# Multi-Hazard Risk Assessments of Water Systems, Elements In Common with Seismic, Security, and Other Risk Studies

Donald Ballantyne[1]


## ABSTRACT

This risk assessment methodology is used to screen mutli-hazard risks for water systems. Multi-hazard risk assessment is becoming more popular as utilities try to balance the risk across multiple hazards. The Federal Government has instituted the Disaster Mitigation Act of 2000 (DMA 2000) that requires to public agencies to conduct multi-hazard assessments if they are to receive future hazard mitigation grant funding. The DMA 2000 methodology employs a similar analytical approach as that developed for water system assessment. . The methodology also has many common components with the Risk Assessment Methodology for Water (RAM-W$^{SM}$) required for evaluation of he security risk to water utilities.

The methodology uses a basic risk equation and quantifies value ranges for each term – hazard, vulnerability, consequences, and correlation factor. The terms are multiplied together resulting in a number representing the risk from a given hazard. Hazard risk is ranked for all hazards and/or for each facility within the system. The ranking can be used to select hazards for further more detailed analysis.

More detailed evaluations can be conducted using fault tree analyses and/or hydraulic network analyses. Benefit/cost analyses are used to justify mitigation measures.


## INTRODUCTION

This paper presents the risk assessment methodology used to screen hazard risk for water systems. The methodology was developed and refined over five multi-hazard risk assessment projects of water systems in the United States and Canada. The evaluated systems range in size from those serving 50,000 to over one million people.

There is increasing attention paid to evaluating risk from an all-hazards perspective. Owners are subjected to risks from multiple hazards, and are interested in mitigating them using a balanced approach. Mitigation alternatives can be developed that can be used to address multiple hazards. Many components of the analysis are common and can be applied at a small additional cost compared to analysis for one hazard.

The United States Congress passed the Disaster Mitigation Act in 2000 (DMA 2000). This law requires public sector organizations to prepare multi-hazard mitigation plans in order to be eligible for future hazard mitigation grant funding from the Federal Government. The same general approach applied to the water systems is required, to comply with DMA 2000. One of the more recent multi-

1 Donald Ballantyne PE, VP Lifeline Services, ABS Consulting (formerly EQE International), Seattle, WA dballantyne@absconsulting.com

hazard risk assessment projects referenced in this paper conducted the evaluation in accordance with the Federal requirements.

Following the September 11, 2001 strike on the World Trade Center, the Environmental Protection Agency was given the responsibility to develop a program to protect the nation's water supply against terrorist attacks. The Risk Assessment Methodology for Water (RAM-W$^{SM}$) used a methodology with the same elements used in the previous water system risk assessment studies.

## RISK EQUATION FORMULATION

Risk can be calculated as:

*Risk = Hazard x Vulnerability x Consequence x Correlation Factor*

Where:

> *Hazard* is the probability of exceedance of a given intensity over a given time period
>
> *Vulnerability* is the probability that the given facility will fail when subjected to the given hazard intensity.
>
> *Consequence* is a measure of loss in terms of dollars, loss of life, or other comparable parameters.
>
> *Correlation Factor* is a measure of the likelihood that the hazard will impact multiple facilities in a single event.

The hazard is often defined as probability of the given intensity being exceeded within the facilities expected 50 year life. A 50 year life is taken as being representative of civil engineering facilities where mechanical equipment may have a 20 year life, buildings a 50 year life, and buried pipelines a 100-year life. A probability of 50 percent in 50 years represents a 72-year return period, and a probability of 10 percent in 50 years represents a 475-year return period, the basis of many building codes. For system failures would result in catastrophic consequences such as dam failure, the probabilities of exceedance would be increased to for example having a return period of 10,000 years.

Vulnerability can be considered using fragility curves, that relate the hazard intensity parameter (ground motion) to the probability of failure. The stronger ground motion, the higher the probability of failure.

Consequence can be quantified using various parameters such as economic impact in dollars, or in catastrophic hazard events, loss of life. Lifeline systems are sometimes described as interconnected facilities (networks) of facilities (nodes) with pipelines or wires making up the network links. Analysis of these systems can become very complex. Simplified methods considering the consequence of failure have been used to take into account the importance (criticality) of each facility within the system. Consequence parameters representing dollar losses are sometimes put in terms of percent of system outage times outage duration. The consequence units can be "customer outage days" that can then be converted to dollars. The consequence term takes into account system redundancy. System facilities that are redundant may have a low consequence of failure.

