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**Revision:** Final

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Abstract

This report presents the systemic model and the performance measure for the seismic assessment of water and waste-water systems. A description of the systems and their main functions along with the description of systems taxonomy are made. Methods to evaluate the systems seismic performance are reviewed and commented. Available performance indicators (measurements) for the single components and for the water and waste-water systems as a whole are reported. The main performance indicators to be used in SYNER-G within the framework of the general methodology for the systemic vulnerability evaluation and the developed software are identified. A short introduction on systems performance indicators is followed by a literature review on the available performance measurements and simulations. Finally, key performance indicators are identified and commented.

Keywords: water, waste-water, component, system, risk, seismic, vulnerability.
Acknowledgments

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1 INTRODUCTION

Water is vital for human survival and for the continuity of all human activities. In general, water system may experience important damages during earthquakes, with significant impact on potable water uses and emergency activities such as fire suppression. This has been observed in almost all past strong earthquakes. The seismic reliability of water networks is possible to be measured based on vulnerability, connectivity, serviceability, maximum flow, redundancy and economic loss.

Waste-water systems have been heavily damaged, over the last twenty years, by natural disasters such as earthquakes, worldwide. The societal and economic disruption caused by waste-water network damages is important, as for example, the impact on public health and environment due to the discharge of raw/inadequately treated sewage.

In the followings, the description of the water and waste-water systems taxonomy is provided. Methods to evaluate the systems seismic performance are described and commented. Available performance indicators (measurements) for the single components and for the water and waste-water systems as a whole are reported and the main performance indicators to be used in SYNER-G within the framework of the general methodology for the systemic vulnerability evaluation and the developed software are identified. A short introduction on systems performance indicators is followed by a literature review on the available performance measurements and simulations. The summary of the available indicators for water and waste-water systems is given in a tabulated format. Finally, key performance indicators are identified and commented.

2 DESCRIPTION OF WATER SYSTEM TAXONOMY

The potable water supply is necessary for drinking, food preparation, sanitation and other everyday functions. Water (which may be non-potable) is also required for fire-extinguishing and cooling equipment.

A potable water system consists of transmission and distribution systems:

- Transmission system stores “raw” water and delivers it to treatment plants. Such a system is made up of canals, tunnels, elevated aqueducts and buried pipelines, pumping plants and reservoirs.
- Distribution system delivers treated water to customers.

The taxonomy of water supply system considered within SYNER-G is described in deliverable D2.1 (General methodology for systemic vulnerability assessment). The following elements of water-supply system are considered (Fig. 2.1):

- Water source
- Treatment plant
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- Pumping station
- Storage
- Supervisory Control and Data Acquisition (SCADA)
- Conduits (pipes, tunnel, canals)

Fig. 2.1 Breakdown of potable water system components

The water-supply system as a whole is composed of a number of point-like critical facilities (water sources, treatment plants, pumping stations, storage tanks) and of the water distribution network itself. The internal logic of the critical facilities and their function in the management of the whole system should be modelled explicitly. The network portion of the system is made of: pipelines, tunnels and canals and the supervisory control and data acquisition (SCADA) sub-system.

2.1 WATER SOURCE

The typical water sources are springs, shallow or deep wells, rivers, natural lakes, and impounding reservoirs. Wells are used in many cities as both a primary and supplementary source of water. Wells include a pump to bring the water up to the surface, various electromechanical equipments and a building to enclose the well and the equipment.

Wells, springs or river catchments are different types of water sources.

Wells are complex components that include several sub-components:

- Electric power (commercial power).
- Well pump.
- Building.
- Electric equipment.
The sub-components can be anchored or un-anchored.

2.2 WATER TREATMENT PLANT

Water treatment plants are complex facilities, generally composed of a number of connected physical and chemical unit processes, whose purpose is to improve the water quality. Treatment processes used depend on the raw-water source and the quality of finished water desired. A conventional water treatment plant consists of a coagulation process, followed by a sedimentation process, and finally a filtration process. Components in the treatment process include pre-sedimentation basins, aerators detention tanks, flocculators, clarifiers, backwash tanks, conduit and channels, coal sand or sand filters, mixing tanks, settling tanks, clear wells, and chemical tanks.

Alternatively, a water treatment plant can be regarded as a system of interconnected pipes, basins, and channels through which the water moves, and where the flow is governed by hydraulic principles.

Water Treatment Plants can be categorized by their size (small, medium or large) and by the anchorage (or not) of their sub-components.

The following sub-components are:
- Electric Power (commercial power).
- Chlorination equipment.
- Sediment flocculation.
- Basins.
- Baffles, Paddles, Scrapers.
- Chemical Tanks.
- Electric equipment.
- Elevated pipe.
- Filter Gallery.

2.3 PUMPING STATION

A pumping station is a facility that boosts water pressure in both transmission and distribution systems. In general, pumping stations include larger stations adjacent to reservoirs and rivers, and smaller stations distributed throughout the water system intended to raise head.

Pumping stations typically comprise buildings, intake structures, pump and motor units, pipes, valves, and associated electrical and control equipment.

They can be categorized according to their size (small or medium/large) and by the anchorage (or not) of their sub-components (equipment and back-up power).

The following sub-components may be considered in a pumping station:

- Building
- Intake structures
- Pumps and motors
- Valves
- Associated electrical and control equipment
2.5 - Definition of system components and the formulation of system to evaluate the performance of water and waste-water systems

- Electric Power (back-up, commercial power);
- Vertical/Horizontal Pump.
- Building.
- Equipment.

2.4 STORAGE

Storage tanks can be located at the start, along the length or at the end of a water transmission/distribution system. Their function may be to hold water for operational storage, provide surge relief volumes, provide detention times for disinfection, and other uses.

Most water systems include various types of storage reservoirs in their transmission/distribution systems. Storage reservoirs can be either tanks or open cut reservoirs.

Water storage tanks can be categorized according to the: type (close, open cut reservoirs); material (wood, steel, concrete, masonry); capacity (small, medium, large); anchorage (yes, no); position (at grade or elevated by columns or frames); type of roof (R/C, steel, wood); seismic design (yes, no); construction type (elevated by columns, built “at-grade” to rest directly on the ground, build “at grade” to rest on a foundation, concrete pile foundation); presence of side-located inlet-outlet pipes; volume (height and diameter), thicknesses; operational function (full, nearly full, less than full).

2.5 SUPERVISORY CONTROL AND DATA ACQUISITION (SCADA)

Various types of in-line components exist along water transmission pipelines, including portions of the supervisory control and data acquisition (SCADA) system located along the conveyance system and various flow control mechanisms (e.g., valves and gates).

In-line SCADA hardware includes a variety of components, including:

- Instrumentation.
- Power Supply (normal, backup).
- Communication components (normal, backup).
- Weather enclosures (electrical cabinets and vaults).

SCADA system components in water transmission systems are the following.

