Chapter 2
Basics of Vulnerability Analysis

Introduction

The natural hazards and local conditions must be taken into consideration when planning infrastructure projects. Many of the problems presented by natural hazards occur because these phenomena are not considered during the conception, design, construction, and operation of the system. The vulnerability analysis described in this document is important for both existing and planned constructions.


José Grases, 1997

The extensive coverage and location of water system components make them vulnerable to different types of hazards

Mitigation and emergency plans are based on the best possible knowledge of the system's vulnerability in terms of: (i) deficiencies in its capacity to provide services; (ii) physical weaknesses of the components to external forces; and (iii) organizational shortcomings in responding to emergencies. Vulnerability analysis identifies and quantifies these weaknesses, thereby defining the expected performance of the system and its components when disasters occur. The process also identifies strengths of the system and its organization (for example, staff with experience in operation, maintenance, design, and construction, who also have experience in emergency response).

Vulnerability analysis meets five basic objectives:

a) Identification and quantification of hazards that can affect the system, whether they are natural or derive from human activity;

b) Estimation of the susceptibility to damage of components that are considered essential to providing water in case of disaster;

c) Definition of measures to be included in the mitigation plan, such as: retrofitting projects, improvement of watersheds, and evaluation of foundations and structures. These measures aim to decrease the physical vulnerability of a system's components;

d) Identification of measures and procedures for developing an emergency plan. This will assist the water service company to supplement services in emergency situations;

e) Evaluation of the effectiveness of the mitigation and emergency plans, and implementation of training activities, such as simulations, seminars, and workshops.

Defining Vulnerability

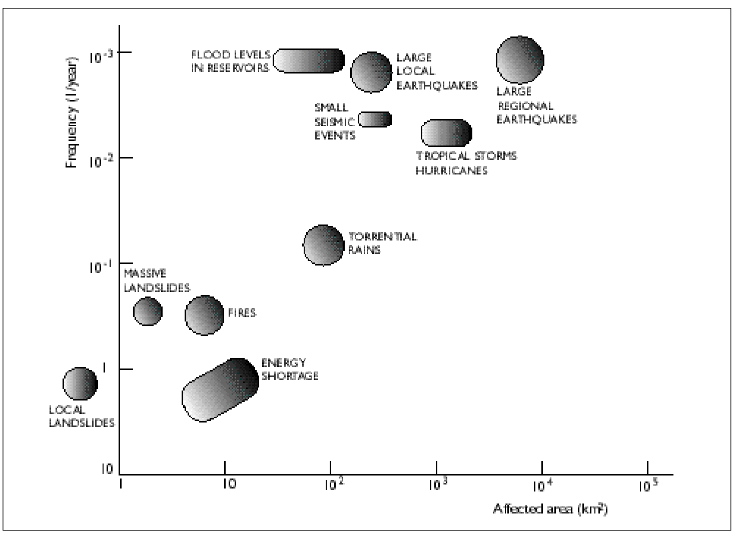
Vulnerability is generally defined as a measure of the susceptibility of an element or combination of elements to fail once they are exposed to potentially damaging natural phenomena. This definition is broad enough to be applied to physical, operative, and administrative aspects of a system. Because there is uncertainty associated with quantifying physical vulnerability, it is expressed as the probability that a certain natural or man-made phenomenon will occur. This is generally expressed as:

P(Hi), or the probability (P) that event (Hi) will occur.

The characterization of the phenomenon, and the nature of the problem, must be determined by the analyst. For example, factors might be ground acceleration, wind speed, river volume, the depth of volcanic ash, level of turbidity of water, etc.

The analysis of statistics on hazards and their consequences leads to a clear distinction between two groups of problems: (a) the danger and intensity of expected events; and (b) the ability of man-made works to resist such events, with a tolerable level of damage.

Figure 2.1 Approximate range of frequency and impact areas of different natural hazards (PAHO/WHO)



Nature of the Problem

In strategies to prevent or mitigate the effects of disasters, it is as important to address the weaknesses of the existing or planned works as it is to define the possible frequency and intensity of expected phenomena. Figure 2.1 shows approximate ranges of frequency and areas of expected impact of hazards along a drinking water pipeline located in north-central Venezuela. This example highlights the uncertainty about expected frequency and areas of impact of the phenomena. The figure also illustrates that the least common phenomena have impacts on larger areas than the more common events. For example, the "maximum regional earthquake" occurs infrequently, but impacts a large area.

Expected Behavior of Physical Components

The development of automated analytical algorithms and the frequent exchange of information on a global scale have helped to predict how construction or installations will behave when subjected to external forces. The degree of uncertainty involved in analyzing vulnerability in man-made works has lessened substantially in recent years.

