Natural Disaster Mitigation in Drinking Water and Sewerage Systems

Guidelines for Vulnerability Analysis

Pan American Health Organization
Regional Office of the
World Health Organization

Disaster Mitigation Series

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Preface and Acknowledgments

For several years, the Pan American Health Organization has provided technical assistance to the water and sanitation authorities in Latin America and the Caribbean in improving their preparedness for natural disasters and other emergencies. In 1993 a book was published that served as a guide for organizing and planning responses to emergency situations that affect drinking water and sewerage systems. In addition to having emergency response capability, it is necessary to identify and carry out measures that will lessen the impact of disasters on components of water systems. Applying disaster prevention and mitigation measures is the next step in the disaster preparedness process.

This book provides basic tools that water service companies can use to evaluate the components of their systems that are vulnerable to major natural hazards (earthquakes, hurricanes, floods, landslides, volcanic eruptions, and drought).

The methodology for vulnerability analysis was presented in a document prepared by Herber Farrer for the Pan American Sanitary Engineering Center in 1996. Based on this work, four case studies were conducted with the financial support of the Humanitarian Assistance Work Group of the Ministry of Foreign Affairs of Germany. The purpose of these studies was to validate the methodology that is presented here. The four studies focused on: experience with earthquakes in Costa Rica, prepared by Saúl Trejos; landslides, prepared by José Grases in Venezuela; floods in Brazil, prepared by Ysnard Machado; and finally, a study prepared by David Lashley in Barbados on hurricanes and volcanic eruptions. The elaboration of this document was possible thanks to the valuable technical contributions of these individuals. In addition, we would like to thank Vanessa Rosales of Costa Rica, who made valuable comments during the final revision of this text.

Introduction

The countries of the Region of the Americas are exposed to a large variety of natural hazards. Earthquakes, hurricanes, volcanic eruptions, landslides, droughts, and floods affect many of the countries of the Region and cause major disasters. The number of deaths, injuries, and persons seriously affected, damage to infrastructure, disruption of public services, and economic losses are on the increase and present a threat to the development of the countries of Latin America and the Caribbean. Table 1.1 lists some major disasters in recent years.

Table 1.1. Selected natural disasters affecting countries of the Region of the Americas and the Caribbean

Year	Event	Name	Area Affected
1987	Earthquake	Napo Province	Ecuador
1989	Hurricane	Hugo	Caribbean
1989	Earthquake	Loma Prieta	California, U.S.A.
1991	Forest Fires		California, U.S.A.
1991	Earthquake	Limón	Costa Rica
1992	Hurricane	Andrew	Florida, U.S.A.
1993	Floods	Mississippi Valley	U.S.A.
1994	Earthquake	Northridge	California, U.S.A.
1995	Hurricane	Luis	Caribbean
1995	Earthquake	Trans-Cucutá	Ecuador
1995	Volcano	Soufrière Hills	Montserrat
1995	Hurricane	Marilyn	Caribbean
1996	Earthquake	Nasca	Peru
1996	Hurricane	Fran	U.S.A.
1997	Earthquake	Cariaco	Venezuela
1998	Earthquake	Aiquile-Totora	Bolivia

If we add to natural hazards the increasing vulnerability caused by human activity, such as industrialization, uncontrolled urbanization, and the deterioration of the environment, we see a dramatic increase in frequency and effects of disasters. Disasters follow a cycle that includes the stage prior to impact, response to the disaster, and reconstruction and rehabilitation activities. The costs of reconstruction consume a major portion of available assets, reduce the resources for new investment, and can delay the development process.

Drinking water and sewerage services are essential in ensuring the health and well-being of populations and as such fulfill an important role in the development process. In emergency or disaster situations these basic services are imperative for the rapid return to normalcy. The impact of a natural disaster can cause contamination of water, breaks in pipelines, damage to structures, water shortages, and collapse of the entire system. Depending on the level of preparedness that the water system authorities have adopted, repair of the system can take days, weeks, and even months.

The best time to act is in the first phase of the disaster cycle, when preventive and mitigation measures can strengthen a system by reducing its vulnerability to hazards.

Drinking water and sewerage supply are the direct responsibility of companies, public or private, that provide the service. A combination of programs are directed at guaranteeing high quality and uninterrupted service to clients. Performance of the systems in emergency situations should be planned in the same way that programs for routine operation and preventive and corrective maintenance are planned. Even during routine operations there are often service interruptions due to equipment failure, breaks in pipelines, and rationing due to low water supply. The risk of damage to water systems in disaster situations dramatically increases with factors such as uncontrolled growth in urban areas, deficiencies in infrastructure, and, above all, the location of system components in areas that are vulnerable to natural hazards.

The forces of nature should not be viewed as uncontrollable, against which no action can be taken. Damage is lessened when measures are taken to strengthen systems and to have response mechanisms in place in the event of an emergency. The implementation of programs that continually update disaster mitigation and emergency response plans guarantee a responsible and effective response to disasters.

Vulnerability analysis, the subject of this document, provides a simple approach for addressing the question: “What is the vulnerability of each component of the system to the impact of hazards existing in an area?” The outcome will assist in defining the necessary mitigation measures and the emergency response procedures should a disaster occur before mitigation measures are carried out, or if the measures do not prevent damage.

Vulnerability analysis is the basis for establishing mitigation and emergency plans for (i) execution of the mitigation measures for different components of the system, (ii) organization and preparation, and (iii) attention to the emergency. It requires a response before, during, and after the disaster and includes a combination of measures with the common objective of reducing the impact on provision of service and enuring that drinking water and basic sanitation services are restored to the affected population in a timely manner.

This book is organized into four chapters. The first explains how an emergency and disaster program is established, and defines the program's content and steps to be taken to develop, execute, and keep the program up to date. The second chapter outlines the principles of vulnerability analysis for drinking water and sewerage systems. It discusses how vulnerability is quantified and how damage probability matrixes are used in the process. The third chapter provides a general description of the major natural hazards and discusses the type of damage they can cause to components of the water system. The fourth chapter presents new approaches to applying vulnerability analysis to different hazards. It provides a detailed description of how to complete the damage probability matrixes.

Three annexes, a short list of definitions, and a bibliography complete this volume.

These guidelines are meant to be consulted by engineers and technical personnel in water service companies to project the performance of drinking water and sewerage systems in case of natural disasters.

Chapter 1

Planning Emergency Preparedness and Response[1]

Introduction

All drinking water and sewerage systems are subject, to a greater or lesser degree, to hazards. Emergency preparedness is vital even when hurricanes, earthquakes, floods, etc., do not pose a direct threat, since accidents and breaks in pipelines can contaminate water and seriously affect service.

Entities operating and maintaining these systems should have strategies directed at reducing the vulnerability of the systems and providing the best possible response once an emergency arises. The emergency plan should establish the necessary procedures to quickly and effectively mobilize existing resources, and, if necessary, to request outside assistance.

Vulnerability analysis is the basic tool for meeting both objectives. Once the hazards specific to a particular zone are identified, vulnerability analysis assists in determining: (a) the physical shortcomings of system components; (b) weaknesses in the organization and support provided by the water service company; and (c) limitations in terms of quantity, continuity, and quality of service.

Vulnerability analysis applies not only to the physical structure of the system, but also to the organization and management of the water authority or company. For example, in the financing division of the company, the analysis would determine whether there are sufficient funds to carry out mitigation and emergency measures, or whether resources have to be reallocated to ensure that mitigation and emergency plans are viable.

This chapter addresses the process involved in planning the emergency preparedness and response program, indicating its content and the steps, in order of priority, necessary to execute the program and keep it up to date.

Emergency Preparedness and Response Program

In areas affected by extreme natural phenomena, there is a tendency to believe that these are rare events that will not recur with the same intensity for many years. Actually, the consequences of these phenomena increase in severity, not because they increase in intensity and frequency, but because the at-risk population and infrastructure continue to grow.

The implementation of mitigation measures not only improves the capacity of emergency response, but protects routine operations and makes the systems more reliable. For example, redundant or “back-up” measures designed for emergencies also safeguard routine operations. Likewise, strengthening routine corrective and preventive maintenance of installations favors effective response during emergencies.

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[1] Additional information on developing an emergency and disaster program can be found in the document *Planificación para atender situaciones de emergencia en sistemas de agua potable y alcantarillado* (PAHO, Cuaderno Técnico no. 37, Washington, D.C., 1993).

The image of the water service company will be improved by acting in a quick and efficient way in an emergency situation. If an emergency program is to become a permanent company program, top company officials must be motivated, vulnerability studies completed, and emergency and mitigation plans carried out.

For the emergency preparedness and response program to be successful, it should be included in the institutional planning process. That is, the program should complement the routine corrective and preventive aspects of operation and maintenance.

To ensure the success of this program, the water service company should: (a) require the broad participation of employees; (b) maintain ongoing promotion and training; (c) carry out simulations and evaluation exercises to test emergency plans; and (d) disseminate information on other incidents (for example, data on damage due to earthquakes presented in Annex 1).

Institutionalization and Organization of the Program

The following aspects should be considered for the institutionalization and organization of the emergency preparedness and response program:

- Legal aspects, including national and institutional standards.
- Institutional organization and coordination, including:
  - Emergency committee
  - Committee for drafting mitigation and emergency plans
  - Emergency operation centers
  - Warning and emergency declarations
- Inter-institutional coordination, including:
  - National emergency commission
  - Other institutions

Legal Aspects

The program should be developed within the existing legal framework of the country and should form part of the national plan. Establishing this from the outset will allow coordination of the plan between the water authority and State institutions, such as civil defense or emergency commissions.

National Standards

Countries have laws, standards, and regulations that establish the institutions responsible for emergency response at the national level, such as civil defense, national emergency agencies, etc. At the local level there are agencies with clearly defined functions and mechanisms for coordination and financing. These standards should be consulted before creating the emergency preparedness program to ensure conformity with regulations, and to ensure that there is adequate support and cooperation between institutional and national plans.

Institutional Standards

Providers of drinking water and sewerage services have their own regulations that define standards of quantity, continuity, and quality of services. Emergency plans will ensure that services are restored to normal conditions as quickly as possible. Disaster conditions pose the greatest risk for public health and may require the use of alternative sources of drinking water and means to dispose of waste water.

The first step that water service companies should take is to support national standards, and to resolve at the highest management level to approve the emergency preparedness and response program. This will give the program the same stature as other institutional programs.

Institutional Organization

The institution providing the services must have an organization that is capable of determining the vulnerability of the systems and their components, implementing mitigation measures, and operating the systems in case of emergencies. It is the responsibility of top management to delegate the development of the program and to approve it. The general director or manager of the company should be a member of the emergency committee.

