Chapter 3
Natural Hazards and Their Impact on Water Systems

Introduction

Evaluation of hazards in the zone or region under study is essential for estimating the vulnerability and possible damage to components. The history of disasters in the region is valuable for such an evaluation.

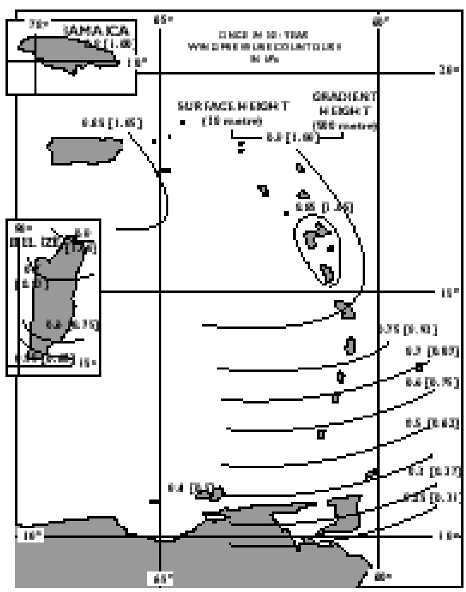
To evaluate earthquake hazards, one should have information on seismic sources and their mean rates of displacement, attenuation, variances, and design standards. Normally, seismic vulnerability analysis is carried out by a team of professionals with expertise in specific techniques for seismic risk analysis along with personnel from the water supply company who are knowledgeable about the system components and their relative importance.

For hurricanes, evaluation is based on historic information which is often included in construction standards and codes. Figure 3.1 reproduces a map of hurricane wind pressure in the Eastern Caribbean that is included in the Caribbean Uniform Building Code (CUBiC). Hurricanes can cause major damage to structures exposed to flooding and high winds, and all companies in high-risk areas are obligated to be aware of the vulnerability level of their buildings, to formulate mitigation plans, and to be prepared for emergency situations.

While there are analytical models to determine precipitation and maximum flood levels, records on areas where flooding events have occurred are fundamental for analysis of this hazard. Floods associated with annual rainy seasons and phenomena such as El Niño in the Pacific pose high risk for contamination of water intake structures and pipelines located near water channels. Typically, the prediction of water levels in rivers and hydrologic risk to the system's components is done by professionals from private consulting companies, specialized institutes, universities, and professionals from the water service company. This information will help prioritize the implementation of mitigation measures and establish emergency procedures.

To estimate the vulnerability of water delivery systems to volcanic eruptions, areas should be identified that may be impacted by eruption materials (primarily lava flows, gases, and ash), watercourses, and sites where landslides and avalanches might occur. Such

Figure 3.1 Map showing wind pressure in Eastern Caribbean (CARICOM, 1985)



documentation is usually available from seismology, vulcanology, and meteorology institutes, as well as from civil defense or emergency response agencies. Structures exposed to lava flows, ashfalls, and landslides suffer the greatest damage. In addition, treatment plants and metal structures such as tanks and valves can be damaged by ashfall and acid rain. A volcanic eruption that coincides with heavy rain can produce landslides or debris avalanches in waterways and extremely destructive floods.

Because these phenomena seriously impact on water services, all companies located in areas of risk must carry out in-depth studies of the vulnerability of their structures, implement mitigation plans, and have response mechanisms in place.

Characteristics of Hazards and Their Effects

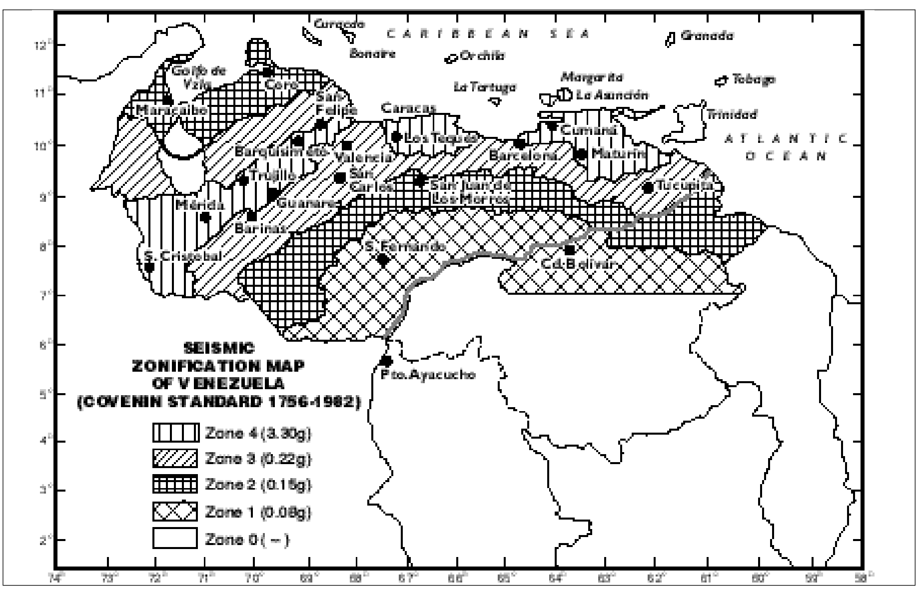
The information presented in this section will assist in completing Matrix 3, Physical Aspects and Impact on Service (presented in Chapter 4). A description of the estimated damage in different components of systems is provided for each type of hazard. This is based on information gathered by the Economic Commission for Latin America and the Caribbean (1991)[2] following selected disasters in the countries of the Americas.

Earthquakes

Information of various levels of complexity is available for seismic hazards, depending on the type of study needed. The most common data include:

- *Evaluation of seismic hazard:* This is based on the seismicity of the region, the seismogenic sources, the correlation of the attenuation and their variance, and the use of ad hoc algorithms of calculation.

Figure 3.2
Seismic zonation map of Venezuela (Covenin standard 1756–1982)



[2] Economic Commision for Latin America and the Caribbean, *Manual para la estimación de los efectos socioeconómicos de los desastres naturales*, Santiago de Chile, División de Planificación de Programas y Operaciones, 1991.

Table 3.1 Types of permanent land displacement due to earthquakes (after O'Rourke and McCaffrey, 1984)[3]

Designation	Description
Fault	Dislocation of adjacent parts of the earth crust, concentrated in relatively narrow fault zones. The main types of faults are strike-slip (lateral) faults, where blocks of crust move horizontally past one another; thrust (reverse) faults, which occur in response to compression, where blocks are pushed together; and normal faults, which occur in response to pulling or tension.
Liquefaction	Temporary state of the soil, in which the resistance to shear stress is very small or nil. This is a characteristic of non-cohesive, saturated soils subjected to vibration. Associated displacement could include: lateral spreads over firm soil with angles under 5° (lateral spread), subsidence, or flotation effects. Lateral displacements can reach meters, even associated with slopes as small as 0.5° or 1°.[4]
Landslides	Massive movement of earth on slopes owing to the inertial force of the earthquake. These can be rock falls and superficial landslides, or the displacement and rotation of large volumes of earth and rock in the case of deep faults.
Densification	Reduction of volume caused by vibrations that compact non-cohesive, dry, or partially saturated soils.
Tectonic lift or subsidence	Changes in topography at the regional level associated with tectonic activity; generally distributed over large areas.

- *Seismic risk zonation maps*: Many countries have developed seismic zonation maps in accordance with specific application requirements, such as building design (see Figure 3.2), verification of high voltage equipment, bridge design, insurance or reinsurance policies, and others. These incorporate known effects of historic events. It is advisable to complement this information with maps that highlight active or potentially active faults and the quality and types of soils; these are also known as "neotechnical maps".
- *Ground-shaking:* Generally, ground-shaking, the predominant characteristics of the soil, the mean return time of a seismic event, and other important factors will be used for design and construction standards. If this information is unavailable, which may be the case in countries without building standards for seismic resistant design, sufficiently small excess probabilities should be chosen for the selection of maximum earth displacements, or the intensity of the earthquake.
- *Potentially unstable areas:* It is not likely that this information will be available on zonation or microzonation maps. Nevertheless, it is important to have reliable information about areas of the system that are in (i) areas where liquefaction can occur, such as saturated deposits, generally found near rivers, old river deltas, and lake or coastal beaches; (ii) landfills or earthworks susceptible to lateral spreading; or (iii) natural or artificial slopes, which are potentially unstable under seismic activity. Table 3.1 describes types of permanent ground displacement resulting from earthquakes. Table 3.2 correlates different types of landslides and Mercalli intensity (Keefer, 1984).

