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A FRAMEWORK FOR WATER DISTRIBUTION SYSTEM EXPOSED TO SEISMIC EVENTS AND EVOLVING CONDITIONS

J.Y. Lee¹, A. Tomar², and H.V. Burton³

ABSTRACT

A water distribution system is challenged by increasing risks and the associated uncertainties caused by dynamic changes in social, economic, urban, and environmental conditions during its service life. The stationary assumption of risks made in customary seismic modeling of water systems may not be appropriate for dealing with such evolving risks and challenges the resilience objectives of water systems and the community functions that they support. This paper presents dynamic seismic risk assessment of a water network incorporating increasing risks from dry climate over its lifetime. A case study shows that, as risks from dry climate accumulate over time, the annual expected cumulative loss of functionality increases and the overall post-disaster restoration curve varies with time. Moreover, dry climate scenario plays a significant role in system performance and post-disaster system resilience. Such increasing risks and the associated uncertainties require sequential reevaluation and adjustment of risk mitigation strategies and post-disaster recovery activities to maintain system serviceability and enhance seismic system resilience. Finally, this paper sheds a light on the potential benefit of using an adaptive decision-making in managing evolving risks to water systems and reducing uncertainties in that it allows flexible and responsive decisions over time.

¹Assistant Professor, Dept. of Civil & Environmental Engineering, Washington State University, Pullman, WA 99164 (email: jiyun.lee@wsu.edu)

²Graduate Student, Dept. of Civil & Environmental Engineering, University of California, Los Angeles, CA 90095

³Assistant Professor, Dept. of Civil & Environmental Engineering, University of California, Los Angeles, CA 90095



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A water distribution system is challenged by increasing risks and the associated uncertainties caused by dynamic changes in social, economic, urban, and environmental conditions during its service life. The stationary assumption of risks made in customary seismic modeling of water systems may not be appropriate for dealing with such evolving risks and challenges the resilience objectives of water systems and the community functions that they support. This paper presents dynamic seismic risk assessment of a water network incorporating increasing risks from dry climate over its lifetime. A case study shows that, as risks from dry climate accumulate over time, the annual expected cumulative loss of functionality increases and the overall post-disaster restoration curve varies with time. Moreover, dry climate scenario plays a significant role in system performance and post-disaster system resilience. Such increasing risks and the associated uncertainties require sequential reevaluation and adjustment of risk mitigation strategies and post-disaster recovery activities to maintain system serviceability and enhance seismic system resilience. Finally, this paper sheds a light on the potential benefit of using an adaptive decision-making in managing evolving risks to water systems and reducing uncertainties in that it allows flexible and responsive decisions over time.

Introduction

A water distribution system is crucial to community seismic resilience in that it supports daily household functions and commercial/industrial operations and prevent further damage and losses after seismic events (e.g. mitigating earthquake-related fires). Under normal and even disturbed conditions, a water distribution network is generally expected to service all sectors of the economy (e.g. housing, businesses). However, experiences with past earthquakes (e.g. 1971 San Fernando, 1994 Northridge, etc.) have highlighted the vulnerability of water distribution systems to major

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²Graduate Student, Dept. of Civil & Environmental Engineering, University of California, Los Angeles, CA 90095

³Assistant Professor, Dept. of Civil & Environmental Engineering, University of California, Los Angeles, CA 90095

seismic events [1]. Moreover, a water system is subjected to evolving conditions, which may require adjustments in risk mitigation strategies and/or emergency management plans, throughout its life-cycle. For example, deterioration due to aging and corrosion may cause mechanical or hydraulic failures of components and increases seismic vulnerability over time [2,3]. The number and type of future consumers are affected by city growth and population distribution over the area, and the projected required demands and pressure heads in the future are highly uncertain. Frequent changes in the physical layout (installation and removal of pipelines partly due to changes in demand/capacity) would substantially change the connectivity and redundancy of the network which are important measures of system resilience. Climate change may cause severe droughts or dry climate and affect significant sources of water for the region [4]. Despite significant role of changing conditions on the overall risk and resilience assessment of the system, most of customary seismic modeling and optimal decision methodologies for a water system have been developed based on the assumptions that risks are stationary over time. Thus, the incorporation of evolving conditions in life-cycle risk assessment is required to maintain the serviceability of a water system under these changing circumstances and enhance the seismic resilience of the community that it supports.