A correlation factor has not typically been used in earthquake analysis of lifeline systems within a limited area because there is a high probability that all of the facilities would be exposed to the hazard all at one time. In this situation, the correlation factor would approach 100 percent. For lifeline systems covering a larger area such a regional power systems, the correlation factor may be smaller as many of the facilities would be outside the earthquake impact area.

This approach has the advantage that the numerical basis and relative magnitude of each term compared to each other term is correct. That is for example, probabilities and percentage of service areas served are combined using the correct units so the results approach realistic values of risk. Other approaches employing high/medium/low values without a numerical basis only provide approximations of the relative risk.

More detailed analyses using fault tree analysis or hydraulic network modeling can be used provide more thorough evaluation of the systems once the hazard screening focuses the effort.

## PROJECT/UTILITY BACKGROUNDS

The general multi-hazard risk assessment methodology has been applied to five water systems, two of which are described below. The other situations are generally described without providing specific system information.

The Portland water system provides retail water service to the City of Portland, Oregon and wholesale water to a number of suburban utilities. The primary source is the Bull Run surface supply (BRS), with a secondary groundwater supply (GWS) from a well field just south of the Columbia River. The Bull Run supply consists of dams, chlorination/treatment facilities, and three parallel conduits in different corridors, each with bridges and trestles. Segments of the conduit system are vulnerable to landslides. The groundwater supply includes wells, a collection piping system, and a major pump station and provides almost 100 percent redundancy with the BRS at winter flow demands. The GWS facilities and Willamette River crossings are particularly vulnerable to liquefaction. Refer to Figures 1 and 2.

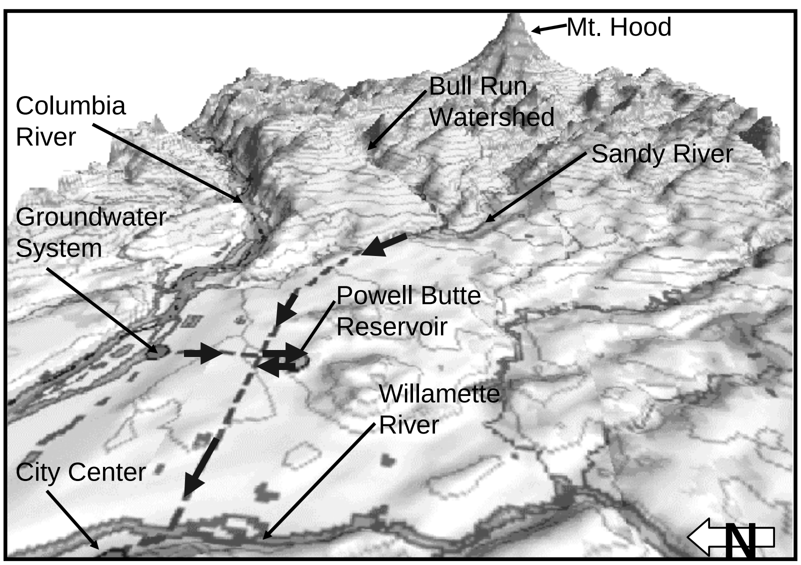


***Figure 1. Portland water system geographic overview***

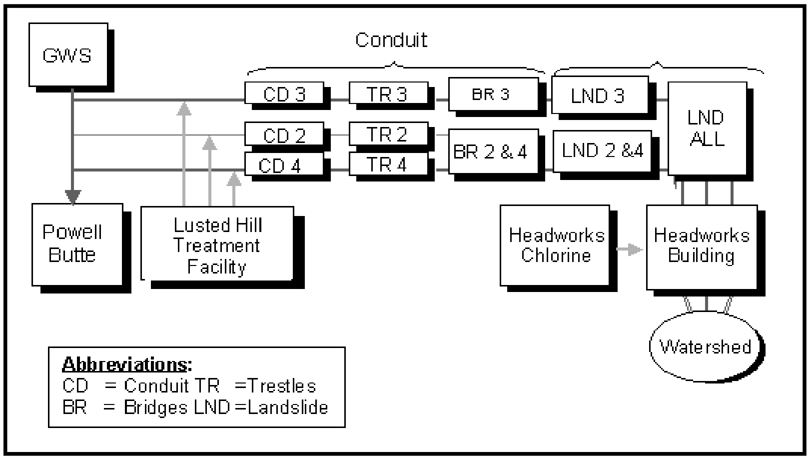


***Figure 2. Portland Oregon supply system schematic.***

Portland is in a region with moderate seismicity, and had evaluated the earthquake vulnerability of a number of their critical facilities. They were ready to proceed with mitigation projects when in the winter of 1995-96, they nearly lost service to at least some customers as a result of a series of storms causing landslides, increased turbidity, and flooding. As a result, they decided to conduct a multi-hazard assessment of the overall system.

