

## SEISMIC RISK SENSITIVITY ANALYSIS OF PIPE VULNERABILITY AND DAMAGE MODELS IN A LARGE DRINKING WATER DISTRIBUTION NETWORK IN CENTRAL CHILE

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**Abstract:** *Drinking Water Distribution Networks (DWDN) are of critical importance in modern cities, in both regular and emergency conditions, given the direct and indirect negative impacts caused by any service disruption on the population and other interdependent lifelines. Buried and surface water network components, such as pipes and tanks, are vulnerable to seismic effects. While the criticality of tanks is evident given their small number, the effect of pipe damage is less visible, especially if they are distant from tanks. Correctly assessing pipe damage effects in large DWDN is difficult given the large system redundancy, and the thousands of kilometres of pipes of different materials and diameters buried on different soil conditions. Consequently, a detailed model of the DWDN capable of identifying possible seismic damage on network pipes and performance consequences is a useful tool. This research describes a hydraulic model built in EPANET for the DWDN of a large conurbation in central Chile formed by the cities of Valparaíso, Viña del Mar, and Concón. A seismic risk assessment was performed considering Peak Ground Velocity for the ground motion intensity measure, three repair rate models, to represent pipe seismic vulnerability, and two damage-state models. A hydraulic analysis was carried out to assess the earthquake performance of the damaged network in terms of unsupplied water demand and entropy. Results of the models considered for seismic performance were significantly dispersed, hence, a sensitivity analysis of risk results was carried out by weighting the different vulnerability models, changing the vulnerability factors due to system properties such as pipe material, soil liquefaction potential, and the threshold values of the parameters of the different damage-state models. Risk results exhibit high sensitivity to the different modelling assumptions. Also, current results show that the water service is shut down completely if damage reaches about 30% of the pipes.*

**Keywords:** *seismic risk sensitivity analysis, water distribution network, pipe damage-states*

### Introduction

The risk of service interruption in water distribution systems located in seismic-prone zones must be assessed and managed to maintain an adequate performance during and after a seismic event. This is particularly important in modern cities because an interruption of the service has direct and indirect negative impacts on the population and also affects other interdependent lifelines. Assessing seismic risk in an efficient, methodic and thorough way is a difficult task, because a Drinking Water Distribution Network (DWDN) is a large and complex system, with high redundancy and thousands of kilometers of pipes of different materials and diameters buried on different soil conditions, along with several other components, such as tanks, valves and pumps. A detailed model of the DWDN under study is required to achieve the goal of understanding its seismic behavior and proposing mitigation strategies. Seismic damage in DWDN has been studied in the past (e.g. (Hamamoto, Ito, y Tokai 2021; Yoon, Lee, y Jung 2021; Choi y Kang 2020; Cimellaro et al. 2016)) usually focusing on pipe damage, given that they outnumber other elements in the system. Pipelines are subjected to wave propagation and soil deformation, which requires appropriate estimations of peak ground velocity (PGV) for the former and permanent ground deformation (PGD) for the latter, since it has been shown that PGV is related to ground strain, whereas PGD is associated with various pipe failure modes (American Lifelines Association 2001; Xu, Jiang, y Qu 2021). For instance, liquefaction-induced deformation, that can

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produce lateral displacement and post-liquefaction settlement, among other phenomena, has caused significant damage in previous earthquakes (Alberto *et al.* 2022). While ground deformation creates more severe damage, it is concentrated in small areas, whereas wave propagation is an extensive phenomenon. With that in mind, this paper will focus on the effect of wave propagation (i.e., PGV) to propose a probabilistic framework for estimating seismic risk in a DWDN, applied to the cities of Valparaíso, Viña del Mar and Concón, a conurbation in the central coast of Chile. A probabilistic seismic hazard analysis will be carried out to simulate consistent maps of PGV, and seismic damage of pipelines will be estimated combining three different Repair Rate (RR) models to account for pipe seismic vulnerability, and two models to sample the damage state of a pipe (leak or break) given its Repair Rate. Results will be processed to obtain seismic risk curves of the Unsupplied Demand of the complete network, and a sensitivity analysis will be carried out to quantify the effect of changing modelling considerations.