3 O'Rourke, T.D.; McCaffrey, M. (1984) *Buried pipeline response to permanent earthquake ground movements*. VIIIth World Conference on Earthquake Engineering, Proc Vol VII, p. 215-222.

4 For example, liquefaction and slides often occur during earthquakes on unconsolidated land with steep slopes and fine soil that easily crumble. Pipelines should be installed in already populated areas, since a project manager will not have the opportunity to choose a location in relation to the geology of the zone. The best that can be done at the design stage is to ensure that there is an adequate distribution of valves and the most flexible possible piping, with the hope of reducing ruptures to a minimum when slides and liquefaction occur (PAHO/WHO, *Manual sobre preparación de los servicios de agua potable y alcantarillado para afrontar situaciones de emergencia. Segunda parte--Identificación de posibles desastres y áreas de riesgo,* page 19, 1990).

Table 3.2
Thresholds of seismic intensity for different types of landslides

Types of landslides or faults	Threshold of seismic intensity
Rock falls or slides and small soil slides Sudden slides of blocks of soils, isolated cases	Closely spaced events in area, of low magnitude on the Richter scale (4–4.5) with Modified Mercalli Intensity (MMI) of VI or more
Sudden slides of blocks of rock, massive quantity of rock; lateral spread	Closely spaced events with magnitude of 5–5.5 on Richter scale; with MMI of VII or more
Rock or soil avalanches. Cracks and breaks in free wall of solid rock Major landslides and massive slumps, frequent in areas with irregular topography	Richter magnitude of 6.5, with MMI of VIII or more MMI of IX or more
Widespread, massive landslides; possible blockage of rivers and formation of lakes	MMI of at least X

- *Rupture length and permanent displacement of active faults:* The Richter scale describes the total energy of the seismic waves radiating outwards from the earthquake as recorded by the amplitude of ground motion traces on seismographs. This scale of magnitude is directly related to the rupture length or surface area of the fault, maximum displacements, and the loss of bearing capacity. Table 3.3 is useful in determining average ranges of loss of bearing capacity in the rupture zones. The table establishes the relationship between Richter magnitudes, ranges of rupture lengths of geologic faults, and range of maximum displacement, which are valid for lateral faults with few deep foci (approximate depths of between 10 and 15 km). The permanent displacements associated with earthquakes, described in Table 3.3, are particularly problematic when they intercept tunnels, buried pipes, or building foundations.
- *Tsunamis or tidal waves:* These result from displacement of the ocean bed associated with large, shallow focus earthquakes. They can cause slides on the ocean floor as well as high waves that affect the landmass. Historically, extensive areas have been affected by this type of phenomenon in seismic zones of the Americas.

Measuring Earthquakes

One of the most commonly used scales to describe the effects of earthquakes is the Modified Mercalli Intensity scale (MMI), which measures effects felt by people and observed in structures, and the earth's surface. A summarized version of the scale is presented in Table 3.4. The magnitude of an earthquake (M) is usually expressed using the Richter scale, which is a measure of the amplitude of the seismic wave, the moment magnitude, or measurement of the amount of energy released. It is estimated from seismograph recordings. Other types of scales incorporate information on the stability of slopes, the quality of buildings and installations, and height of tidal waves.

Calculating a System's Physical Vulnerability

To calculate physical vulnerability of a system, potential hazards and seismic history are taken into account (see Annex 1 for examples of the effects of specific seismic events). Following are suggestions that should facilitate vulnerability calculations.

Table 3.3
Range of magnitudes, rupture length and maximum permanent displacement

Range of Richter magnitudes	Range of surface rupture lengths of the geologic fault (km)	Range of permanent displacement (cm)
6.1 - 6.4	10 - 20	40 - 60
6.5 - 6.8	20 - 40	70 - 100
6.9 - 7.2	50 - 120	110 - 160
7.3 - 7.6	130 - 240	180 - 240

Vulnerability matrices based on statistical data: The "walkdown" inspection is a preliminary inspection of the system. The results, generally supported by simple calculations, can be synthesized in damage probability matrices, which are based on statistical information and/or the experience of those conducting the inspection.

Vulnerability matrices based on analytical studies: As discussed earlier, in the production, transport, and distribution of drinking water, as well as in sewerage systems, there are components for which there is very limited or no statistical information. This is the case for intake towers in large reservoirs or surge tanks. In such cases it is important to evaluate mathematical models and translate the results obtained to damage probability matrixes.

General Effects of Earthquakes

Depending on their magnitude, earthquakes can produce faults in rocks, in the subsoil, settlement of the ground surface, cave-ins, landslides, and mudslides.[5] Vibration can also soften saturated soils

Table 3.4
Modified Mercalli Intensity (MMI) Scale (abbreviated)

MMI	Description
I	Detected by sensitive instruments
II	Felt only by persons in resting position
III	Vibrations described as those caused by a truck passing are felt inside buildings
IV	Movement of dishes, windows, lamps
V	Dishes, windows, lamps break
VI	Facades and chimneys fall, minor structural damage
VII	Considerable damage in poorly constructed buildings
VIII	Walls, monuments, chimneys fall
IX	Movement in masonry building foundations, large cracks in the soil, pipes break
X	Destruction of most masonry structures, large cracks in the earth, railroad ties bend, landslides and cave-ins occur
XI	Few structures survive; bridges collapse
XII	Total damage; presence of waves on earth surface; lines of sight and level distorted; objects thrown in the air

5 Heavy rainfall can also produce cave-ins, landslides, and mudslides.

(known as liquefaction), reducing the capacity of structural resistance. Liquefaction, combined with seismic waves of the soil (produced by tectonic forces), can result in severe damage or total destruction to water system components.[6]

The degree of damage is usually related to:

- The magnitude and extent of the earthquake;
- The seismic-resistant design of the works, their construction quality, level of technology, maintenance, and condition at the time of the event;
- The characteristics of the soil where installations are located and of adjacent zones. It is possible that while structures resist the earthquake, a nearby landslide could cause damage. Another example of secondary effects would be flooding resulting from dam failure.

Most pipelines for drinking water, sewage, and storm water are placed underground and buried so that they are out of sight. Buried and surface structures perform differently in an earthquake.

Damage Caused by Earthquakes

a) Surface structures: It is usually possible to make a visual assessment of damage to surface structures immediately after impact. Structural resistance in these works depends on the relation between their rigidity and mass, whereas in buried pipes, it is not the mass, but ground deformation produced by an earthquake that is relevant.

i) *Buildings, Warehouses, Dwellings, and Engine Houses*: Buildings for administration, supply warehouses, and housing for technicians, operators, and other staff, as well as various types of housing for machinery will suffer damage such as cracks and partial or total collapse. The level of damage will depend on the seismic resistant design and materials used in the construction of these works.

ii) *Water Tanks:* The mass determined by the volume of water stored can be very large, resulting in large demand placed on tanks in an earthquake. If the tanks are elevated there is the additional risk that they will resonate with the vibration of the earthquake. The tendency of elevated structures to vibrate in sympathy with the ground frequency is greatest when they are built on large layers of unconsolidated deposits[7]. Besides the effects of the earthquake on the tank, water oscillation and waves can bring additional risks, especially when interior baffle plates have not been designed. Depending on the quality of design, construction, and maintenance of the tanks, combined with the magnitude of the earthquake and the response of the soil, damage can range from very minor to major, including collapse. Major damage may result if there is a high volume of runoff.

- Partially buried tanks. Partially buried tanks[8] (including those for regulation or storage for cities and towns) generally constructed of stonework, concrete, reinforced concrete, or other materials, can suffer damage such as:
    - Cracks in the walls, floor, covering, or in areas where these elements meet, such as in the entrance or exit of pipes, which may require simple repairs or require total reconstruction;
    - Partial cave-in of the cover, interior columns or part of the walls or floor, requiring either minimal repairs or total reconstruction;
    - Total collapse of the structure.

6 Later in this chapter is a list of the damages that could affect different parts of these systems.
7 UNDRO, *Prevención y mitigación de desastres*, Vol. 8, Aspectos de saneamiento, 1982.
8 Included here are tanks for regulation or storage for cities and towns.