The Greater Vancouver Regional District (GVRD) is located in British Columbia, Canada. Their supply comes from three lakes that independently feed south into the distribution system (Figure 3). The pipelines crossing the Burrard Inlet and the Frazier River are vulnerable to liquefaction.

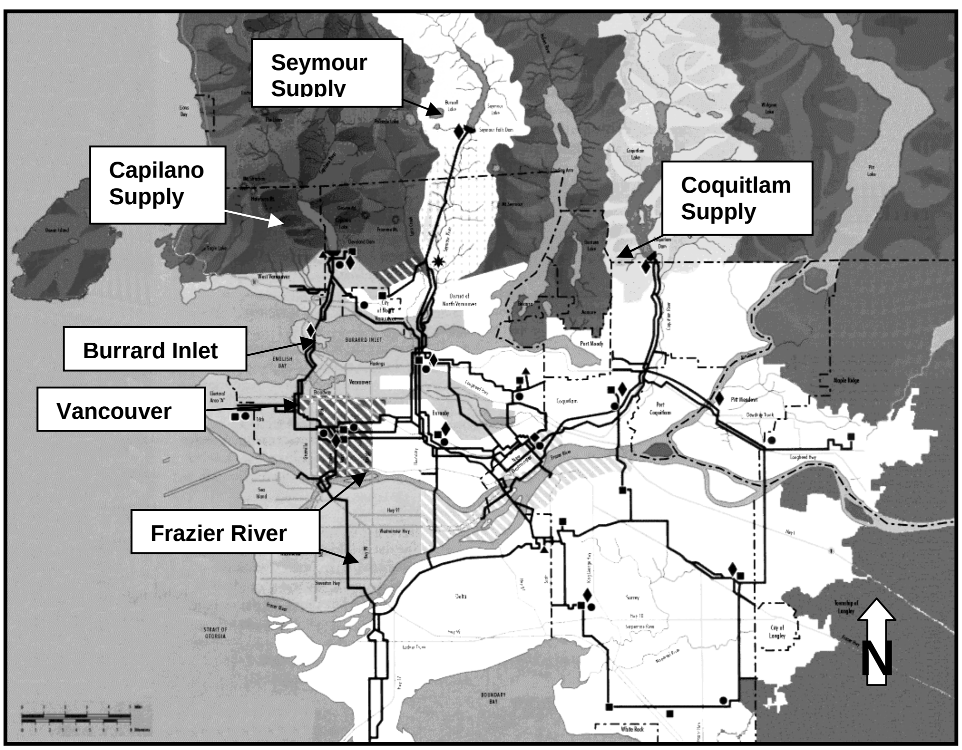


***Figure 3. Greater Vancouver Regional District water supply.***

In 1993, the GVRD conducted an earthquake vulnerability assessment. In 2000, the GVRD evaluated the status of implementation of the 1993 report recommendations, and conducted a multi-hazard assessment of the system driven in part by flooding and other regional hazard events.

In 2002, a water utility serving a suburban Portland, Oregon community elected to conduct a multi-hazard assessment (including a detailed seismic evaluation) in parallel with a security vulnerability assessment. The system has a single primary supply but has interties that would allow it to operate should it's main supply be disrupted. For this project, many of the evaluation elements were common between the multi-hazard and security risk assessment. The resulting recommendations were able to integrate and prioritize the results across hazards.

A suburban Seattle, Washington water utility integrated a multi-hazard risk assessment, a security risk assessment, and seismic upgrade project. The utility is highly dependent of the Seattle Public Utility supply. The multi-hazard assessment was conducted in accordance with the DMA-2000 regulations. The consequence analysis developed in the security vulnerability assessment was integrated into the multi-hazard assessment so that both studies had a common basis.

The fifth system where the methodology is applied provides wholesale water to water utilities in a densely populated region of Northern California. The system has multiple supplies and multiple treatment facilities. It is subjected to earthquakes, flooding, and other hazards common to utilities across the United States.

## HAZARD IDENTIFICATION AND QUANTIFICATION

In each of the five projects, the first step was to identify and quantify hazards. A list of the hazards considered for the Portland project is shown in Table 1. Hazards are identified and quantified through a literature search, discussions with regional emergency management personnel, and discussions with utility personnel. The probability of occurrence of a hazard event is taken for one that will produce an intensity that will cause failure of at least one significant water system component.