- *Instruments attached to the pipeline* may include flow and pressure devices that are sometimes installed in a venturi section of pipeline.
- *Instruments attached to a canal* may include various types of float instruments, which are used to assess the water level in the canal.
- *Remote Terminal Units (RTUs) and Programmable Logic Controllers (PLCs)* are most commonly solid state devices. An RTU device picks up the analog signals from one or more channels of SCADA system devices at one location. The RTU converts these signals into a suitable format for transmission to a central SCADA.
computer, often at a location remote from the devices. A PLC can control when pumps are turned on or off, based on real time data or pre-programmed logic.

- Most water systems have used manual recorders to track pressures, flows and gradient information. These recorders are still in use in many water systems. The recorders sometimes report on the same information as the automated SCADA system, often using the same instruments. Also, since the installation of automated SCADA system hardware is often relegated to a few locations in the water system, the manual recorder may be the only recording device at a location.

- **SCADA Cabinet** is a metal enclosure that is mounted to a floor or bolted to a wall.

- Most SCADA systems include battery backups.

- **Communication Links.** The remote SCADA system is connected in some manner to the central location SCADA computer system. The most common links are radio, leased landlines and, to a lesser extent, microwaves; the use of public switched landlines is rare.

- **Canal gate structures.**

The location of the valves is often important when deciding how a pipeline system performs as a whole; damage to a pipeline between two valves will need to be isolated by closing the valves. Thus, SCADA systems can be categorized according to: the intervals between valves on conduits, the anchorage of cabinet and inside equipments, and the number and type of communication links.

### 2.6 CONDUITS

Transmission conduits are typically large size pipes (more than 400mm in diameter) or channels (canals) that convey water from its source (reservoirs, lakes, rivers) to the treatment plant.

Transmission pipelines are commonly made of concrete, ductile iron, cast iron, or steel. These could be elevated/at grade or buried. Elevated or at grade pipes are typically made of steel (welded or riveted), and they can run in single or multiple lines.

Canals are typically lined with concrete, mainly to avoid excessive loss of water by seepage and to control erosion. In addition to concrete lining, expansion joints are usually used to account for swelling and shrinkage under varying temperature and moisture conditions.

Distribution of water through conduits can be accomplished by gravity, or by pumps in conjunction with on-line storage. Except for storage reservoirs located at a much higher altitude than the area being served, distribution of water would necessitate, at least, some pumping along the way. Typically, water is pumped at a relatively constant rate, with flow in excess of consumption being stored in elevated storage tanks. The stored water provides a reserve for fire flow and may be used for general-purpose flow should the electric power fail, or in case of pumping capacity loss.
Conduits are artificial channels made for the conveyance of fluids (Fig. 2-2). They fall into two categories:

- Free-flow conduits guide the fluid as it flows down a sloping surface.
- Pressure conduits confine and guide fluid movement under pressure.

Free-flow conduits may be simple open channels or ditches, or pipes or tunnels flowing partially full. A pressurized conduit can be a pipeline or tunnel flowing under internal pressure.

Conduits can be categorized mainly according to the flowing (gravity or pumped systems) and secondarily to the appurtenances along the aqueduct (turnouts, gates, valves, etc.).

### 2.6.1 Pipes

Pipes can be free-flow or pressure conduits, buried or elevated. Several materials can be used. In order to avoid contamination of treated water, potable water pipes are most of the time pressurized.

Pipes can be categorized according to:

- Location (buried or elevated).
- Type (continuous or segmented).
- Type of joints (rigid, flexible).
- Capacity (diameter).
- Geometry (wall thickness).
- Type of coating and lining.
- Depth.
- History of failure.
- Appurtenances and branches.
- Corrosiveness of soil conditions.
- Age.
- Pressure.
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The selection of material type and pipe size are based on the desired carrying capacity, availability of material, durability and cost.

Moreover, pipes can be categorized according to the type of consumer (industries, critical and commercial facilities, housing).

2.6.2 Tunnels

Whatever the content (potable or waste-water, road or railway), tunnels are confined structures. They are often not redundant, and major disruption to the utility or transportation system is likely to occur should a tunnel become non-functional.

Tunnels may be categorized according to:

- Construction technique.
- Liner system.
- Geologic conditions.

For a more detailed assessment, the shape of the section, the depth, the length and the diameter of the tunnel, the liner thickness might be a useful information.

2.6.3 Canals

Canals are free-flowing conduits, usually open to the atmosphere, and usually at grade. They tend to be larger than pipelines operated under pressure. The advantages of using a canal include the possibility of construction with locally available materials, longer life than metal pipelines, and lower loss of hydraulic capacity with age. The disadvantages include the need to provide the ultimate flow capacity initially and the likelihood of interference with local drainage. Flumes are open-channel sections that carry water in elevated structures.

Canals can be formed by cutting a ditch into the ground, building up levees, or a combination of the two. Most often, canals are concrete-lined to reduce water losses. Canals can traverse both stable and unstable geologic conditions.

Canals can be:

- Open cut or built up using levees.
- Reinforced, unreinforced liners or unlined embankments.

Flumes sections are commonly made of wood or metal. The support systems can be built of wood, concrete or steel. The support structures might be a few feet high where the flume runs along a contour, or very tall where the flume crosses a creek or river. Flumes are specialized structures and are not specifically addressed here.

Moreover, they can be categorized according to the: material (wood, steel, concrete); appurtenances and branches location; age of construction; geometrical characteristics (width, depth, capacity); section (orthogonal, trapezoid etc); inclination.
3 DESCRIPTION OF WASTE-WATER SYSTEM TAXONOMY

Waste-water system can alternatively be called sewer network. Sewer network is comprised of components that work together to:

- Collect.
- Transmit.
- Treat.
- Dispose of sewage.

The taxonomy of waste-water system considered within SYNER-G is described in deliverable D2.1 (General methodology for systemic vulnerability assessment). The following elements of waste-water system are considered (Fig. 3-1).

- Conduits (pipes, tunnels).
- Treatment plant.
- Lift station.
- Supervisory Control and Data Acquisition (SCADA).

![Diagram of Waste-Water System](image)

**Fig. 3-1 Breakdown of waste-water system.**

The Waste-water system as a whole is composed of a number of point-like critical facilities (treatment plants, pumping stations) and of the distribution network itself. The internal logic of the critical facilities and their function in the management of the whole system should be modelled explicitly. The network portion of the system is made of pipelines and tunnels.

### 3.1 CONDUITS

Conduits are artificial channels made for the conveyance of fluids. Mainly free-flow conduits that guide the fluid as it flows down a sloping surface are present in waste-water system.
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Free-flow conduits may be pipes or tunnels flowing partially full. Collection sewers are generally closed conduits that carry normally sewage with a partial flow. They could be sanitary sewers, storm sewers, or combined sewers. Interceptors are large diameter sewer mains, usually located at the lowest elevation areas.

![Conduits Diagram](image)

**Fig. 3-2 Breakdown of waste-water conduits.**

In general, mains in the sanitary sewer system are underground conduits that normally follow valleys or natural streambeds. Waste-water conduits are usually designed as free flow channels except where lift stations are required to overcome topographic barriers. Sometimes the sanitary sewer system flow is combined with the storm water system prior to treatment.