- Elevated tanks. Elevated tanks[9] of average or large size are usually constructed from steel or reinforced concrete.
  - Tanks supported by steel frames with adequate diagonal bracing perform well in earthquakes. Their most vulnerable point is where pipes (which form the supporting structure) penetrate the ground. However, different kinds of design, construction, and maintenance of steel tanks, combined with diverse earthquake magnitude and response of the supporting soil, can produce:
    - Light damage, such as shear of the diagonal supports, which can be repaired or replaced quickly;
    - Damage in the supporting structure and/or in the storage tank can vary from minor to very serious. The most severe damage will likely occur in the connection between the supporting structure and the pipes;
    - Collapse of the structure.
  - Concrete tanks can be affected by earthquakes in the following ways:
    - Loss of exterior stucco. This is easily repaired although scaffolding may be required;
    - Damage to pipes entering or leaving the tank or to superimposed elements such as access ladders. These elements do not compromise the structure and their repairs can range from slightly to moderately difficult;
    - Cracks in the supporting structure or storage tank which can occur in the areas of overlap of an excessive number of steel reinforcements, at points where the pipes cross the concrete walls, in the connection between the storage tank and support structure, or in the foundation of the support structure;
    - Toppling or leaning of the structure, or foundation failure. This is usually of serious significance;
    - Collapse of the structure.

  According to the UNDRO study (1982), the survival index of elevated reinforced concrete tanks is less than that of steel tanks, and the precautions for their construction are less clearly defined. Reinforced concrete structures can hide more damage than steel structures, so any damage that exceeds superficial loss of stucco should be examined by a specialist. What appear to be simple cracks can cause major problems when a subsequent earthquake occurs.
- Small elevated tanks. Small water storage tanks used for individual dwellings, small groups of houses, schools, small industry, etc., are built of a large variety of materials. The support structure may be built of wood, structural steel, reinforced concrete, etc. The tank may be of corrugated or smooth iron, asbestos cement, fiberglass, reinforced concrete, etc.
    - Corrugated iron tanks collapse frequently during earthquakes, but experience shows that this is more often due to poor maintenance than to instability.
    - Damage in the support structure and/or in the tank may require simple repairs, or if the structure collapses, require tank replacement. It may be possible to salvage part of the material from wooden and metal structures (except where there is corrosion).

iii) Dams and Reservoirs: Only dams and reservoirs for drinking water supplies are addressed here. Seismic activity in reservoirs can cause large waves that will overtop the dam. Cave-ins or landslides falling into the reservoir can generate damaging "internal" tidal waves. Floods

[9] Included here are tanks for regulation or storage for cities and towns.

resulting from the rupture of a dam can have very serious and unpredictable consequences for populations located downstream from the dam.

- Rock-fill dams are more flexible than those of concrete and more resistant than earth dams. However, the clay or concrete used to make these dams water-tight can crack in an earthquake, resulting in leaks. Possible damage would include:
  - Small, medium, or large cracks or leaks;
  - Collapse of reservoir embankments;
  - Total collapse of the dam.
- In earth dams, earthquakes cause failure of foundations, cracks in the core, landslides in the dams, waves in the reservoir causing landslides in the dykes, and overtopping or collapse of the core wall. Other damages include:
  - Small leaks which should be immediately repaired to avoid the increase of erosion;
  - Accumulation of soil because of landslides, which may need to be dredged;
  - Collapse of the dam.
- Concrete dams can crack or the foundations can fail. As in all dams, there is the danger that waves will overtop the dam. Possible damage could include:
  - Cracks or small leaks that should be repaired immediately;
  - Cracks that would require the reservoir to be emptied for repair (implying loss of stored water);
  - Accumulation of soil due to slides;
  - Collapse of the dam.

b) Earthquake Damage to Underground or Buried Works: Underground works include:

- piping and conduits of drinking water, sewage, and storm water; chambers, valves and domestic installations;
- underground water intakes such as wells, drains, and galleries.

These works differ significantly from surface works since, for the most part, damage will not be visible, making actual damage assessment much slower and more labor intensive. For example, within 15 days of the Mexico City earthquake[10], the major damage to the drinking water mains had been repaired, but months were required to complete smaller repairs, and it was much more complex and time-consuming to repair the sewage and storm drain networks.

Certain damage can affect the quantity and quality of water supplied.

The earthquake exerts inertial force on above-ground structures,

10 ECLAC, *Daños causados por el movimiento telúrico en México y sus repercusiones sobre la economía del país,* October 1985.

but buried structures such as pipes and rigid connections can be damaged as the earth undergoes deformation. Less damage can be expected in relatively more flexible pipelines (PVC or steel, for example) compared with rigid pipes such as compressed mortar, concrete, cast iron, and asbestos cement, especially if they have rigid joints.

i) Influence of Soil Type on Damage. In embankments built of infill, or in soft soils, earthquakes can break buried pipes. Failures also occur in pipelines located in areas where there is a change of soil type, as in changes in density of natural fill.

The liquefaction of soil is one of the most damaging effects of the earthquakes since it reduces foundation support. A large part of damage to pipes in alluvial terrain or water saturated sand occurs because of liquefaction. For example, in Japan, in an area of saturated sands, earthquake vibrations practically converted the soil into a liquid in which the pipes and chambers "floated", causing major damage to the installations.

José Grases, 1997

In many cases, construction materials are not adequate to resist seismic forces.

Large diameter pipes placed at a shallow level suffer more damage than those of smaller diameter, since they have less resistance to "Rayleigh waves" which are dispersed over the earth's surface in a similar, though less obvious, way as waves of water. Another area of potential damage is in the proximity of pipes to buildings that collapse. The rupture of pipes that enter or leave buildings can wash out public network pipelines to which they are connected.

ii) Seismic Risk Maps Showing Ground Quality. Given the difficulty of locating damage in existing pipelines, a review of seismic risk maps of the areas affected will show the most vulnerable areas, for example:

- Areas with deep layers of soft soils, sands and sedimentary gravel, swamps and infilled areas (i.e., subsoils that do not absorb seismic vibrations as do hard rock);
- Areas with layers of loose sand that is saturated with water and other non-cohesive soil strata in which the soil can soften;
- Faults in the rock strata (pipelines that cross these faults can suffer damage).

iii) Locating Damage in Pipes:

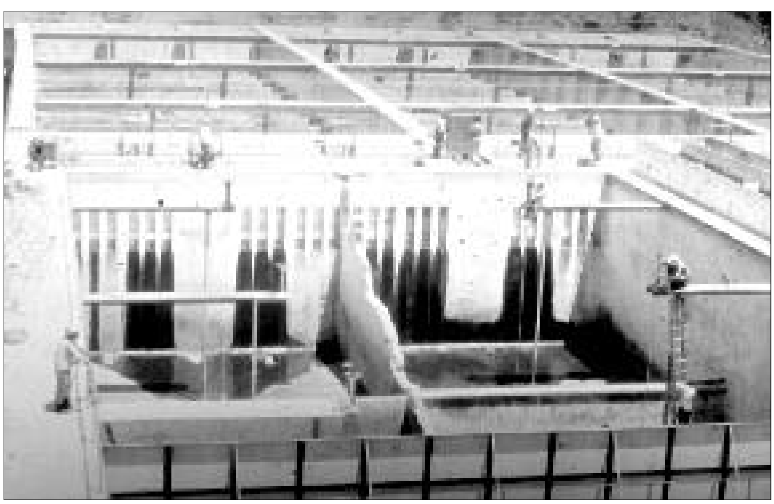
- ❑ *Damage to drinking water pipelines.* Damage commonly produces water seepage in areas close to the breaks in the pipes or connections. To determine the magnitude and extent of damage and to make urgent repairs, it is necessary to excavate the lines to find the broken pipe. However, where there are highly permeable soils or low water pressure, it is possible that breaks will be detected only after service is restored. Some indications of this kind of damage are as follows:

- New leaks evidenced by increased pressure in the network after the breaks initially discovered are repaired;
- Areas of a city or town that continue without water service or have lower pressure after repairs have been made. This might be due to damage in pipes feeding these zones, which should be identified and repaired.
- Detecting leaks can be very time-consuming, especially if the necessary equipment and expertise are not locally available. It can be difficult to determine which leaks were caused by the earthquake and which existed before the event.
- Flow meters installed at appropriate points in the mains of the network can detect the existence of leaks.