## Network model construction

The DWDN of Valparaíso, Viña del Mar and Concón was modelled in the EPANET software (US EPA 2014) because of its simplicity, widespread use and open-source nature. EPANET models consider a set of basic components such as junctions, pipes, valves, reservoirs and tanks, which are defined based on available data of the network. EPANET allows the user to implement advanced water network elements such as pumps, time patterns, water quality features, etc., however, due to the limited amount of available information for the authors, many assumptions and simplifications were undertaken. In the next paragraphs, the overall process of modelling the real-life water network elements into EPANET will be described.

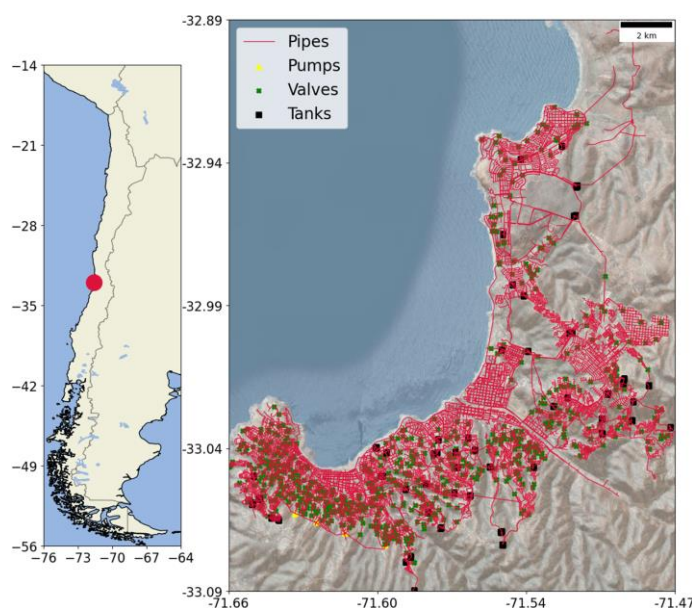


Figure 1: Drinking water distribution network of Valparaíso, Viña del Mar and Concón conurbation.

### *Software and raw data sources used in network modelling*

Data necessary to build the EPANET model was provided by ESVAL, the private company that currently serves the conurbation under study. The supplied dataset includes GIS shape files with points representing the water tanks and valves, and polylines representing the pipes (Fig. 1). These elements were included in EPANET using the [TANKS], [VALVES] and [PIPES] objects respectively. The vertices from the pipes' polylines shapefile were used as the EPANET object [NODES], which are required to input the water demand values in them.

Shapefile attributes include (among the most important): tank elevation, pipe diameter, pipe material, pump head, and valve diameter. Table 1 shows a summary of the available raw data. Water demand data was included as yearly average flow registered by ESVAL flowmeters, whose locations were available; however, since they did not match the pipe polylines, it was impossible to directly assign demand values to the network. To address this issue, a Python script was

implemented to assign a flowmeter demand to the closest pipe polyline vertex. Most of the water supply comes from tanks located over elevated terrain, which allows gravity to transport water to the lower sectors. However, there are many tanks located in low terrain that need pumps to provide water to the inhabitants of the city. ESVAL data includes the location, head and power for each pumping station, but no pump operation curve, which is ideally required in EPANET for a proper pump representation in the model. Hence, we simplified our model by taking the head data from the pumping stations and added them to the elevation data of their associated tanks. This simplification implies that all the water pumping regime is constant, or in other words, a steady-state pumping.

Component	File	Main attributes
Tanks	Shapefile (.shp)	Latitude, longitude, elevation, min./max. levels
Pipes	Shapefile (.shp)	Latitude, longitude, diameter, material
Valves	Shapefile (.shp)	Latitude, longitude, diameter, pressure, setting
Demand	MS Excel spreadsheet (.xlsx)	Latitude, longitude, monthly volume

Table 1: Summary of the raw available data, format and attributes

#### Model components setup and settings

All components described in the previous section were integrated using Python 3.7 scripts. The tanks' shapefile was not connected to the pipes' shapefile; therefore, we connected them manually by creating additional pipes whose attributes were defined as the same attributes from the connecting end. Pipes and valves are all considered to be in "good condition" and have no previous deterioration. In reality, pipes can be up to 50 years old, but for the sake of simplicity and availability of data, this aspect will not be considered. All [PIPES] objects are created given an "OPEN" state. Once the EPANET model was created, the hydraulic simulation was run, and an iterative process was applied to correct the orientation of the valves, until the pressure values in the pipes were in the acceptable range defined by ESVAL (Figure 2a).