***Table 1. Hazards Screened***

| **Hazard Category/Type** | **Hazard Category/Type** | **Hazard Category/Type** |
|---|---|---|
| ***Natural*** | ***Human/Technological*** | ***Transportation*** |
| River Flooding, Dike Failure | Staff Unavailable (Public Health, Labor Dispute) | Airplane |
| Snow Melt/Rain on Snow | Intentional Act | Airplane Fuel Dump |
| Land/Rock Slides/Debris Flow | Bureau Building Piping Failure/Flood | Truck/Car Structural Impact |
| Tree Fall | Bureau Building/Facility Fire/Explosion | Marine River Crossing |
| Winter Snow/Ice Storms | Chemical Release | Light Rail |
| Prolonged Freezing | Computer Disruption | ***Lifeline Service Loss*** |
| Earthquake | Groundwater Contamination | Electrical |
| Seiche | Dams Failure | Wire Communications |
| Volcanic Activity | Mechanical Failure | Wireless Communications |
| Fire in Watershed | Third-Party Damage | Sewer |
| Urban Firestorms | Operational Error | Natural Gas/Propane |
| Turbidity | | Liquid Fuel |
| Microbial Contamination | | Treatment Chemical Supply/Delivery |

The probability of occurrence can be estimated to be in one of three categories as for example:

- High Probability **-** Damaging intensity to occur in less than 50 years (mid point of 25 years). The probability of occurrence in 50 years is 100 percent.

- Moderate Probability – Damaging intensity to occur once every 50 to 250 years (mid point 72 years). The probability of occurrence in 50 years is 50 percent.

- Low Probability – Damaging intensity to occur once every 250 to 1,000 years (mid point 475 years). The probability of occurrence in 50 years is 10 percent.

Hazards with recurrence intervals greater than 1,000 years are beyond the planning horizon for each of the five projects.

**VULNERABILITY ASSESSMENT**

Once the hazard intensity is established, a representative scenario event that could produce the hazard intensity is "applied" to each system facility, and the probability of failure determined. For each hazard (other than an intentional act (security), the vulnerability can categorized to be in one of three groups as for example:

- High Vulnerability – likely, greater than 50% probability (mid point 70%), to result in loss of service for extended period when subjected to associated hazard intensity.

- Moderately Vulnerability – possibly, 10 % to 50% probability (mid point 25%), result in loss of service for extended period when subjected to hazard intensity.

- Low Vulnerability – unlikely, less than 10 % probability (mid point 7%) to result in loss of service for extended period when subjected to hazard intensity.

**CONSEQUENCE ANALYSIS**

The consequences of failure of the facilities are also categorized into one of four groups:

- Very High Consequences **-** result in loss of service to entire system (100%). This could occur if all water sources became unavailable or something occurred in the transmission system that would make it entirely inoperable. No VH consequences were identified any of the systems due to system redundancy.

- High Consequence – result in loss of service to a significant part of system (30% to 50%, depending on the proportion of customers affected). This could occur if there were failures distribution lines or failure of a key pump station that resulted in loss of service to a significant area of the system.

- Moderate Consequence – result in loss of service to localized area within service area (10%). This could occur for example as the result of failure of one pump station.

- Low Consequence – would not result in loss of service but may require aggressive response actions to maintain service. 1% loss of service used for analysis.

## CORRELATION OF HAZARDS

The correlation of hazards is applicable to losses that could also cause the unavailability of system interties  A factor of 1 indicates no correlation, that is to say, the hazard in question would not be expected to affect the availability of system interties. Other correlation factors are 5 (low correlation), 25 (moderate correlation), and 75 (high correlation). For example, flood event could be expected to impact multiple watersheds (depending on the regional topography). Such impacts may cause the system interties to be unavailable, and thus a high correlation factor was used.

## HAZARD RISK TABLE EXAMPLE

Table 2 combines the hazard, vulnerability consequences, and correlation factor in a table format.

***Table 2, Example Hazard Risk Table***

| HAZARD | | | |
|---|---|---|---|
| Rank | Probability Occurrence in 50 years | Return (years) | Range |
| H | 100% | 25 | 0 - 50 years |
| M | 50% | 72 | 50 - 250 years |
| L | 10% | 475 | > 250 years |
| **VULNERABILITY** | | | |
| | Probability of Failure | | |
| H | 70% | Likely | >50% |
| M | 25% | Possibly | 10 - 50% |
| L | 7% | Unlikely | < 10% |
| **CONSEQUENCES** | | | |
| | System Impact | | |
| VH | 100% | Entire system | |
| H | 40% | 1 or 2 pressure zones | |
| M | 10% | Limited area | |
| L | 1% | No outage | |
| **CORRELATION** | | | |
| VH | 75 | Very high correlation | |
| H | 25 | High correlation | |
| M | 5 | Moderate correlation | |
| L | 1 | No correlation | |