Characteristics and conditions of structures, such as the resistance of materials, condition of foundations, impurities in the concrete, material used, and condition of pipes, etc., cause the greatest uncertainty about the behavior of existing works when quantifying vulnerability to a certain hazard (Hi).

Quantification of Vulnerability

The vulnerability of a specific component or system is expressed as the conditional probability of occurrence of a certain level of damage (Ej), given that hazard (Hi) occurs. This is denoted as:

$$P(Ej /Hi)$$

The following four levels of damage are frequently used to describe Ej when referring to damage and performance of equipment:

E1 = no damage

E2 = slight damage; equipment is operative

E3 = reparable damage; equipment is out of service

E4 = severe damage or total loss; equipment is out of service

Once a natural phenomenon has occurred (e.g., earthquake, hurricane, flood, etc.) the component or system should be described in terms of one, and only one, of the four conditions listed above. Table 2.1 shows probabilities corresponding to severe damage and/or total loss for different levels of Mercalli intensity in eight elements that form part of a drinking water production and distribution sys-

Table 2.1
Probability of levels of severe damage and/or ruin to a water supply and distribution system (earthquake occurring during dry season)

Mercalli intensity	Surge tank	Earth dam	Large diameter pipes		Pumping plant and substations	Bridge	Tunnels	Treatment plant
			Level	Slope				
VI	--	--	--	--	--	--	--	--
VII	--	0.05	--	0.02	0.02	--	--	--
VII	0.05	0.20	--	0.15	0.10	0.05	0.02	--
IX	0.4	0.50	0.05	0.40	0.30	0.15	0.10	0.15
X	0.70	0.80	0.20	0.80	0.60	0.30	0.30	0.40
P(1)	2.2 X 10^{-3}	4 X 10^{-3}	0.4 X 10^{-3}	3.1 X 10^{-3}	2.3 X 10^{-3}	1.1 X 10^{-3}	0.7 X 10^{-3}	0.9 X 10^{-3}

*Annual probability of severe damage and/or ruin occurring in an area 15 km south of the Caracas Valley.
Source: PAHO/WHO, Case Study. *Vulnerabilidad de los sistemas de agua potable y alcantarillado frente a deslizamientos, sismos y otras amenazas naturales.* Caracas, Venezuela, 1997.

tem. The values of P (Er/Ii), where Er represents total ruin and Ii represents the five grades of Mercalli intensity (see Chapter 3 for a description of Mercalli intensity). This table combines analyses made regarding the expected response of the components of the system taking into consideration the design and construction criteria existing when the studies were conducted.

When to Conduct Vulnerability Analysis

Vulnerability analysis should be carried out in institutions and infrastructure if the effects of natural disaster would cause an emergency situation or place demands on the system that would exceed response capacity. For example, businesses that produce or sell petroleum and its derivatives have established criteria for acceptable levels of social risk (see Figure 2.2). When a level of risk is not acceptable, engineering measures must be adopted to reduce that risk. These criteria should be adapted to apply to drinking water supply and sewerage systems.