### Seismic hazard

The seismic hazard of the region under study was characterized using 50,000 earthquake scenarios generated using the recurrence model developed for Chilean seismicity (Poulos *et al.* 2019), which consists of interface and intraslab seismic sources associated with the subduction of the Nazca Plate under the South American Plate. All sampled earthquakes had magnitude  $M_w \geq 5$ , and importance sampling (Jayaram y Baker 2010) was used to increase the proportion of high impact earthquake scenarios by considering a uniform distribution of earthquake magnitudes, instead of the true underlying probability distribution of magnitudes (i.e., a mixture of truncated exponential distributions). Moreover, only seismic sources close to the cities were considered, and the hypocentre of each earthquake realization was sampled assuming a uniform distribution inside each seismic source. Once magnitudes and hypocentres were obtained, PGV maps were generated for each network component using the ground motion model (GMM) developed by Parker (Parker *et al.* 2022) and considering the regional adjustment factors for South America. The rupture distances (i.e., the closest distances from the sites to the rupture surface), which is required by the GMM to estimate PGVs, were computed using the source scaling relations developed by Strasser (Strasser, Arango, y Bommer 2010). Moreover, the spatial correlation of PGV was also considered by using the model developed by Goda (Goda y Atkinson 2010), which only depends on the distances between sites.

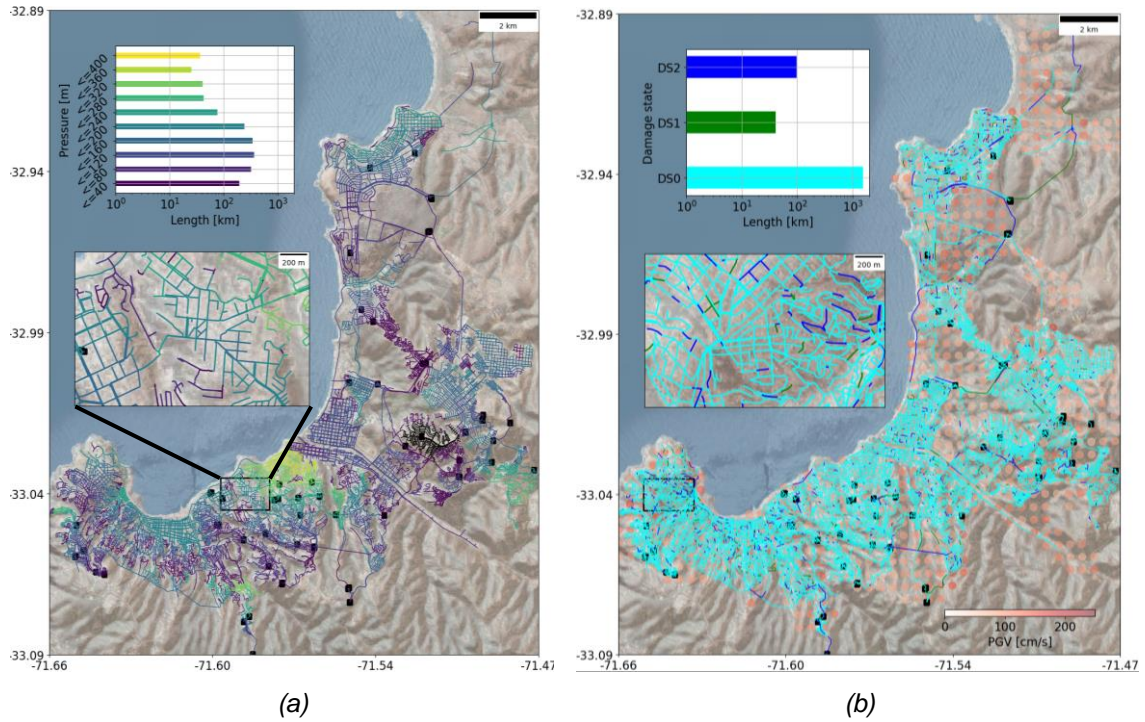


Figure 2: Left: pressure distribution in the undamaged network. Right: damaged scenario for one realization with unsupplied water demand of 70%, showing undamaged (cyan), leaking (green) and broken (blue) pipes.