This paper investigates evolving conditions affecting a water distribution system, assesses its temporal seismic performance and risk, and suggests adaptive decision-making to enhance system's seismic resilience. The effect of evolving conditions on life-cycle performance assessment is illustrated with a simple water distribution network exposed to seismic events as well as the cumulative impact of dry climate. Coupled with well-developed seismic modeling of water distribution systems and hydraulic network model, sequential risk assessments incorporate diminished water sources due to dry climate (potentially caused by global climate change) based on three hypothetical dry climate scenarios. Finally, an adaptive decision methodology is suggested as a way of continuously reevaluating and adjusting risk mitigation and/or emergency management strategies by reducing the accumulated uncertainties over time.

Temporal Seismic Performance Assessment Incorporating Increasing Risks: A Water Distribution Network in Los Angeles, California

Earthquake has the potential for causing disruptions to water distribution systems and the community functions that they support. Failures of such systems result in significant economic losses and social disruptions in many densely populated urban areas around the world. Moreover, a water system distributed over large geographic area is continually subjected to changes in environmental and urban settings, increasing operational and social demands, limited resources, and structural deterioration during its lifetime. Such increasing risks combined with its geographic layout, interdependence and complexity will make decision methodologies even more complicated.

This section presents temporal seismic performance assessment of a water distribution network in Los Angeles, California, coupled with the cumulative impacts of dry climate on its performance. Dry climate and the associated diminished water resources have been one of the major concerns in California [5] and are selected as evolving risks to a water system in this case study. Time-variant seismic performance assessment combined with dry climate scenarios presented in this section will be used to support evolving decisions regarding risk mitigation and emergency management strategies.

Network Description

The hypothetical water distribution network is assumed to be located in Los Angeles, California. The network is modeled as a graph consisting of 9 demand nodes or junctions (J1 to J9), 2 pressure reducing valve nodes (VJ1 and VJ2), 14 pipelines (P1 to P14) and 2 valve links (V1 and V2) as shown in Fig. 1 [6]. Two reservoirs are represented as source or supply nodes (J10 and J11) in the graph. Both reservoirs have initial hydraulic grade line (HGL) elevations of 1300 m, which have been modified from the original network [6] to avoid negative pressures as dry climate effect accumulates over time. Demand requirements at each node along with nodal elevations are shown in Table 1. Length, diameter, and material for each link are given in Table 2.

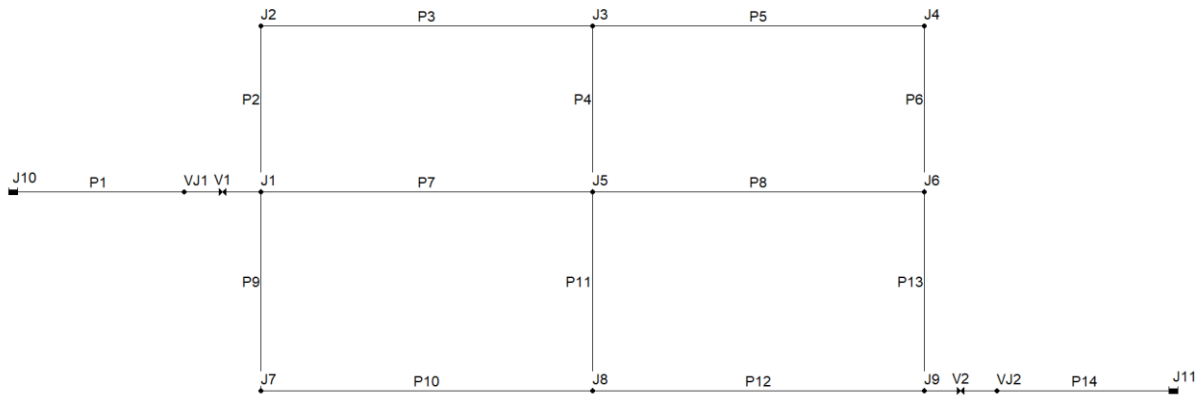


Figure 1. Topological structure of the hypothetical water distribution network.

Table 1. Demand requirements and elevations at nodes.