Emergency Committee

As part of the development of the emergency preparedness and response program, an emergency committee should be established. Company managers should be members of the committee, and will be responsible for coordinating the program's activities. Typically, staff holding the following positions will make up this committee:

- General director or manager of the company
- Supervisors in areas of production, operation, and maintenance service
- Planning director
- Finance director
- Engineering director
- Procurement director
- Public relations director
- Representative of the committee responsible for drafting the emergency plan

The functions and responsibilities of this committee are to:

- Participate in the committee responsible for drafting mitigation and emergency plans;
- Coordinate the drafting, approval, execution, and evaluation of the plans;
- Establish and maintain communication and coordinate activities with the public entities responsible for emergency response at the local or national level;
- Maintain contact with commercial suppliers or providers of equipment, producers of chemicals, and professional associations that can contribute to disaster and emergency response;
- Carry out periodic review and updating of the emergency plan;
- Develop necessary budgets for implementing the plan and present them to the appropriate units;
- Declare internal emergency alerts if an emergency has not been declared by national authorities;
- Provide and supervise ongoing training of personnel in emergency procedures.

At the regional and local levels, emergency committees should also be established and include directors in the areas of administration, production, operation, and maintenance.

Drafting Committee for Mitigation and Emergency Response Plans

This committee is multidisciplinary and usually consists of personnel from different areas of the company. The major responsibility lies in the areas of operations and engineering, but planning, administration, and finance must also be represented.

The functions and responsibilities of the committee are to:

- Develop mitigation and emergency response plans;
- Establish the terms of reference and coordinate specialized vulnerability studies;
- Evaluate the effectiveness of the plan during simulations and in actual situations.

Emergency Operations Center

Once the emergency committee is installed, a center or various centers should be established where the committee and key personnel can meet during emergency simulations, the warning period, and actual emergencies. Typically, regular office space is allocated for this function, but the emergency plan should specify at least one alternate site that can be used if the first is inoperable. The emergency operations center should have the following characteristics:

- Minimal vulnerability to the most common hazards in the area
- Quick access routes
- Location within the drinking water and sewerage service area
- Reliable communication facilities, including telephones, fax, radio transmitter and receiver, television, and radios with commercial, civil band, and ham radio frequencies
- Back-up power system
- 24-hour security
- Detailed plans of all systems and copies of the emergency plan and of pertinent documentation
- Adequate equipment and furnishings for meetings and office work
- Transportation and computer equipment
- Safe
- Registry of activities
- One-week supply (at a minimum) of equipment and food.

Warnings and Emergency Declarations

Warnings and emergency declarations activate the emergency plan both at the onset and conclusion of an emergency.

The national emergency committees provide warnings or declare emergency situations at the national or regional level. These declarations should be sufficient to activate the emergency plan of the water service company. However, the company’s emergency committee should have the ability to declare emergencies in the case of damage or failure in the system, such as temporary loss of intakes, accidents that affect the service, drought, etc. These declarations are of special importance since they activate all the procedures established in the plan, including those involving the use of funds.

Inter-Institutional Coordination

Coordination among institutions is basic to emergency and disaster response. Without such coordination chaos will result, impacting the users of the service and the ability to carry out rehabilitation.

National Emergency Committee

The water company’s emergency plan should be developed in coordination with the national plan. In most cases, the leading institution (civil defense, national emergency committee) collaborates in the development of the sectoral plan and can provide resources and channel technical assistance for required studies and analysis.

Other Service Institutions

The water company's emergency plan should consider necessary coordination with other public service companies such as energy, communications, police, firefighters, etc. Agreements and mutual assistance among institutions facilitate efficient response. It is important to have detailed knowledge of the human resources, material, and equipment available at the local level.

Vulnerability Analysis

This is carried out in accordance with directives presented in this document.

Mitigation Plan

The outcome of the vulnerability analysis will be the mitigation plan, which comprises improvement and structural retrofitting measures directed toward increasing the reliability of system components and of the system as a whole.

The mitigation plan will prioritize the activities to be carried out and will specify those responsible for executing the plan, a timeframe for completion, and estimated costs. The plan should also consider the need to adapt selected buildings to function as emergency operations centers.

Emergency Response Plan

Once the vulnerability analysis has been carried out, the emergency plan should be drafted. The plan will include the procedures, instructions, and necessary information for preparing, mobilizing, and using the company's resources in the most effective way in case of emergency.

The plan should be designed to respond to emergencies and disasters with the resources that are currently available within the company, assuming that an emergency could occur at any moment. In other words, it should not be an ideal, but a realistic plan. With time, as mitigation measures are carried out and equipment is obtained for emergencies, the plan will be modified.

The plan should be kept up to date and be available at any time for use by persons involved in emergency response. Its success will depend on how simple and practical it is to carry out, as well as on the knowledge of the persons involved, obtained through periodical training and simulation exercises.

At a minimum, the plan should comprise the following:

1. Objective: hazards to which plan is directed
2. Geographic area of application
3. Relationship to the national emergency plan (that of the national emergency commission or civil defense agency)
4. Organization: central, regional, and local emergency committees, and those responsible for drafting the plan (functions and responsibilities)
5. Description and operation of the system (document with sketches)
6. Emergency operations centers
7. Warning and emergency declarations
8. Personnel plan (training); key personnel and their addresses
9. Security plan
10. Transportation plan

11. Communications
12. Supply plan
13. Emergency supply warehouse/stores
14. Institutional coordination
15. Coordination with private companies and suppliers
16. Response to neighboring supply systems operated by other companies
17. Damage assessment
18. Priorities for water supply
19. Alternative sources of water supply and disposal measures for waste water
20. Information for the press and public
21. Procedures for operation in emergency situations
22. Procedures for inspection following an emergency
23. Use of water tank trucks, portable tanks, and other means of transporting drinking water
24. Management of funds for:
    - Emergency committee
    - Drafting, evaluation, and control committee for emergency plan
    - Emergency operations centers
    - Warning and emergency declarations
25. Necessary budgets for implementation of the plan, including:
    - System plans
    - Operation plans
    - Results of first phase of vulnerability analysis
26. Training of clients in the correct use of water in emergency situations
27. Management of information during the emergency

If companies manage several cities or have regional operations, it is convenient for each city and region to have it’s own plan, with the plans integrated at the central level.

Chapter 2
Basics of Vulnerability Analysis

Introduction

José Grases, 1997

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

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.

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

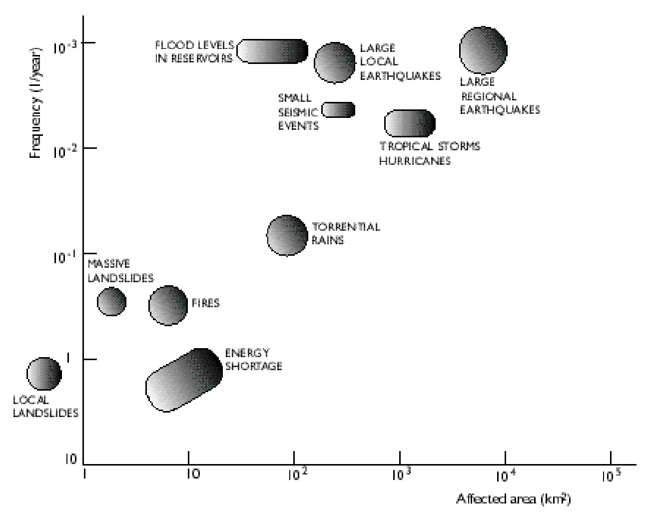
Vulnerability is generally defined as a measure of the susceptibility of an element or combination of elements to fail once they are exposed to potentially damaging natural phenomena. This definition is broad enough to be applied to physical, operative, and administrative aspects of a system. Because 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.

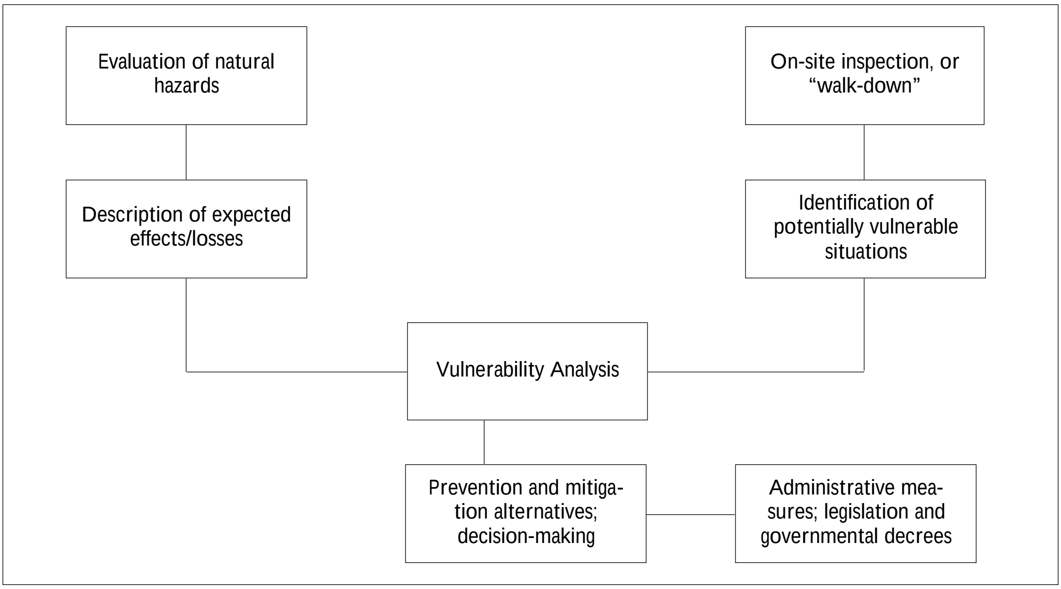
Calculating Physical Vulnerability

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.

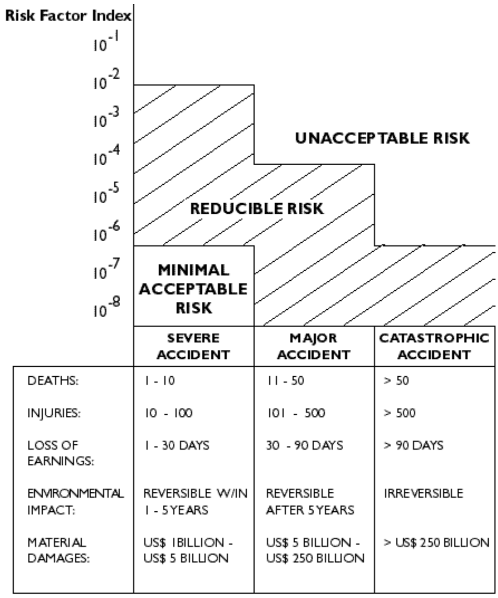
System Vulnerability

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.

José Grases, 1997

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

José Grases, 1997

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

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.

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.

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.