### Pipe vulnerability

One of the possible goals of risk assessment is to identify critical network components, in order to determine adequate mitigation strategies to guarantee normal network functionality. Clearly, tanks and pumps are critical elements, due to their role and reduced number. However, it is not straightforward to establish the same for pipes. With this in mind, it is possible to study pipe importance by assuming only them might be damaged when subject to an earthquake, because this would isolate the effect of pipe damage on the network functionality. Pipe damage is modeled with vulnerability functions that represent the Repair Rate (RR) of an element after a seismic event, which is the average number of failures per unit of length. This is a function of Peak Ground Velocity (PGV), Permanent Ground Deformation (PGD), and pipe properties. Given a failure, two possible damage states are defined for a pipe, leak and break. Most studies consider the assumption that when a pipe is damaged due to PGV, 80% of the time this corresponds to leaks and 20% to breaks, while the percentages are reversed when damage is due to PGD (American Lifelines Association 2001). Since there are no models to estimate PGD in the zone under study, this research considered only PGV to compute the Repair Rate. This was carried out with three different models from the literature, that were combined into one RR estimation.

The first RR model was proposed by ALA (American Lifelines Association 2001):

$$RR_{ALA} = 0.00126 K_1 PGV^{1.173} + \epsilon \tag{1}$$

$$K_1 = K_m \cdot K_d \tag{2}$$

, where  $RR$  is in [rep/km];  $PGV$  is in [cm/s];  $K_1$  is a correction factor that considers pipe material ( $K_m$ ) and diameter ( $K_d$ ); and  $\epsilon$  is the regression residual. This model is based on 18 earthquakes from the Americas and Japan, including Kobe, Loma Prieta and Mexico City.

The second model was developed for Japan (Isoyama et al. 2000):

$$RR_{ISO} = 3.11 \times 10^{-3} C (PGV - 15)^{1.30} + \epsilon \tag{3}$$

$$C = C_m C_d C_t C_l \tag{4}$$

, where  $RR$  is in [rep/km];  $PGV$  is in [cm/s];  $C$  is a correction factor that considers pipe material ( $C_m$ ), diameter ( $C_d$ ), topography ( $C_t$ ), and liquefaction potential ( $C_l$ ); and  $\epsilon$  is the regression residual. This model is based on the damage caused by the Kobe earthquake (1995) to the Ashiya and Ishinomiya cities.

The third model was developed for New Zealand (Bellagamba et al. 2019):

$$\ln RR_{Bel} = f_0(PGV) + \sum_{i=1}^n C_i(h_i) + \epsilon = a + b PGV + a_0 PGV^{b_0} + \epsilon \quad (5)$$

, where  $RR$  is in [rep/km];  $PGV$  is in [cm/s]. The  $RR$  value depends on  $PGV$  according to the function  $f_0$ , and a series of correction factors  $C_i$  that depend on parameters  $h_i$ . After rearranging the expression, the regression parameters  $a$ ,  $b$ ,  $a_0$  and  $b_0$  depend on the pipe performance group, material, diameter and soil cyclic resistance ratio (CRR). This model is based on the Christchurch earthquake and provides a detailed quantification of uncertainty  $\epsilon$ .

For each pipe, the  $PGV$  was computed as the average of its end nodes, and this value was used to compute the Repair Rate according to equations (1) to (5). Then, the predictions of the three models were combined using equal weights for the base case, and other weight values for the sensitivity analysis presented in a following section. Once a  $RR$  value was computed for a pipe, the total number of failures was sampled from a Poisson distribution:

$$f(x, \lambda) = P(X = n) = \frac{\lambda^n e^{-\lambda}}{n!} \quad (6)$$

where the Poisson distribution parameter,  $\lambda = RR \cdot L$ , is the expected number of failures of a pipe with length  $L$  and  $RR$  expected repairs per unit of length; and  $n$  is the total number of failures, considering leaks and breaks,  $n = n_{breaks} + n_{leaks}$ . As expected, longer pipes should have on average more failures, given the same  $RR$ . As it was mentioned before, most studies use the ALA (American Lifelines Association 2001) and HAZUS (FEMA 1997) assumption to determine  $n_{breaks}$  and  $n_{leaks}$ . Thus, given a pipe, one may obtain a  $PGV$  value from the seismic hazard map, compute the associated  $RR$  value with Equations (1) to (5), sample  $n$  from Equation (6), and then sample the nature of each failure considering that 80% of them are leaks. The major drawback of this assumption is that the proportion of breaks and leaks is independent of the  $PGV$  level, which is not realistic, since it is expected that for very low  $PGV$  values all failures should correspond to leaks, whereas for very high  $PGV$  values all failures should be breaks. To take this into consideration, a more realistic model may be proposed, making the proportion of leaks and breaks a function of  $PGV$ . In particular for this study, based on results obtained from elsewhere (Lanzano et al. 2014), it was considered that for  $PGV < 45$  cm/s all failures are leaks, while for  $PGV > 95$  cm/s failures correspond to breaks only. For intermediate  $PGV$  values, the probability of a break may be obtained by linearly interpolating between these points.

