apartment Building Still without Power. Available online: https://globalnews.ca/news/9614407/residents-flooded-kelowna-bc-apartment-building-still-without-power/ (accessed on 22 March 2024).

5. The Spec. 'It was just torrential': Water Main Break Floods Parts of Kirkendall Neighbourhood. Available online: https://www.thespec.com/news/hamilton-region/it-was-just-torrential-water-main-break-floods-parts-of-kirkendall-neighbourhood/article_63870dae-44f5-5272-80d2-6c09cc746595.html (accessed on 22 March 2024).
6. Kleiner, Y.; Rajani, B. Forecasting variations and trends in water-main breaks. *J. Infrastruct. Syst.* **2002**, *8*, 122–131. [CrossRef]
7. Paez, D.; Filion, Y.; Castro-Gama, M.; Quintiliani, C.; Santopietro, S.; Sweetapple, C.; Meng, F.; Farmani, R.; Fu, G.; Butler, D.; et al. Battle of postdisaster response and restoration. *J. Water Resour. Plan. Manag.* **2020**, *146*, 04020067. [CrossRef]
8. Shi, P.; O'Rourke, T.D. *Seismic Response Modeling of Water Supply Systems*; Cornell University: Ithaca, NY, USA, 2006.
9. HATCH. *Development and Application of Flood Depth-Damage Curves for the Muskoka River Watershed*; HATCH: Mississauga, ON, Canada, 2023.