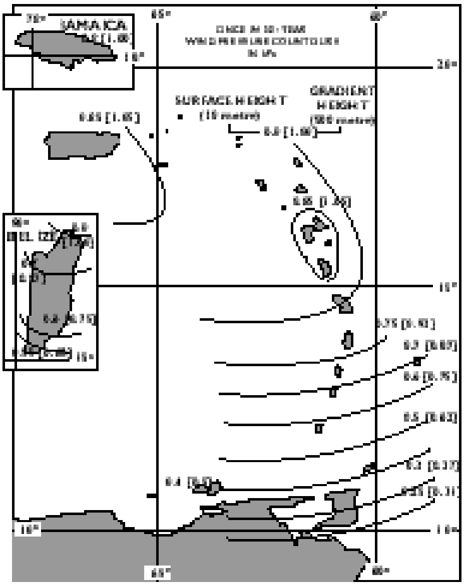
To evaluate earthquake hazards, one should have information on seismic sources and their mean rates of displacement, attenuation, variances, and design standards. Normally, seismic vulnerability analysis is carried out by a team of professionals with expertise in specific techniques for seismic risk 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

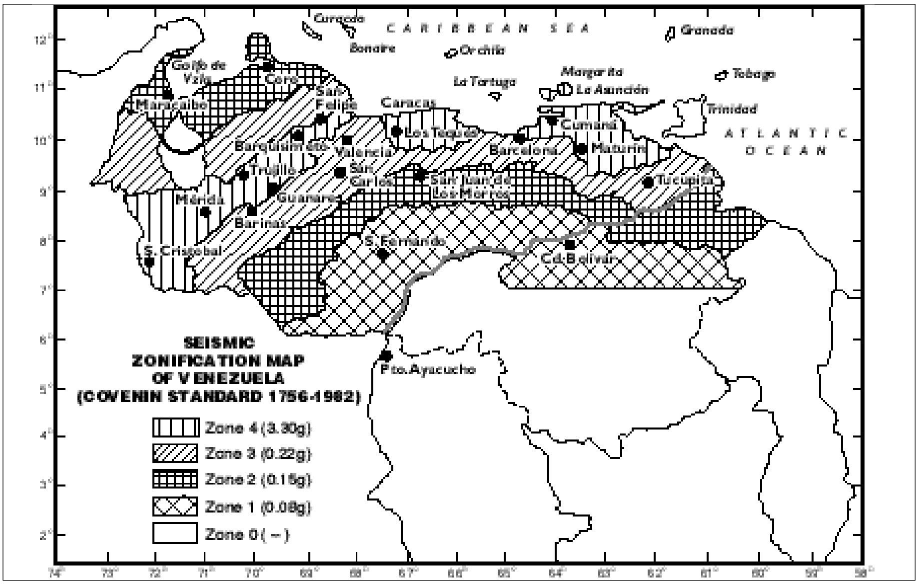
The information presented in this section will assist in completing Matrix 3, Physical Aspects and Impact on Service (presented in Chapter 4). A description of the estimated damage in different components of systems is provided for each type of hazard. This is based on information gathered by the Economic 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)



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[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).

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[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

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[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.

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[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

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[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.

The earthquake exerts inertial force on above-ground structures,

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

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[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).

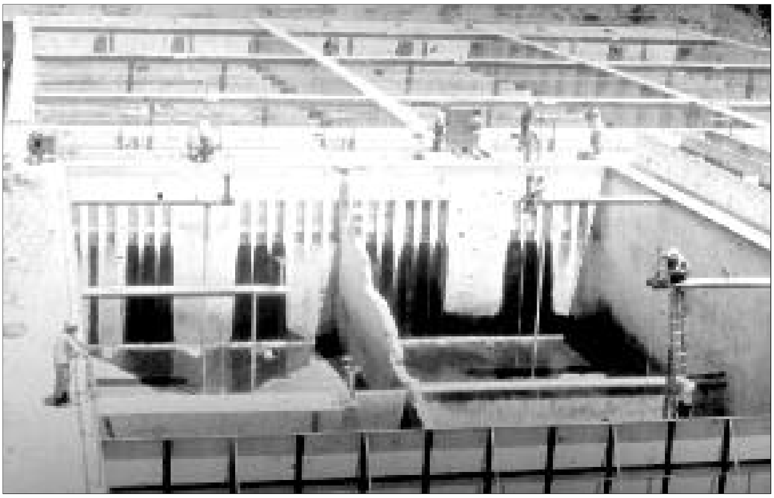
iii) *Locating Damage in Pipes:*

❑ *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.

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[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.

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[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

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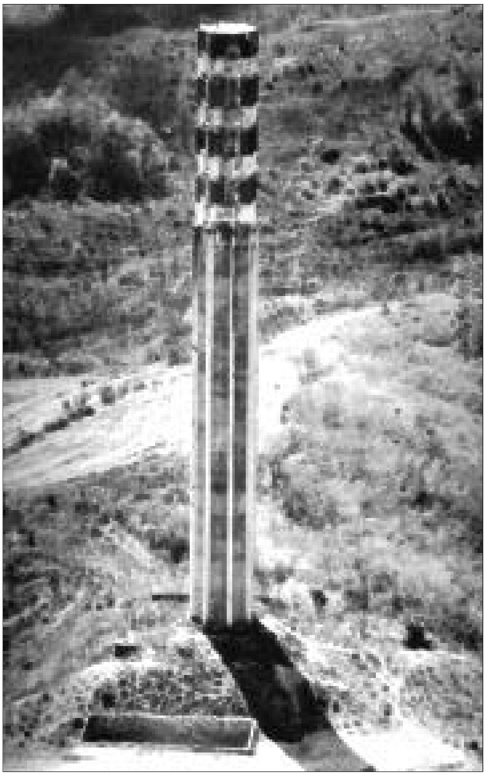
[13] Simpson, R.H. *The hurricane disaster potential scale.* Weatherwise, 27, 169-186, 1974

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;

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[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

José Grases, 1997

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.

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[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.

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[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.

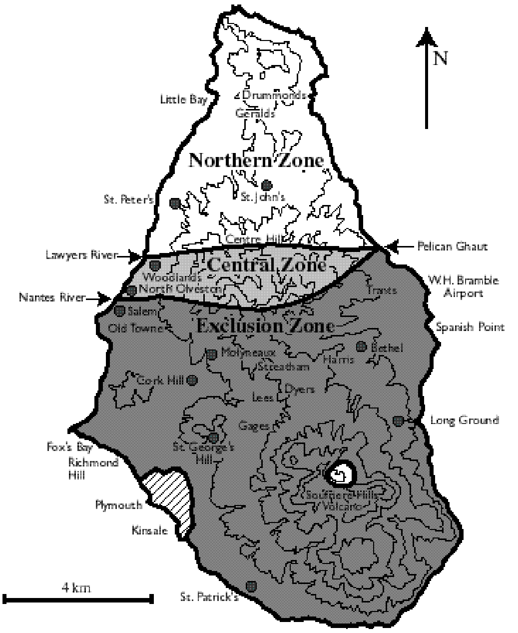
Evaluation of Hazard

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.

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.

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;

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[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.

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[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.

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

Chapter 4
Vulnerability Analysis

Introduction

This chapter outlines the methodology for vulnerability analysis for different kinds of natural hazards, and the most important points for analysis.

Using a matrix allows easy visualization of the elements involved in vulnerability analysis. Four matrices are presented, addressing operative aspects, aspects of administration and response capacity, physical aspects and impact on the service, and mitigation and emergency measures. Each of these matrices has a general heading and space where the name and type of system can be entered. The information required for the matrices on operative and administrative aspects and response capacity is the same, regardless of the type of hazard evaluated. Annex 2 provides an example of matrices completed during an analysis of the water system in Limón, Costa Rica.

The analysis process requires knowledge of the system, its components, and its operation, as well as characteristics of potential hazards to the system. It is also necessary to have an understanding of organizational and legal factors affecting the operation of the system.

Identification of Organization and Prevailing Regulations

National and regional organization. Before carrying out the vulnerability analysis, it is necessary to identify the national and regional organizations, their standards of operation, and the resources that are available for water supply and disposal in emergency situations and during the recovery phase following a disaster. For example, public service companies typically maintain portable electrical plants and heavy equipment for construction, which can be used for repair of the drinking water and sewerage systems.

Legislation. General legislation covering emergency and disaster response as well as specific legislation relating to aspects of different phenomena should be identified. These might include:

i) Legislation and regulations regarding disaster response as they pertain to civil defense, emergency commissions, and national, regional, and local organizations, etc.;
ii) Legislation regarding civil responsibility in disaster management (e.g., pertaining to businesses and officials);
iii) Seismic codes and regulations applied in existing and new structures. Ascertain whether codes have been updated to conform with prevailing knowledge about seismicity in a country or region. The same applies to construction standards and regulations in areas susceptible to other hazards (e.g., hurricanes, floods, and volcanic eruptions).

Description of the Area, System, and its Operation

Description of the area: The area served by the system should be described using data such as location (including distance to other population centers, characteristics of region in which it is found); climate (temperature, precipitation); population (rate of growth, density); urban structure (residential, industrial, and commercial zoning, type of housing); public health and sanitation (health services, trash collection); socioeconomic development (economic activity, unemployment); and data on the geology, geomorphology, and topography of the zone. It is also important to include information on services such as communication systems, access routes, and general public utilities.

Physical and functional description of the system: Physical data about the system should include the most relevant information about each component, such as materials, diameters, masses, anchorings, etc., using blueprints, plans, and details. The functional description of the system will specify flow, levels, pressures, and service quality. The description will include information on operation of the system, specifying, together with respective diagrams in the case of drinking water, data such as amount supplied, capacity, continuity of service, and water quality. For sewerage systems, in addition to the diagrams, data will include coverage, drainage capacity, quality of effluents, and receiving bodies. Also to be taken into account are seasonal variations (summer and winter) that could affect modes of operation and condition of the services.

Methodology

Matrix 1A — Operation Aspects (Drinking Water Systems)

In the first column of Matrix 1A the analyzed component of drinking water systems will be noted (e.g., the intake, treatment plant, storage tanks, area supplied, etc.). In the second column, include the capacity of the component, using corresponding units such as volume (m^3), volume of flow (m^3/s), or others; in the third, the current demand; and in the fourth, the surplus or shortage, expressed in the same units used to describe capacity. In the fifth column, the presence and performance of instruments for remote warning systems associated with each of the components should be recorded (e.g., accelerographs, limnimeters, etc.). If a component necessary for the system is not present (e.g., a reservoir), "zero" capacity will be entered in the second column, and a deficit recorded in the fourth column.

In the lower left section of Matrix 1A there is a space to enter the names of entities and institutions that might provide warnings to the water authority about the development or occurrence of natural phenomena. Provide a description of how these entities function. In the lower right section, there is a list of different information channels within the water company and communication systems for providing information to the public.

Matrix IB — Operation Aspects (Sewerage Systems)

For sewerage systems, the collection area, distribution system, treatment plant, and final disposal are noted for each component in the first column of Matrix 1B. Enter coverage for zones in the second column; capacity and deficit in the third column, if they exist; and the presence of remote warning systems in the fourth column. Complete the lower part of the form, indicating information and communication channels, as in Matrix 1A.

