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Full-Scale Water Supply System Pipe Burst Analysis Method and Application in Case Studies †

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Abstract: This paper presents an EPANET pressure-dependent analysis-based method for analyzing bursts in every pipe in a water supply system (WSS) and applies the method to large Finnish WSSs. EPANET is enhanced with the per-junction required and minimum pressures, a flow- and pressure-controlled pump battery component and a full control system model to accurately capture the dynamic behavior of the whole system, including the effect of control system parameters and settings. The results are combined with population and income data, and the correlations of the various physical and hydraulic parameters affecting the burst effects are analyzed.

Keywords: pipe burst; resilience; asset management; EPANET

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1. Introduction

Pipe bursts are problems that are becoming more and more common as the water distribution infrastructure keeps aging. Bursts have various negative effects, including the loss of water services, damage to property and streets [1] and water quality problems that can potentially cause public health issues [2].

There are many studies published on detecting and localizing bursts and the mechanisms causing bursts. Limited focus is devoted to analyzing the effects of bursts on water supply systems (WSSs) and the water service [3,4]. A thorough analysis of the effects of bursts and the areas sensitive to bursts would be a valuable tool for network asset management. The socio-economical aspects of bursts are also rarely analyzed.

This paper presents a method for analyzing the effects of pipe bursts in large water supply systems (WSSs), including their potential for damaging the built environment, the number of people affected by the loss of service and the socio-economic status of the affected people. The method was applied to four large Finnish WSSs, and the results were summarized and analyzed to find correlations between properties and effects.

2. Materials and Methods

Our method was developed in Fluidit Water [5] version 2.5. The hydraulic simulation is based on an in-house version of the OpenWaterAnalytics EPANET simulator [6]. Enhancements over the OWA's version that are relevant for this study include support for flow- and pressure-controlled pump batteries [7], along with the upper bound for the pump battery head and flow, support for modeling complex network control algorithms [7] and node-specific minimum and required pressure values for the pressure-dependent analysis.

The developed automated pipe burst analysis tool used the simulation start and end times, pipe burst start and end times and the relative burst hole size, r_D, as input parameters. The effects were analyzed for every pipe in isolation by adding a junction to the midpoint of the pipe, i, connecting a new pipe representing the soil, with length $L = 2.0$ m and diameter $D_{i,burst} = r_D \cdot D_i$, to a reservoir, the head of which equals the ground elevation. The new

pipe was opened at the burst start time for the burst duration. The simulation continued for a few hours after closing the burst to analyze any lasting and cascade effects. The tool tracked the leaked volume and the sums of the demand deficit, number of connections (i.e., demands), inhabitants, and the low-income and high-income inhabitants (the lowest- and highest-income deciles) experiencing pressure deficit caused by the burst.

The method was applied to four large Finnish WSSs: Turku, HS-Vesi serving the Hämeenlinna region, Tampere and Jyväskylä. A complete up-to-date, all-pipe model, including every control station, water tower, water source and customer connection was available for each system. The models included exact models of the real control system algorithms [7] controlling water production and distribution. All models used the Darcy–Weisbach method for calculating friction losses in the pipes.

Select properties of the network models and population estimates based on the Grid Database [8] are shown in Table 1. The network length ranges from 867 to 1266 km, and the population served is between 82,000 and 248,000. The population density is reflected in the average pipe diameters, ranging from 115 to 190 mm. The share of low-income people is greater than the number of high-income people, except in the more rural HS-Vesi network. The shares of both high and low-income people are higher than 10% in all networks. Tampere and Jyväskylä have more varying topography, which manifests in higher average pressures. In total, the analyzed network length is 4028 km, and the population served is 641,000.

Table 1. Summary of the analyzed networks: network length, average inner diameter, revenue and non-revenue water (RW and NRW, respectively), average pressure, the number of inhabitants, population density and number and share of the people in the highest and lowest income deciles.

WSS	Length	Avg. Diam.	Demand [m³/d]			NRW	Avg. Press.	Inhabitants (Estimated)					
	[km]	[mm]	RW	NRW	Total	[l/s × km]	[mwc]	Total	[1/km]	High Income		Low Income	
Turku	867	190	46,000	6900	52,900	0.093	47.4	187,000	216	26,000	14%	35,000	19%
Tampere	937	189	41,000	9100	50,100	0.110	53.1	248,000	265	39,000	16%	44,000	18%
Jyväskylä	957	151	22,000	2600	24,600	0.030	51.8	123,000	129	16,000	13%	24,000	19%
HS-Vesi	1266	115	14,000	2200	16,200	0.020	47.0	82,000	65	11,000	14%	11,000	13%
Total	4028	148	123,000	20,800	143,800	0.040	49.3	641,000	159	92,000	14%	114,000	18%

Yearly water use was available for every connection in all the systems. Demand patterns and non-revenue water (NRW) volume were modeled on pressure zone levels. NRW was modeled using emitters with an exponent of 1.0. Emitters were scaled based on the pipe lengths, diameters and average pressure to match the NRW measurements. The number of inhabitants and high- and low-income people were estimated by dividing the number of people in each 250 × 250 m statistical cell unit in the national Grid Database [8] proportionally to the total demand of connections within the cell. The number of floors, n, was taken from the Building Database [9] and each connection's required pressure $p_{req} = 22 + 3\,(n-1)$ [mwc]. Minimum pressure, p_{min}, was set to 5 mwc for all connections.

