Appendix D Supplementary Notes on Component Vulnerability Modeling

D.1 Introduction

This Appendix includes materials to supplement Chapter 4, Volume I, with reference to component vulnerability modeling. Section D.2 covers how a power function may be used for very simplified component vulnerability modeling. Section D.3 covers how a triangular distribution may be used for simplified modeling of component fragilities. Section D.4 covers how a major water treatment plant may be treated as a subsystem.

D.2 Use of a Power Function

For components subject to damage by ground movements and accelerations, preliminary, judgment-based damage functions can be constructed, using simple tools like the triangular distribution. This appendix explores briefly the power function and the triangular distribution.

The power function has the form

Damage (repair cost, functionality, restoration time) = $Y = A * X^B$

in which A and B are coefficients to be determined and X is some measure of intensity for a specific natural hazard. The power function has an "S" shape if

$A > 0$ (as is required for components with some vulnerability)

$X \geq 0$, and

$1.0 < B < 0$.

This power function can be used to develop a deterministic component vulnerability model. If one enhances the power function with an error term (see discussion of pipeline vulnerability models in Chapter 4, Volume I) , then the power function can be construed statistically.

D.3 Use of a Triangular Distribution

The triangular distribution is one of the simplest of probability density functions – only the uniform distribution is simpler. The triangular distribution creates a well-behaved S-shape curve. It is a 3-parameter distribution (see Evans Hastings & Peacock, 1993). Some form of the predictive hazard parameter is used as the x variable (for instance, x may be equal to Modified Mercalli Intensity for earthquake damage)

The triangular distribution takes the form (see Figure 12):

Y = Ymax = $\boldsymbol{f}$(a,b,c,x)

In which:

> x =‘a’ at the lower left corner of density function triangle
>
> *‘b’* at the lower right corner of triangle
>
> *‘c’* at the coordinate of apex of triangle
>
> $Y = ((x\text{-}a)^2) \div ((b\text{-}a)*(c\text{-}a))$ for x   c
>
> $Y = 1 \text{-}(((b\text{-}x)^2) \div ((b\text{-}a)*(b\text{-}c)))$ for x>c

The triangular distribution can be used to generate damage ratios for individual components or structures, where the damage ratio represents repair cost normalized by replacement value. Total damage implies a damage ratio of 1. Where damage saturates at a damage ratio less than 1, the distribution can be scaled to saturate at this lower level (Ymax < 1).

A damage function using the triangular distribution can be readily constructed from estimates of incipient damage (i.e., the x-coordinate of point “a”), the hazard level at the most probable failure point or highest rate of accumulation of damage (point “c”), the hazard level at which damage saturates (point “b”), and the damage ratio at damage saturation (Ymax, if less than 1).

A major challenge in the use of this functional form is the selection of the hazard parameter predicting damage, and its functional form:

X = f(pga, pgd, SA, MMI, v_{max}, relative displacement, etc.)

In which:

pga	=	peak ground acceleration
pgd	=	peak ground displacement
SA	=	Spectral Acceleration
MMI	=	Modified Mercalli Intensity
$\boldsymbol{v_{max}}$	=	Maximum velocity

In earthquake, some components will be vulnerable to accelerations, some to velocity, some to relative displacements (e.g., structural drifts) or permanent ground deformations. In wind, a key damage parameter would be wind velocity for exposed components. For flooding, the parameter of choice may be height of water above the base elevation of the vulnerable component. The functional form must then be decided. 'x' may be a linear function of the hazard parameter, or x may be logarithmic or some other form.

Analytical methods using simple physical models may provide insight into the selection of the appropriate predictive hazard parameter and its functional form. Where statistical data are available, these judgment-based damage functions can serve as prior distributions in a Bayesian approach to vulnerability modeling (Der Kiureghian, 2002).

D.4 Water Component Subsystems

In some cases, a complete system model is not needed. Small, sub-system models will suffice to support water utility decisions regarding the impacts of natural hazards. These sub-systems themselves contain their own nodes and links.

Example: A hilltop reservoir with a small local piping system.

Subsystem modeling is especially useful for water treatment plants, which contain themselves a great many components. This section illustrates how one may decide to model a water treatment plant as a sub-system. Of course, not all components within a water treatment plant are treated in terms of this example. Chemical, electric power, and telemetry systems, for instance, are not modeled in this example, which emphasizes the flow of water.