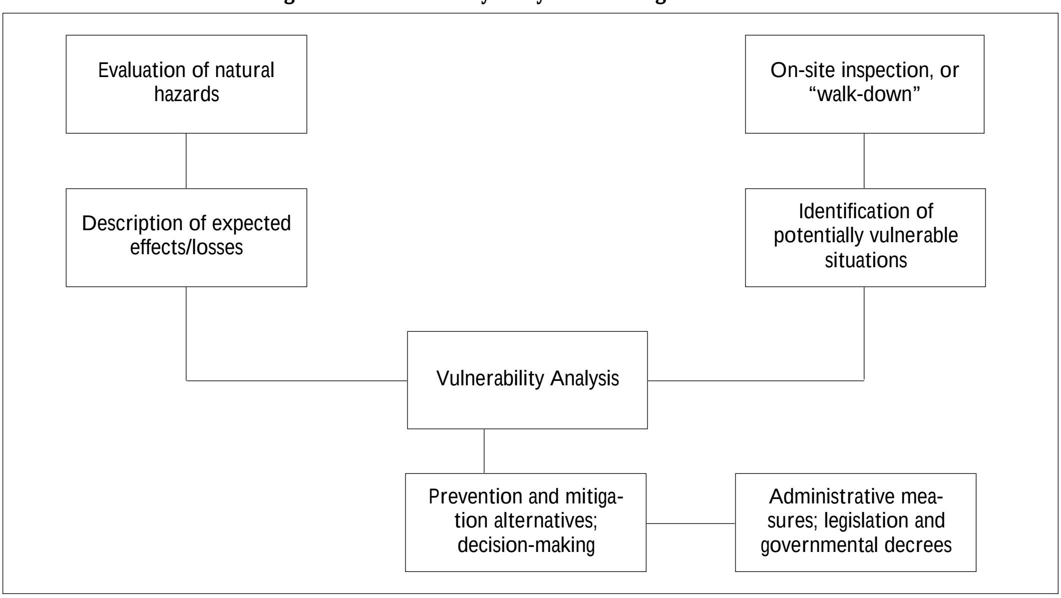
Calculating Physical Vulnerability

General Scheme

Figure 2.2 shows the general approach to evaluating vulnerability and mitigation measures. The so-called "walk-down," or preliminary evaluation, corresponds to a Level-1 analysis and is based on site inspections and simple calculations. A Level-2 analysis requires a more rigorous examination. In either case, the results should be quantified to facilitate decision making by the responsible authorities.

Whether conducting a Level-1 or Level-2 analysis, certain results can be based on previously collected data. For example, the calculation of the number of breaks in pipelines by unit length can be based on existing data (see Annex 3). In many components, however, such data do not exist (such as in surge tanks, high dissipation towers, thin-wall differential tanks, or other components). In such cases, it is advisable to use the methodology outlined in this document.

Figure 2.2
Diagram for vulnerability analysis and mitigation measures



Damage Probability Matrices

Damage probability matrices (described below) are helpful in quantifying results of the physical vulnerability analysis. Using Ej to represent a determined level of damage, the results of the vulnerability analysis can follow the format used in Table 2.2. For example, P42 represents the probability that if hazard H2 occurs, it can be expected that the loss to the component described for that matrix will reach E4. For any phenomenon, i, the following condition applies:

$$(p1i + p2i+ p3i+p4i) = 100\%.$$

Table 2.2
Format for the damage probability matrix

Level of damage	$P(E_j/H_i)$*			
	H_1	H_2	H_i	H_n
E_1	P_{11}	P_{12}	P_{1i}....................	P_{1n}
E_2	P_{21}	P_{22}	P_{2i}....................	P_{2n}
E_3	P_{31}	P_{32}	P_{3i}....................	P_{3n}
E_4	P_{41}	P_{42}	P_{4i}....................	P_{4n}

* Conditional probability that if hazard (H_1) occurs, the level of damaje will be E_j.

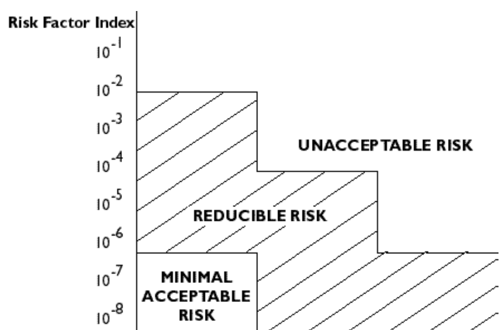
System Vulnerability

Vulnerability analysis should be conducted by a team of professionals with extensive experience in the design, operation, maintenance, and repair of a system's components.

The vulnerability detected in a system, whether physical, operational, or administrative, will be synthesized in matrices that record basic information to be used in the elaboration of the emergency and disaster mitigation and response plans. The matrices used to identify the strengths and weaknesses of the system are listed below (they are described in greater detail in Chapter 4).

- Matrix 1: Operation aspects (Matrix 1A for drinking water and Matrix 1B for sewerage systems)
- Matrix 2: Administrative aspects and response capability
- Matrix 3: Physical aspects and impact on service
- Matrix 4: Emergency and mitigation measures (Matrix 4A for administration and response capacity and Matrix 4B for physical aspects)

Figure 2.3
Criteria for acceptable levels of social risk



	SEVERE ACCIDENT	MAJOR ACCIDENT	CATASTROPHIC ACCIDENT
DEATHS:	1 - 10	11 - 50	> 50
INJURIES:	10 - 100	101 - 500	> 500
LOSS OF EARNINGS:	1 - 30 DAYS	30 - 90 DAYS	> 90 DAYS
ENVIRONMENTAL IMPACT:	REVERSIBLE W/IN 1 - 5 YEARS	REVERSIBLE AFTER 5 YEARS	IRREVERSIBLE
MATERIAL DAMAGES:	US$ 1BILLION - US$ 5 BILLION	US$ 5 BILLION - US$ 250 BILLION	> US$ 250 BILLION

Necessary information includes: a detailed description of organizational and legal aspects; the availability of resources for emergency response; the characteristics of the zone where different components of the drinking water supply and sewerage system are located; the vulnerability of the physical components; and the response capacity of the services.

Before beginning the study, the team should compile diagrams and plans; information on materials, dimensions, and volumes; and any other information that characterizes the system.