❑ *Damage to Sewage Pipes.* Surface seepage of waste water can be indicative of an area of damage. However, since these are usually open channel flow pipelines, without pressure, there may be fewer visible leaks than in drinking water pipes where pressure can facilitate detection of damage. Manholes can facilitate the visual assessment in successive chambers to locate sections with leaks (by comparing the levels of waste water in neighboring chambers). Breaks in the pipes, if they did not exist before, can be a product of the earthquake. Where the drinking water supply is interrupted as a result of the disaster, there will be no return waste water. Normalization of the drinking water supply must occur before final inspection of the waste water system can take place.

❑ *Storm-water Drainage System.* If a disaster occurs during the rainy season, the review of this system would be similar to that discussed for the sewerage system. However, if it occurs in the dry season, a visual inspection of damage could be carried out by following waste water channels and major sewer mains, accessible sewer mains, if they exist, and by inspection of neighboring reaches from adjacent manholes.

iv) *Risk of Contamination of the Drinking Water System.* If pipes from the drinking water and waste water systems break simultaneously, the waste water will penetrate the drinking water system (especially if there is a considerable volume of waste water spread on the ground). This occurs because pipes for drinking and waste water are usually built parallel to each other, along the same streets. In certain cases there is ground water that covers the drinking water and sewerage networks. Ground water contaminated by breaks in the sewage system can infiltrate the drinking water system through broken joints. This is likely to occur if



José Grases, 1997

Certain damages can seriously impact drinking water supply.

Table 3.5
Number of breaks in drinking water pipeline following the 1985 earthquake in Chile (M=7.8)

Pipe diameter (mm)	Asbestos cement pipe		Cast iron pipe		PVC pipe		Steel pipe		Galvanized iron pipe	
	Gran Valparaiso	San Antonio Province	Gran Valparaiso	San Antonio Province	Gran Valparaiso	San Antonio Province	Gran Valparaiso	San Antonio Province	Gran Valparaiso	San Antonio Province
50	49	24	72	7	-	2	-	-	20	2
75	239	51	29	5	4	4	-	-	2	-
100	298	81	23	15	7	31	18	2	1	-
125	18	9	-	18	-	-	-	-	-	-
150	61	15	8	5	5	8	1	-	-	-
200	32	20	4	3	-	1	-	11	-	-
225	-	-	14	-	-	-	-	-	-	-
250	4	12	-	1	-	-	-	-	-	-
400	-	3	-	8	-	-	3	3	-	-
500	-	-	1	-	-	-	-	14	-	-
600	-	-	-	-	-	-	27	2	-	-
700	-	-	-	-	-	-	14	-	-	-
Total	701	215	151	62	17	46	63	32	23	2

Percentaje of network by type of material

Material	**Gran Valparaíso**	**San Antonio Province**
Asbestos cement	55	72
Cast iron	30	19
PVC	7	2
Steel	6	6
Galvanized iron	2	1
Total	**100%**	**100%**

Source: Andrade and Seal, 1985.
Note: San Antonio Province and Gran Valparaíso were located in the epicenter of the 1985 earthquake.

Tabla 3.6
Types of damage by kind of material in the 1985 earthquake in Chile
(Gran Valparaíso and San Antonio Province)

Asbestos cement	**%**	**Cast Iron**	**%**
Joints	10	Lead work	75
Cross section	80	Cut	15
Longitudinal profile	10	Holes	10
Total	**100**	**Total**	**100**
Galvanized pipe	**%**	**Steel**	**%**
Cross section	50	Welded joints	50
Holes	50	Holes(*)	50
Total	**100**	**Total**	**100**

Source: Andrade and Seal, 1985.
(*) Pipes weakened by corrosion
Note: All of the defects in the PVC piping occurred in the joints.

there is negative pressure as a result of breaks in the system or because of rationed drinking water.

c) Effects of Earthquakes on Ground Water Collecting Works. In areas where water is taken from deep wells or filter galleries, the earthquake can cause the ground water to flow into newly opened fissures resulting in a decrease, and even the exhaustion of the flow obtained from these

Table 3.7
Expected performance of gas piping exposed to earthquakes[11]

Component	**Performance**
Welded steel piping	If there is no corrosion, it is unlikely that damage will occur due to seismic waves. Critical zones include: change in soil type, crossing of faults, unstable soils, rigid connections to structures or other pipes. They can be designed to resist major permanent displacement.
PVC pipes	There are limited data on PVC pipe performance in earthquakes, but it is assumed that they are not very vulnerable because of their flexibility and low friction in the soil. Their resistance to permanent displacement is less than that of steel, but better than that of other pipes with connections.
Support structures	Seismic activity can be more intense in river and road crossings or flooded areas.
Storage elements	Underground storage (e.g., in caves) or in gas fields (pervious rock) is less vulnerable than storage in surface tanks.
Service meters	When adjacent to buildings they have been damaged because of twisting of elements or collapse of masonry.
Liquid natural gas tanks (unpressurized to -260º F)	These are generally of the best design. Critical elements are: foundations, soil-structure interactions, rigidity to shear stress, and waves in the tank.

11 Gas supply systems are used as an example because of the similarities to distribution pipes in water systems.

intakes. Contamination is also a hazard when cracks or faults connect surface water or water from latrines with ground water, rendering intakes useless.

- *Damage to Medium, Deep, or Large Diameter Wells:* Given the variety of wells that exist, various types of damage can occur, including:
  - Settling of soil around the well, resulting in slight to severe damage;
  - Collapse and total loss of the well (for example, as a result of a fault that traverses the well and causes its collapse, or because of cave-ins that cover it);
  - Slight to severe damage in the pumping mechanism.
- *Damage to Filter Galleries or Drains[12]:* In underground galleries or drains, the earthquake can cause various types of damage, including:
  - Cracks in the walls, pipes or beams that form the drain or filter gallery. Cracks may be relatively easy to repair (if the filter gallery is accessible) or require interior reinforcements or replacement of the facing of the drain.
  - Partial cave-in of part of the filter galley, drain, or manholes;
  - Total collapse of the filter gallery or drain;
  - Damage to pumping equipment (if it exists).

d) Contamination of Drinking Water Sources. The risk of ground water contamination was mentioned in the previous section, but a more common hazard is the contamination of surface sources of drinking water. This may occur because of the presence of animal carcasses, or the discharge of petroleum, industrial or toxic wastes into bodies of water, posing one of the greatest large-scale hazards to health in the event of an earthquake. In such cases, it will be necessary to immediately identify alternative sources, and construct (or rehabilitate) intakes and distribution systems for drinking water.

To estimate damage as a result of seismic action, special attention should be given to the stability of foundation soils, including the points described above. The typing of components should consider the interaction with other components that could modify their dynamic response during ground shaking. Tables 3.5, 3.6, and 3.7 provide a synthesis of the expected performance of pipes during intense earthquakes.

The expected effects of earthquakes on drinking water and sewerage systems can be summarized as follows:

- Total or partial destruction of intakes, conveyance structures, treatment facilities, storage, and distribution;
- Breaks in delivery and distribution pipes and damage in connections between pipes or with tanks, resulting in a loss of water;
- Interruption of electric power, communications, and access routes;
- Change in water quality because of landslides;
- Variation (decrease) in the flow of underground or surface collector works;
- Change in the site of water outlets in springs;
- Damage from interior coastal flooding caused by tsunamis.

12 A filter gallery is a type of intake that is similar to a drain, but constructed at greater depth, such as a tunnel, with small openings in the walls that allow ground water to penetrate it.

Table 3.8
Hurricanes affecting Puerto Rico between 1893 and 1996.