| SYSTEM VULNERABILITY | | *SECURITY* | | NATURAL H | |
|---|---|---|---|---|---|
| SYSTEM / COMPONENT | Consequence of Failure (% people without water) | Security | | Floods | |
| Hazard Probability (% in 50 years) | | 50% | | 50% | |
| Correlation Factor (See note 1) | | 1 | | 75 | |
| ***North Side*** | | | | | |
| Watershed | 1% | 70% | 0% | 7% | 3% |
| Intake Structure | 1% | 70% | 0% | 7% | 3% |
| Lowlift Pump Station | 1% | 70% | 0% | 70% | 26% |
| Treatment Plant | 1% | 70% | 0% | 7% | 3% |

## HAZARD RISK ANALYSIS RESULTS

After each facility and its corresponding consequence of failure, is evaluated for each hazard and its corresponding probability of occurrence, the results can be sorted by hazard (Table 3) or facility (Table 4). The "Average" risk shown in the tables is the average for each facility "exposed" to the hazard. For example, a facility not located in a flood plain would not be exposed to flood. The "Maximum" risk is for the facility with the highest risk for the selected hazard (Table 3), or the hazard that presents the highest risk to the selected facility (Table 4). The results of the analysis are used to prioritize more detailed analysis and/or mitigation.

***Table 3, Hazards Ranked by Risk Levels***

| Hazard | Average | Maximum | Risk |
|---|---|---|---|
| Floods - | 3.6% | 26.3% | VH |
| Earthquake | 3.1% | 18.8% | VH |
| Security (malevolent act) | 1.9% | 10.5% | VH |

| Hazard | Average | Maximum | Risk |
|---|---|---|---|
| Building / Facility Fire / Explosion | 1.3% | 7.5% | H |
| Winter Snow / Ice Storms | 1.0% | 7.5% | H |
| Land / Rock Slides / Debris Flow | 2.5% | 6.3% | H |
| Microbial Contamination | 3.8% | 3.8% | M |
| Urban Firestorms | 1.1% | 3.8% | M |
| Building Piping Failure / Flood | 0.7% | 3.8% | M |
| Treatment Chemical Supply / Delivery | 0.7% | 2.6% | L |
| Truck / Car Structural Impact | 1.0% | 2.1% | L |
| Mechanical Failure | 0.5% | 2.1% | L |
| Operational Error | 0.4% | 2.1% | L |
| Electrical | 0.4% | 2.1% | L |
| Tree Fall | 0.4% | 2.1% | L |
| Third-party Damage | 1.1% | 1.1% | L |
| Natural Gas / Propane | 0.2% | 0.4% | L |
| Liquid Fuel | 0.1% | 0.4% | L |
| Turbidity | 0.4% | 0.4% | L |
| Prolonged Freezing | 0.3% | 0.3% | L |
| Volcanic Activity | 0.0% | 0.2% | L |
| Chemical Release | 0.1% | 0.1% | L |
| Wire Communications | 0.1% | 0.1% | L |
| Sewer | 0.1% | 0.1% | L |
| Fire in Watershed | 0.1% | 0.1% | L |
| Staff Unavailable | 0.1% | 0.1% | L |
| Airplane Crash | 0.0% | 0.0% | L |
| Airplane Fuel Dump | 0.0% | 0.0% | L |
| Wireless Communications | 0.0% | 0.0% | L |

***Table 4, Facilities Ranked by Hazard Risk Levels***

| Facility | Average | Maximum | Risk |
|---|---|---|---|
| Lowlift Pump Station | 3.7% | 26.3% | VH |
| Treatment Plant | 2.0% | 18.8% | VH |
| Reservoir A | 6.5% | 18.8% | VH |
| Reservoir B | 6.5% | 18.8% | VH |
| Distribution System | 5.0% | 10.5% | VH |
| Highlift / Clearwell | 1.4% | 9.4% | H |
| Watershed | 0.7% | 2.6% | L |
| Intake Structure | 1.8% | 2.6% | L |
| Disinfection System | 0.7% | 2.6% | L |
| Pump Station 1 | 0.5% | 2.6% | L |
| Pump Station 2 | 0.5% | 2.6% | L |
| Computer System | 0.1% | 0.4% | L |
| SCADA System | 0.1% | 0.4% | L |
| Administration Building | 0.1% | 0.4% | L |
| Operations Office | 0.1% | 0.4% | L |
| Operations Shop | 0.1% | 0.4% | L |

## APPLICATION TO SECURITY VULNERABILITY ASSESSMENTS OF LIFELINE SYSTEMS

September 11, 2001 changed the world we live in. The Environmental Protection Agency was given the responsibility to develop a plan to protect our nations drinking water supplies from terrorists. Working with the American Water Works Research Foundation and Sandia National Laboratories, a

Risk Assessment Methodology for Water (RAM-W$^{SM}$) was developed to evaluate the security risk of water systems.