Figure 13 presents but one example of a water treatment plant. (modified from Eguchi et al., 1983) Major flows enter A from S1, an aqueduct, and then proceed through the plant. Bypass capability from A to H, the outlet, is available, but without chlorination capability. Minor flows also enter C, a screen house, which is especially needed for debris in the spring and the fall. B is the inlet control building for both raw water sources and hence from A and C.

The inlet control building leads to aeration channels and the mixing area, where the flows enter coagulation and mixing basins. D, the chemical building, does not actually constitute a node or link in the system of water flows, although chlorination piping and other conduits connect various systems with D to other parts of the plant. So, D can be analyzed separately from the main flow of water.

Water flows from the coagulation and sedimentation basins to filter basins at E. In the illustrative plant, there are ten coagulation and sedimentation basins and twenty filter basins. As a result, there is considerable redundancy in the plant in the event of natural hazard damage. Water treatment plants with fewer basins would be expected to have far less redundancy.

The backwash system is relevant for the longer recovery system. The plant may be able to operate for some short time (say, one day) before backwashing is indispensable. G represents the backwash system, which recycles water through a variable filter, I, which represents the filter being cleaned at a specific time. From I, flows proceed to J, the waste washwater tank, from where flows can be redirected by a valve into B, the inlet control building.

Figure 13 presents a flow diagram of the nodes and links here modeled as well as the backwash system. Table 4 lists the significant nodes and links in the illustrative analysis here. Of course, the number of nodes and links in this simplified model could be multiplied significantly. For recovery purposes, many elements of the chemical building could be analyzed. In general, electric, power, communications, and chemical systems could be surveyed. Backup generators could be evaluated. Table 4 contains only essential items for response and recovery.

For earthquakes, one could analyze the probability of plant functional failure from modes such as:

a. pipe rupture throughout the plant

b. structural failure to the inlet control building B, chemical building D, or filter building E

c. rupture of chlorine tanks

d. low flows from the creek or failure at the screen house C AND structural failure of the diversion structure A, and

e. severe spalling of the outlet channels.

Other failure modes must be considered for diverse natural hazards affecting the same plant.