Event	Date
San Roque	16 August 1893
San Cariaco	8 August 1899
San Felipe II	13 September 1928
San Nicholas	10 September 1931
San Ciprián	26 September 1932
Santa Clara (Betsy)	12 August 1956
Hugo	18 September 1989
Marilyn	16 September 1995
Hortense	9–10 September 1996

Hurricanes

Depending on the type of study conducted, information on various aspects of hurricanes should be considered. The most commonly available information includes:

- *Historical record:* A review of previous events is important in determining vulnerability. For example, the Hurricane Commission of the Faculty of Engineering and Survey of Puerto Rico has published information on the most hazardous hurricanes originating in the Lesser Antilles of the Caribbean (1996). Table 3.8 lists major hurricanes that have affected Puerto Rico in the last century, revealing that a major event has occurred nearly every decade.
- *Wind speed:* The damage potential of hurricanes is directly related to wind speed and the height of waves. The Saffir-Simpson[13] scale includes five categories of hurricanes, as shown in Table 3.9.
- *Forces on buildings:* In design and construction standards, there are procedures for determining the demands on different parts of a structure. The specification of design wind speeds must be made in relation to a particular averaging period during which the wind is measured. Different countries use different averaging periods in defining design wind speeds. For example, typical

Table 3.9
Saffir-Simpson Scale (Simpson, 1974)

Saffir-Simpson category	Maximum sustained wind speed		Height of waves	Potential damage
	(m/s)	(km/h)	(m)	
1	32.7 - 42.6	118 - 153	1.0 to 1.7	Minimal
2	42.7 - 49.5	154 - 178	1.8 to 2.6	Moderate
3	49.6 - 58.5	179 - 210	2.7 to 3.8	Extensive
4	58.6 - 69.4	211 - 250	3.9 to 5.6	Extreme
5	$\geq$ 69.5	$\geq$ 251	$\geq$ 5.7	Catastrophic

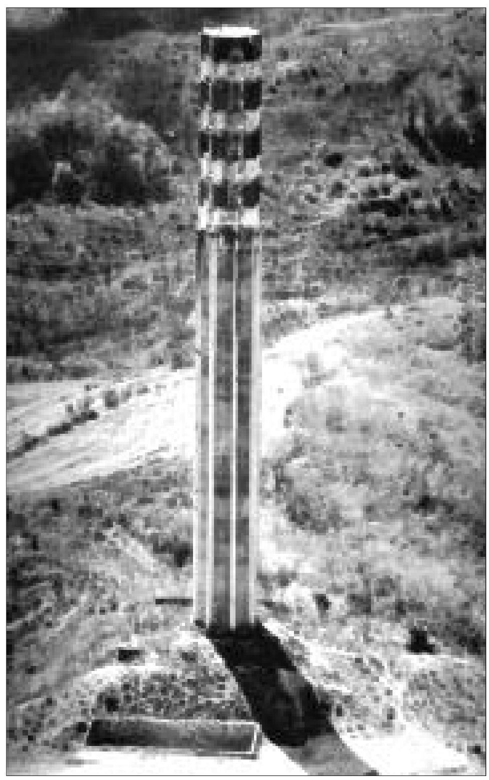
13 Simpson, R.H. *The hurricane disaster potential scale.* Weatherwise, 27, 169-186, 1974

Table 3.10
Comparison of criteria used in the definition of design wind speeds[14]

Country	Averaging period	Approximate equivalent wind speeds (mph)			
Canada	1 hour	120	113	91	79
Caribbean (CUBIC)	10 minutes	127	120	96	84
Venezuela	78 seconds	158	149	120	105
Barbados	3 seconds	181	171	137	120

averaging periods are 1 hour (Canadian code), 10 minutes (Caribbean Uniform Building Code—CUBiC), 3 seconds (Barbados Association of Professional Engineers Code), and 78 seconds (Venezuelan code). Table 3.10 lists the equivalent wind speeds for a 120-mph wind expressed for each averaging speed and shows the need to specify the averaging speed.

- *Storm surge:* This term describes an increase in the level of the sea and its effects on coastal areas owing to a decrease in atmospheric pressure associated with the passage of the eye of the hurricane and strong winds. When a hurricane enters the coastal area, water levels can reach heights of 4 meters. Strong winds can increase these heights to 6 meters. This phenomenon has great destructive potential in low-lying, densely populated coastal areas.
- *Effects on land.* The intensity of rainfall associated with hurricanes is a potential source of flooding and slope instability.


José Grases, 1997

In carrying out vulnerability analysis, priority should be given to potential damage to components of the water system that will directly affect the community, quality, or quantity of service.

Calculating Vulnerability of Components

Vulnerability to hurricane-force winds is influenced by type of construction, and in large part can be estimated by determining whether elements of the infrastructure comply with existing building standards.

Calculating Physical Vulnerability of the System

Recommendations used in carrying out vulnerability analysis for seismic events also can be applied in calculating the physical vulnerability of a system to hurricanes.

The first step in vulnerability analysis is a detailed review of all the structures within a system. These structures include: surface intakes that are periodically washed out by floods (these can be replaced by more secure intakes such as bottom intakes and filter galleries); anchors and supports of conduits that cross or are located very close to waterways and are vulnerable to strong currents;

[14] PAHO, *Disaster mitigation guidelines for hospitals and other health care facilities* (Vols. 1-4), Washington, D.C., 1992.

and unprotected pipelines that are very close to waterways. When identifying potential risk the following should be considered:

- *Influence of topography*: Topography in the installation area can modify the intensity of hurricane winds.
  - a) Gradual slopes in valleys can increase average wind velocity because of "Bernoulli" effects;
  - b) Deep, closed valleys offer protection against strong winds;
  - c) Dense forests surrounding an installation can reduce wind force.
- *Energy supply*: Topography should be taken into account in evaluating the vulnerability of high voltage wires. These can be damaged by gusts of wind, causing interruptions in power supply.
- *Watercourses:* Watercourses can be affected by flooding, thereby altering expected flood levels, damaging or breaking pipes, exceeding the capacity of existing drains, and increasing turbidity in runoff.
- *Drains:* The type of drainage has a significant effect on the expected discharge capacity of the system and needs special study. Closed systems, which employ pipes, are more susceptible to blockage and maintenance is more difficult. Lack of maintenance has resulted in serious flooding in urban areas.
- *Contamination*: Flooding and/or blocked drains increase the risk for contamination of rivers, streams, and wells, as well as damage in flooded areas, such as in supply warehouses.
- *Damage to infrastructure:* Structures adjacent to waterways can be damaged by strong currents. These include bridges, access routes, catch basins, and pipes, among others.


Osorio, 1997

Intensive rainfall and flooding associated with hurricanes can cause greater damage than winds to water systems.

General Effects of Hurricanes

Wind primarily causes damage to above-ground works. The risk of damage increases in direct relation to the height of structures and the surface exposed to the wind.

Damage Produced by Hurricanes

Buildings, housing, and engine houses for drinking water and sewerage systems will behave similarly to construction in other sectors in the event of hurricanes.

- *Damage to Elevated Tanks.* If the wind is strong enough, it can demolish storage tanks causing the sudden spill of stored water (which could amount to thousands of cubic meters) in addition to damage to connecting pipes and in adjoining installations. While the main structure may survive, access stairs, protective railing, or in- and outflow pipes could be damaged. Type of tanks that are susceptible to such damage include:

- Tanks for public drinking water supply for towns and cities, which probably store the largest quantities of water;
- Intermediate-sized tanks for industry, markets, schools, etc.;
- Small tanks for domestic use.

The most common effects of hurricanes on the drinking water and sewerage systems include:

- Partial or total destruction of buildings, including broken windows, roof damage, flooding, etc., due to the force of winds;
- Ruptures in pipelines in exposed crossings over rivers and streams as a result of strong currents;
- Breaks and uncoupling of pipes in mountainous terrain as a result of landslides and water currents;
- Damage to elevated and ground-level tanks;
- Contamination of water in tanks and pipes;
- Breaks in pipelines and structural failure because of earth settling associated with flooding;
- Damage to electrical transmission and distribution systems resulting in the interruption in operation of equipment, instruments, and communication.

Floods

Generalities

Flooding occurs as a result of rain, abnormal increases in ocean level, massive snowmelts, or a combination of these phenomena. Precipitation is the result of a series of factors, including:

- Latitude. In general, precipitation decreases with latitude since lower temperatures cause a decrease in atmospheric moisture.
- Distance from the source of moisture. The closer a zone is to sources of moisture, such as oceans and lakes, the higher the probability of rainfall.
- Presence of mountains. Ascending elevation generally favors precipitation. Rainfall is usually more intense on the sides of mountains exposed to the wind.