Node	Demand, L/min	Elevation, m
J1	2208.71	734.568
J2	2038.81	733.044
J3	1699.01	731.520
J4	2378.62	713.232
J5	1529.11	733.044
J6	2548.52	716.280
J7	2038.81	733.044
J8	1699.01	731.520
J9	2548.52	722.376
VJ1	0	734.568
VJ2	0	722.376

Hazard Scenarios

The hypothetical water network is assumed to be exposed to seismic hazards and dry climate during its lifetime, which are two major hazards in California. It is assumed that the water network is distributed in a small geographic area and experiences the same level of ground motion for a given earthquake scenario. Under this assumption, a site-specific seismic hazard curve has been developed for the location of Los Angeles City Hall (latitude: 34.053° N, longitude: 118.243° W) as

shown in Fig. 2 ($V_{S30} = 760$ m/s is assumed).

California has been experiencing extreme droughts and dry climate [5]. Although the driving force behind California's drought is still being debated, it is clear that increasing frequency and severity of extreme weather will affect significant sources of water for the region, and combined with the increase in population and agricultural industry, dry climate will aggravate California's ecosystems and regional economy. To the best of authors' knowledge, only a limited number of work has been done for assessing the effect of increasing risks from dry climate on life-cycle performance of a water distribution network.

Table 2. Link parameters.

Link	Length, m	Diameter, mm	Material
P1	457.20	400	CI
P2	304.80	250	DI
P3	609.60	100	DI
P4	304.80	150	DI
P5	609.60	100	AC
P6	304.80	250	AC
P7	609.60	400	DI
P8	609.60	100	AC
P9	365.76	200	STL
P10	609.60	100	STL
P11	365.76	100	STL
P12	609.60	100	PVC
P13	365.76	300	PVC
P14	457.20	300	CI
V1	-	400	-
V2	-	300	-

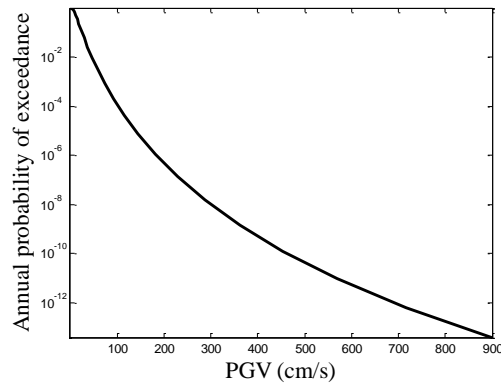


Figure 2. Seismic hazard curve for the site of interest.

There are several models to estimate future dry climate conditions. The Seasonal Autoregressive Integrated Moving-Average (SARIMA) model is widely used for generating nonstationary correlated values in a time series of temperature while explaining seasonal effects in data [7,8]. Or multi Global Climate Models (GCMs) provide forecast of dry climate conditions over larger geographic areas. Since the aim of this case study is to show the effects of dry climate

on the performance of a water system rather than accurately forecasting future climate, three simple dry climate scenarios are considered in the study as shown in Table 3: Scenario 1 considers only seismic effects on the network, Scenario 2 describes local dry climate effects on the projected amount of water supplied by J10, and Scenario 3 considers the temporal change in the amount of water at both supply nodes, J10 and J11. For Scenarios 2 and 3, dry climate has the cumulative impact on the performance of the water network during its lifetime (40 years assumed here) by reducing HGL elevations of source nodes by half. The HGL elevation at time t , $H(t)$, is:

$$H(t) = h_0 \cdot D(t) \quad (1)$$

where h_0 is the initial HGL elevation at the source node and $D(t)$ is the HGL decreasing function.

Table 3. Dry climate scenarios.

Scenario	Decreasing function
1	No dry climate. $D(t) = 1$
2	Only J10 will be affected by dry climate with $D(t) = 1 - 0.01t$
3	Both nodes (J10 and J11) will be affected by dry climate with $D(t) = 1 - 0.01t$

System Performance Measure

Over the past few decades, a considerable number of studies have attempted to define reliability and resilience of a water distribution system [9,10,11,12]. The reliability of a water system is generally defined as its ability to supply the demands at demand nodes above minimum pressure heads in a given period of time. In this context, the study defines system performance as the ratio of available water supply to the required water demand. For example, nodal serviceability metric is the demand satisfaction ratio at a given node while system serviceability index (SSI) is defined as the ratio of post-earthquake water supply to pre-earthquake demands in the system as follows:

$$SSI_j = \frac{\sum_{i=1}^n q_i}{\sum_{i=1}^n d_i} \quad (2)$$

where SSI_j is the system serviceability index for a given seismic hazard j , n is the number of demand nodes in the system, q_i is the actual water flow supplied to the user at node i under the j^{th} seismic hazard, and d_i is the water demand at node i . The relationship between q_i and d_i depends on the value of pressure head h_i at node i . The detailed information can be found in [13,14,15]. In this study, SSI is used to represent the extent of physical damage and flow conditions in the post-disaster restoration curves. It should be noted that SSI does not assess water quality or potability, which is another important concern in post-disaster community resilience.