### 3.1.1 Pipes

Waste-water pipes are most of the time free flow conduits.

The typology of waste-water pipes is the same as in potable water pipes. More specific pipe materials used for collection sewers and interceptor sewers are similar to those for potable water. The most commonly used sewer material is clay pipe manufactured with integral bell and spigot end. Concrete pipes are mostly used for storm drains and for sanitary sewers carrying non corrosive sewage (i.e. with organic materials). For the smaller diameter range, plastic pipes are also used.

### 3.1.2 Tunnels

The typology of waste-water tunnels is the same as in potable water tunnels.

### 3.2 WASTE-WATER TREATMENT PLANT

Waste-water treatment plants in the sanitary sewer system are complex facilities which include a number of buildings and underground or on ground reinforced concrete tanks and basins. Common components at a treatment plant include trickling filter, clarifiers, chlorine tanks, recirculation and waste-water pumping stations, chlorine storage and handling, tanks, and pipelines. Concrete channels are frequently used to convey the waste-water from one location to another within the complex. Within the buildings there are mechanical, electrical, and control equipment, as well as piping and valves. Conventional waste-water treatment consists of:

- preliminary processes (pumping, screening, and grit removal),
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- primary settling to remove heavy solids and floatable materials,
- secondary biological aeration to metabolise and flocculate colloidal and dissolved organics.

_Preliminary treatment_ units vary but generally include screens to protect pumps and prevent solids from fouling grit-removal units and flumes. Additional preliminary treatments (flotation, flocculation, and chemical treatment) may be required for industrial wastes.

_Primary treatment_ typically comprises sedimentation, which removes up to half the suspended solids.

_Secondary treatment_ removes remaining organic matter using activated-sludge processes, trickling filters or biological towers. Chlorination of effluents is commonly required.

Waste sludge may be stored in a tank and concentrated in a thickener. Raw sludge can be disposed of by anaerobic digestion and vacuum filtration, with centrifugation and wet combustion also currently used.

Waste-water treatment plants can be categorized by their size (small, medium or large) and by the anchorage (or not) of their sub-components.

The following sub-components are considered in SYNER-G for waste-water treatment plant:

- Electric Power (commercial power).
- Chlorination equipment.
- Sediment flocculation.
- Chemical Tanks.
- Electric equipment.
- Elevated pipe.
- Building

Also, the treatment level could be considered (primary, secondary, tertiary).

### 3.3 LIFT STATION

Lift or pumping stations serve to raise sewage over topographical rises or to boost the disposals. They are typically used to transport accumulated waste-water from a low point in the collection system to a treatment plant. If the lift station is out of service for more than a short time, untreated sewage will either spill out near the lift station, or back up into the collection sewer system. Pumping stations consist primarily of a wet well, which intercepts incoming flows and permit equalization of pump loadings and a bank of pumps, which lift the waste-water from the wet well. The centrifugal pump finds widest use at pumping stations. Thus, a plant is usually composed of a building, one or more pumps, electrical equipment, and, in some cases, back-up power systems. Lift stations are often at least partially underground.

They can be categorized according to their size (small or medium/large) and by the anchorage (or not) of their sub-components (equipment and back-up power).
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The following subcomponents may be considered in a pumping station (except for the back-up power):

- Electric Power (commercial power).
- Vertical/ Horizontal Pump.
- Building.
- Equipment.

3.4 SUPERVISORY CONTROL AND DATA ACQUISITION (SCADA)

Various types of in-line components exist along waste-water transmission pipelines, including portions of the supervisory control and data acquisition (SCADA) system located along the conveyance system and various flow control mechanisms (e.g., valves and gates).

In-line SCADA the hardware includes a variety of components, including:

- Instrumentation.
- Power Supply (normal, backup).
- Communication components (normal, backup).
- Weather enclosures (electrical cabinets and vaults).

SCADA system components in waste-water transmission systems are the following:

- Instruments attached to the pipeline may include flow devices that are sometimes installed in a venturi section of pipeline.

- *Remote Terminal Units (RTUs) and Programmable Logic Controllers (PLCs)* are most commonly solid state devices. An RTU device picks up the analogic signals from one or more channels of SCADA system devices at one location. The RTU converts these signals into a suitable format for transmission to a central SCADA computer, often at a location remote from the devices. A PLC can control when pumps are turned on or off, based on real time data or pre-programmed logic.

- **SCADA Cabinet** is a metal enclosure that is mounted to a floor or bolted to a wall.

- Most SCADA systems include battery backups.

- Communication Links. The remote SCADA system is connected in some manner to the central location SCADA computer system. The most common links are radio, leased landlines and, to a lesser extent, microwaves; the use of public switched landlines is rare.

The location of the valves is often important when deciding how a pipeline system performs as a whole; damage to a pipeline between two valves will need to be isolated by closing the valves. Thus, SCADA systems can be categorized according to: the intervals between valves on conduits, the anchorage of cabinets and inside equipments, and the number and type of communication links.
4 PERFORMANCE INDICATORS OF WATER AND WASTE-WATER SYSTEM COMPONENTS

Water and waste-water systems are very complex infrastructures composed by several individual components (e.g. water system consists of water source, water treatment plants, pipelines, tunnels, canals, storage tanks, pumping stations and SCADA; waste-water system includes waste-water treatment plants, lift stations, pipelines and tunnels). The overall performance of a system depends on the individual performance of its components. For that reason, some specific performance measures can be defined for each component and for the whole system. Different component Performance Indicators (PIs) are used for different type of system analysis.

For individual water and waste-water systems components, the proposed single performance indicators are summarized in the following tables.
### Table 4.1 Summary of Water Component Performance Indicators (WCPIs)