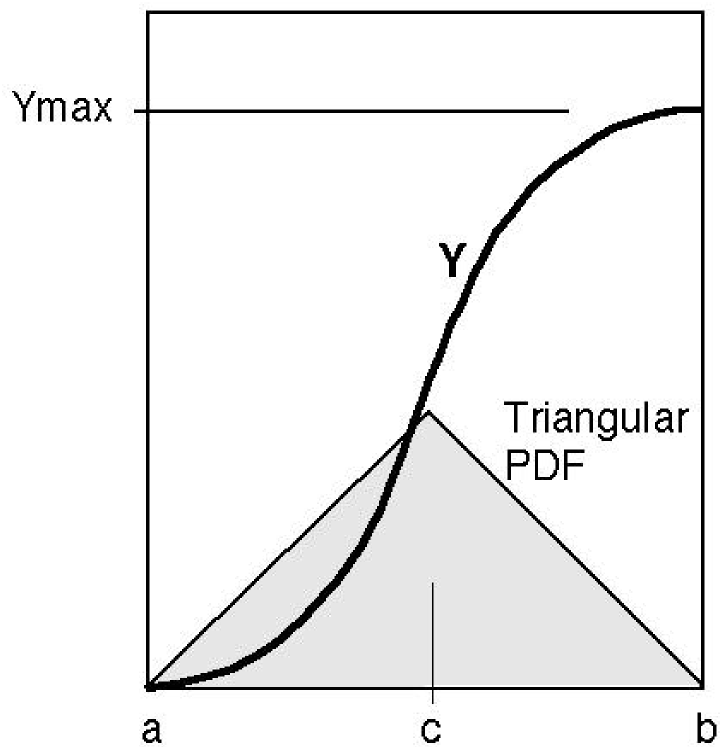

Figure 12: Triangular Distribution

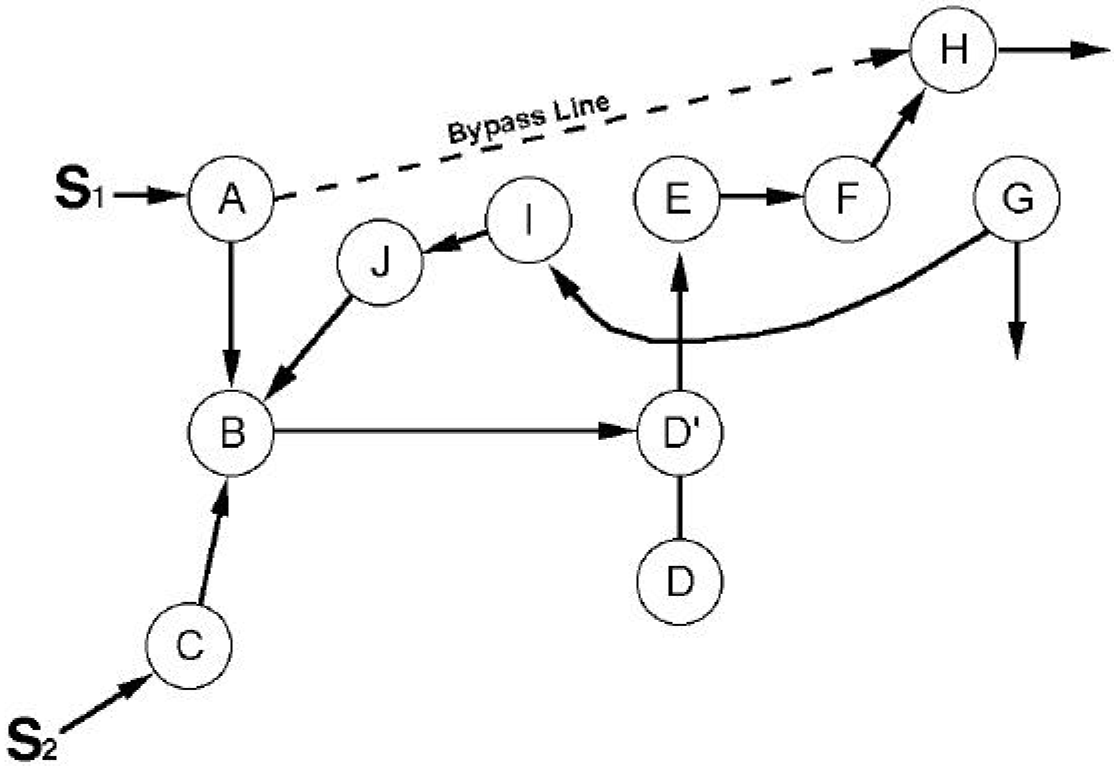

Figure 13. Flow Diagram for A Water Treatment Plant

Legend:

S_1	=	Main supply source
S_2	=	Variable supply source
A	=	Diversion structure
B	=	Inlet control building
C	=	Screen House
D	=	Chemical building
D’	=	Connection between aeration channels and mixing area
E	=	Filter building
F	=	Pipe gallery and post-chlorination area
G	=	Backwash area
H	=	Outlet building (for flows into main transmission line, or aqueduct)
I	=	Filter being backwashed
J	=	Waste/wash water tank

Node/ link	Description	Function(s)	Essential Process, Equipment, or Structures	Illustrative Description of System Features if Failure Occurs
A	Diversion Structure	To divert water to inlet control building or to bypass line	Concrete building pipes	Adequate flows would be needed from S_2, the creek
B	Inlet Control Building	To divert water from either A or C to grit collection and aeration channels	Concrete building pipes	Plant shutdown
C	Screen House	To screen debris, from source S_2	Concrete building pipes; power-driven equipment	Only required if S_1 fails in which case S_2 is required for flows
B to D’	Grit Collection, Aeration of Water	To collect grit and aerate water	Concrete channels	Possible long-term substructure problems if soil is saturated
D	Chemical Building	To provide sources of chemicals, power, and information	Concrete building; chlorine tanks	Capacity to chlorinate is essential in the short-run; plant shutdown for failures here are very possible.
D’ to E	Mixing, Coagulation, and Sedimentation Basins	To add alums and other chemicals; also mixing, coagulation, and sedimentation	Coagulation basins; sedimentation basins	Extreme redundancy in illustrative WTP given the number of basins; possible long-term substructure problems may require closing some basins
E	Filter Building	To filter, chlorinate water	Concrete building underdrains (6 inches, 15 cm)	Extreme redundancy in illustrative WTP, but extensive damage could lead to severe long-term problems
F	Post-Chlorination	Chlorination outlet	Concrete building; pipes	If pipe rupture occurs, plant operations might be stopped to repair damages
H	Outlet Building	To transport finished water to main transmission line (aqueduct)	Concrete channels	Failure could lead to channel failure