Matrix 1A - Operation Aspects

Name of Drinking Water System:

COMPONENT	COMPONENT CAPACITY	CURRENT DEMAND	DEFICIT (-) SURPLUS (+)	REMOTE WARNING SYSTEMS

INTER-INSTITUTIONAL INFORMATION AND WARNING SYSTEMS
☐ Civil Defense
☐ Meteorological Institute
☐ Volcanology Institute
☐ Seismology Institute
☐ Other (list):

WATER COMPANY INFORMATION AND WARNING SYSTEMS
☐ UHF Radio
☐ VHF Radio
☐ Telephone
☐ Other (list):

INFORMATION SYSTEM FOR PUBLIC
☐ Radio
☐ Television
☐ Printed Brochures
☐ Other:

Matrix 1B - Operation Aspects

Name of Drinking Water System

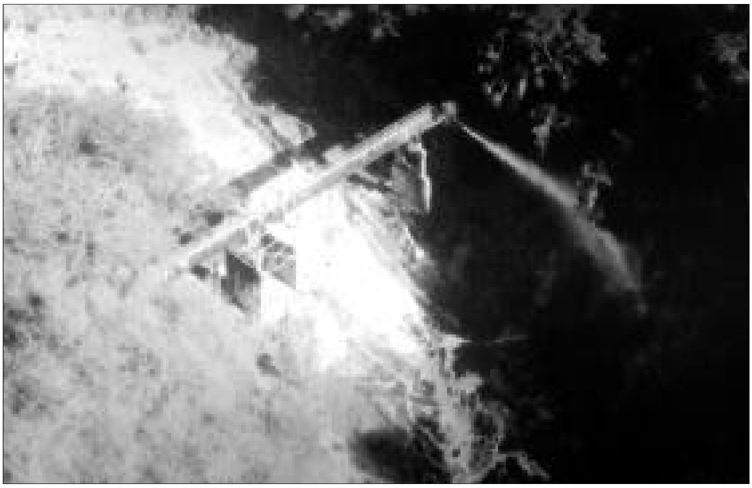
COMPONENT	COVERAGE %	CAPACITY	REMOTE WARNING SYSTEMS

INTER-INSTITUTIONAL INFORMATION AND WARNING SYSTEMS
- ☐ Civil Defense
- ☐ Meteorological Institute
- ☐ Volcanology Institute
- ☐ Seismology Institute
- ☐ Other (list):

WATER COMPANY INFORMATION AND WARNING SYSTEMS
- ☐ UHF Radio
- ☐ VHF Radio
- ☐ Telephone
- ☐ Other (list):

INFORMATION SYSTEM FOR PUBLIC
- ☐ Radio
- ☐ Television
- ☐ Printed Brochures
- ☐ Other:

Matrix 2 — Administration and Response Capacity



José Grases, 1997

If maintenance is lacking, a simple leak can be responsible for the collapse of the system.

Matrix 2 facilitates the evaluation of weaknesses and limitations related to the administration of the system. To complete this information it is important to know operation standards and available resources that could be used for the supply of drinking water and disposal of waste water in emergency situations and in the rehabilitation phase. The information needed to complete this form is the same for drinking water and sewerage systems.

Institutional Organization

In the first column of Matrix 2 the strengths and weaknesses of institutional organization should be noted. Distinctions should be made between central, regional, and local levels, and, if necessary, separate matrices should be completed for each of these levels. Indicate whether the following are in place:

- Emergency response plans; specify when periodical reviews and updating of the plans take place;
- Mitigation plans;
- Inter-institutional coordination;
- Permanent emergency committee; list the members and their responsibilities;
- Committee responsible for developing a mitigation plan.

Operation and Maintenance

In the second column of Matrix 2 strengths and weaknesses in operation and maintenance at the central, regional, and local levels are described. Indicate whether the following apply:

- Planning programs include the topic of disasters;
- Disaster and mitigation measures are included in operation programs and manuals;
- Disaster and mitigation measures are included in preventive maintenance programs;
- Availability of personnel trained in areas related to disaster prevention, mitigation, and emergency response;
- Availability of equipment, machinery, materials, and accessories for carrying out preventive programs and for service rehabilitation in case of emergency (specify the kind of equipment and machinery).

Matrix 2 - Administration and Response

NAME OF SYSTEM: ______________________________

TYPE OF SYSTEM: ☐ DRINKING WATER ☐ SEWERAGE

INSTITUTIONAL ORGANIZATION	**OPERATION AND MAINTENANCE**	**ADMINISTRATIVE SUPPORT**
A. EMERGENCY RESPONSE PLANS ☐ YES ☐ NO Date of most recent review:	A. PLANNING PROGRAMS ☐ YES ☐ NO	A. AVAILABILITY AND MANAGEMENT OF MONEY ☐ YES ☐ NO AMOUNT
B. MITIGATION PLAN ☐ YES ☐ NO	B. OPERTAION PROGRAMS AND MANUALS ☐ YES ☐ NO	
C. INTER-INSTITUTIONAL COORDINATION ☐ YES ☐ NO	C. PREVENTIVE MAINTENANCE PROGRAMS ☐ YES ☐ NO	B. LOGISTICAL SUPPORT FOR PERSONNEL (TRANSPORT AND SUPPLIES) ☐ YES ☐ NO
D. COMMITTEE FOR DEVELOPING MITIGATION PLANS ☐ YES ☐ NO	D. TRAINED PERSONNEL ☐ YES ☐ NO	
E. EMERGENCY COMMITTEE ☐ YES ☐ NO Members of Commitee: Name: Responsibility:	E. AVAILABILITY OF EQUIPMENT ☐ YES ☐ NO Type of Equipment and Machinery:	C. CONTRACT WITH PRIVATE COMPANY ☐ YES ☐ NO Name:

Administrative Support

In the third column of Matrix 2, enter information about administrative support systems. Indicate whether:

- Funds are available for emergency situations, emergency supplies; enter the amount reserved for these purposes;
- Logistic support for personnel exists (e.g., warehoused supplies and transport);
- There are simple procedures for contracting businesses and services to support mitigation measures and rehabilitation; provide details about these companies and whether they are in a registry of service providers.

The institutional capacity to carry out mitigation measures and to respond to the impact of disaster can be evaluated by analyzing the results of these three columns.

Matrix 3—Physical Aspects and Impact on the System

In the heading for Matrix 3, record the type of hazard that could impact the physical systems for drinking water or sewerage, as well as the area that would impact operations. To arrive at such an estimate, it is necessary to simulate possible events and analyze the expected consequences to the system. Disaster simulations will assist in creating risk maps, or maps of the system superimposed over areas showing the expected effects of a hazard. These estimates should also include the population, institutions, and environmental elements potentially affected.

Priorities for analysis can be noted for the entire system. Three priority levels correspond to the following levels of damage:

- Priority 1 (High): More than 50% of components and/or the intakes and distribution system are impacted;
- Priority 2 (Medium): Between 25% and 50% of components affected, without affecting the intakes and distribution system;
- Priority 3 (Low): Less than 25% of components affected, without affecting the intakes and distribution system.

Exposed Components

In the first column of Matrix 3, list the components directly exposed to the hazard. The components should preferably indicate the direction of flow of water and must be classified in the following manner: intakes (different types) and their structures, main pipelines, treatment plants, pump stations, storage tanks, and aqueduct systems.

Condition of Components

In the second column of the matrix, record the condition of the component, using descriptive terms. For example for galvanized pipes, indicate whether corrosion is present, rather than using general categories (such as “good” or “average”).

Estimates of Potential Damage

In the third column of the matrix, describe the nature of the expected impact on each of the exposed elements. Table 4.1 illustrates the types of damage that could occur in some components as a

Matrix 3 - Physical Aspects and Impact on Service

NAME OF SYSTEM: ____________________
TYPE OF SYSTEM: ☐ Drinking Water ☐ Sewerage
TYPE OF HAZARD: PRIORITY(1): ☐ 1 ☐ 2 ☐ 3
AREA OF IMPACT: ____________________

EXPOSED COMPONENTS	**CONDITION OF COMPONENT**	**ESTIMATED DAMAGES**	**REHABILITATION TIME 100 (days)**	**IMMEDIATE REMAINING CAPACITY**		**IMPACT ON SERVICE(2) (Connections)**
				Units	**%**	

(1) Priority 1 (High): More than 50% of components and/or the intakes and distribution system affected;
Priority 2 (Medium): Between 25% and 50% of components affected, without affecting the intakes and distribution system;
Priority 3 (Low): Less than 25% of components affected, without affecting the intakes and distribution system.

(2) Number of connections affected in terms of quality, quantity, and/or continuity of service.

Table 4.1
Effects of natural disasters (PAHO, 1982)[21]

Service	Expected effects	Earthquake	Hurricane	Flood	Tsunami
Drinking water supply and disposal of waste waters	Damage to civil engineering structures	●	●	●	❍
	Rupture of water mains	●	◗	◗	❍
	Interruption of power supply	●	●	◗	◗
	Contamination (chemical or biological)	◗	●	●	●
	Disruption of transportation	●	●	●	◗
	Scarcity of personnel	●	◗	◗	❍
	Network overload (due to movements of population)	◗	●	●	❍
	Scarcity of equipment, replacement parts and supplies	●	●	●	◗

● Serious possibility ◗ Less serious possibility ❍ Minimal possibility

result of natural disasters. Detailed descriptions of natural hazards and their effects on water systems are given in Chapter 3. Consult corresponding sections for hurricanes, earthquake, floods, landslides, volcanic eruptions, and droughts to complete this section of Matrix 3.

Rehabilitation Time

In column four of Matrix 3, enter the estimated rehabilitation time (RT) for the analyzed component. The methodology for making this estimate was developed by the Pan American Center for Sanitary Engineering (CEPIS). It can be applied to structural components such as pump stations, storage tanks, treatment plants, or pipelines. The method is also valid for watersheds, aquifers, or large reservoirs, although specialized analysis is required in these cases.

The rehabilitation time depends on:

- The type and magnitude of damage, which is determined after carrying out a detailed analysis;
- The availability of personnel, materials, financing, and transportation as required, to carry out repairs;
- Accessibility of site where repairs are to be made.

Because of these factors, rehabilitation time can be estimated only in terms of ranges.

The rehabilitation time, expressed in number of days, is estimated for each affected component and for the system as a whole. To make these estimates, extensive experience is needed in repairs and reconstruction, detailed knowledge of the drinking water supply system, and awareness of available resources from the water supply company, civil defense, private companies, or other entities.

To estimate rehabilitation time for the entire system, "parallel" or "series" calculations are made using the repair times of the components. "Series" calculations are used when repairs are made sequentially; or “parallel” when components are repaired simultaneously. This method also applies by repair stages; for example the rehabilitation time (RT) can be established for a specific component at 25%, 50%, and 100% of its capacity. This is expressed as RT25, RT50, and, finally, RT, which is equivalent to RT100.

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[21] PAHO/WHO, *Environmental Health After Natural Disaster,* Scientific Publication, 1982.

For example, to calculate partial rehabilitation time for a large diameter pipe damaged by a landslide, factors to be considered are:

i) Time required to report the damage, close valves, and mobilize personnel, equipment, and materials to begin repairs;
ii) Time needed to reach affected areas;
iii) Time required to carry out repairs (depending on the extent of damage and the available resources);
iv) Required waiting period before initiating operation (for example, setting time of concrete for anchors);
v) Required time for putting system in operation (e.g., fill pipes).

The sum of these time segments corresponds to RT100 or rehabilitation of the pipeline to 100% of its capacity. Using this method assists in comparing rehabilitation times for different types of damage and determining the most critical components when prioritizing the execution of mitigation or retrofitting measures. The emergency plan should include procedures for obtaining alternative water sources if necessary during the rehabilitation period.