## Hydraulic model with damage

Once pipe damage has been determined by following the procedure of the previous section, the next step was to model it in the hydraulic model. On one hand, a leakage was represented with the [EMITTERS] object in EPANET, which is an optional component associated to a junction that produces a water loss as a function of the pressure. The water flow through an emitter is computed in EPANET with a generalized form of the Torricelli equation that characterizes flow through a hole in a tank, as in Equation (7), where the water flow  $Q$  is a function of the junction pressure  $H$ , the emitter exponent  $n$ , and the flow coefficient  $C$ , which in turn is a function of the cross-section area of the hole  $A$ , the gravity acceleration  $g$ , and the discharge coefficient  $C_d < 1$ , that depends on energy losses due to turbulence. In EPANET,  $C$  can be defined individually for each emitter, while  $n$  is defined globally for the whole model.

$$Q = \frac{C_d A (2g)^n}{C} H^n = C H^n \quad (7)$$

Therefore, an emitter may be completely characterized by selecting an emitter exponent  $n$ , a hole cross-section area  $A$ , and a discharge coefficient  $C_d$ . Please, notice that both  $A$  and  $C_d$  are random variables because holes may vary in size, while energy losses depend on different variables, such as hole aspect ratio. If a pipe has multiple leaks, they are all randomly generated and then combined into one equivalent emitter by summing their flow coefficients  $C$ . Based on



previous studies (Klise et al. 2017; Yoo, Kang, y Kim 2016), the hole cross-section area is assumed to follow an uniform distribution, as a function of the pipe cross-section area,  $A_0$ .

$$A \sim U(0.05A_0, 0.10A_0) \quad (8)$$

Similarly, the discharge coefficient  $C_d$  is assumed to follow a normal distribution as a function of the head pressure  $H$ , in meters of water column (Schwaller, van Zyl, y Kabaasha 2015):

$$C_d \sim \begin{cases} 0.5 & , H < 20 \\ N(0.575, 0.026) & , 20 \leq H < 30 \\ N(0.650, 0.030) & , 30 \leq H < 45 \\ N(0.725, 0.035) & , 45 \leq H < 60 \\ N(0.800, 0.039) & , 60 \leq H \end{cases} \quad (9)$$

On the other hand, pipe break was modeled by modifying the network by: (i) removing the pipe; (ii) replacing it with two half-pipes that go from the pipe end nodes to the midpoint of the original pipe, where its height is linearly interpolated from the heights of the end nodes; (iii) adding an empty reservoir to both free ends of the new half-pipes (i.e., reservoir's head is equal to its height); and (iv) adding a check-valve on both half-pipes, so water can only flow into the reservoirs and not from them. By following this procedure, the broken pipe disconnects parts of the network and allows for considerable water and pressure losses. Whenever a pipe experiences both leaks and breaks, only the latter is modeled, because the water and pressure losses of the former are negligible in comparison. Additionally, at most one break is modeled for each pipe, because any following break will have no effect on the network.

Having modeled a damaged DWDN, like the one shown in Figure 2b, a pressure-driven hydraulic simulation was carried out in EPANET. The performance of the network was measured considering the Unsupplied Demand  $UD$  as output variable, as defined in Equation (10), where  $q_{D_i}$  is the water that is actually supplied to node  $i$  by the network, and  $D_i$  is the water demand required by node  $i$ . It may be noticed that a value of  $UD = 0$  implies that the DWDN is fully operational, while  $UD = 1$  means that no water is provided to the entire network.

$$UD = 1 - \frac{\sum_i q_{D_i}}{\sum_i D_i} \quad (10)$$

## Seismic risk and sensitivity analysis

A risk analysis (Poulos, de la Llera, y Mitrani-Reiser 2017; Jayaram y Baker 2010) was carried out considering the 50,000 seismic scenarios. For each one, the damage state of the pipes was sampled as explained before, a hydraulic simulation was run, and the Unsupplied Demand was computed. Results of  $UD$  were then combined in a risk curve, as shown in Figure 3, where the curve in red corresponds to the results obtained when the ALA assumption for pipe breaking probability was used, while the blue curve corresponds to the PGV-dependent model being considered. It may be noticed that selected model greatly affects the results, because ALA's rule underestimates the number of pipe breaks for seismic scenarios with large magnitudes. Also, Figure 4 shows that the DWDN is very robust in both cases, presumably due to its high redundancy, since high return periods are observed for the entire range of  $UD$ .