Table 4: Exemplary Vulnerability Table for a Selected Filtration Plant (ignoring specific component failure modes)

Other Possible Examples

5.3.2 Pressure regulating stations

5.3.3 Inlet/outlet structures piping (at lake or river)

5.3.4 Electric power distribution sub-stations

5.3.5 Filtration/treatment plants

5.3.6 Booster pumping station

Appendix E Supplementary Information on Water Systems Evaluations

E.1 Introduction

This section supplements Chapter 5, Volume I. Section E.2 covers some of the formalization of a connectivity evaluation. Section E.3 covers rapid means to evaluate component operational importance.

E.2 Toward the Formalism of a More Complex Connectivity Evaluation

To begin a connectivity evaluation, one first defines the system in terms of m components, starting with sources, then links, intermediate nodes, and finally demand nodes (service zones, service connections and/or fire hydrants). One is then concerned to define a number of system states. Each system state can be a simulation of a specific natural hazard event (scenario). To be estimated is which and how many nodes are reachable through some pathway by some source. Being reachable does not imply that adequate water supplies or water pressures will be available. Connectivity evaluations thus overestimate the chances that a water system will perform well after natural hazard events.

The formal evaluation below follows Eguchi et al. (1983). Many other accounts are available of how to evaluate combinations of series and parallel systems. (See for instance Chapter 15 in Meeker and Escober, 1998). One first defines a connectivity matrix C such that

$\mathbf{c}_{i,j}$ = 1 if node i is immediately connected to node j and water flows from i to j and

$\mathbf{c}_{i,j}$ = 0 otherwise.

If flows are bi-directional, then

$\mathbf{c}_{i,j} = c_{i,j}$

Such an m-by-m connectivity matrix can be defined for the m components modeled for the system.

Natural hazard event and component vulnerability models (plus possibly simulations) will define whether or not ci,j = 1. Binary component vulnerability models will not require any simulations. However, if component vulnerability models yield the probability of functionality for a component, and these probabilities range from 0 to 1, then simulation may be needed to define specific system states. For instance, if the probability of a link’s failing in a specific natural hazard event is 0.3, then approximately 30% of the simulations for that natural hazard event should exhibit the component as failing.

A reachability matrix R is defined as having the following values:

$\mathbf{r_{i,j}}$ = 1 if directly or indirectly water can flow from node i to node j and

$\mathbf{r_{i,j}}$ = 0 if water cannot flow from node i to node j.

To derive a reachability matrix from a connectivity matrix, one defines the following Boolean function B:

$$B(x) = 0 \quad \text{if } x = 0 \text{ and}$$

$$= 1 \quad \text{if } x > 0,$$

and R is computed as follows:

$$R = B(I + C + \ldots + C^{n-1})$$

$$= B[(I+C)^{n-1}]$$

in which C is the connectivity matrix and I is the identity matrix.

Thus, for each natural hazard event and for each simulation of this natural hazard event resulting in a system state, one could use the above formulas to define a reachability matrix and so determine whether or not a specific demand node is connected directly or indirectly to some water source.

These formalisms are not here exemplified because it is our judgment that more complex situations should proceed directly to hydraulic evaluations. The degree of formalism in connectivity evaluations at some point equals or exceeds the degree of formalism in hydraulic evaluations. Moreover, connectivity evaluations overestimate the chances that the water system will provide service, and do not at all meet the need to assess whether or not adequate fire flows are present.

E.3 Prior Assessments of the Operational Importance of Components

There may be circumstances under which it is desirable to develop a prior sense of the operational importance of water utility components. This section applies to connectivity models and especially to hydraulic models of the water system.

The water system model can be used to assess the operational importance of each component or assembly. In a system model, each component can be ‘failed’, one-by-one, and the system-wide impact evaluated. For a pipeline, a failure may mean that the water pressure must be reduced such that the hydraulic head is equal to the elevation of the break. Incomplete breaks may be modeled by introducing water demands along the pipe. Valves may fail ‘open’ or ‘closed’. Failure of a water tank may be simulated by removal of the water source.

Assessing component impact on the system requires the selection of an ‘objective function’ as the measure of system performance. Candidate objective functions may include water delivery volume (if inventory is critical), or water volume weighted to emphasize impacts on critical customers or fire flow. The time element can be considered by multiplying the reduction in water delivery rates by the time to repair the component or subsystem.