Hydraulic Simulation

Network hydraulic analysis is performed using EPANET software based on the assumptions that 1) demand requirements are constant over time although there are substantial uncertainties in future demands and 2) aging of the system is not considered (i.e. roughness coefficients are

assumed constant). Aging combined with highly uncertain demand requirements may have significant impacts on system performance during normal and disturbed operations. To clearly show the effects of dry climate on seismic system performance, however, this study considers only cumulative impact of severe dry climate on HGL elevations of source nodes (as shown in Table 3) and one type of pipeline mechanical failure, pipe leak, caused by seismic events.

Two damage states of a pipeline are considered: 1) DS0: no damage and 2) DS1: major leak. In hydraulic simulation, major leak is modeled by creating a hole which has a diameter of 90% of pipe diameter. Leakage from pipe damage, d_{leak} , is modeled as [16]:

$$d_{leak} = C_d A p^\alpha \sqrt{\frac{2}{\rho}} \quad (3)$$

where C_d is the discharge coefficient, A is the area of the hole, p is the gauge pressure inside the pipe, α is set to 0.5 in the study, and ρ is the density of the fluid.

Pipeline repair rate (RR) is defined as the number of repairs per km [1] and modeled as a function of PGV as follows (suggested by American Lifelines Alliance 2001):

$$RR = K_I \cdot 0.002416 \cdot PGV \quad (4)$$

in which K_I is the modification factor used to adjust the fragility with respect to the backbone curve based on material, connection type, soil type and pipe diameter. The locations of seismic pipeline damage are modeled as a Poisson process with a mean rate of RR. Discrete event simulation is used to model repairs of damaged pipelines following the earthquake based on the assumptions that a pipeline is repaired within 2 days and only one repair crew is involved in the recovery activities.

Results and Discussion

A 40-year time horizon is considered in the study. Seismic system performance is evaluated at every 10-year interval from the beginning of the considered duration to quantitatively assess temporal variations in risks to the water distribution network and estimate post-disaster restoration trajectories under the combined effects of earthquakes and dry climate. Fig. 3 shows the effect of dry climate scenarios on the annual expected cumulative loss in serviceability. Cumulative loss of serviceability is measured as the area above the post-disaster restoration curve (such as Fig. 4). All possible earthquake scenarios and the associated probabilities of occurrence are considered to obtain the annual expected cumulative loss of serviceability at each time interval. The stationary assumption of structural load used in customary seismic modeling of water distribution systems can be justified if earthquakes are the only hazard in the site of interest. Thus, the conditional failure rate or hazard function of each component in the network is constant, and consequently, seismic system performance (represented as the annual expected cumulative loss of serviceability) also becomes constant over time as shown in Dry Climate Scenario 1 in Fig. 3. The stationary seismic modeling may not be appropriate for the water system continually challenged by dry climate over its lifetime. In this case, risk increases over time due to the reduced capacity of the network and seismic system serviceability decreases with time as shown in Dry Climate Scenarios 2 and 3 in Fig. 3. It should be noted that continuously accumulated risks from dry climate accelerate the rate of increase in the annual expected cumulative loss of serviceability. Thus,

reduced capacity of the system should be captured in the system’s fragility curve to enhance customary risk assessment and loss estimation tools. Moreover, future performance estimation of the water network considerably depends on dry climate scenarios: the annual expected cumulative loss of serviceability at 40 years increases tenfold as severer dry climate is assumed. It highlights the importance of better models to accurately forecast dry climate in the future.

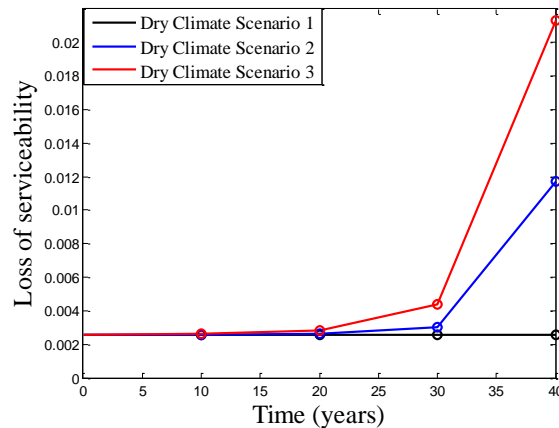


Figure 3. Annual expected cumulative loss of serviceability for three dry climate scenarios at each time interval.