Remaining Capacity

In the fifth column of Matrix 3, enter the estimated remaining operation capacity of the component being analyzed using units (such as flow in pipes, volumes in reservoirs and tanks) and the percentage relative to the capacity prior to the impact of the disaster. The rehabilitation time (RT) and remaining capacity are good indexes of the vulnerability of particular components.

Impact on Service

The sixth column shows the impact on service for each exposed element. In calculating this impact, take into account not only total interruption of service but deterioration in terms of quality and quantity. Quantifying this impact is done by calculating the number of connections that are not functioning or the number with a significant decrease in quality (deterioration of drinking water quality, for example) or quantity (as evidenced by water rationing).

This information is essential to the vulnerability analysis and should be given special emphasis. It should be elaborated by professionals with extensive experience in operation, maintenance, design, and repair of drinking water systems, as well as the determination of external forces in different situations. This information, together with the rehabilitation time, will be used in the emergency plan to indicate the need to provide alternative water sources, the time when service should be implemented, and the priority connections and installations in a water supply and sewerage system.

Matrix 4A — Mitigation and Emergency Measures (Administration and Operation)

Reduced operative and administrative vulnerability can be achieved with measures such as improvements in communication systems, provision of adequate numbers and types of transport vehicles, provision of auxiliary generators, frequent line inspections, detection of slow landslides, repair of leaks in areas of unstable soils, and planning for emergency response. Such preventive measures will optimize the operation of the system and minimize the risk of failure under normal conditions of service

Matrix 4A - Mitigation and Emergency Measures (Administrative and Operational Aspects)

Name of system: ❑ Drinking Water ❑ Sewerage

AREA	MITIGATION		EMERGENCY	
		COST		COST
A) INSTITUTIONAL ORGANIZATION				
B) OPERATION AND MAINTENANCE				
C) ADMINISTRATIVE SUPPORT				
D) OPERATIONAL ASPECTS				
SUBTOTAL				
TOTAL				

as well as reducing losses in case disaster occurs.

Mitigation and emergency measures for each potentially vulnerable component are entered in Matrix 4A. In each case, estimated costs for mitigation measures and costs for emergency measures should be calculated as they correspond to organization, administration, operation, and maintenance.

Matrix 4B — Mitigation and Emergency Measures (Physical Aspects)

Matrix 4B integrates mitigation and emergency measures for physical components. They are listed in the same order as in Matrix 3. This matrix should be completed by the same team of professionals that carried out the physical vulnerability analysis.

Matrix 4B is divided into two sections. In the first, mitigation measures for physical components are listed, such as retrofitting, substitution, repair, placement of redundant equipment, improved access, etc. Priority of action should be specified for each component depending on whether it requires: (a) greater rehabilitation time; (b) greater frequency of repair; and/or (c) is a critical component. Costs associated with implementing these measures should likewise be noted. In the second section of the Matrix—the emergency plan—the necessary emergency measures and procedures are noted assuming that mitigation measures have not been carried out.

Mitigation measures to reduce vulnerability of certain components of drinking water and sewerage systems include:

- Replace equipment or accessories if in poor condition, and monitor components periodically if they are in average condition (for example, electrical pumps, auxiliary generators, and valves);
- Repair elements, equipment, and accessories that are defective;
- Replace elements, equipment, and accessories that are inadequate or nonfunctioning;
- Obtain missing components, equipment, and accessories (for example, auxiliary generators in areas where there are prolonged or frequent electrical outages).

Mitigation measures to be considered to reduce vulnerability to the impact of specific hazards are outlined below:

Active Landslides

- Relocate components if possible or use drainage ditches in the unstable zone;
- Construct small retaining walls around the structures, or provide small anchors on the pipes;
- Change rigid components and place flexible piping in sinusoidal reaches;
- Bury pipes in solid rock in areas with steep slopes and little topsoil cover;


Osorio, 1997

Water system authorities should take emergency measures to ensure that the population has a safe and reliable source of drinking water in case of disaster.

MatriX 4B - Mitigation and Emergency Measures (Physical Aspects)

Name of System: ☐ Drinking Water ☐ Sewerage

COMPONENT	MITIGATION		EMERGENCY PLAN	
		COST		COST
TOTAL				

- Plant and maintain the vegetation coverage of the site or watershed. Remove vegetation from top and toe of very steep embankments.

Floods

- Construct underground river passes for pipelines and adequate settling basins;
- Install automatic shut-off for horizontal pumps;
- Plant and maintain vegetation cover of the watershed; use landfill to raise ground level.

Volcanic Activity

- Relocate components if possible or provide permanent covers to protect storage and treatment tanks and settling basins;
- Construct protective walls and underground river passages for pipes.

Earthquakes

- Provide structural retrofitting of the components;
- Protect sites against landslides, rockslides, and floods;
- Retrofit or change cracked elements or those of poor quality material; replace rigid connections and accessories.

Annex 1
Examples of Effects of Earthquakes on Pipeline Systems*
(1969 - 1997)

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[*] Compiled by José Grases, Venezuela, 1997.

Place and Date	Intensity(M) Magnitude (MMI)	Reported Damage
Santa Rosa, California, U.S.A. 1 October 1969	5.7 (M)	Minor damage to storage tanks, pumping stations, and dams. Significant damage to distribution pipes.
San Fernando, California, U.S.A. 9 February 1971	6.6 (M)/ VIII–IX (MMI)	Damage to hydraulic structures were major impact of San Fernando earthquake in terms of supply sources and pipes. Pronounced fluctuations in water levels in wells occurred. The most important effects on the drinking water system occurred in the dams, reservoirs, water tanks, main tanks, pipes, and sewers. Van Norman Lakes and another series of reservoirs of the San Fernando Valley suffered severe damage. The lakes formed part of the Los Angeles aqueduct. The upper part of the Van Norman Lake dam fractured and the crest sank. One of the intakes was destroyed.
Managua, Nicaragua. 23 December 1972	6.25 (M) V–IX	The distribution system consisted of 16-inch cast iron pipes. Smaller pipes were 4-inch PVC. On 30 December there was pressurized water in the mains in areas beneath the city. Approximately 100 breaks were identified in the conduits. The eastern section of the city did not have water service on that date. The roofs of pumping stations collapsed. There was damage in the tank owing to differential settling and to breaks in the joints attached in the floor. The tank had to be emptied for inspection and later repair.
Guatemala 4 February 1976	7.5 (M)	Earthquake associated with the northeast edge of the Caribbean plate. Rupture of the Motagua fault at a length of some 250 km with an average lateral displacement of 100 cm. Damage occurred in numerous installations, although damage to pipes was not reported.
Cotabato, Mindinao Island, Philippines. 17 August 1976	7.9 (M)	The main supply to the city of Catabato was through an intake from the Dimapato River, 16 km away, with an elevation of 116 m, which remained in good condition. The pipelines consisted of 20 cm pipes for a total of 5.5 km followed by 26 cm pipes for 10.5 km. The 26 cm pipe broke when a bridge cover collapsed on top of it.

San Juan and Mendoza, Argentina. 23 November 1977	7.4 (M)	The earthquake caused damages of varying importance, the most serious was in the Caucete, San Martín, and 25 de Mayo Departments. The water distribution system of the city of Caucete had breaks along its entire length (approx. 40 km); this was aggravated by the high water table level and liquefaction.
Mexico. 19 September 1985	8.1 (M) VIII–IX (MMI)	Mexico City operated and maintained some 72,000 km of pipes. Aquifers provided some 80% of the water supply, distributed to the city through aqueducts from the north, west, and south. The pipes were from 5 cm to 305 cm in diameter. Significantly, underground pipes suffered more damage than surface pipes. The majority of large diameter pipes were broken because of rigid joints in the system, such as T-connectors, cross connections, valves, and pipes connected to structures.
San Salvador, El Salvador. 10 September 1986	5.4 (M)	Some 2,400 breaks were reported as a result of the earthquake, primarily in the drinking water supply system. The detection of the ruptures was fairly rapid because of reduced pressure. The length of the damaged pipeline was an estimated 80 km, 20% of the line’s total length. An estimated 65 km of the sewerage system was damaged (22% of the total). San Salvador is located in a zone of volcanic ash deposits. The ruptures were attributed to differential settling and to deformations imposed by seismic waves. Failures occurred in the drinking water network, including in flexible steel piping.
Napo Province, Ecuador. 5 March 1987	6.8 (M)	This earthquake in northeastern Ecuador, was preceded three hours earlier by a 6.1 magnitude earthquake with its epicenter near the Reventador volcano, in an area of complex geologic faulting. Avalanches and mudslides, owing to saturation from the rains prior to the earthquake, affected some 40 km of the trans-Ecuador oil pipeline. This conduit came from the deposits in Agrio Lake, particularly between Salado River and the San Rafael Falls. Some 17 km of oil pipeline disappeared as a result of this earthquake, and two bridges collapsed because of the large slides and/or backwater effects in the area.

Spitak and Leninakan, Armenia. 7 December 1988	6.8 (M) VIII (MMI)	The water source for Lininakan was located some 32 km north of the city and transported to the city through three pipes. Two of the sources originated in the mountains and were not treated before being distributed to the city. Pipes that were 500–600 mm in diameter, one of steel and the other of a mixture of steel and cast iron, transported water for industrial use. The three pipes passed through a slope some 7 km north of the city. Approximately 1 km of pipe was buried in this slope. A rock slide some 4.5 km wide covered and damaged pipes located along a river.
Loma Prieta, California, U.S.A. 17 October 1989	7.1 (M) VI–VIII (MM)	Interruptions in the electrical power system affected treatment plants and pumping stations. Portable electrical plants were used in operation centers and pumping stations. The water mains in the area of the canals of the Calaveras fault, constructed in the 1950s, 4 and 6 inches thick, and of cast iron with bell and spigot connections suffered significant damage. There were many breaks in residential connections. Many pipes located in uncompacted fill and in alluvial soils were damaged. Damage to pipes in compacted soils was less frequent.
Limón, Costa Rica. 22 April 1991	7.4 (M) VIII (MMI)	Serious damage occurred in the Banano River basin, through surface soil slides, causing tubidity of 100,000 UNT. In the drinking water pipe system, four types of failure were observed: cracks in intermediate segments in the body of the pipe; in joints between two segments of pipe; in the joints owing to separation by tension; and in the joints from "telescopic" compression.
Erzincan, Turkey. 13 March 1992	6.8 (M) VIII (MMI)	There were approximately 250 km of distribution piping in the city. Asbestos-cement pipes of 80 cm were damaged in certain places. The distribution pipes were primarily of 60 cm cast iron; there were also 8 to 12.5 cm PVC pipes and 20 to 25 cm asbestos-cement pipes. Damage was reported in settling tanks and in the pumping stations, but did not affect their operation. A simple break was found in the connection of an 80 cm steel transmission pipe. In the water mains 25 ruptures were reported. Breaks were found in the joints of the PVC and asbestos-cement pipes.