While the risk curve of Unsupplied Demand is a useful result, additional information is required to better understand the seismic performance of the DWDN. For instance, the network is composed by tens of thousands of kilometers of pipes, thus a natural question would be how much of that total pipe length ( $L_{tot}$ ) must be broken ( $L_{br}$ ) for the system to reach a certain level of  $UD$ . This is illustrated in Figure 4a, that shows the PGV-dependent model results. It may be inferred that the DWDN collapses when around 20%-30% of its pipes (in terms of length) are broken, although it may collapse before if some critical pipes suffer severe damage (e.g., those directly connected to the tanks). For small values of total broken pipe length ratio ( $L_{br}/L_{tot}$ ), the  $UD$  increases rapidly and linearly until around 4% of the total pipe length is broken, where the  $UD$  may take values roughly between 40% and 70%. After that point, the behavior is more nonlinear, and the variance tends to decrease. It may be also noticed on the secondary histograms that most seismic scenarios produce small values of  $UD$ , and only a small group of them cause major losses. This is also better appreciated in Figure 4b, that shows how only scenarios with magnitude  $M_w > 8$  produce values of  $UD$  greater than 10%, with a significant variability in the results. Further studies

are required to better understand which scenarios are causing more damage and why, as well as which pipes are more critical to produce higher *UD* values, which will be addressed in a journal publication that is currently under preparation.

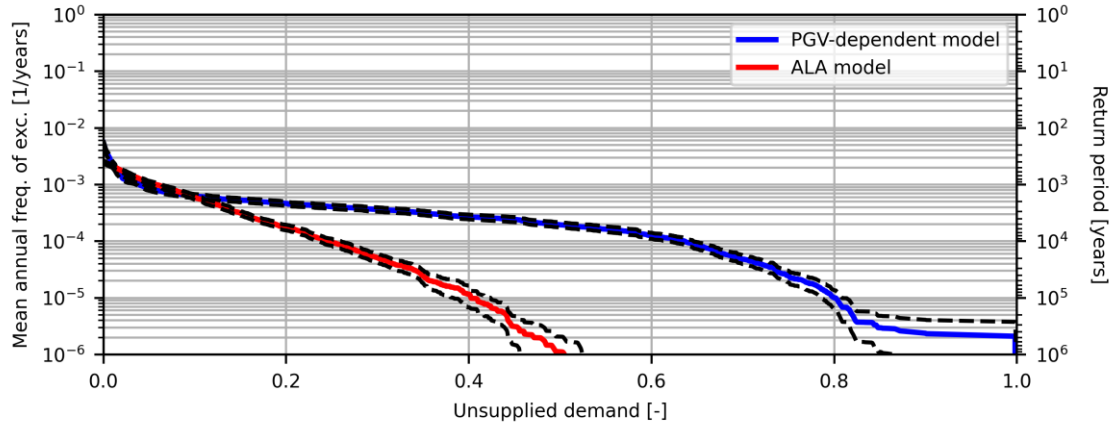


Figure 3: Risk curve of unsupplied demand considering ALA's and a PGV-dependent model for pipe breaking probability. Dashed curves represent the 95% confidence interval