Analysis was run on a Microsoft Azure virtual machine with a 16-core Intel Xeon Platinum 8272CL @ 2.60 GHz processor and 32 GB of memory installed, running Ubuntu 22.04 Linux distribution. Simulations were performed for a 27 h long period. The burst was set to start at the peak hour of 20:00 and last for three hours until 23:00. The relative burst diameter was 0.3. All simulations were performed in parallel, utilizing all available cores. The simulations took 0.5–2.0 h for each of the networks. Finally, correlation and multi-variate linear regression on the results dataset were performed in R version 4.3.3.

3. Results

The results from all the burst simulations were collected into one dataset, containing the results for 40,963 pipe elements. The results are also available in a map-based format for the utilities. Table 2 shows a summary of the pipe parameters and burst analysis results. The full capacity for a pipe is flow causing 5 m/km head loss. Half of the bursts are such

that only a few dozen people experience pressures below the required, with 75% of the leaks resulting in the deficit being less than 0.1 m³ during and after the three-hour-long burst event.

Table 2. Summary of the analyzed pipes and the burst analysis results.

Variable	Percentile						
	1%	10%	25%	50%	75%	90%	99%
Diameter [mm]	33	54	94	102	150	259	500
Full Capacity [l/s]	0	6	34	70	110	172	675
Pressure [mwc]	24	37	44	51	59	66	75
Daily Flow [m³/d]	0	0.6	3	23	104	389	3221
Leak Volume [m³]	4	15	43	64	142	384	1486
Demand Deficit [m³]	0	0	0	0	0.1	0.7	12
Affected Inhabitants	0	0	0	36	267	2123	4444
Affected Low Income	0	0	0	7	37	314	636
Affected High Income	0	0	0	9	33	459	820

Figure 1 shows the linear correlation analysis of the results, along with the *p*-values for the statistically insignificant correlations of $p > 0.005$ at a 95% confidence level. The strongest correlation is between the pipe capacity and the burst leak volume. Daily flow is positively correlated with the leak volume, but daily flow is not completely uncorrelated with the pipe capacity. The deficit is positively correlated with the number of affected inhabitants but is not statistically significant. The deficit, leak flow and pipe capacity all have positive correlations with the affected inhabitants but are statistically insignificant. Pressure does not correlate much with the leak volume or the affected inhabitants.

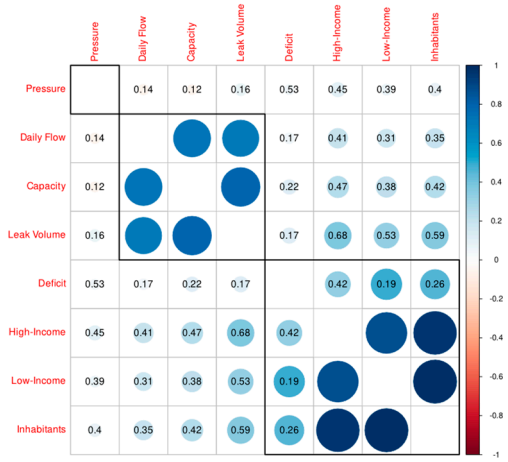

Figure 1. Linear correlation analysis of the variables and the *p*-values for insignificant correlations.

The share of high-income inhabitants of all the affected inhabitants was 18.2%, and the share of low-income inhabitants was 15.1% when examining all bursts with the number of affected inhabitants larger than zero. For the top 1% of bursts, with a total deficit of at least 1.0 m³, the shares were 14.5% and 12.9%, respectively. The shares of the high- and low-income people of the total population were 14.4% and 17.7%, respectively.

4. Conclusions and Discussion

This article presents a hydraulic water supply system simulator-based method for analyzing the effects of pipe bursts in a full-scale water distribution network. The method was applied to four different large Finnish WSSs, and the results for pipe components were analyzed statistically and via linear regression.

Most of the pipe bursts do not have a direct effect on customer water services. The results analysis indicates there was a linear correlation between the pipe capacity and daily

flow with the burst leak volume. While the deficit and the affected inhabitants did exhibit correlations with the daily flow and pipe capacity, it was not statistically significant. Pipe pressure did not exhibit a significant correlation with the leak volume, deficit or affected inhabitants.

The results indicate bursts tend to affect the highest-income earners a few percentage points more than the lowest-income people. It could be argued that high-income people have better means to cope with disruptions in water services, and thus, the result does not necessarily indicate significant inequality. More research is needed to understand the causes, as, in general, both the poor and the rich tend to live in the network periphery.

Additional research is needed to better understand the underlying causes for the observations, e.g., how the properties of each pressure zone, such as the number of people, various resilience indices, and pumping station and water tower capacities, affect the severity of bursts. It would be beneficial to analyze the results from a customer perspective too, as this research only analyzed the data on pipes, not what kind of properties affect the issues and the severity of them for each junction in the model. This would produce a useful representation of the most vulnerable areas in the networks.

The presented simulation-based method remains a viable tool for an overall understanding of the effects of pipe bursts in a whole network. This information can be very useful when the utilities plan their network asset management and rehabilitation actions, allowing resilience and reliability to be taken into consideration.

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