Operational importance modeling requires consideration of the water system layout. Where we have a ‘series’ subsystem, all components in the series whose failure means loss of function of the entire subsystem (or link) will have the same operational importance. This consideration helps in simplifying and reducing the number of perturbations in the system necessary to develop the operational importance matrix.

The method described here addresses only single-link failures. Multi-link failures often have non-linear effects, where the impact of the failure of multiple components in different links has much greater impact on the system than the sum of the impacts of individual components. On the other hand, multiple failures within an individual link may not increase outage area (loss severity) but only outage duration (time to repair multiple failures). An example of this would be where a pipeline experiences multiple break (and leaks) from a hazard such as liquefaction, landslide or temperature effects. Any single break will reduce flow and pressure, creating an outage area. Further breaks only extend repair time, or possibly change the restoration strategy from one of repair to one of complete replacement.

Appendix G. Details of Demonstration Water System Evaluation

G.1 Introduction

In chapter 6, summary systems risk evaluations are provided for a hypothetical water system. This system is shown in Chapter 6 (see, for instance, Figure 34, volume I). Moreover, broad results of analyzing this system relative to three hypothetical events are provided. These hypothetical events are a flood/scour event, an expansive soils event, and an earthquake event.

This appendix provides details for the analyses of these three hypothetical events. Section G2 describes how the water system is modeled before the natural hazards events. Section G3 describes the hypothetical flood/scour event. Section G4 describes the hypothetical expansive soils event. Section G5 describes the hypothetical earthquake.

G.2 Modeling the Hypothetical Water System Before the Hypothetical Natural Hazards Events

Briefly, in Figure 35 (volume I), a raw water reservoir located to the west of the water distribution system provides gravity service to two water treatment plants. Pumping Station B conveys water from Water Treatment Plant No. 1 south to Reservoir No. 3 and then by gravity from this point. Water Treatment Plant No. 2 provides potable water via gravity to the northern service areas with each pressure zone level being served by a pump station and water reservoir (i.e. Pump Station D pumps to Reservoir 6/Pump Station C pumps to Reservoir 5). A second supply source is from a groundwater well located on the East Side of the distribution system near Pumping Station E.

Prior to simplifying the water system hydraulic model, one should verify that all major distribution loops are included. The subsystem evaluation requires isolating other service areas. However, it became evident that certain connections/facilities needed to operate in order to properly reflect the water system ability to provide water to this area. In general, without these connections, there could not be any backflow into the system, which would thereby increase the risk/vulnerability of this area. A steady state model of the partial water supply and distribution system is shown in Figure 14 and depicts (as contours) the steady state pressures based on an estimated maximum day demand without fire flow.

G.3 A Hypothetical Flood/Scour Event

G.3.1 Overview of the Scenario

As shown in Figure 15, a water main break is assumed as a result of flooding/scouring along a segment of stream located on the water distribution system eastern edge. The vulnerability of the water distribution system based on this natural event is evaluated as based on beginning with the pre-natural hazard water system (Figure 14). Steps for evaluating the disrupted system are discussed in the following sub-sections.

G.3.2 Immediate Water System Condition After the Flood

First, it is assumed that the flood event occurs as shown in Figure 15. Next, the steady state model would reflect the post natural hazard water system conditions of this water main being broken completely do to the scouring and full exposure of the pipe.

Based on this water main break, the main is modeled with a demand, equal to the maximum day flow through the pipe, at the break and with a fire flow demand of 2500 gpm (20,000 cu.ft/sec) on either side of the main break. The model yields a consistent pressure drop in the vicinity of the break. Before the event, the pressures in the area were close to 200 psi (14kg/sq cm), whereas after the event the pressures in the vicinity ranged from 100-to150 psi (7 to 10.5 kg/sq cm), as shown in Figure 15.

Since the disrupted system was modeled with an additional demand, the model still responded so that the flow was still conveyed through the pipe. The model simulation was steady state. An alternative model approach is to evaluate the disrupted system based on extended period simulation to determine the amount of contaminants introduced into the system. (Note that the pressure system may not be a major problem at this time.)