Matrices 1A and 1B—Operation Aspects

The operation aspects in Matrices 1A and 1 B refer to aspects of the performance of the system. Data for each component, e.g., flows, levels, pressure, and quality of service should be reviewed. For drinking water services, it is essential to know the capacity of the system, the amount supplied, the continuity of service, and quality of water. For sewerage systems, it is necessary to know the coverage, drainage capacity, and quality of effluents.

The description should be accompanied by diagrams showing how the system functions. It should also note different modes of operation and conditions of service because of seasonal variation. This information is included in both Matrix 1A and Matrix 1B (operation aspects for drinking water and sewerage systems, respectively).

Aspects relating to the capacity and continuity of service in components of the drinking water system include: intakes, pipelines, treatment plants, storage tanks, and the supply area, among others. This information will determine how the supply of drinking water will be affected by failure in one or several of the system components. For sewerage systems, the information is similar, with the main differences being in the conveyance, treatment plants, and final disposal of the waste water.

Also included in this matrix is information about how the water supply company communicates information and warnings about the emergency situations, failures in components of the system, and service restrictions affecting users. The information systems that the water service company may utilize include:

- *Inter-institutional information and warning systems*, such as systems connecting the water service company and civil defense agencies, meteorological institutes, geophysical institutes, among others, that provide warnings about the proximity or possibility of a specific natural phenomenon occurring. This information will facilitate decision making for water service company personnel.
- *Information and warning systems within the company* will identify defective performance of components through remote communication devices, and will instruct personnel on emergency response procedures.
- *Information for system users* will be communicated using the mass media and news bulletins. This will alert users to conditions and restrictions in the delivery of drinking water and sewerage services following a disaster.

Matrix 2: Administration and Response

To evaluate limitations of the systems, it is important to know performance standards and available resources that could be used for water supply and disposal of waste water in emergency situations and in the rehabilitation phase. This information will be compiled in Matrix 2—Administration and Response. Ability to respond to a disaster can be determined by considering aspects of institutionalized disaster prevention, preparedness, and mitigation measures; operation and maintenance of the system; and the level of administrative support provided in the company.

The following information about institutional organization should be documented:

(i) Existence of mitigation and emergency plans
(ii) Membership and responsibilities of the emergency committee
(iii) Existence of a committee responsible for drafting the mitigation plan
(iv) Evaluation of the warning and information system
(v) Inter-institutional coordination with energy and communications companies, municipal authorities, civil defense, and other institutions.

The system's operation and maintenance have a direct influence on the vulnerability of the system and its components, and should be evaluated in terms of:

(i) Existence of suitable planning, operation, and maintenance programs that incorporate disaster prevention and mitigation measures;
(ii) Presence of personnel trained in disaster prevention and response;
(iii) Availability of equipment, replacement parts, and machinery.

Location can be the principal cause of vulnerability of components of the water system.

The water service company's administration is responsible for facilitating prompt and efficient response in repairing damage to components of a system in case of disaster. The company should have administrative mechanisms that will allow, among other things:

(i) Expedient dispersal and management of funds and emergency supplies in emergency situations;
(ii) Logistical support for personnel, storage, and transportation;
(iii) Ability to contract private companies to assist in rehabilitation and application of mitigation measures.

Matrix 3—Physical Aspects and Impact on Service

In most cases, vulnerability of drinking water and sewerage systems to disasters is closely linked to weaknesses in the physical components of the system. Drinking water and sewerage systems are spread over large areas, composed of a variety of materials, and exposed to different types of hazards. Different types of hazards should be considered for each component depending on its location in the system and risks present in an area. Each hazard should be prioritized depending on its possible impact on the system. For example, intakes located at high altitudes could be more susceptible to strong rains and/or landslides, and less susceptible to earthquakes. To identify the areas of impact on the system, it is advisable to superimpose system diagrams over maps showing existing hazards.

To determine the level of service that can be provided during an emergency, it is important to estimate the time it will take to repair damage, what the system's capacity will be following a disaster, and how damage will affect service in terms of quality, continuity, and quantity. This information, along with that relating to specific hazards should be entered in Matrix 3.

José Grases, 1997

The incorrect selection of sites or design are the prinicpal cause of system vulnerability

Matrices 4A and 4B—Mitigation and Emergency Measures

The desired outcome of vulnerability analysis is, logically, the application of prevention and mitigation measures to correct weaknesses revealed by the study. Technical recommendations and cost estimates to apply measures should form part of the analysis. Some mitigation measures will be technically complex and require additional studies on engineering designs and costs. Mitigation measures are applied to the most vulnerable components, whether found in operational, administrative, or physical elements. Information about these measures is presented in Matrices 4A and 4B.