<table>
<thead>
<tr>
<th>A/A</th>
<th>Approach</th>
<th>Component</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Functionality analysis</td>
<td>Pipeline</td>
<td>Certain critical pipelines serving critical facilities remain operational during and following an earthquake.</td>
<td>ALA (2005)</td>
</tr>
<tr>
<td>2</td>
<td>Acceptable damage rate evaluation</td>
<td>Pipeline</td>
<td>An acceptable damage rate should be about 0.03 to 0.06 breaks per 1,000 feet (305m) of equivalent 6-inch (15.2cm) diameter pipe, in order to confirm with the service restoration target.</td>
<td>ALA (2005)</td>
</tr>
<tr>
<td>3</td>
<td>Redundancy analysis</td>
<td>Pipeline</td>
<td>Especially for transmission pipelines (Function Class II: Normal and ordinary pipeline use, common pipelines in most water systems.).</td>
<td>ALA (2005)</td>
</tr>
<tr>
<td>4</td>
<td>Operability</td>
<td>Pipelines, Storage facilities, Pumping station</td>
<td>Estimation of the performance of pipelines after the comparison of the condition of existing pipeline with the ideal pipe with appropriate design and construction practice. Water storage facilities and pump structures needed to supply water pressure to rest network.</td>
<td>ASCE 7-02 provisions</td>
</tr>
<tr>
<td>5</td>
<td>Acceptable damage states</td>
<td>All components</td>
<td>JWWA defines important facilities and for them defines the damage state that complies with the acceptable performance criterion.</td>
<td>JWWA Guidelines (1997)</td>
</tr>
</tbody>
</table>
| 6   | Flow analysis                         | Junctions/ Nodes                 | *Head Ratio (HR)*. For each node, this index is defined as the ratio of the water head in the seismically damaged network to the reference value for non-seismic, normal operations conditions:  
  \[ HR_i = \frac{H_{seismic}}{H_{reference}} \]  
  The determination of the water head requires a flow analysis on the network. Hence this index expresses a functional consequence in the i-th component of the physical damage to all system components. When interactions with other systems are modeled, \( HR_i \) expresses the functional consequence in the i-th component of the physical damage to components of all the systems, i.e. it is the value of the index that changes due to the inter- and intra-dependencies, not its definition. |
<table>
<thead>
<tr>
<th>A/A</th>
<th>Approach</th>
<th>Component</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
</table>
| 7   | Probabilistic performance of water supply systems | Pipe      | Damage Consequence Index (DCI): Measures the impact of each Pipe i on the overall system serviceability and can be used to identify critical links that significantly affect the system seismic performance. The index is defined at the component level in terms of a system-level PI that measures serviceability, the System Serviceability Index (SSI), defined afterwards. Thus, it is a PI that reflects at component-level the functional consequence of damage to all systems' components (and incorporates the effect of the inter- and intra-dependencies, when modeled). The DCI for the i-th pipe is defined to reflect the consequence from damaging the pipe, including pipe breaks and leaks. It is expressed as:  
\[
DCI_i = \frac{E[SSI] - E[SSI/L_i]}{1 - E[SSI]}
\]

in which \(E[SSI]\) is the (unconditional) expected value of SSI from a set of simulations in which the i-th pipe might or might not be damaged; and \(E[SSI/L_i]\) is the conditional expectation of SSI from another set of simulations under the same seismic hazard, but given that the i-th pipe is damaged. As damage to the i-th pipe is certain in the calculation of \(E[SSI/L_i]\), theoretically, \(E[SSI/L_i]\) is always smaller than \(E[SSI]\) where the pipe might or might not be damaged. Therefore, DCI, is always positive, and it is the percent reduction of SSI given that the i-th pipe is damaged. DCI can be effectively estimated as:
\[
DCI_i \approx \frac{1}{m_1} \sum_{i=1}^{m_1} SSI_i - \frac{1}{m_2} \sum_{j=1}^{m_2} SSI_j
\]

in which \(m_1\) is the number of all Monte Carlo samples, and \(m_2\) is the number of Monte Carlo samples where damage occurs in the i-th pipe. | Wang et al. (2010) |
**Upgrade Benefit Index (UBI):** Similarly to the DCI, the index measures the impact of an upgrade of an individual pipe on the overall system serviceability, and reflects at the component level the systemic functional consequence of damage to the whole system(s). It is defined as:

\[
UBI_i = \frac{E_{\text{upgrade}}[SSI] - E[SSI]}{1 - E[SSI]}
\]

in which \(E_{\text{upgrade}}[SSI]\) is the expected value of SSI given that the i-th pipe is “upgraded.” By “upgrade” it is meant that the probability of pipe damage given an earthquake is significantly smaller than its value before upgrade. UBI is the percent increase of SSI given that the i-th pipe is upgraded, and its relative value is a measure of the pipe impact on the overall system serviceability. UBI can be used to identify critical links in seismic mitigation, as those with relatively large UBI values. The meaning of DCI, on the other hand, is complementary to UBI but less direct since it is related to the consequence of damage. When the probability of damage in the i-th pipe after upgrade is small compared to its pre-upgrade value, say \(E_{\text{upgrade}}(L_i)/P(L_i) \leq 0.1\), and can be approximated as zero, the UBI can be effectively evaluated by means of conditional sample analysis. In the run for system risk assessment, a subset of the samples in which the i-th pipe is observed intact can be treated as an equivalent set of Monte Carlo samples with the pipe upgraded. UBI can then be estimated as:

\[
UBI_i \approx \frac{1}{m_2} \sum_{j=1}^{m_2} SSI_j - \frac{1}{m_1} \sum_{i=1}^{m_1} SSI_i

1 - \frac{1}{m_1} \sum_{i=1}^{m_1} SSI_i
\]

---

<table>
<thead>
<tr>
<th>A/A</th>
<th>Approach</th>
<th>Component</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
</table>
| 8   | Probabilistic performance of water supply systems | Pipe | *Upgrade Benefit Index (UBI):* Similarly to the DCI, the index measures the impact of an upgrade of an individual pipe on the overall system serviceability, and reflects at the component level the systemic functional consequence of damage to the whole system(s). It is defined as: 

\[
UBI_i = \frac{E_{\text{upgrade}}[SSI] - E[SSI]}{1 - E[SSI]}
\]

in which \(E_{\text{upgrade}}[SSI]\) is the expected value of SSI given that the i-th pipe is “upgraded.” By “upgrade” it is meant that the probability of pipe damage given an earthquake is significantly smaller than its value before upgrade. UBI is the percent increase of SSI given that the i-th pipe is upgraded, and its relative value is a measure of the pipe impact on the overall system serviceability. UBI can be used to identify critical links in seismic mitigation, as those with relatively large UBI values. The meaning of DCI, on the other hand, is complementary to UBI but less direct since it is related to the consequence of damage. When the probability of damage in the i-th pipe after upgrade is small compared to its pre-upgrade value, say \(E_{\text{upgrade}}(L_i)/P(L_i) \leq 0.1\), and can be approximated as zero, the UBI can be effectively evaluated by means of conditional sample analysis. In the run for system risk assessment, a subset of the samples in which the i-th pipe is observed intact can be treated as an equivalent set of Monte Carlo samples with the pipe upgraded. UBI can then be estimated as: 

\[
UBI_i \approx \frac{1}{m_2} \sum_{j=1}^{m_2} SSI_j - \frac{1}{m_1} \sum_{i=1}^{m_1} SSI_i

1 - \frac{1}{m_1} \sum_{i=1}^{m_1} SSI_i
\] | Wang et al. (2010) |
in which $m_1$ is the number of all Monte Carlo samples, and $m_2$ is the number of Monte Carlo samples where no damage occurs in the $i$-th pipe. It can be easily shown (Wang et al., 2010) that the UBI and DCI are related as:

$$UBI_i = DCI_i \frac{P(L_i)}{P(\overline{L}_i)} = DCI_i \frac{P(L_i)}{1 - P(L_i)}$$

which suggests that, as far as upgrading benefit is concerned, both the consequence of damage (DCI) and the likelihood of damage (the odds ratio $P(L_i) / P(\overline{L}_i)$) should be factored in. For example, for two pipes with equal damage consequence (DCI), the one with high odds of damage should be upgraded first. On the other hand, among the pipes that have the same odds of damage, the one with a high damage consequence has a high upgrade priority. These rather intuitive deductions are consistent with current practices in water system upgrades, whereby priority is given to non-redundant links with high flow rate and high repair rate, which correspond to severe damage consequence (i.e., DCI) and high damage probability (i.e. $P(L_i) / P(\overline{L}_i)$), respectively.
Table 4.2 Summary of Waste-Water Component Performance Indicators (WWCPiS)