G.3.3 Modeling the Restoration of the Water System

A first step in restoring the system is to isolate the broken water main. The time of restoration will depend on several variables including the accessibility of the break location. For instance, if the break occurs over a creek/river where severe erosion has occurred and the bridge has been washed out, then the repair must be closely coordinated with other emergency workers in the area. Other variables include size of line, accessibility to needed repair joints and appurtenances, and availability of personnel and equipment.

The first step in the restoration of the system is modeled with the break isolated by closing pipes near the break additionally with fire flows (2,500 gpm, or 20,000 cu ft/sec). This isolation of the break has a major impact on the system. First, the system demands are met by backfeeding in the system from an alternate supply source as shown by flow arrows on Figure 16. Second, in the area which the broken main normally feeds, the pressures drop significantly. Pressures in these areas ranged from –25 to 100 psi (-1.75 to 7 kg/cm) as is shown in Figure 16.

G.3.4 Restarting the System After Repairs

After repair and restoration, the system conditions are brought back to the pre-natural hazard water system condition as shown in Figure 17. Following the startup of the water system, water utility managers and operators may evaluate such matters as follows:

1. System redundancy
2. Safety
3. Availability of resources (e.g., people, equipment, material)

4. Response time to water system outage
5. Duration of repair
6. Evaluate steps taken to restoration of system, determine the critical path for repair

Ideally, water utility managers and operators should evaluate the existing water system model and the constraints placed on the system to determine if the model responds in the appropriate manner. In practice, response may initially proceed according to previous successful responses to other incidents.

The model results indicate that the areas with high demand are still serviced and pressures are still within requirements. The flow direction on several pipelines is reversed in order to meet the demands. Without system redundancy, users in the system would be without water service until repair, disinfection (chlorination), and recharging of the system could occur.

G.4 A Hypothetical Expansive Soils Event

G.4.1 Outline of Natural Hazards Disruption

As shown in Figure 18, expansive soil conditions exist in the foothills of this water system. These are assumed to cause the disruption and subsequent shutdown of Water Treatment Plant No. 1 and Pump Station B. In addition, the primary water transmission line from WTP No. 1 to Reservoir No. 3 is assumed to be damaged by the same geologic conditions. Initial leaks are assumed to occur followed by a subsequent pipe failure. As with the flood scenario (section G.3), the steady state model (Figure 14) of the water system is the basis for the pre-event water system condition. (Chapter 4, volume 1, discusses the vulnerability of facilities to such natural hazards as expansive soils.)

G.4.2 The Immediate Condition of the System After the Disruption

For evaluating the immediate impacts of the expansive soils event(s), the steady state model was used based on several conditions which included additional fire flow demand of 2,000 gpm (16,000 cu ft/sec) placed on the west side as a result of expansive soils disruption. The fire flow occurred near the hazard condition due to an assumed leakage in a natural gas pipeline.

Water Treatment Plant and Pumping Station B building is assumed to sustain structural damage and therefore has been taken out of service. Pipeline leakage is assumed to occur between WTP No.1 and Reservoir No. 3 that is equal to 10 percent of the flow in the pipeline. It is assumed that the water system operators do not detect the leakage at first. The Water Treatment Plant is shut down. This is modeled by closing all pipes from the plant. Pressures are decreased in the portions of the water system for which the water treatment plant is the primary feed. Note that Reservoir No. 3 supplies the demand in this portion of the system. Residual pressures have dropped across the system as shown in Figure 19. At this time, it is not assumed that the Water Treatment Plant is bypassed with raw water for fire demand purposes.

On the assumption that Reservoir No. 3 is 75 percent full when the natural hazard occurs, the reservoir will augment the fire flow and domestic demand. The demand after the pipes have been closed is approximately 14,700 gpm (118,000 cu ft/sec). Given this demand, it would take approximately four (4) hours for the reservoir to drain. The only feed to this reservoir is the water treatment plant that is now out of service. The water system residual pressures are shown in Figure 19. Pressures throughout the entire system are affected. The most significant drop in pressures occur in the area on the west side of the system in which customers could not be serviced. Owing to the higher elevations in this area, the system could not adequately backfeed into this affected area.

G.4.3 Modeling the Water System Restoration

Initially, the water treatment plant pump station is modeled with a third of the normal capacity. The system demands still could not be met, as shown in Figure 20. Reservoir No. 3 is modeled as empty since the demand would use all the flow introduced into the system and the reservoir would not fill.

