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

* 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.

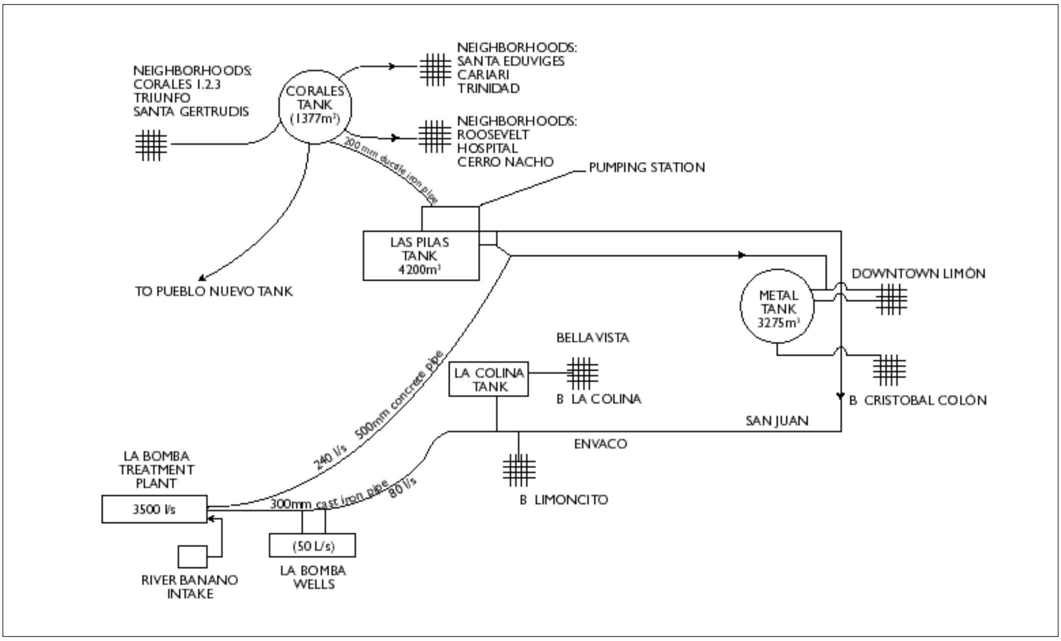
In 1991, there were three sources for Limón's drinking water supply, with a maximum installed capacity of 500 l/s, and average production of 391 l/s. The water system can be divided into three subsystems: Banano River (which produced 71% of Limón's supply), Moín (produced 21%), and the La Bomba wells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

[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.

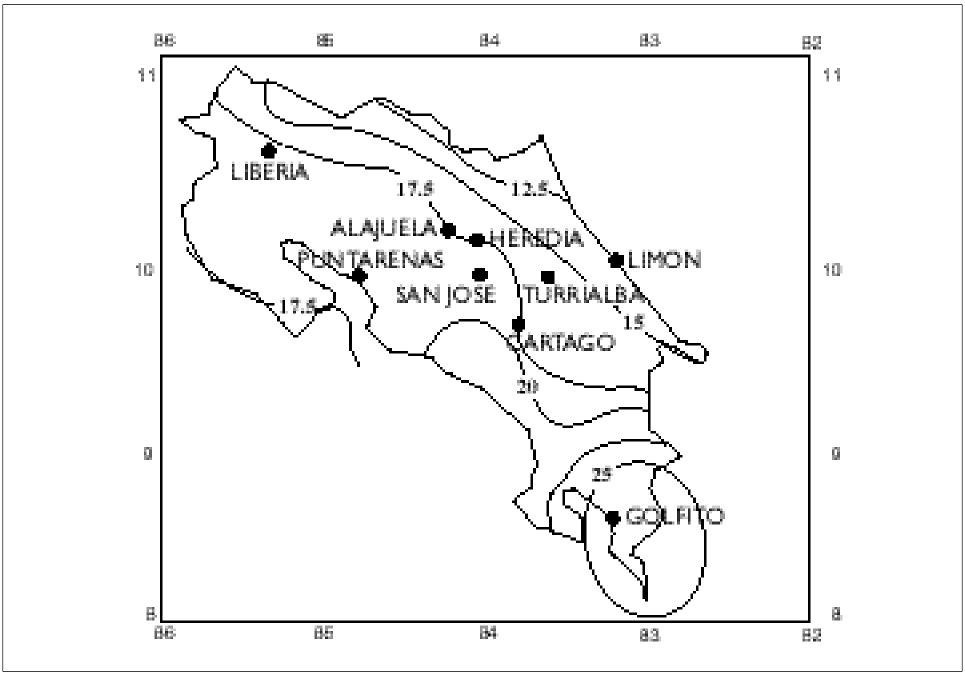
A more detailed description of each of the components of the subsystem, as well as the other Limón subsystems are available in the case study.

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

(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	
	Install generator	75,000	Install provisional generator (lease)	360,000
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

[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 x 0.35 x 2.6 + 12.7 x 4.0 x 2.6 + 1.0 x 4.0 x 2.60 = 144 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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