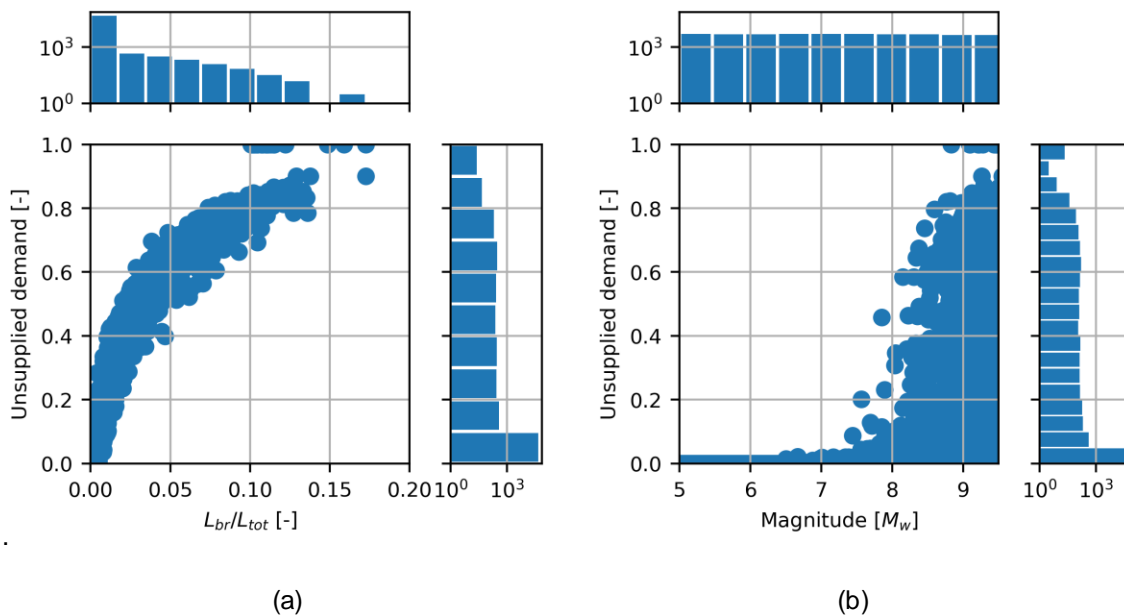


Figure 4: Summary of the risk analysis with the PGV-dependent model for pipe breaking probability. Left: non-linearity of the Unsupplied Demand as a function of the total length of broken pipes. Right: damage to the network as a function of event magnitude

Given that ALA's rule for pipe breaking probability is assumed in most previous studies, a sensitivity analysis was performed considering it as the base case, to study the impact of the Repair Rate model in the risk curve. As it was mentioned before, the three *RR* models of Equations (1) to (5) were combined with equal weights to estimate seismic damage for each pipe for the base case. Figure 5 compares the results of this approach and those of using only one of the three *RR* models. It may be noticed that the impact of the selected *RR* model is considerable. While the ALA Repair Rate model provides the lowest Unsupplied Demand values, below 20% in all cases, the Isoyama *RR* model produces the highest impact on the DWDN, reaching values of approximately  $UD = 80\%$  for the same seismic scenarios. The Bellagamba *RR* model on the other hand, generates a curve that goes roughly between the base case and the Isoyama model.

Another variable of interest for the sensitivity analysis is how much the pipe breaking probability of ALA's model affects the risk curve. Figure 6 illustrates this effect, by considering different values

for this parameter, i.e., 10%, 20%, 40%, 60% and 100%. It may be concluded that the effect of pipe breaking probability is considerable since the presence in the network of broken pipes greatly controls the risk curve. While for the base case (probability of pipe breaking of 20%) the Unsupplied Demand does not go beyond 50%, the risk curve moves towards the right as the probability of pipe breaking increases. Ultimately, when only breaks are allowed to occur, the risk curve is similar to the one obtained with the PGV-dependent model for pipe breaking probability. Moreover, the maximum Unsupplied Demand is around 30% when the probability of pipe breaking is halved.

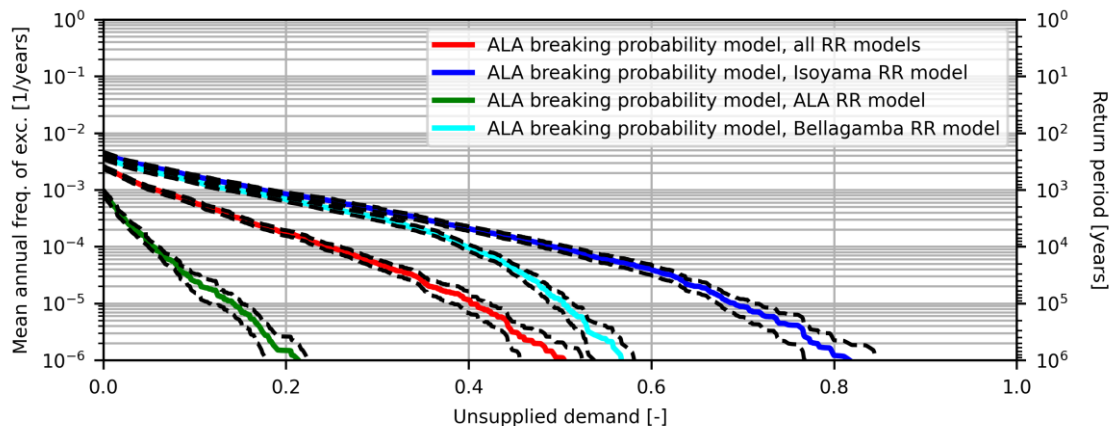


Figure 5: Effect of selecting a different Repair Rate model on the Unsupplied Demand risk curve