Factors Affecting Runoff in a Watershed

The most relevant factors are as follows:

Climatic Factors

- Precipitation: form (rain, hail, snow, etc.), intensity, duration, distribution over time, distribution over a region, previous precipitation, and moisture level in soil;
- Interception: vegetation type; composition, age and density of strata; season of the year; size of storm;
- Evaporation: temperature, wind, atmospheric pressure, nature and relief of the evaporation surface;
- Transpiration: temperature, solar radiation, wind, humidity, and vegetation cover.

Physiographic Factors

Pipelines tha cross rivers or ravines should be designed to accomodate flood levels.

- Characteristics of the watershed: size, shape, slope, and orientation;
- Physical features: ground use and coverage; infiltration conditions such as type of soil, and geologic features such as permeability and capacity for formation of ground waters; topography, including the presence of lakes, marshes, and artificial drainage;
- Characteristics and transport capacity of the channel: size, shape, slope, roughness, length, and tributaries;
- Storage capacity: backwater curves

Variations and Patterns of Precipitation

Determining the precipitation time distribution, or periods with high rainfall probability, and, consequently the greatest periods of risk, is an important aspect of planning disaster and emergency response. The rainfall pattern, combined with other factors, such as soil characteristics, topography and geologic conditions, and area of the watershed determine the quantity of rainfall that will generate runoff.

Evaluating Flood Hazards and Risk Mapping

Flood hazard analysis requires the determination of flood zones and channels affected based on: duration of the phenomenon, runoff, and maximum probable flood levels. This information is used to develop flood risk maps. Typically, civil defense agencies, emergency management agencies, universities, and meteorological institutions maintain such maps. The superimposition of risk maps over diagrams of the water supply system will show structures that are likely to be affected by flooding.

General Effects of Floods

The magnitude of flood damage is related to:

- The level that waters reach in the flood, the violence and speed of currents, and the geographic area covered;
- The quality of design and construction of the works, and whether or not precautions have been taken for a certain level of flooding;
- The ability of the ground where installations are located to resist erosion, cave-ins, or landslides brought on by persistent or torrential rain.

Contamination of Drinking Water By Floods

The most serious consequence of flooding is large-scale contamination of drinking water. In such situations water-borne illnesses, usually associated with poor hygiene and sanitation, can affect a large part of the population. Such illnesses include typhoid and cholera, where they are endemic, as well as dysentery, infectious hepatitis, and gastroenteritis. Because of the serious risk of appearance of these illnesses, methods of water treatment with chemical sterilization (such as chlorine) or boiling water for human consumption are of primary importance.

Contamination of drinking and ground water can be caused by:

- Contamination of surface sources of drinking water due to animal cadavers near intakes, excessive increase in the turbidity of water, or pollution from other types of contaminants;
- Flood levels that surpass the height of well head walls, or waters that flow directly over wells and other intakes;
- The rise of water levels in sewer outfalls can cause waste water to back up and flood the interiors of homes, lower levels of buildings, and public throughways. In homes this occurs through toilets and washbasins; in streets it occurs through manholes and rainwater sinks. (This kind of reflux can be avoided if the installation of automatic or manual shut-off valves to prevent backflow are included in the design and construction of the system. However, this feature is rare in countries of the Region of the Americas.)
- If fuels mix with flood waters, it will be more difficult to boil water for sterilization.

Physical Damage Caused by Floods

- ❑ Damage to pipelines and appurtenances (such as different types of chambers and valves) may include:
  - Soil erosion leading to sections of pipe being uncovered, displaced, or washed away;
  - As ground water levels rise, pipes and chambers can be displaced and float, causing ruptures in the installations;
  - Displacement and total loss of sections of pipe.
- ❑ Damage to partially buried tanks. These tanks are usually located in high terrain and flood damage is rare. However, the following has been observed:
  - Erosion of foundations, causing cracks and/or partial cave-in of tanks, especially when constructed of masonry rather than reinforced concrete;
  - If a large part of the tank is underground, flooding combined with high ground water levels (likely in terrain where there has been prolonged rainfall), can cause the tank to float. The risk is greater if the tank is not full of water.
- ❑ Damage to pumping equipment and electrical installations. This may occur in the following cases:
  - If the flood level is sufficient, it can wet electrical engines, pumps, starters, or switchboards;
  - Voltage lines can fall owing to erosion at the base of the poles causing damage to lines, switchboards, and substations.
- ❑ Damage to intakes, dams, and other surface construction. If the dynamic forces of the flood are strong enough they can cause erosion around any of the installations. These conditions have an impact on water intakes and corresponding structures such as channels and water conduits, engine houses, treatment plants, etc.

- Damage to dams and reservoirs. Dams and reservoirs located in river channels are at high risk to flooding. Dams designed for drinking water supply are vulnerable particularly if there is limited overtopping capacity. If the spillway and waste gates are inadequate, there is a risk that the dam could collapse, causing yet another disaster and enormous additional losses as a result of the avalanche of stored water.

To summarize, the main impact of floods on drinking water and sewerage systems are:

- Total or partial destruction of intakes located in rivers or ravines;
- Sedimentation, resulting in silting up of components;
- Loss of intakes because of changes in the course of rivers;
- Breaks where exposed pipe crosses ravines and/or rivers;
- Breaks in distribution pipelines and connections in coastal areas as a result of wave action, and in areas adjacent to water channels;
- Contamination of the watershed;
- Damage to pumping equipment;
- Indirect impacts such as the interruption of electricity and communications, and road blockages.

Landslides

There are many factors that bring about landslides, and there is still uncertainty as to their prediction, speed at which they occur, and area affected. However, there are certain parameters that help to identify and recognize potential areas of failure, and which allow measures to reduce the risk of slope failure. For example, inspection of pipelines and other components of a system begin with aerial photographic analysis of the areas adjacent to an installation. Using scales of 1:25,000 to 1:50,000, important evidence can be collected about ongoing slides, which should be evaluated on-site after the aerial survey. Topographic maps are an excellent source of information, particularly for extensive slide areas.

José Grases, 1997

Construction of infrastructure, deforestation, and other human activities can destabilize soils, increasing the risk of landslides.

Historical Slide Areas

In general, areas where slides have occurred in the past are highly susceptible to recurring slides. Information sources include reports about landslides in the local press, national or international journals, and zonation maps showing areas of geologic instability, inventory of geologic risks, etc.

Geology of a Region

Knowledge of the geology and topography of an area assists in estimating the susceptibility of slopes to movement. Slides are most common in the types of terrain described below:

- *Rugged slopes:* In rough terrain, landslides can occur in any type of geologic material. However, they most commonly occur along the length of the zone of contact between rock and residual or collegial soils.
- *Steep rocks or banks exposed to water flows:* In steep rocks or banks exposed to stream currents, landslides are common. If the bank consists of unconsolidated soils or materials, the weakest slide point is located at the maximum point of curvature of the stream and will receive the greatest impact of water.
- *Areas of drainage concentration and filtration:* A careful study of the drainage network and areas of water concentration is extremely important. Seepage as a result of the slide is likely to occur in areas below reservoirs, irrigation canals, or depressions with standing water. The importance of recognizing the potential danger of surface drainage, especially in porous and fractured rock, needs special emphasis.
- *Hilly terrain:* The presence of rolling terrain with characteristics that are inconsistent with those of the general slopes of the area and present rough slopes at high elevations are generally indicative of old slides. Once an old slide is identified, this serves as a warning that the general area has been unstable in the past and new disturbances can reactivate movement.
- *Areas of concentrated fractures:* The movement of slopes can be structurally controlled by planes of weakness such as faults, joints, deposit planes, and foliation. These structures can divide a rock mass into a series of individual units that can act independently of one another.

Topography and Stability

Topographic maps are an excellent source of information for detecting landslides. Areas where landslides occur frequently can be identified on maps and specific conditions can be analyzed.

Rainfall

Rainfall has a strong effect on the stability of slopes by influencing the shape, incidence, and extent of slides. Rainfall can saturate residual soils, thereby activating slides. There are three aspects of rainfall that are important:

- The climatic cycle over a period of years, for example, high vs. low annual precipitation;
- Accumulation of rainfall in a given year in relation to normal accumulation;
- Intensities of a given storm.

Erosion

Erosion is the result of natural and human activities. Natural agents include: water runoff, ground water, waves, currents, and wind. Human activity that causes erosion includes any kind of undertaking that produces increased water velocity, especially on unprotected slopes. Among the leading causes are deforestation, over-grazing of pasture, and the presence of certain types of vegetation that do not increase the soil's resistance to erosion.