<table>
<thead>
<tr>
<th>A/A</th>
<th>Approach</th>
<th>Component</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Operability</td>
<td>Collection* and treatment systems</td>
<td>Achieving performance objective (% probability of achieving)</td>
<td>ALA (2005)</td>
</tr>
<tr>
<td>2</td>
<td>Functionality</td>
<td>Collection and treatment systems</td>
<td>Estimation of violation of maximum duration e.g. 7 days, 30 days</td>
<td></td>
</tr>
</tbody>
</table>

*The collection and conveyance system is the system of pipes that collects the sewage from the sources and conveys it to a central point for treatment and/or disposal.
5 METHODS TO EVALUATE WATER AND WASTE-WATER SYSTEMS PERFORMANCE

5.1 REVIEW OF AVAILABLE LITERATURE ON METHODS TO EVALUATE WATER SYSTEM SEISMIC PERFORMANCE

Water is vital for human survival and for the continuity of all human activities. In general, water system may experience important damages during earthquakes, with significant impact on potable water uses and emergency activities such as fire suppression. This has been observed in almost all past strong earthquakes. Reliability assessment of water networks comprises a complex, yet essential process. Many issues should be taken into account, such as the variations in demands, the reliability of individual components and their locations, the fire-fighting requirements and others.

The seismic reliability of water networks is possible to be measured using different indices of physical nature or not, like vulnerability, connectivity, serviceability, maximum flow, redundancy and economic loss (ATC 25-1, 1992). Connectivity analyses measure post-earthquake integrity, the extent to which links and nodes in a network are connected or disconnected. Serviceability analyses estimate the remaining or residual capacity between selected nodes following an earthquake. Serviceability is a performance assessment measure that tends to focus more on the hydraulic perspective and less upon the underlying robustness of the network in terms of its layout.

Closely related to reliability is redundancy, a characteristic of the overall system performance that is often neglected. Redundancy in a water supply network indicates the existence of reserve capacity of the network and also the existence of alternative routing (supply paths to the demand nodes in case the supply links go out of service) (Awumah et al., 1991). The redundancy of water supply system under earthquake risk can be evaluated from three points of view; 1) along with reliability when assessing system performance, 2) in order to design a new network, 3) for efficient seismic mitigation of the existing network.

In several cases, reliability assessment is related with mitigation prioritization procedure. Multi-criteria analysis (MCA) is more efficient than traditional benefit-cost analysis, as it copes with the uncertain judgment of experts. Moreover, the model should consider customers importance, pipeline properties and hazard factors. Hence, a fuzzy analytic hierarchy process (FAHP) to support the MCA for renewal prioritization of the lifeline systems can be developed. This optimized fuzzy prioritization method can be applied as an evaluation tool (Alexoudi et al., 2009), where uncertain and imprecise judgments of experts are translated into fuzzy numbers.

Seismic risk of water system has been investigated extensively (Ballantyne et al., 1990; Taylor, 1991; Shinozuka et al., 1992; Hwang et al., 1998; Shi et al., 2006; Wang, 2006). System reliability of San Francisco auxiliary water supply system and the effects of water supply performance on fire following earthquakes are described in Scawthorn et al. (2006) research for both 1906 San Francisco and 1989 Loma Prieta earthquakes. Seismic risk assessments have been reported for the water supply systems in Memphis Tennessee (Chang et al., 2002).
The methods presented in the selected references in this section can be classified in the following four levels:

- **Level I (Vulnerability Analysis):** The scope is to estimate the percentage of the physical damages in a specific region based on the vulnerability analysis of water components. The latest can be estimated through appropriate fragility curves or/and Monte-Carlo technique.

- **Level II (Connectivity Analysis):** A vulnerability analysis is essential, as a first step, in order to estimate the physically damaged components (pipes, nodes). In a second stage, the damaged components should be removed from the network. Furthermore, some of the remaining nodes which can be completely isolated from all supply nodes must be removed from the original network. In a third stage, a connectivity analysis may be performed (simplified- Level Ila or advanced- Level IIb).

- **Level III (Flow Analysis):** Firstly, water head, flow rate and amount of leakage at each demand node are calculated under intact (pre-earthquake) conditions as well as the quantity of flow and head loss in each pipe. After the evaluation of the physical vulnerability of the pipes (break, leak), a flow analysis is performed involving the newly formed network. It is assumed that, when a pipe is broken, a shutdown device will be automatically activated at the starting and terminating nodes of the pipe so that the water leakage is prevented. It is also postulated that capabilities of the supply nodes are not reduced by seismic damages.

- **Level IV (Serviceability Analysis):** Vulnerability estimation of water system components beside with a flow analysis is repeated for different seismic intensities using Monte-Carlo simulations. When the task is completed, average values of the flow rate and water pressure are calculated at each node together with their ratio to the corresponding parameters under intact condition. The above procedure comprises a full serviceability analysis (Level IVb). Moreover, a simplified serviceability analysis (Level IVa) can be accomplished connecting the pipeline break rate with a simple Serviceability Index.

The majority of the studies performed for water system can be categorized as **Level I** that means simple physical vulnerability studies of water system components (ATC-13, ATC-25, NIBS, 2004). The performance index used in Level I studies is the “Damage Ratio” that describes the expected number of failures per unit length or per link or per node of the system. Moreover, the “Damage Ratio” can be considered as a percentage of the damaged nodes/links.

A simple connectivity analysis (Level II) of the network can be accomplished using Graph Theory (clustering coefficient of a graph, Redundancy Ratio, Service Ratio Reachability Ratio) and Statistical Methods (Level Ila). Level IIb studies can be found in Shinozuka et al. (1977) and O’Rourke et al. (1985) that use minimal cut set paths in reliability evaluation of lifeline networks. Moreover, techniques available for tracing the minimal paths and minimal cut sets have mainly been presented in literatures as connectivity analysis of the network (Jasmon and Kai, 1985; Fotuhi-Firuzabad et al., 2004). Another example of Level II analysis is the study performed by Kawakami (1990), which uses the “Damage Ratio” and “Service Ratio” as performance indexes. Service Ratio indicates the ratio of normally supplied houses to the total number in the system. Dueñas-Osorio et al. (2007a) propose the concept of “Connectivity Loss” in order to quantify the average decrease of the ability of distribution...
vertices to receive flow from the generation vertices. Dueñas-Osorio et al. (2007b) introduce “Redundancy Ratio” as the appropriate parameter to measure the performance of water system. Moghtaderi-Zadeh et al. (1982) propose “Reachability” of water as performance index, indicating the probability that a certain amount of water flow would reach key locations (nodes). Conclusively, “Damage Ratio”, “Service Ratio”, “Connectivity Loss”, “Redundancy Ratio” and “Reachability” are the performance indicators used in such Level of Analysis (Level II).