The risk equation formulation is the same as we have been using for earthquake risk assessments of water systems. The only difference was that there was no detailed information on the hazard. The RAM-W$^{SM}$ approach set the hazard probability at "1". The associated hazard intensity is taken to be the "design basis threat", a threat that the owner would like to design to resist. For example, the design basis threat might be defined to be three people with hand tools, small explosives, hand guns, and a motor vehicle. Defining this threat keeps the evaluator on track, and keeps them from considering for example a "weapon of mass destruction". This approach is directly comparable to using the "design basis earthquake."

The vulnerability parameter was estimated using the same general approach, with a given hazard, what is the probability that the attackers will be successful.  The consequence analysis is exactly the same as that used for the earthquake and multi-hazard analysis. The correlation factor is applicable as well. The correlation factor is low because there is a very low probability that a terrorist cell would attack more than one or two system facilities at any one time.

## FAULT TREE ANALYSIS

For the Portland system, the system reliability was evaluated for the two highest-risk hazards, earthquake and intense rain. Based on Figure 2, a logical model was built connecting the components by two possible means: "OR" or "AND" gates. This logical model assumes that all components are independent of each other. The term reliability is used for the probability that a component, subsystem or system to be functional.

An "OR" gate indicates that a component is functional if at least one of the connecting components is functional. For example, water to Powell Butte Reservoir is supplied if either the GWS "OR" the Bull Run supply is functional. Assuming that these events are independent, the only case when the reservoir does not receive water is when both supplies are nonfunctional. A system formed by "OR" gates is known as a parallel system. If we define PGWS and PBRS as the probabilities that the GWS and Bull Run supplies are functional, then the probability of supplying water to Powell Butte Reservoir, PPBR, is (Devore, J, 1995):

$$P_{PBR} = 1 - [(1 - P_{GWS})(1 - P_{BRS})] \quad (2)$$

It should be noted that (1 - PGWS) and (1 - PBRS) are the probabilities of the GWS and BRS of not being functional.

"AND" gates indicate that the top component is functional if all of the sub-components are functional. Assume that the BRS subsystem from Figure 2 is only formed by the watershed and headworks chlorine. These two components need to both be functional in order for the BRS to be functional. Failure of any of these components will cause failure of the entire Bull Run supply. These components are said to be in series and the reliability of a system PS with m independent components with functional probabilities Pi, i = 1, …, m is (Devore, J, 1995):

$$P_S = \prod_{i=1}^{m} P_i \quad (3)$$

Equation 3 shows that (1) failure of any component causes the system to fail, and (2) system reliability is smaller than any individual reliability. For example, if three components in series each have a 90 percent reliability, the "system" (probability of all three components remaining function is only 73 percent (0.90 x 0.90 x 0.90).

Based on these characteristics of series and parallel systems, a connectivity analysis of the Portland supply system was performed by assembling all of the components from the GWS and BRS. Some of the components in these subsystems are made of sub-components.

Subsets of the system shown in Figure 2 were evaluated to consider different system capacities (e.g. with different combinations of the three conduits). The results of the reliabilities of each of those configurations were combined for earthquake with the outcome displayed in Figure 4 showing flow versus probability of supplying at least "x" flow. Figure 4 also shows the performance goals set by Portland for 100-year-return, and 500-year-return earthquakes. The existing system met the performance goals for the 100-year event, but mitigation was required to meet the 500-year performance goal.