Erosion can undercut structural foundations, pavements, infill, and other engineering works. In mountainous terrain, erosion increases the instability of slopes which can lead to damage or loss of roads and other structures.

Liquefaction as a Result of Earthquakes

Slope failure and soil liquefaction are among the effects of earthquakes that can cause major material and human losses. The majority of slope failures during earthquakes result from liquefaction of non-cohesive soils. However, failures in cohesive soils have also been observed during seismic events.

Characteristics of Landslides

The main factors influencing the classification of slides are:

- Type of movement
- Type of surface of the fault
- Coherence of the failed mass
- Cause of the fault
- Displacement of the mass
- Type of material
- Rate of movement

Massive Collapse or Slumping

These are sudden failures of vertical or near-vertical slopes that result in the loosening and free fall of a block or several blocks of rock. Falling rock generally sets off a landslide.

In soils, the slides are caused by undercut slopes due to stream or human erosion. In rock masses they are caused by undercutting due to erosion, and an increase in pressure due to the presence of water. Landslides also result from differential weathering effects on soil.

Soil collapse or massive slumping are relevant to water supply and sewerage systems since they can cause one or several blocks to fall, resulting in damage to structures or to lower slopes.

Planar Collapse

Planar collapse is the movement of soil or rock along the surface of a well-defined fault. These slides can occur either gradually or very rapidly. In mountainous regions, massive rock slides are disastrous especially in rainy periods, and in many cases cannot be prevented.

Rotational Slides

Rotational slides tend to occur slowly, in a spoon shape, and the material begins to fail by rotation along a cylindrical surface. Cracks appear in the crown of the unstable area and hummocks form at the foot of the slope. Finally, with substantial displacement, the mass leaves a scar in the crown.

The principle causes for this type of failure are an increase in the angle of the slope, weathering, and filtration forces. Consequences are not generally catastrophic even though the movement can cause serious damage to structures in the path of the slide or in the surrounding area. When there are early signs of failure, slopes can be stabilized.

Lateral Collapse

Failures due to lateral slides are a kind of planar fault that occurs in soils and rocks. The mass undergoes deformation along a planar surface that represents a weak area; the blocks separate progressively. This type of failure is common in river valleys and is also associated with cracked and hardened clay soils, shale, and strata with horizontal domes with a continuous weak zone. They also occur in gradual slopes that are found in areas of residual soils or rock.


José Grases, 1997

Landslides can block access to water system installations, impedeing the inspection and repair of elements affected by disaster.

Avalanches

Avalanches are the rapid movement of soil and rubble, which may or may not begin with the rupture along the surface of fault, especially where water is present. All vegetation and loose soil and rock can be carried away. The main causes of avalanches are: high filtration pressure, high rainfall, snowmelt (as in the case of Nevado del Ruiz in 1985), earthquakes, and gradual displacement of rock strata. Avalanches occur suddenly without warning and generally are not foreseeable. The effects can be disastrous, burying extensive areas at the foot of the slope and disturbing natural drainage areas[15].

Creep

Creep is the slow and imperceptible movement or deformation of the material of a slope due to low stress levels. It usually affects only the surface of the slope although deep levels can be affected where there are less resistant strata. Creep is the result of filtration or gravitational forces and is indicative of conditions favorable to slides.

General Effects of Landslides

Landslides can cause devastating damage, as in the case of the rock slide that buried the entire town of Yungay, Peru, in 1970. The degree of impact of slides depends mainly on the volume and speed of the mass, but also on the extent of the unstable area and the disaggregation of the moving mass.

The most common slides are: rock falls from escarpments of highly fractured rocky masses; soil slides on slopes; mud flows, avalanches, and debris falls that can move great distances through valleys and river channels; and creep that can cover huge surfaces. Rock falls, flows, and avalanches mainly affect surface structures, while slides can also affect buried elements. The most dangerous are those that occur suddenly and at high speeds (rock falls, flows, and avalanches). There are usually warning signs for landslides (cracks, soil undulation, etc.); they can occur suddenly or very gradually, and move quickly or very slowly. For example, creep involves the surface of the soil and moves very slowly.

15 PAHO/CEPIS/WHO, Case Study. *Terremoto del 22 de abril de 1991, Limón, Costa Rica.* Pub/96.23, Lima, 177 pp., 1996.

Landslide Damage

- *Diversion Structures.* Surface diversion structures (such as rock barrages, diversions, and intakes) located in mountainous regions can be buried or washed out from the impact of flows, avalanches, and landslides. Earthen or rock fill dams constructed for water supply can fail because of slides on their embankments or overtopping of the dam as a result of slides into the reservoir.

  In mountainous areas, slides around surface intakes pose a high risk for water contamination because of increased turbidity. Such damage can cover huge areas in the case of slides caused by earthquakes or extreme rainfall. Slides resulting from the 1991 earthquake in Limón, Costa Rica, affected some 30% of the watershed. In just one of these slides, 8,000 hectares were devastated. In another watershed, which served as the main source of drinking water for the city of Limón, 27 slides were detected. These slides caused unexpected increases in levels of turbidity, exceeding the capacity of the treatment plant, and made it necessary to discontinue operation of the intake pump located in the river[16].


José Grases, 1997

Pipelines located on slopes are exposed to breaks and deformation because of slow moving landslides (creep) and sudden collapse of slopes.

- *Distribution System.* The principal damage to the water distribution system includes washout and destruction of sections of pipe, canals, valves, and pumping installations located over or in the path of slides, flows, and avalanches. Owing to the length of pipelines, damage to these systems occurs more frequently than damage to intakes. When slow slides occur, displacement of pipes or canals can be gradual but will eventually cause breaks (these pipes can be relocated if slides are detected). Water seepage around fissures in canals will increase the speed of slides. In the case of sudden slides, sections of pipe or canals can be totally destroyed due to the sudden force of the phenomenon.

  Such damage can be localized in the case of slides occurring on one slope, or widespread, particularly when caused by earthquakes or heavy rainfall in mountainous zones or in flat areas where soils are subject to liquefaction or expansion. In such cases pipe or canals located in the middle of slopes or along the edges of sharply angled slopes will be the most affected, as well as conduits built over rivers and ravines. In mountainous zones, open canals or unburied pipes located at the foot of rocky escarpments can be obstructed or destroyed by rock falls. This is also true for pipes located in massive slide areas.

16 PAHO/CEPIS/WHO, Case Study. *Terremoto del 22 de abril de 1991, Limón, Costa Rica.* Pub/96.23, Lima, 177 pp., 1996.

Pipes or canals located at the bottom of rotational slides can be displaced and lifted from their original position, while those situated toward the top will lose support soil. In these slides, the pipes located toward the foot of a slide area are subject to compression and those located toward the top are subject to tension forces. Where there is slow or minimal displacement, flexible piping arranged in a wavelike form is the most resistant, although the joints can fail.

- *Landslide Damage to Treatment Plants.* Damage to treatment plants occurs when they are located over or in the path of a slide, flow, or avalanche, beneath a rocky escarpment, at the foot of slopes without protection, in an area of in-fill, or in expansive or liquid soils. In case of flows and avalanches, the installations are filled with earth and rocks; in the case of liquefaction, the entire plant can be destroyed. Where there are slow slides and expansive soils, uneven terrain can cause damage to pipes, connections, foundations of buildings, or electrical generators.

The expected impacts of landslides on drinking water and sewerage system components include:

- Total or partial destruction of all installations, in particular intake and distribution structures, located on or in the main path of active slides, especially in unstable mountainous zones with steep slopes or in slopes with steep grades that are susceptible to slides;
- Contamination of water in surface intakes in mountainous areas;
- Indirect impacts such as the interruption of electrical service, communication or blockage of roads.

Volcanic Eruptions

Volcanoes are built by the accumulation of lava, ashflows, and tephra, built around a vent that connects with reservoirs of molten rock, or magma, below the surface of the earth. Molten rock forces its way upward and may break through zones of weakness in the earth's crust. When an eruption begins, the molten rock may pour from the vent as lava flows, or may erupt violently into the air as dense clouds of lava fragments (pyroclastic flows). Accumulations of molten rock may move downslope as ashflows, and finer particles may be carried large distances through the air (Tillling, 1998).