Northridge, Los Angeles, California, U.S.A. 17 January 1994	6.7 (M)	Los Angeles water was provided by two aqueducts from a valley. Aqueduct no. 1 suffered damages in four places, but it was operated using low levels of pressure for four weeks after the earthquake while repairs were made in Aqueduct no. 2. There were breaks in concrete pipes of 54–77, 78–85, and 120 inches. The tunnels were inspected and did not have major damage with the exception of some small breaks around Terminal Hill. These cracks were sealed with urethane resin. To the north of Terminal Hill a 77-inch steel pipe suffered damage through compression. Simi Valley, 20 km west of the epicenter, recieves water from the Jensen treatment plant. Water is diverted to two large storage tanks east of Simi Valley. The tunnel was not damaged, but pipes of 78 and 51 inches split. The main damages in the distribution pipes occurred because of vibrations and intense movements. Pipes with the most damage were those of iron with rigid joints and signs of corrosion. In the area of Newhalla, six of the seven tanks inspected had to be taken out of service because of broken and damaged valves. In the area of Valencia, one of the tanks suffered a total collapse as a result of tearing of the material in the bottom of the tank. Spillage from this tank damaged the adjacent tank.
Kobe, Japan. 17 January 1995	7.2 (M) IX-X (MMI))	Approximately 75% of the drinking water in Kobe was supplied from the Yodo River through two mains which were out of service after the earthquake, leaving more the 1.5 million inhabitants without water supplies. Twenty-three breaks occurred in the 1.25 m water main, apparently of concrete. The underground water pipes suffered severe damage. A pump station and treatment plant also failed.
Cariaco, Venezuela. 9 July 1997	6.9 (M)	An earthquake occurring along the southeast border of the Caribbean Plate caused a rupture along some 50 km of the El Pilar fault with lateral displacement to the right of 40 cm. Buried pipe and waste water treatment installations suffered damage. A drinking water supply pipe that crossed the fault at an angle of 30° to 35°, 5 km from Cariaco, failed as a result of bending compression forces.

Annex 2

Application of Vulnerability Analysis: Case study of Limón, Costa Rica

Introduction

The case study carried out in Costa Rica[22], along with three conducted in Brazil, Venezuela and Montserrat, for floods, landslides, hurricanes, and volcanic eruptions, served to validate the use of the methodology presented in this document by water authorities in carrying out vulnerability studies for the most common natural hazards.

Case Study of Limón, Costa Rica

The vulnerability analysis, conducted in 1996, was a retrospective study of the drinking water and sewerage system in Limón, Costa Rica.[1] The technical data corresponded to a study carried out in 1991, prior to the April 1991 earthquake that seriously impacted the area. The study concludes that had mitigation measures been applied to the water system in Limón, there would have been a savings of some US$4 million in repairs to the system following the 1991 event, and much of the impact on thousands of people would have been lessened.

While the case study evaluated the entire water system in the area, for the purpose of using the vulnerability matrixes, analysis of the Banano River system, which supplies drinking water to the city of Limón, and the sewerage system are presented here.

Limón is the largest city in Limón Province, and is located 160 km from San José, the Costa Rican capital. In 1991, some 55,000 persons were served by the city's aqueduct, accounting for 10,764 domestic connections. Nearly 100% of the population had piped drinking water, while only 20% were connected to the sewerage system.

In 1991, there were three sources for Limón's drinking water supply, with a maximum installed capacity of 500 l/s, and average production of 391 l/s. The water system can be divided into three subsystems: Banano River (which produced 71% of Limón's supply), Moín (produced 21%), and the La Bomba wells (produced 8%).

Following are some of the most important characteristics of the Banano River subsystem (see Figure A1) which are used in the vulnerability matrixes:

- Water intake: Water was taken from the Banano River subsystem using a pumping station (three electrical pumps) located on the river, with a capacity of from 120 l/s to 350 l/s.

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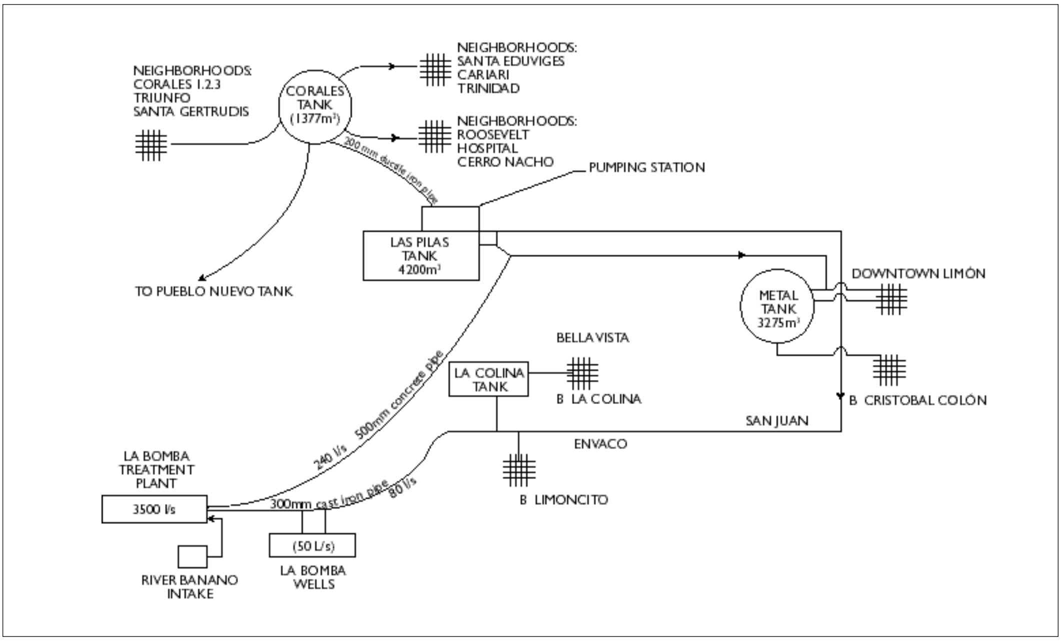
[22] This analysis was compiled from a case study carried out by Saúl Trejos on the drinking water and sewerage system in the city of Limón, Costa Rica (PAHO/WHO, *Estudio de caso: Terremoto del 22 de abril de 1991, Limón, Costa Rica;* 1996). Differences between the case study and the material presented in this annex are a result of certain modifications in the way data were compiled and presented in the vulnerability analysis.

Figure A1.
Water Conveyance and Distribution for the Banano River Subsystem



- The conveyance pipeline was made up mainly of 350 mm diameter pipe, installed in 1981, with Tyton type jointss. The pipe is located primarily in alluvial soil and clay.
- Treatment plant: The settling tank consisted of a reinforced concrete tank; in addition there were units for rapid mixing, flocculation, sedimentation, and filtration.

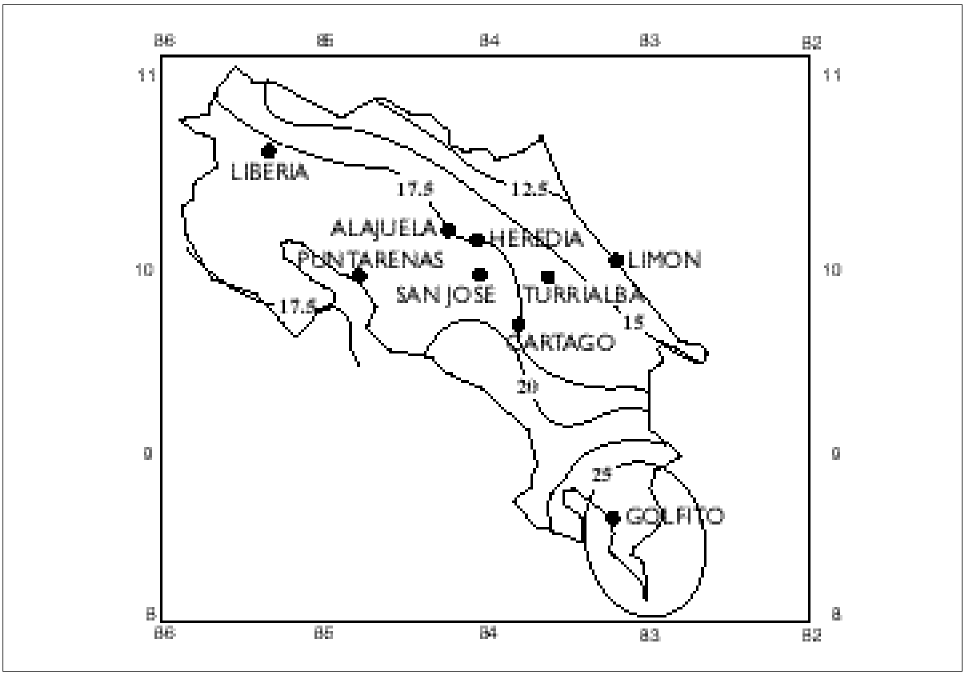
A more detailed description of each of the components of the subsystem, as well as the other Limón subsystems are available in the case study.

Seismic Hazard in the City of Limón

There is a record of numerous seismic events in the Atlantic region of Costa Rica, where Limón is located. Strong earthquakes affected the region of San Fernando de Matina Fort in 1798. The 1822 San Estanislao earthquake, with an estimated magnitude of 7.5, had a strong impact on the Matina region and caused soil liquefaction, a small tsunami on the Atlantic coast, and was felt from Monkey Point to Bocas del Toro in Panama. There are indications that the earthquake of 20 December 1904, while originally attributed to faults in the area of Dulce Gulf, actually occurred in the Caribbean rather than southern Pacific region of the country. On 26 April 1916 there was an earthquake in the Bocas del Toro region; on 7 April 1953 there was an earthquake in Limón with a magnitude of at least 5.5; and the earthquake on 22 April 1991 in the Valley de la Estrella had a magnitude of 7.4. There have also been series of small earthquakes (between 4.0 and 5.0 magnitude) that are believed to have originated in the Atlantic region, but because of the scarcity of population, there are few reports of their having been detected. Accelerometers were not installed in this area until after the 22 April 1991 earthquake.

Seismic risk in Costa Rica is illustrated in Figure A.2. While the city of Limón is located in a zone of relatively low seismic risk, it sustained major damage in the 1991 earthquake.

Figure A2.
Isoaccelerations for a 100-year return period (Costa Rica)



Source: CEPIS, 1996.

Five damage probability matrixes, as described in Chapter 4, are presented here with data pertaining to the case study.

Matrix 1A - Operation Aspects

Name of Drinking Water System: Banano River System (Limón, Costa Rica)

COMPONENT	COMPONENT CAPACITY	CURRENT DEMAND	DEFICIT (-) SURPLUS (+)	REMOTE WARNING SYSTEMS
Basin	38,000 1/s	252 1/s	3,548 1/s	
Banano River intake	350 1/s	252 1/s	98 1/s	
Pipeline	350 1/s	252 1/s	98 1/s	
Treatment Plant	350 1/s	252 1/s	98 1/s	
River Banano wells	51 1/s	51 1/s	01 1/s	
300 mm pipelines	68 1s	83 1s	-15 1s	
500 mm pipelines	240 1/s	218 1/s	22 1/s	
Metal tank	3,275 m^3	1,334 m^3	1,941 m^3	
Colina tank[1]	150 m^3	2,147 m^3	-1,997 m^3	
Intermediate pumping station	4,200 m^3	2,374 m^3	1,826 m^3	
Corales tank	1,377 m^3	2,927 m^3	-650 m^3	
Pieline network	374 1/s	4,53 1/s	-79 1/s	

INTER-INSTITUTIONAL INFORMATION WARNING SYSTEMS

☒ Civil Defense
☐ Meteorological Institute
☐ Volcanology Institute
☐ Seismology Institute
☒ Other: Red Cross
☒ Firefighters
☒ ICE
☒ Executive power

WATER COMPANY INFORMATION AND WARNING SYSTEMS

☒ UHF Radio - 30 KHz network
☐ VHF Radio
☒ Telephone - not reliable in emergencies
☐ Other

INFORMATION SYSTEM FOR USERS

☒ Radio
☒ Television
☐ Printed Brochures
☒ Other: Press releases

(1) Only supplies a small sector.