Many researchers have contributed to the advancement of seismic reliability methods for water supply systems from the flow and serviceability analysis viewpoint (Level III). Examples of Level III studies are those of Shinozuka et al. (1981) that developed, for the first time, a methodology to assess seismic reliability of transmission pipeline system to the city of Los Angeles, in terms of the degree of serviceability. It was assumed that the system is considered serviceable when its fire-fighting capabilities remain intact in the aftermath of an earthquake. Monte Carlo simulation was carried out in order to estimate the probability of serviceability on the basis of simulated states of physical damage of the system under seismic condition. Furthermore, a Level III study is the one performed by Isoyama and Katayama (1981) that developed a Monte Carlo simulation method for evaluating the seismic reliability of Tokyo water supply system during the post earthquake period using maximum possible flow method. The method was intended for relatively large water supply systems, considering network topology, supply and distribution station capacities, and system operating strategies. Moreover, O’Rourke et al. (1985) simulated the serviceability of seismically damaged water supply system for the city of San Francisco through a flow analysis. Performance of the system was defined explicitly as the ratio of available to required water flow at a standard operating pressure of 14 m near the location of the predicted fire outbreak (Level III). The performance indexes used in Level III analyses account the probability distribution of the percentage of customers who would lose their service after a specific earthquake.

**Level IV** approaches require complex hydraulic analyses, which are time consuming and require expertise and availability of several data. For this reasons, a number of researches have developed simplified models to assess the serviceability of pipeline networks under various amounts of pipe damages. A diagram correlating the Serviceability Index (SI) to average break rate is proposed in HAZUS (NIBS, 2004 – Level IVa). If SI is over 90%, the capability of water system for fire suppression is high, compared to SI below 20%. Generally, the performance indexes of Level IV studies involve the system ability to meet hydraulic requirements including existing and future water needs (i.e. fire flow, maximum day or MD and maximum hour or MH domestic needs, storage needs, etc) and to properly size future facilities.

The works of Markov et al. (1994), Hwang et al. (1998), Javanbarg et al. (2006) and Shi (2006) can be classified as Level IVb analyses. In particular Markov et al. (1994) developed a special algorithm for the hydraulic analysis of the seismically damaged network and calculated serviceability measures for the auxiliary water supply system in San Francisco. Hwang et al. (1998) performed a hydraulic simulation analysis to assess the serviceability of the water supply system in the city of Memphis. The serviceability of a system was determined based on the connectivity and flow analysis of a seismically damaged network, which was established through a Monte Carlo simulation. Javanbarg et al. (2006) evaluated the performance of water supply in Osaka City considering hydraulic analysis and modelling both breakage and leakage as the damage states of pipeline systems. Two performance parameters were considered; availability index, which is the ratio between the output
available water pressure in damaged network and the required pressure at each demand node within the undamaged network, and serviceability index, which is the ratio between the output available water flow in damaged network and the required water flow volume at each demand node within the undamaged network. Shi (2006) developed a hydraulic network model for earthquake simulation of water network operated by the Los Angeles Department of Water and Power. The model accounted for flows and pressures in a heavily damaged system and provided a method for simulating pipeline leakage and breakage.

Besides models classified in the above four categories (Level I to IV), other models have been also proposed, such as redundancy approaches (Awumah et al., 1991; Kalungi and Tanyimboh, 2003; Hoshiya and Yamamoto, 2002; Hoshiya et al., 2004) and studies for the identification of critical links of water supply systems under earthquakes (Wang et al., 2010). Wang et al. (2010) describe a process for seismic risk assessment and identification of critical links of water supply systems under earthquakes. Probabilistic performance of water supply systems is reflected by the System Serviceability Index (SSI)- a ratio of sum of the satisfied customer demands after an earthquake, and two other performance indices like Damage Consequence Index (DCI) and Upgrade Benefit Index (UBI). With the aid of Monte-Carlo simulations in conjunction with a special hydraulic analysis computer program (GIRAFEE), the seismic risk of the system is evaluated for a hypothetical seismic damage scenario. The concept of efficient frontier is then employed to identify critical links of the system.

Awumah et al. (1991) and Kalungi and Tanyimboh (2003) have been extensively studied the redundancy for water networks. They developed an entropy-based measure of redundancy and examined through a series of network simulations a range of network layouts when a link goes out of service. However, one or two damaged components are taken into account for redundancy estimations, therefore these methods cannot be applied to a heavily damaged system. Hoshiya and Yamamoto (2002) and Hoshiya et al. (2004) proposed a redundancy index for the lifeline systems under seismic risk based on the entropy of an event of damage modes conditioned on system damage. In particular Hoshiya and Yamamoto (2002), consider the physical probability of connectivity between nodes within a network as a remarkable parameter in redundancy analysis. However, the leakage state of damage of pipelines may not be considered in simulations.

5.2 REVIEW OF AVAILABLE LITERATURE ON METHODS TO EVALUATE WASTE-WATER SYSTEM SEISMIC PERFORMANCE

Over the last twenty years, waste-water systems have been heavily damaged by natural disasters as earthquakes, worldwide. The societal and economic disruption caused by waste-water network damages is important, as for example, the impact on public health and environment due to the discharge of raw/inadequately treated sewage.

There is limited real data specifically referring to the vulnerability of waste-water system components and furthermore to the post-earthquake functionality of waste-water networks. However, relevant damage databases have been assembled for buildings associated to the waste water systems and of course for certain waste water components (pipes, tunnels, reservoirs and treatment plants). In general almost all available methodologies use “water” damage databases for waste-water systems. Moreover, the vulnerability analysis for waste-
water system components is performed using the same fragility curves with the components of the water supply system (ATC-13; ATC-25; NIBS, 2004).

Nevertheless, there are some differences between water and waste water systems that should be mentioned:

- Waste-water facilities are, in general, located in low-level areas to take advantage of transporting sewage via gravity. As a result, waste-water treatment and pumping facilities typically have larger exposure to earthquakes, because they are more likely to be located in soft and loose alluvial soils exposed to large ground deformations and probably to liquefaction.

- Gravity sewers differ from water pipelines because:
  - They are generally buried deeper.
  - The pipe body/materials and joints are typically weaker as they are not designed for pressure.
  - They are more buoyant as they are partially filled with sewage. This makes them more vulnerable to flotation in areas with high groundwater tables or liquefaction. Similarly, manholes are vulnerable to displacement under surcharged conditions.
  - Sewer pipelines can generally withstand more damage and remain functional (even partially) compared to pressurized water pipelines. Damaged sewers often continue to operate, transporting sewage until the sewer pipe is offset (shear) and/or separated to the point that sewage flow is blocked. By comparison, pressurized pipelines (such as water pipelines) will discharge far greater amounts of water than gravity pipelines given the same physical leak size.

- Furthermore, waste-water lift stations differ from water booster stations. They are designed with a deep wet well (typically over 5m deep and in extreme cases approaching 30m deep) where sewage is collected by gravity. Water booster stations are usually located on grade or in shallow vaults. Therefore, lift stations can be vulnerable to liquefaction or excessive buoyant forces in areas with high groundwater tables.