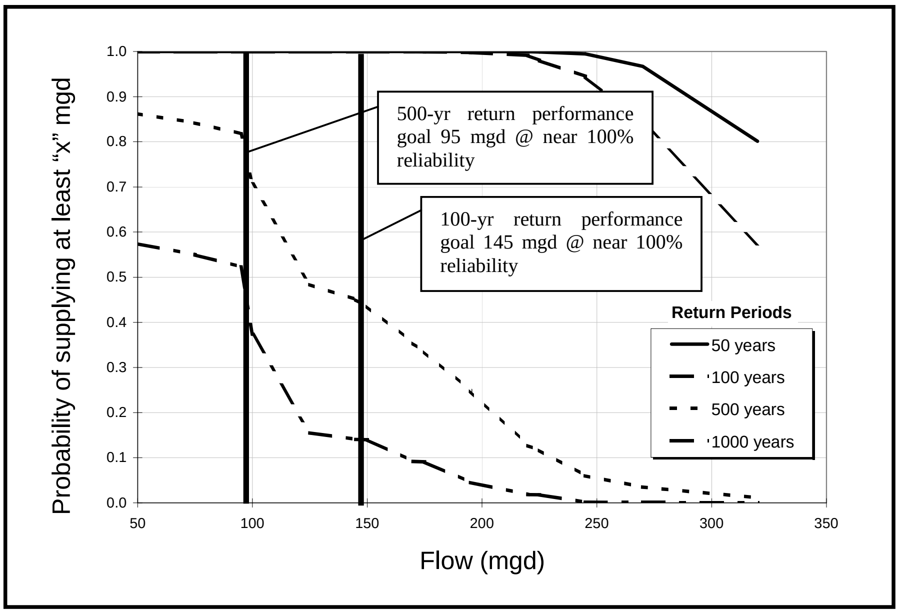


*Figure 4. Earthquake reliability of the Portland Water Supply System.*

The results of this assessment were used to select the combinations of mitigation measures that would provide the best reliability. For example, it became clear that Portland should focus mitigation on one subsystem (e.g., one conduit/corridor including bridges, trestles, and pipeline) rather than on a reduced level of mitigation for multiple subsystems (e.g., one bridge on each conduit/corridor).

## HYDRAULIC ANALYSIS OF DAMAGED SYSTEM

The third evaluation methodology to be employed was the use of a hydraulic network analysis program to analyze the system in the undamaged state and the post-earthquake damaged state. HAZUS 99 incorporates both the hydraulic network analysis and water system component earthquake loss estimation modules required to perform this analysis. Analysis software has only been developed for earthquake hazards as earthquakes tend to damage many system components during one event whereas other hazards tend to damage only one component during any single event. A schematic of the methodology is shown in Figure 5.

The results of distribution analysis show the expected reliability of the overall system following a given earthquake scenario. Specifically, the damage state of each system component and pipeline segment are calculated in accordance with the fragility relationships in the software). The hydraulic analysis then determines the reliability of the system to move water from point "A" to point "B" comparing pre- and post-earthquake conditions. The importance of each pipeline segment is shown in terms of the flow through the pipe compared to flow in other pipes. This information is then used to compare the expected system performance, to performance goals, and to prioritize system improvements to effectively reach those goals.