Dry climate poses another challenge to customary decision methodologies aimed at ensuring the adequate functionality of water systems in that diminished water sources will lead to an additional topology optimization to what is already a multi-objective optimization problem. Conventional decision-making for aging or damaged water systems induced by aggressive service or environmental conditions has focused on the selection of pipe sizes or pipelines to be repaired that maximizes the benefits resulting from the changes to the network in a pre-defined network topology. If one or more water sources may gradually lose its capacity to supply water to the system, however, the entire layout of the network should be rearranged to be supplied by other sources, which may induce flow redistribution. As such, network topology should be optimized along with conventional multi-objective optimization when a water system is affected by dry climate and seismic hazards.

The restoration curves for the water distribution network at a given PGV of 91.92 cm/s, corresponding to three dry climate scenarios described in Table 3, are illustrated in Fig. 4. System performance or functionality is represented by System Serviceability Index (SSI) in the figure. Dry climate scenario plays a significant role on post-disaster system resilience and affects both the initial loss of serviceability and the overall system restoration as shown in Fig. 4. As described previously, the restoration curve under only seismic effects (Scenario 1) is independent of hazard occurrence time due to constant conditional failure rate of each component over time. On the other hand, the initial loss of serviceability as well as the overall restoration path for Scenarios 2 and 3 vary with the time of occurrence because cumulative dry climate impact on water capacity increases the risks to the water system with time. For example, the initial loss of serviceability for Scenario 3 is 0.7 at 40 years from the beginning of the considered duration while the initial loss is 0.3 at the beginning. Moreover, considering that the same amounts of utility resources are available for all scenarios, longer restoration time is expected for the water system exposed to severer dry climate. It implies that the continued accumulation of risk from dry climate may require

adjustments in emergency management plans and post-disaster recovery activities to achieve system resilience goals.

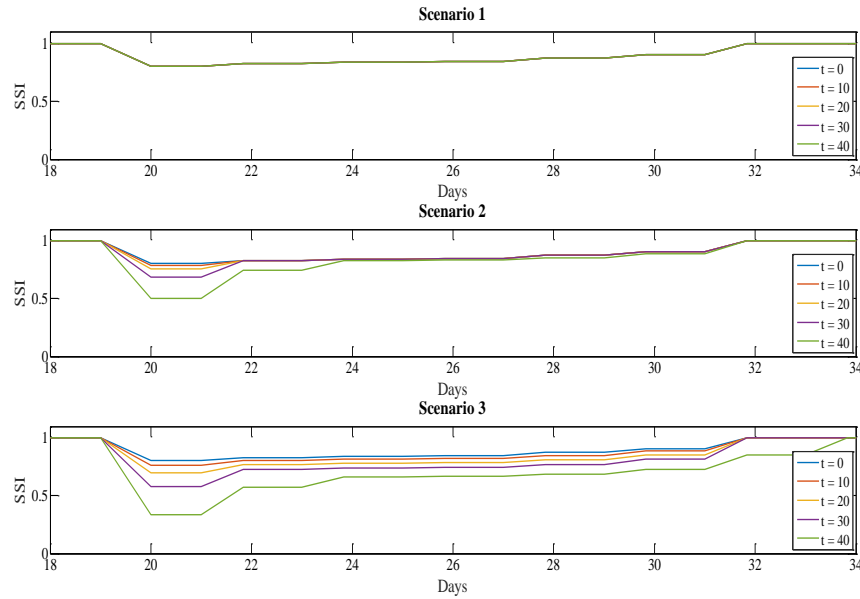


Figure 4. Restoration curves for the water distribution network under three dry climate scenarios (at a given PGV of 91.92 cm/s).