The required effort to assess the performance of waste-water systems varies with the level of analysis and the complexity of the system. Most of the available methodologies are limited in the estimation of vulnerability, replacement cost and restoration time (ATC-13; ATC-25; NIBS, 2004), without any specific assessments of network performance.

According to ALA (2004), the performance of waste-water systems can be assessed in three levels: Simplified, Intermediate and Advanced.

- **Simplified Assessment**: It can be a deterministic one, where the result is calculated directly (no uncertainty taken into account), using scenario events without using the probability of the event in the calculations. A normal probabilistic risk assessment is also possible, using approximations (e.g., high, medium, and low) for the three risk components (hazard, vulnerability, consequence).

- **Intermediate Assessment**: It is a probabilistic risk assessment using a mean or median value for each of the three risk parameters, with minimal consideration of the variability of each term.
D2.5 - Definition of system components and the formulation of system to evaluate the performance of water and waste-water systems

- **Advanced Assessment:** It is again a probabilistic risk assessment incorporating the variability of one or more of the risk parameters to capture their randomness and uncertainty.

The three levels of assessment are summarized below:

**Level I: Simplified Assessment**

**Step 1:** This is a screening assessment for either the collection system or the treatment plant(s). The risk of loss of function is calculated for each component and for each relevant hazard, using the risk equation.

\[
\text{Relative Risk} = \text{Hazard} \times \text{Vulnerability} \times \text{Consequence} \quad (5.1)
\]

**Step 2:** The “system” is considered by the consequence term, but no system method is prepared.

**Step 3:** A “feel” for the variability of the result can be estimated by using the extremes of the ranges for each of the parameters in the risk equation.

**Step 4:** The correlation factor is incorporated to the risk equation.

**Step 5:** After proper review and validation the highest risk components and hazards are selected for an Intermediate or Advanced Assessment.

**Step 6:** There is no repair cost or outage time evaluation.

**Level II: Intermediate Assessment**

**Step 1:** The quantitative hazard intensity and vulnerability is defined using ranges (i.e. high, medium, low).

**Step 2:** The results for each sewer branch and flow train in the treatment plant are properly reviewed and combined; the probability of loss of function is estimated for each one.

**Step 3:** The outage time can be calculated by combining the total number of pipeline failures or man-hours for the treatment plant and lift station restoration. The results can be divided by the available manpower to estimate the system restoration time.

**Step 4:** The repair cost can be calculated by applying a repair cost-damage relationship to each component, and summing the results. Repair cost-damage relationships are typically developed in terms of percent of replacement cost, so replacement costs of each component must be developed.

It must be mentioned that probabilistic assessments to address uncertainties are not required for this level of assessment.

**Level III: Advanced Assessment**

**Step 1:** A spreadsheet method is in general developed incorporating the connectivity of the system. For each component (including pipeline segments), the specific seismic scenario probability of loss of function is calculated by multiplying the hazard probability of occurrence by the probability of loss of function. The probabilities of loss of function for each component along the pipeline branch or treatment plant train are then combined, and the sub-system or
system probability of loss of function is calculated. A method is designed to show where loss of function occurs and where sewage overflows take place. Then each branch and flow train through the plant is analyzed, and the results are combined. Depending on the complexity of the system, as for example in the case of the treatment plant, the method can take the form of a fault tree.

**Step 2:** The outage time is calculated by developing restoration rates for pipelines and other system components. The repair rates are applied to the various components until they are all repaired. This is performed in incremental steps and the method can be run at each step, showing the status of the system in progressive time increments.

**Step 3:** The same procedure can be used to calculate repair costs, except if the connectivity module is not required. Damage relationships for repair costs are applied rather than loss of functionality estimates. The total repair cost for the specific scenario is estimated as the sum of the repair cost of the individual components.

**Step 4:** A probabilistic estimate is made taking into account the variability of the risk parameters and quantification of the uncertainty of the results. Both the hazard intensities and the vulnerability relationships cover a range with a distribution of probabilities.

**Step 5:** At the end the functionality assessment is the probability of collecting (or treating) the sewage flow through the selected portions of the system. This result is updated in time steps until the system is totally restored.

### 5.3 WATER AND WASTE-WATER SYSTEMS PERFORMANCE INDICATORS

In general, the performance measures used to assess the performance of water and waste-water systems can be defined by:

- **Inventory Functions:** physical characteristics, numbers of facilities.
- **Engineering:** structural integrity, deterioration.
- **Operational Reliability:** Connectivity/ Serviceability/ Operability/ Functionality.
- **Direct/ Indirect consequences in economy (e.g Cost/Benefit Analysis, capital and financial resources).**
- **Demand:** e.g. pressure and flow (for water system).
- **Safety and Security.**

ALA (2002) proposes some performance metrics for water system that are related to:

- Percent (%) served (in total or by sector) within a specific number of days with raw water with adequate fire flow pressures, and/or
- Percent (%) served (in total or by sector) within a specific number of days with fully treated water

These metrics could be measured alternatively in terms of number of service connections, populations served, or volume of water served (i.e., cubic feet or gallons) for the whole water system.
D2.5 - Definition of system components and the formulation of system to evaluate the performance of water and waste-water systems

Each water component, according to ALA (2002), can have different importance with respect to a set of performance objectives. Their importance can be accounted according to Component Criticality Rating (CCR), that is:

- **LSR = Life Safety Rating** (based on fraction of time occupied: 5-Continuously occupied, 4-Hazardous materials release potential, 3-Occupied 50% of time, 2-Occupied 25% of time, 1-Occupied 10% of time).
- **FFR = Fire Flow Rating** (significance to fire fighting).
- **DWR = Drinking Water Rating** (significance to drinking water supply).
- **DPR = Damage Potential Rating** (potential for causing damage to adjacent facilities).

Essential to the evaluation of water system performance is a system vulnerability model, which identifies if the final nodes (service zones, service connections, fire hydrants) have (a) flows with adequate fire flow and pressures or (b) potable water supply that meets stringent safe drinking water health standards.

For waste-water system, ALA (2004) proposes as performance indicators, capacity measures (e.g. flow of wastewater at selected points); measures of reliability (such as frequency and magnitude of sanitary or combined sewer overflows (SSOs, CSOs), and the frequency and magnitude of discharge of inadequately treated sewage, percentage treated, etc.); measures of safety and health (similar to reliability examples as they impact water quality); and financial measures. The Environmental Protection Agency National Pollution Discharge Elimination System (EPA NPDES) permits requirements incorporate relevant performance measures such as discharge volume and water quality.