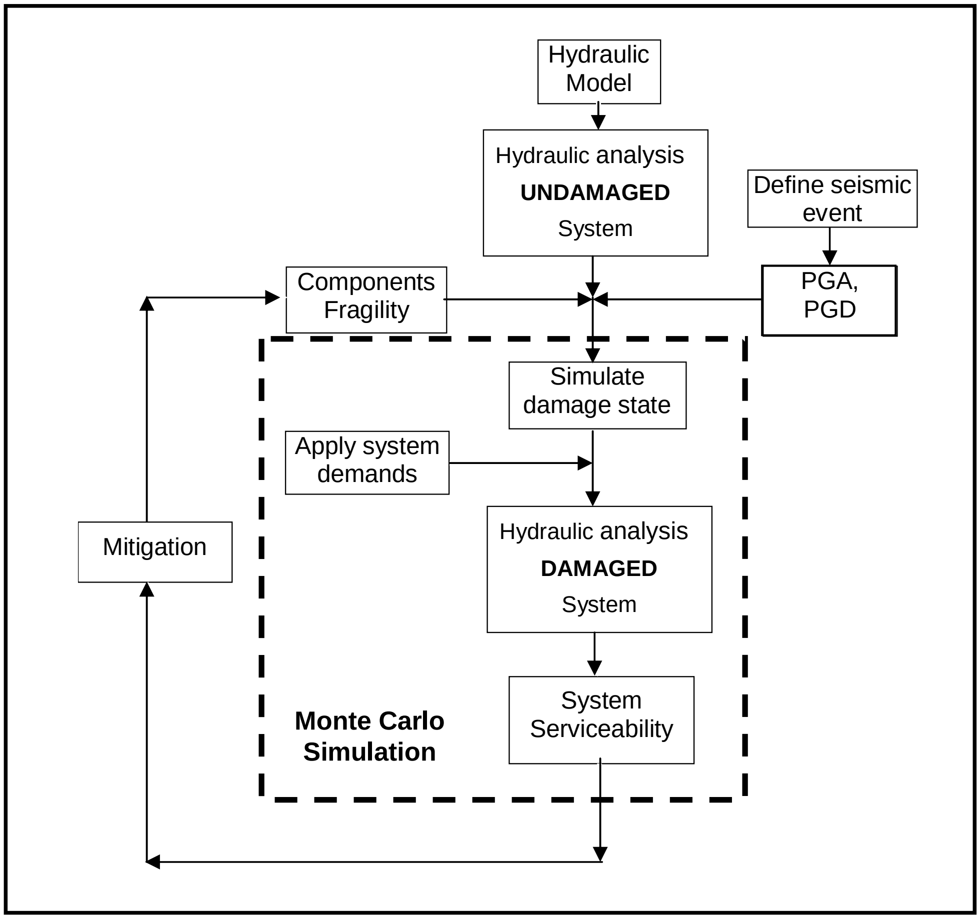


***Figure 5. Hydraulic network analysis schematic of undamaged and damaged system. Boxes inside the dashed line are probabilistic based used the Monte Carlo simulation.***

## BENEFIT-COST ANALYSIS

A benefit-cost analysis was performed in the Portland study by developing a benefit-cost ratio (BCR). The BCR is the annualized avoided loss cost, A, divided by the annualized cost of mitigation, M, so:

$$BCR = A/M \tag{4}$$

The annualized cost of mitigation, M, includes the capital cost, C, of any construction or acquisition, interest on the invested money, plus the cost of operating and maintaining the new facilities.

The annualized avoided loss cost, A, includes: 1) repair in post-disaster conditions, R, 2) loss of income, I, and 3) societal loss, S, or:

$$A = R + I + S \tag{5}$$

For the capital cost of mitigation, C, the cost of repair after a 500 year-return earthquake was assumed.

The loss of income, I to the City of Portland occurs when no water is delivered, and is valued at $53 million annually/365 days/yr = $0.15 million/day. Societal losses, S, are the loss of income to individuals and businesses that cannot function as a result of loss of water service. Societal losses are difficult to estimate, but can be bounded. An upper estimate would be based on the assumption that the productive society would cease without water. Assuming an annual average income of $25,000 per household for the 280,000 households served by Portland (assumes 3 people/household), the daily loss would be about $70/household or about $20 million per day. Income loss estimates for the shutdown of large electronics plants served by Portland are on the order of $1.5 million/day each. For all of industry, plus commercial and residential economic impacts, this could total the same estimate of $20 million/day. However, shutdown of industries following an earthquake (one of the 2 most significant hazards) may not be attributable entirely to loss of water supply. Other contributing factors could include damage to the industrial facilities and loss of other lifeline services such as electrical power or natural gas. For purposes of the study, $10 million/day was used as the estimate for the societal cost for the loss of water.

The project report shows calculations of the BCR both with and without societal losses. It should be noted that repair costs and loss of income are small compared to societal losses. Societal losses are not a direct cost to the City of Portland water utility but are a cost to City property owners, and thus owners of the water system. Use of the BCR with societal costs was thus justified.

## CONCLUSIONS

Five water systems were evaluated with up to four risk evaluation methods. The hazard/risk screening and risk quantification method is effective in quantifying the risk associated with individual components for multiple hazards in a lifeline system. The fault tree analysis is effective in quantifying the supply “system” reliability, and was employed for the highest risk hazards. The hydraulic analysis of damaged distribution system is effective for scenarios where the system is damaged in multiple locations such as earthquakes. The benefit-cost analysis is useful to justify proceeding with mitigation.

## ACKNOWLEDGMENTS

Project Managers and staff with the Portland Oregon Bureau of Waterworks, the Greater Vancouver Regional District, Burnaby, British Columbia, Canada, and the other three unnamed utilities are gratefully acknowledged for their project support.

## REFERENCES

ABS Consulting (Seattle, WA), 2002, *Emergency Management Plan*, prepared for the Greater Vancouver Regional District, August.

Devore, J., Probability and Statistics for Engineering and the Sciences, 4th Edition, Duxbury Press, New York, 1995.

EQE International (Seattle WA), 2000, *System Vulnerability Assessment*, prepared for Portland Bureau of Water Works, September.

Kennedy/Jenks Consultants (Federal Way, WA) in Association with EQE Engineering and Design, 1993, *A Lifeline Study of the Regional Water Distribution System*, prepared for Greater Vancouver Regional District.

National Institute of Building Sciences (NIBS), 1999, HAZUS 99, Federal Emergency Management Agency, Washington DC.

Sandia National Laboratories, 2002, Risk Assessment Methodology for Water Systems (RAM-W$^{SM}$), Albuquerque, NM.