Matrix 1B - Operation Aspects

Name of Sewerage System: Drainage system for the city of Limón, Costa Rica			
COMPONENT(1)	COVERAGE %	CAPACITY	REMOTE WARNING SYSTEMS
Collection networks:			
• Cuenca Central	80	72 1/s	Not present
• Pinta	72	16 1/s	Not present
• Corales	85	18 1/s	Not present
• Cangrejos	45	12 1/s	Not present
• Portete	15	1 1/s	Not present
Pumping station		75 1/s	Not present
Pipeline		75 1/s	Not present

INTER-INSTITUTIONAL INFORMATION AND WARNING SYSTEMS
☒ Civil Defense
☐ Meteorological Institute
☐ Volcanology Institute
☐ Seismology Institute
☒ Other: Red Cross
☒ Firefighters
☒ ICE
☒ Executive power

WATER COMPANY INFORMATION AND WARNING SYSTEMS
☒ UHF Radio - 30 KHz network
☐ VHF Radio
☒ Telephone - not reliable in emergencies
☐ Other

INFORMATION SYSTEM FOR USERS
☒ Radio
☒ Television
☐ Printed Brochures
☒ Other: Press releases

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(1) Waste water is not treated.

Matrix 2 - Administration and Response

NAME OF SYSTEM: Drainage system for the city of Limón, Costa Rica

TYPE OF SYSTEM: ☐ DRINKING WATER ☒ SEWERAGE

INSTITUTIONAL ORGANIZATION	OPERATION AND MAINTENANCE	ADMINISTRATIVE SUPPORT
A. EMERGENCY RESPONSE PLANS ☐ YES ☒ NO Date of most recent review	A. PLANNING PROGRAMS ☒ YES ☐ NO	A. AVAILABILITY AND MANAGEMENT OF MONEY ☒ YES ☐ NO AMOUNT: Approx. US$2,100.00 (available for both drinking water and sewerage system)
B. MITIGATION PLAN ☐ YES ☒ NO	B. OPERATION PROGRAMS ☒ YES ☐ NO	
C. INTER-INSTITUTIONAL COORDINATION ☐ YES ☒ NO	C. PREVENTIVE MAINTENANCE PROGRAMS ☒ YES ☐ NO	B. LOGISTICAL SUPPORT FOR PERSONNEL (Transport and supplies) ☒ Yes ☐ NO
D. COMMITTEE FOR DRAFTING MITIGATION PLANS ☐ YES ☒ NO	D. TRAINED PERSONNEL ☒ YES ☐ NO	
E. EMERGENCY COMMITTEE ☐ YES ☒ NO (Not completely formed) Members of Committee: Name: Responsibility:	E. AVAILABILITY OF EQUIPMENT AND MACHINERY ☒ YES ☐ NO Type of Machinery and Equipment:	C. CONTRACT WITH PRIVATE COMPANY ☐ YES ☒ NO (Legal flexibility is lacking) Name:
	• For water distribution networks, there is equipment for maintenance under routine conditions	
	• There is a large amount of equipment available for medium-sized emergencies.	
	• Stock is available for maintaining electrical/mechanical equipment	

Matrix 2 - Administration and Response

NAME OF SYSTEM: Acqueduct for the city of Limón, Costa Rica

TYPE OF SYSTEM: ☒ DRINKING WATER ☐ SEWERAGE

INSTITUTIONAL ORGANIZATION	**OPERATION AND MAINTENANCE**	**ADMINISTRATIVE SUPPORT**
A. EMERGENCY RESPONSE PLANS ☐ YES ☒ NO Date of most recent review	A. PLANNING PROGRAMS ☒ YES ☐ NO	A. AVAILABILITY AND MANAGEMENT OF MONEY ☒ YES ☐ NO AMOUNT: Approx. US$2,100.00 (available for both drinking water and sewerage system)
B. MITIGATION PLAN ☐ YES ☒ NO	B. OPERATION PROGRAMS ☒ YES ☐ NO	
C. INTER-INSTITUTIONAL COORDINATION ☐ YES ☒ NO	C. PREVENTIVE MAINTENANCE PROGRAMS ☒ YES ☐ NO	B. LOGISTICAL SUPPORT FOR PERSONNEL (Transport and supplies) ☒ Yes ☐ NO
D. COMMITTEE FOR DRAFTING MITIGATION PLANS ☐ YES ☒ NO	D. TRAINED PERSONNEL ☒ YES ☐ NO	
E. EMERGENCY COMMITTEE ☐ YES ☒ NO (Not completely formed) Members of Committee: Name: Responsibility:	E. AVAILABILITY OF EQUIPMENT AND MACHINERY ☒ YES ☐ NO Type of Machinery and Equipment:	C. CONTRACT WITH PRIVATE COMPANY ☐ YES ☒ NO (Legal flexibility is lacking) Name:
	• For water distribution networks, there is equipment for maintenance under routine conditions	
	• There is a large amount of equipment available for medium-sized emergencies.	
	• Stock is available for maintaining electrical/mechanical equipment	

Matrix 3 - Physical Aspects and Impact on the Service

NAME OF SYSTEM: Aqueduct for the city of Limón, Costa Rica (subsystem of Banano River)

TYPE OF SYSTEM: ☒ DRINKING WATER ☐ SEWERAGE

TYPE OF HAZARD: Seismic PRIORITY(1): ☒ 1 ☐ 2 ☐ 3

AREA OF IMPACT: Limón Province, Costa Rica

EXPOSED COMPONENTS	CONDITION OF COMPONENT	ESTIMATED DAMAGES SERVICE(2)	REHABILITATION TIME 100 (days)	IMMEDIATE REMAINING CAPACITY		IMPACT ON SERVICE(2) (Joints)
				[ ]	%	
Basin	n/a	Increase in turbidity to 600 UNT	365	0	0	7,148
Banano River intake	Vulnerable to breakdowns	Control panels toppled	4	0	0	7,148
Pipeline	Rigid joints	Not expected	0	350 1/s	100	0
Treatment plant	Good condition	Wall failure	60	0	0	7,148
La Bomba wells	Good condition	Interruption in electrical supply	4	0	0	1140
300 mm distribution pipes	In critical condition because of age	54 failures in joints	19	0	0	2,280
500 mm distibution pipes	Pipe material is fragile	144 failures in joints	56	0	0	6,008
Metal tank	Good condition	Not expected	0	3,275m^3	100	0
Colina tank	Average condition	Cracking in walls	6	0	0	3,683
Intermediate pumping station	Acceptable	Cracks in foundation	10	0	0	0
Corales tank	Good condition	Not expected	0	1,377m^3	100	0

(1) Priority 1(High): More than 50% of components affected and/or the intakes and conveyance capacity.
Priority 2 (Medium): Between 25 and 50% of components affected, without affecting the intakes and conveyance.
Priority 3 (Low): Less than 25% of components affected, without affecting the intake and conveyance.

(2) Number of joints affected in terms of quality, quantity, and/or continuity of service.

Matrix 3 - Physical Impact on the Service

NAME OF SYSTEM: Drainage network for the city of Limón, Costa Rica

TYPE OF SYSTEM: ☐ DRINKING WATER ☒ SEWERAGE

TYPE OF HAZARD: Seismic PRIORITY(1): ☒ 1 ☐ 2 ☐ 3

AREA OF IMPACT: Limón Province, Costa Rica

EXPOSED COMPONENTS	CONDITION OF COMPONENT	ESTIMATED DAMAGES SERVICE(2)	REHABILITATION TIME 100 (days)	IMMEDIATE REMAINING CAPACITY		IMPACT ON SERVICE(2) (Joints)
				[ ]	%	
Collectors: Cuenca Central	Good	17 breaks; 22 sites of damage	21	58 l/s	80	270
Pinta	Good	4 breaks; 5 sites of damage	6	13.5 l/s	85	45
Corales	Good	4 breaks; 1 site of damage	6	15.8 l/s	89	37
Cangrejos	Good	3 breaks; 4 sites of damage	5	9.4 l/s	80	44
Portete	Average	1 site of damage	2	0.6 l/s	75	4
Pumping station	Average	Interruption in electrical supply	4	0	0	1,183
Pipeline	Good	Not expected	0	75 l/s	100	0

(1) Priority 1 (High): More than 50% of components affected and/or the intakes and conveyance capacity.
Priority 2 (Medium): Between 25 and 50% of components affected, without affecting intakes and conveyance system.
Priority 3 (Low): Less than 25% of components affected, without affecting the intakes and conveyance system.

(2) Number of connections affected in terms of quality, quantity, and/or continuity of service.

Matrix 4A - Mitigation and Emergency Measures (Administration and Operation)

Name of system: Aqueduct of the city of Limón, Costa Rica ☒ Drinking Water ☐ Sewerage

AREA	MITIGATION MEASURES		EMERGENCY MEASURES	
		COST US$		COST US$
A) Institutional Organization	• Development of emergency preparedness and response program as outlined by PAHO/WHO - Insitutionalization and organization of the program - Carry out vulnerability analysis (Level 1) - Develop mitigation plan - Develop emergency response plan - Training and dissemination of plan • Within the program: - Produce directives for development of emergency plans - Create emergency response committee - Establish national committee for drafting mitigation and emergency plans - Create regional emergency center - Formalize inter-institutional coordination agreements	20,000.00 25,000.00 27,450.00	- Follow known emergency procedures; - Improvise Emergency Operations Center for operation and maintenance procedures; - Through regional emergency committees, coordinate with other institutions and make first contacts and integration with regional headquarters.	5,000.00 5,000.00
B) Operation and Maintenance	• Complete the radial network (AyA-Limón) • Compile and document operation and maintenance programs • Obtain information on repair of TCCR pipes from manufacturer • Develop lists of key personnel in the company and from other institutions	100,840.00 (Global)	- Carry out damage assessment - Request headquarters to move operation and maintenance staff with experience in emergency management from unaffected zones to the disaster area; - Prioritize repair of damage; - Schedule and oversee rehabilitation work;	15,000.00 (Global)