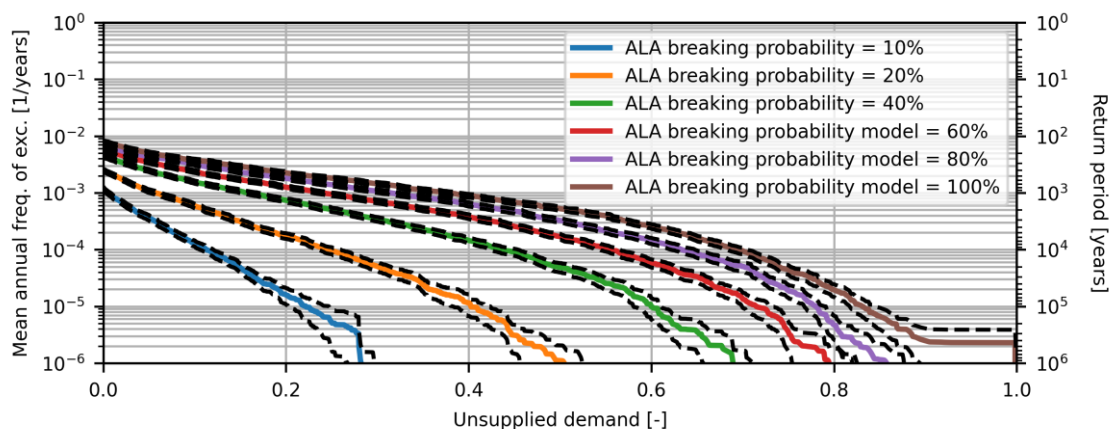


Figure 6: Effect of changing the pipe damage-state sampling model, between ALA with different threshold values, and a PGV-dependent rule

## Conclusions

This article presented a hydraulic model developed for the Drinking Water Distribution Network of a large conurbation in the central coast of Chile, considering the cities of Valparaíso, Viña del Mar and Concón. The model was calibrated with real data obtained from ESVAL, the private company that provides the drinking water distribution service to the conurbation; and implemented in EPANET. A seismic risk assessment was performed considering 50,000 scenarios of Peak Ground Velocity maps, generated with adequate models for the seismicity of the region. The effect of seismic damage was restricted to pipes only, to isolate the effect of their failure on the overall performance of the network and study its impact. Seismic damage was estimated using three Repair Rate models, and two pipe breaking probability models, by using a cascading sampling algorithm. Pipe seismic damage was incorporated in the hydraulic model by using emitters for the case of leakages; and with a modification of the network topology for the case of breakings, by interrupting the water flow through a broken pipe and modeling the water loss. A pressure-driven analysis was carried out in EPANET for the simulated scenarios and the Unsupplied Demand was computed for each one of them, to quantify the performance of the



DWDN. Results were combined in a risk curve that suggests that (i) the DWDN is robust due to its redundancy, since high return periods were obtained; (ii) the network collapses when around 20-30% of the pipes, in terms of length, are broken; (iii) the performance of the lifeline follows a nonlinear relationship with the total length of broken pipes and event magnitude; and (iv) only a small subset of the seismic scenarios cause major performance loss on the network, although the variability is rather important. A sensitivity analysis was performed to study the importance of modelling assumptions, such as the Repair Rate model considered, and the pipe breaking probability model used. It is concluded that the effect of both aspects may not be neglected, since they produce major variations in the risk curves. For instance, changing the selected RR model may change the highest obtain Unsupplied Demand value from 20% to 80%; while a variation in the pipe breaking probability in ALA's model may produce a similar change, from 50% to 100%. Moreover, using a PGV-dependent model for estimating the pipe breaking probability, instead of ALA's rule, may have a similar impact. Further research is needed to quantify the effect of modelling assumptions on the risk results, to better understand pipe criticality and its impact on the performance loss, and to identify which seismic events tend to produce more damage to the network, all of which will be addressed in a journal article currently under preparation.

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