During restoration, Water Treatment Plant No.1 and Pumping Station B have been fully restored with the water system residual pressures, as shown in Figure 21. At this point, the leak is detected although system demands are being met, and the potential for contamination of the water along this pipeline segment could occur. It is assumed that Reservoir No. 3 is filled at this stage.

During the next stage of restoration, the pipe leak is isolated (Figure 22). Once again, the west side system experiences low pressures. It is again assumed that Reservoir No. 3 empty. The system then experiences the same condition during the Water Treatment Plant restoration, and customers are without service.

Once the leaking pipeline is repaired, the system will require disinfection (chlorination) owing to the contamination introduced at the break.

Finally, full restoration of the system occurs and pre-hazard conditions are restored (Figure 23).

G.5 A Hypothetical Earthquake Affecting the Water System

G.5.1 The Assumed Immediate Damage

As shown in Figure 24, a local earthquake is assumed to cause liquefaction of soil along major stream tributaries. The soil liquefaction is assumed to result in several pipe failures in the vicinity of these streambeds and has further caused structural damage to Pumping Station A and D. Figure 14 again summarizes the pre-earthquake condition of the water system.

G.5.2 Modeling the Immediate Post-Earthquake

The steady state model is applied based on several different conditions as a result of the various types of pipe breaks that occurred. A total of 15 pipe breaks and leaks are simulated within the area of liquefaction along the streambed corridor. The number of breaks/leaks is based on one occurrence for every one kilometer of pipelines contained in the liquefaction zone. (More precise estimates could be determined through an application of previous chapters for a specific scenario earthquake). These fractures are spaced sporadically in the system since actual system failure would not be distributed in a systematic pattern within high liquefaction susceptibility zones. Pipes having over 24-inches (600 mm) in diameter are modeled with only leaks and with the leakage flow rate equal to approximately 10 percent of the maximum day flow conveyed through the pipe. Pipes less than or equal to 24-inches (600 mm) in diameter are modeled as having a break.

Immediately after the event the system is modeled with 15 pipe fractures and 2 pumping stations operating at a lower capacity. Pumping Station A is reduced by 50% while Pumping Station D is reduced by 75% as a result of structural damage to the buildings. Additionally, a fire was placed in a shopping center area. The entire system is impacted when this occurred and a majority of the system incurred pressures below 50 psi (3.5 kg/cm) as shown in Figure 24.

G.5.3 Modeling the Restoration of the Water System

The next phase of modeling covers system restoration. Initially, the pipe breaks are isolated with Pumping Stations A and D still operating at 50% and 25%, respectively. The system pressures are restored to operating levels since the breaks no longer placed additional demands on the system. The system is able to backfeed areas where pipe breaks have occurred. Several areas of outages exist where pipe closure and/or lack of demand lead to lack of flow. The pressure contours and direction of flow are shown in Figure 25.

During the next stage of restoration, the pumping station capacity is increased to 75% capacity for Pumping Station A and 50% Capacity for Pumping Station D and half of the pipe breaks are assumed to be repaired. The pressures throughout the system were generally unaffected (Figure 26) from the previous scenario but the flow was directed through the pipes that were previously closed for repair.

Finally, the pumping stations are fully stored and all breaks are repaired. The pressures in the system were slightly changed but not significantly (Figure 27). The main change is the ability for the flow to be restored to normal operating patterns and the system is no longer required to backfeed areas to maintain service.

After the full restoration of the pumping stations and pipeline breaks, the identification of pipeline leakage is confirmed and located. Until this stage, even though a “Boil Water” order had been issued, the undetected leaks have been introducing possible contaminants into the system. The lack of detection had resulted from the focus on other system problems. This condition is modeled by isolating the pipes connected to the leaks. Owing to the location of the leaks and since all the leaks occurred on transmission mains larger than 24-inch diameter (600 mm), the impact is significant. As shown in Figure 28, pressures drop throughout the system during the repair of the leaks.

G.5.4 Restarting the Water System

During this final stage, system pressures and water quality have been restored and the water system returned to its normal operating conditions before the earthquake.

The earthquake impact on the water distribution system is significant. However, while the pipe breaks were being repaired, the system was able to backfeed to service customers. The paramount health concern pertains to the contaminants introduced into the system at the leakage points, which are detected late in the restoration process. Restoration of customers (with a "Boil Water" order in effect) until leakage is detected is gradual, which results in reduced customer service as the leaking pipes are removed from service for repair.