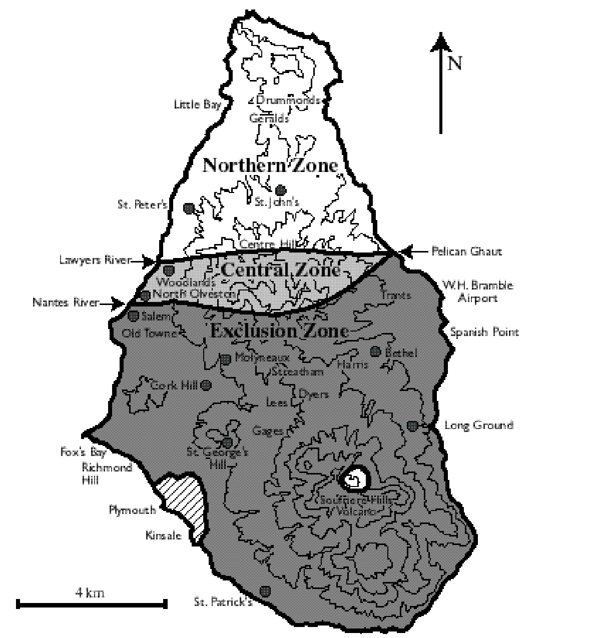
Volcanoes are classified by the type of eruption that occurs. For example, the Hawaiian type erupts with burning lava flowing from deep fissures, often resulting in extensive lava flows. The nature of the activity depends largely on two factors: the viscosity of the magma and the quantity of gas given off. The gases can be produced with the magma or result from the contact of magma with underground or surface waters, producing vapor.

The extension and depth of lava flows depend on their volume, fluidity, speed of advance, and ability to spread laterally. These flows are affected by surrounding topography, and can be diverted through shallow valleys, or drainages, especially in the case of the most viscous flows. Volcanic eruptions can last days or even years, as in the case of the Irazu Volcano in Costa Rica that spewed ash on the capital city of San José for two years.

Areas of Impact

Information on areas of direct impact can be obtained from a historic analysis of events. These areas would include those that might be covered by lava or affected by acid rain and ashfall, as in the case of waterways. Figure 3.3 shows a risk map of the area of expected impact based on a study of the Soufriere Hills Volcano on the island of Montserrat.

Figure 3.3
Volcanic Risk Map, Montserrat
(PAHO/WHO)[17]



Exclusion Zone	Access prohibited except for scientific monitoring or national authorities.
Central Zone	Access to residents only, residents under high state of alert. All residents must have 24-hour access to means of evacuation. Hardhat area residents must have hadrhats and protective masks.
Nothern Zone	Area of significantly lower risk; adequate for scientific monitoring or national authorities.

Evaluation of Hazard

Evaluating the volcanic hazard consists of developing risk maps, including possible effects on the population, rivers, infrastructure, etc.

Recurrence

The historic and prehistoric record indicates that eruption frequency can be very erratic. Volcanoes such as Mount St. Helens (U.S.A.) or Chichón (Mexico) have erupted one or two times per decade. In contrast it has been determined that there have been some 23 major eruptions of Mont Pelée (Martinique) over 8,400 years. Of the five eruptions of Mont Pelée occurring since the 15th century, two were destructive; in 1902 an estimated 29,000 inhabitants of Saint Pierre perished during Pelée's eruption.

General Effects of Volcanic Eruption on Water Systems

A volcanic eruption can cause a chain of disasters whose consequences can be greater than those of the actual eruption, and include:

- Seismic effects generated by the volcanic eruption;
- Flooding and or snow, earth, or mud slides resulting from heating of the earth and localized ground shaking;
- The eruption of ashes, dust, gases, rocks, and lava.

Damages Caused by Volcanic Eruptions

The principal types of damage caused by volcanic eruptions are listed below:

- Contamination of Drinking Water:
  - Contamination of surface drinking water sources due to deposit of ash, the effect of gases or toxic substances, or animal cadavers near intakes or in open water canals;

[17] *Vulnerability assessment of the drinking water supply infrastructure of Montserrat.* Barbados, July, 50 pp. + annexes.

- Contamination of ground water is relatively unlikely, unless the ashfalls are very extensive and/or contain high levels of contaminants, or if they enter well openings (particularly those without protective coverings), thereby polluting stored water;
- Filters or water treatment plants can be contaminated by ashfall in settling tanks, flocculation tanks, or filters;
- Contamination of open tanks or reservoirs.

◆ Damage to Pipelines, Partially Buried Tanks and Other Installations. Lava flows, if abundant and with enough erosion capacity, can cause damage even in buried installations such as:
- Drinking or waste water pipes. Pipes, chambers, and valves can be unearthed, displaced, or crushed;
- Semi-buried tanks or reservoirs can be partially or totally destroyed.

◆ Damage in Surface Works and Buildings. Lava flows or lava fragments thrust large distances can cause damage to practically any type of installation. Depending on the violence of the eruption, the distance of the works to the focus of the eruption, and other factors, damage can vary between slight and total destruction.

The principle effects of volcanic eruptions are:
- Total destruction of components in the direct path of flows are generally restricted to the channels that originate in the volcano;
- Obstruction of intakes, settling basins, pipelines, flocculators, sedimentation tanks, and filters due to ashfall;
- Change in water quality in surface water intakes and in reservoirs because of ashfall;
- Contamination of rivers, streams, and wells in the path of lahars or mudflows;
- Destruction of access routes and of electrical transmission and communication lines;
- Fires.

Droughts

General Effects of Droughts

Droughts, unlike other natural disasters, do not occur suddenly, but are slow-onset disasters resulting from insufficient rain or snow over a period of months, and, sometimes, years. Its effects are principally seen in the decrease or extinction of sources of drinking water. Surface water such as rivers and ponds will usually suffer the effects of drought before ground water, owing to two main factors:

- Surface water generally flows much faster than water filtered through soils, and will reach the sea faster.[18] River volume is quickly affected by drought (or heavy rain) unless there are lakes or artificial reservoirs to regulate annual variations in precipitation and the flow of a corresponding river.
- Ground water has two characteristics that are very effective in minimizing and delaying the effect of the drought (especially if hydrogeologic conditions are favorable). First, the pervious soil provides large water storage capacity, and second, runoff is slow. This speed, which is on the order of a few meters per day[19], implies that the flow is the result of rain infiltration over many years, and fluctuations are less dependent on annual changes in levels of precipitation.

18 For example, with river flow of only 0.1 m/s, surface water would move 8.65 km/d and would take some 12 days to go 100km.

19 With normal velocity on the order of 1m/d, it would take some 274 years to go 100 km.

Damage Caused by Droughts

- *Damage in Surface Sources of Drinking Water*: Depending on the characteristics of surface water sources and the type of drought, impacts could include a decrease in the normal volume of drinking water, which, depending on its severity, could result in moderate to severe rationing or the total extinction of some sources.

  Contamination of sources of drinking water can occur due to:
  - Decrease in the self-cleansing capacity of rivers or ponds because of reduced flow;
  - Increased concentration of pesticides, insecticides, or industrial wastes;
  - Decreases in free oxygen resulting in contamination from fish kill-off;
  - Contamination caused by dead animals near intakes for drinking water.

  It may be necessary to increase or vary chemical additives to lessen health risks or turbidity. Alternative sources may need to be constructed or put into operation.[20]
- *Alternative Drinking Water Sources.* Depending on the duration of the drought and local hydrogeologic characteristics, there can be new demands on ground water for emergency drinking water supplies and for industrial and agricultural use. The resulting decrease in the water table will reduce the productivity of wells, and require increased pumping to obtain the required flow. This may entail an increase in operation costs for wells and a decrease in the productivity of pumps.

  To supplement or replace surface water sources it may be necessary to:
  - Construct and equip emergency wells to supplement drinking water supply;
  - Take over wells used for other purposes (industry, recreation, or agriculture) to provide the public with drinking water.

In summary, the main effects of droughts on drinking water and sewerage systems include:
- Decrease in the flow of surface or ground water;
- Rationing and suspension of service;
- Reliance on water from tank trucks, with the consequent loss of water quality and increase in costs;
- Abandonment of the system.

[20] In many cases this can be accomplished by using underground water intakes such as deep wells.