Adaptive Decision-Making for Water Distribution Systems Exposed to Evolving Conditions

In addition to increasing risks from dry climate as described in the previous section, a water distribution system is continually challenged by aging and structural deterioration, increasing customer demands, shifts in social and political preferences, and tightening budgets over its lifetime. The overall quality of life-cycle engineering decision-making for a water system depends on stochastic models of these time-evolving conditions. Due to substantial inherent uncertainties and an incomplete knowledge base, however, such changing conditions and their effects on life-cycle performance of a water system cannot be accurately predicted, even when the state-of-the-art modeling is employed. For example, in the previous section, deterministic dry climate scenarios have significant impacts on temporal evolution of system performance and the incorporation of uncertainty in climate modeling will make it even more difficult to predict life-cycle performance of the system. Moreover, models that clearly show the relationship between life-cycle evolutions (particularly changes in social and political circumstances) and system performance have yet to be explored in any depth. One reasonable way to handle such evolving conditions and to reduce the associated uncertainties is providing some flexibility in methods for future decision-makers to make decisions when more information or updated modeling becomes available.

Adaptive decision-making is a structured process that enables systematic and efficient learning, aimed at reducing uncertainties over the course of the management timeframe. As shown in Fig. 5, it provides an iterative process of planning, implementing, monitoring, evaluating, and adjusting strategy [17]. At the time of any decision, only limited information and knowledge are available to understand and characterize the projections of evolving conditions. The initial risk estimates often deviate from the actual future risks because uncertainties can lead to significant

inconsistencies between predicted and observed risks. Consequently, the results from conventional decision-making may underestimate future risks and the associated consequences. Adaptive decision-making holds great potential for dealing with such challenges by incorporating lessons learned into future decisions through explicit mechanisms for linking new information from monitoring to the decision. For example, monitoring results can be used to update unknown parameters of predictive models, system response to management actions, or unknown state of nature. In this context, adaptive decision-making is a useful tool to explicitly recognize evolving risks, continuously reevaluate the risks, and improve decisions through learning sequentially over time.

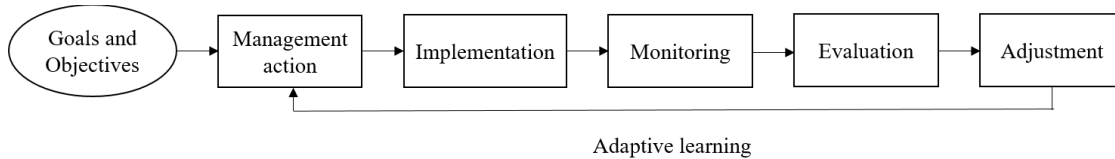


Figure 5. Adaptive management process.

While important and promising, its application to civil infrastructure is still limited. To reduce uncertainty and deal with the continued accumulation of knowledge, sequential Bayesian updating can be utilized in adaptive decision-making processes. Or, as Linkov et al. [18] recommended, adaptive management can be integrated with multi-criteria decision analysis, because two methods complement each other providing a more comprehensive decision framework. A structured, rational, transparent adaptive decision-making might be able to better estimate life-cycle system performance in response to changing conditions and to provide management strategies being more responsive to such evolution by achieving its resilience objective.

Conclusions

A water distribution system faces major challenges arising from increasing risks and the associated uncertainties caused by dynamic changes in social, economic, urban, and environmental conditions during its service life. For the purpose of relaxing the stationary assumptions in customary risk assessment and improving decisions in response to evolving risks, this study has investigated dynamic seismic risk assessment combined with the effects of increasing dry climate by considering a water distribution network located in Los Angeles, California as a case study. Three simple dry climate scenarios have been assumed to test the impact of evolving conditions on system performance. Dry climate has continually accumulated risks to the water system, leading to gradual decrease in system serviceability over time. The shape and extent of increase in the annual expected cumulative loss of serviceability are highly dependent on dry climate scenarios. Moreover, the accumulated risks from dry climate play a significant role in determining the post-disaster restoration curves of the water system. Thus, seismic risk assessment of water distribution systems should be coupled with the assessment of such evolving risks to improve short-term disaster recovery activities as well as mid- and long-term system resilience in a life-cycle context.

This study has assumed deterministic dry climate scenarios to show the role of evolving risks in performance prediction. It will be increasingly difficult to achieve reliable forecasts of system behavior if uncertainties are considered in all stages of life-cycle performance analysis. Adaptive decision-making is introduced as a tool to reduce such uncertainties and to enhance

system's adaptive capacity to future changing conditions far beyond the limits for which there is practical experience. It allows continuous adjustments in risk mitigation strategy and post-disaster recovery plan as knowledge and experience are gathered in an iterative learning process. Future research on adaptable, learning-based decision methodologies for water distribution systems combined with dynamic risk assessment will allow system managers to improve the quality of decisions in the face of uncertainties and limited resources and enhance system resilience in the long-term.

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