	• Provide specifications for materials and accessories listed in column 2b. • Provide specifications for equipment listed in column 2b, as well as the following items to be maintained at the local level: 2 compressors, 1 backhoe, 1 electrical plant, 2 sump pumps, equipment for clearing obstructions from sewerage system.		- Contract local personnel and machinery; - Request headquarters to provide equipment and materials from other areas (vehicles, radios, drainage pumps, backhoes, equipment to replace breaks, etc.) - Set water rationing and distribution schedule - Maintain a registry of actions carried out - Immediately transfer funds to the affected zone and increase petty cash amounts in the zone, as well as in the purchase and transport sections - Provide instructions on a 24-hour, 7-day per week basis for immediate response to needs of affected area (cash, personnel, materials and equipment)	5,000.00 (Global)
C) Administrative Support	• Establish standards and regulations to ensure that financial resources are available for emergencies and that the procedures for accessing emergency funds are flexible • Establish procedures to facilitate the transfer of personnel from areas not affected to the disaster area; ensure that procedures for contracting local personnel are flexible • Create mechanisms for transferring current lists of available stock, repair materials, and equipment and vehicles to regional divisions • Develop through the procurement department, a list of private construction companies with available equipment	25,000.00 (Global)		
D) Operational Aspects	• Brace control panels • Install diesel generator (250 hp) • Establish AyA-ICE agreement for priority electrical supply • Construct pre-treatment system • Brace chlorine cylinders	100 75,000.00 300,000.00 100	- Repair control panels - Install provisional generator (leased) - Repair wooden substructure and substitute screens with materials available locally (e.g., wood) - See measures for the Banano River intake, listed above	 3,600.00 20,000.00 3,600.00

	• Replace wood and asbestos cement screen, substructure for flocculators and settling basins with less fragile material (aluminum, fiberglass, plastic, etc.) • Install two diesel generators (100 and 30 hp)	200,000 40,000		
TOTAL		**198,290.00**		

Matrix 4B - Mitigation and Emergency Measures (Physical Aspects)

Name of System: Acqueduct of the city of Limón, Costa Rica ☒ Drinking Water ☐ Sewerage

COMPONENT	MITIGATION		EMERGENCY	
		COST US$		COST (US$)
Banano River basin	Conduct Level-2 seismic vulnerability study	80,000	Ration water supply for three months from the Moin subsystem (carry out connections and distribute water using tank trucks)	161,900
	Study alternative sources	10,000	Drill aditional wells in La Bomba	70,900
	Improve condition of 2 wells in La Bomba	5,000	Divert nearby surface water sources to the treatment plant	130,000
Banano River intake	Brace control panels	100	Repair control panel	360,000
	Install generator	75,000	Install provisional generator (lease)	
Treatment plant	Construct pretreatment system	300,000	Repair wooden substructure and flocculator screens	20,000
	Brace chlorine cylinders	100		
	Replace wood and screen for flocculators and settling tanks with less fragile material	200,000		
La Bomba wells	Arrange agreement with ICE for priority electric service	0		
	Install 2 electric generators (100 and 50 hp)	40,000		
Pipeline (300 mm)	Replace entire line	1,092,500	Acquire 300 mm pipes and repair the 54 expected breaks	90,000
	Conduct seismic vulnerability study	40,000		
Pipeline (500 mm)	Install 52 seismic-resistant joints	390,000	Acquire 500 mm pipes and repair the 144 expected breaks	360,000
	Identify personnel with welding equipment in area	0		
Total		**2,232,700**		**1,192,800**

Annex 3
Method for Estimating Damage in Pipes as a Consequence of Intense Earthquakes

Introduction

Following is a methodology for estimating the expected number of breaks in pipelines affected by seismic activity. It is based on a study made of the earthquake in Limon, Costa Rica, 1991.[23]

Evaluation of Seismic Hazard

Step 1. Assign a hazard factor by soil profile type (FSPT) as shown in Table A3.1

Table A3.1

Soil profile	Description	FSPT
Rocky	Rocky strata or very consolidated soils with propagating waves in excess of 750 m/s.	1.0
Hard	Well-consolidated or soft soils with depths of less than 5 meters.	1.5
Soft	Soft soil strata with depths in excess of 10 meters.	2.0

Step 2. Assign a hazard factor for potential soil liquefaction (FPSL) as shown in Table A3.2.

Table A3.2

Hazard	Description	FPSL
Low	Well-consolidated soils and with high drainage capacity, adjacent strata without appreciable sand content.	1.0
Moderate	Soils with moderate drainage capacity, adjacent strata with moderate sand content.	1.5
High	Poorly drained soils, high water table, adjacent strata with high sand content; river deltas and alluvial deposits.	2.0

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[23] PAHO/WHO, Estudio de caso: *Terremoto del 22 de abril de 1991*, Limón, Costa Rica; 1996.

Step 3. Assign hazard factor for permanent displacement of the soil (FPDS) as shown in Table A3.3

Table A3.3

Hazard	Description	FPDS
Low	Well-consolidated soils, low slopes, well-compacted fill. Not located near river beds or geologic faults.	1.0
Moderate	Consolidated soils, slopes less than 25%; compacted fill; close to river beds or geologic faults	1.5
High	Poorly consolidated soil, slopes greater than 25%, located in or near river beds or geologic faults	2.0

According to this process, the seismic hazard factor of the area is characterized by the product:

FSPT x FPSL x FPDS

Values of less than 2 are considered of low seismic hazard; between 2 and 4 moderate seismic hazard; equal to or greater than 4, high seismic hazard.

Estimating Vulnerability

The vulnerability of different pipe systems to seismic activity is expressed by the number of expected failures per kilometer. As an example, the number of breaks caused by an earthquake in cast iron pipes for different degrees of Mercalli intensity are given in Table A3.4. Values are assigned to damage from: i) propagation of seismic waves only and ii) propagation of waves and permanent deformation in the soil. These are called basic damage indices and depend on the seismic hazard factor (SHF) calculated in the previous section.

Table A3.4

Mercalli intensity	Basic damage indexes (faults per km)	
	SHF(*) <2	SHF(*) $\geq$ 2
VI	0.0015	0.01
VII	0.015	0.09
VIII	0.15	0.55
IX	0.35	4.00
X	0.75	30.0

(*) Seismic Hazard Factor

For the calculation of the seismic vulnerability take the following steps.

Step 4: Select the basic damage index as shown in Table A3.4.

Step 5: If the pipe is not of cast iron, it is advisable to use the correction factor given in Table A3.5

Table A3.5

Material	Correction factors
Steel	0.25
Cast iron	1.00
PVC	1.50
Asbestos cement	2.60
Reinforced concrete	2.60

These factors can be affected by the general condition of the pipe and/or years of use, and should be judged by the professional responsible for making the evaluation. For pipes that are old or in poor condition values in Table A3.4 can increase by as much as 50%; if its status is considered average this percentage should not exceed 25%; for pipes in good condition is it not necessary to modify the values in Table A3.4.

Step 6: Available data indicate that pipes with smaller diameters tend to be more vulnerable. An increase in the correction factor of up to 50% can be applied for pipes measuring 75 mm or less in diameter; the correction factor for pipes between 75 mm and 200 mm can increase up to 25%. For pipes with diameters of more than 200 mm the given values should not be increased.

Calculation of Expected Breaks

To illustrate the calculation of number of breaks in pipes per kilometer, the following example is useful. The pipeline is located in an area where earthquakes measuring IX in Mercalli intensity are expected. The pipeline is reinforced concrete, which is relatively new and in good condition; it is 500 mm in diameter and 15.5 km in length. Three sections are subject to the following three levels of seismic hazards (as presented in Table A3.4):

Section 1: 1.8 km long in areas of low seismic hazard (SHF<2);
Section 2: 12.7 km long in areas of moderate seismic hazard (SHF>2);
Section 3: 1.0 km long in areas of high seismic hazard (SHF>2).

The total expected breaks equal:

$$1.8 \times 0.35 \times 2.6 + 12.7 \times 4.0 \times 2.6 + 1.0 \times 4.0 \times 2.60 = 144 \text{ breaks/km.}$$

If the piping were of flexible steel, the number of faults calculated per kilometer would be ten times less, i.e., 144 x (0.25/2.60) = 14.

Definitions

Component: Discrete part of a system capable of operating independently but designed, constructed, and operated as an integral part of the system. Examples of individual components are wells, pumping stations, storage tanks, reservoirs, pipes, etc.

Drinking water system: Components constructed and installed to collect, transmit, treat, store, and distribute water to users. In broad terms, it also comprises the watershed and aquifers.

Emergency: Situation presented by the impact of a disaster.

Emergency and preparedness program: Comprises the emergency and mitigation plans.

Emergency plan: Measures to be applied before, during, and in response to the impact of a disaster.

Hazard: Phenomenon of nature or caused by human activity whose occurrence poses danger for persons, property, installations, and the environment.

Impact: Effects on the environment and on man-made works as a result of a disaster.

Mitigation plan: Measures and works to be implemented before the occurrence of a disaster, with the objective of reducing the impact on the components of the systems.

Natural disaster: Occurrence of a natural phenomenon in a limited space and time that disrupts normal patterns of life, causing human, material, and economic loss.

Natural phenomenon. Manifestation of the forces of nature such as earthquakes, hurricanes, volcanic eruptions, etc.

Operative capacity: Capacity for which a component or system was designed.

Preparation: Measures that should be implemented before the occurrence of a disaster.

Prevention: Preparedness activities meant to diminish or prevent the impact of disaster.

Redundancy: Ability of system components to operate in parallel fashion; this allows continuity of service, despite the loss of one or more components.

Reliability: Ability of a component or system to resist hazards. Quantified as the complement of probability of failure.

Risk: The evaluation, based on conditional probability, that the consequences or effects of a specific hazard will exceed predetermined values.

Sewerage system: Components constructed and installed to collect, transmit, treat, and dispose of water and treatment products.

Vulnerability analysis: Process to determine critical components or weaknesses of systems to hazards.

Vulnerability: Susceptibility to the loss of an element or group of elements as the result of a disaster.

Water authority: Public, private or combined entity responsible for the provision of drinking water and sewerage service.

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Drinking water and sewerage services play a critical role in the development process as they are essential for the health and well-being of populations. In Latin America and the Caribbean, the impact of natural disasters frequently results in severe damage to these systems, representing important economic losses and serious disruptions in the quality of services. Factors such as uncontrolled urban growth, deteriorating and inadequate infrastructure, and, above all, the location of these systems in areas that are vulnerable to natural hazards have resulted in a striking increase in the frequency of disasters and the severity of damage. This situation presents obstacles for development and hazards to the health of affected populations.

Prevention and mitigation measures taken before a disaster strikes can strengthen systems thus avoiding or reducing damage and human and material losses.The institution of programs that continually update mitigation and emergency plans also ensures a more responsible and efficient response in the event of a disaster.

Vulnerability analysis—the topic of this publication—provides a simple approach for assessing the vulnerability of system components to the impact of hazards in a particular area.The outcome of the analysis will define the necessary mitigation measures and emergency response procedures should a disaster occur.

These guidelines are meant to be used as an analytical tool by engineering and technical personnel working with drinking water and sewerage services to diagnose the behavior of these systems in the event of a natural disaster.

Other books on this topic published by PAHO/WHO include:

Manual para la mitigación de desastres naturales en sistemas rurales de agua potable (Quito, 1998) (*Manual for Natural Disaster Mitigation in Rural Drinking Water Systems*, available in Spanish only).

Planificación para atender situaciones de emergencia en sistemas de agua potable y alcantarillado (Cuaderno técnico No. 37, Washington, D.C., 1993) (*Response Planning for Emergency Situations in Drinking Water and Sewerage Systems,* available in Spanish only).

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