Potential metrics recommended for the performance of waste-water system according to ALA (2004), are:

- **Public health/backup of raw sewage**: This accounts the probability of achieving performance objective (e.g. – 90% probability of achieving), the probabilities of occurrence (e.g. 50% in 50 years) and different criteria as a function of method of contact (backup into buildings, overflow onto city streets).
- **Discharge of raw/inadequately treated sewage**: Metrics commonly used quantify the impact on public health and the environment (e.g. flow associated with biochemical oxygen demand, dissolved oxygen of the receiving water).
- **Direct damage/financial impact**: Direct damage to wastewater system components can include cleanup and repair costs associated with flood inundation of a treatment plant or repair cost of the collection system (pipelines, tunnels etc) while secondary damage (economical cost) can be occurred to commercial or industrial facilities (e.g., factories shut down) due to loss of wastewater service.
- **Security system performance**: The performance objective is stated in terms of probability of limiting raw sewage discharge when subjected to a design basis threat

Moreover, performance indexes for waste-water system can account “Societal Factors” (ALA, 2004):

- **Fines and/or jail time - resulting from illegal discharges.**
o Loss of public confidence – resulting from release of raw sewage, backup of raw sewage into households, or discharging partially treated sewage into the receiving body.

o Political – resulting from peer pressure from other regional wastewater organizations, or local politicians concerned about discharge of raw or partially treated sewage in their area.

o Public health and safety – injury or death to utility staff or the public due to exposure to raw or partially treated sewage, chemical release, or building collapse

In addition, several other factors (economic factors) can describe waste-water performance (ALA, 2004) such as:

o Substantial fines levied by regulating authorities.

o Direct loss - repair costs of facilities damaged in hazard events.

o Capital improvement plan – identify and prioritize projects to optimize a capital improvement plan.

o Project design – define capacity, reliability or other parameters to optimize a new project.

o Level of service (outage time) – define expected service outage times associated with various events with associated probabilities of occurrence.

Available performance indicators for water and waste-water systems are summarized in Tables 5.1 and 5.2.

Different System Performance Indicators are used for different types of system analysis of water and waste-water systems. In the framework of SYNER-G, the proposed PIs at component and system level are closely connected to the approach that will be followed for the assessment of systemic vulnerability and loss in WP5. The PIs that will be used for both systems have to be in accordance to the adopted systemic approach. For example, if a flow analysis is used for the analysis of water supply system, Head Ratio and Average Head Ratio are the appropriate PIs at component and system level accordingly. For a probabilistic performance analysis of water supply systems, Damage Consequence Index and Upgrade Benefit Index can be used at the pipes level, and System Serviceability Index can be used at the system level. Finally, if a simplified connectivity analysis is used, Damage Ratio and Service Ratio are the Performance Indicators at the system level.
### Table 5.1 Summary of Water System Performance Indicators (WSPIs)

<table>
<thead>
<tr>
<th>A/A</th>
<th>Analysis Type</th>
<th>Description</th>
<th>Comments</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Connectivity</td>
<td>Examines:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>a) “Damage ratio”: the degree of physical damage to the system (defined as the expected number of failures per unit length or per link).</td>
<td>Propose a diagram between failures/km and Service ratio (%).</td>
<td>Kawakami (1990)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) “Service ratio: indicates the ratio of normally supplied houses to the total number in the system. This value increases as restoration proceeds.</td>
<td>Application for the restoration process of water transmission system in the City of Tokyo.</td>
<td></td>
</tr>
<tr>
<td>1b</td>
<td>Connectivity</td>
<td>Uses:</td>
<td>Dueñas-Osorio et al. (2007a) examine the loss of connectivity of a water distribution system.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>a) Formal graph theoretic notions to define characteristic measures of the network, such as an importance ordering of the vertices, the characteristic path length and redundancy.</td>
<td></td>
<td>Dueñas-Osorio et al. (2007a, 2007b), Dueñas-Osorio and Venuru (2009)</td>
</tr>
<tr>
<td>1c</td>
<td>Connectivity</td>
<td>Examines:</td>
<td>Application for the water distribution system in the East of San Francisco.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>a) The “Reachability” of water to certain key nodes.</td>
<td></td>
<td>Moghtaderi-Zadeh et al. (1982)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) The probability that a certain amount of water flow would reach key locations.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1d</td>
<td>Connectivity</td>
<td>Estimate:</td>
<td>For simplified evaluations, a graphical portrayal of the system is adequate.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) Reachability matrix.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2a</td>
<td>Serviceability</td>
<td>Examines:</td>
<td>Application for the water distribution system in Shelby County, TN.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>a) Probability distribution of the percentage of customers who would lose their service after an earthquake.</td>
<td></td>
<td>Adachi and Ellingwood (2008)</td>
</tr>
</tbody>
</table>
D2.5 - Definition of system components and the formulation of system to evaluate the performance of water and waste-water systems

<table>
<thead>
<tr>
<th>A/A</th>
<th>Analysis Type</th>
<th>Description</th>
<th>Comments</th>
<th>Reference</th>
</tr>
</thead>
</table>
| 2b  | Serviceability                    | Evaluate: Their particular systems ability to meet hydraulic requirements including existing and future water needs (i.e. fire flow, maximum day or MD and maximum hour or MH domestic needs, storage needs, etc) and to properly size future facilities. | The water system operating conditions are defined below:  
  - Pre-Natural Hazard Water System Condition.  
  - Post Natural Hazard Water System Condition.  
  - Water System Restoration.  
| 3   | Investment cost for upgraded      | Examines:  
  (a) Life cycle cost minimum criterion (minimum expected costs on seismic investment).  
  (b) Cost benefit ratio criterion.  
  (c) Positive value balance criterion.                                                                                                                                                                                                                                  | Application for water supply lifeline network located in the metropolitan area of Japan.                                                                                                                                                                                                                                                 | Imai and Koike (2010)            |
| 4   | Performance level criterion       | Accounts:  
  a) Restoration process after the physical damage of the network.                                                                                                                                                                                                 | ALA (2005):  
  - Considers 90% of customers restored within 3-days following an earthquake having a 10% chance of exceedance in 50-years.  
  - A typical water utility will be able to isolate most of the leaking and broken pipes within 1 day or so. Propose a diagram between equivalent damage ratio (km) and Percentage (%) of customers with water. | ALA (2005)                       |
### Average Head Ratio (AHR)

This index is defined as the average over the network nodes of the HR index:

$$AHR = \frac{1}{n_N} \sum_{i=1}^{n_N} HR_i$$

where $n_N$ is the number of nodes in the water supply system.

### System Serviceability Index (SSI)

The index is defined as the ratio of the sum of the satisfied customer demands after an earthquake to that before the earthquake:

$$SSI = \frac{\sum_{i=1}^{n} Q_i}{\sum_{i=1}^{n_0} Q_i}$$

where $n$ and $n_0$ are the number of satisfied demand nodes after and before the earthquake, and $Q_i$ is the demand at the $i$-th node.

The SSI varies between 0 and 1. A single value can be determined for a given condition of the network. Its probabilistic characterization, in terms of either its full distribution or its expected value $E[SSI]$ that enters in the definitions of Damage Consequence Index (DCI) and Upgrade Benefit Index (UBI), requires running multiple simulations for different earthquake realizations. The above definition assumes that the demand remains fixed before and after the earthquake, since it looks only at a single system, without considering the interactions of the water supply system with the other systems.

Wang et al. (2010)
<table>
<thead>
<tr>
<th>Performance Objective Category</th>
<th>100-Year Return Event (40% in 50 years)</th>
<th>500-Year Return Event (10% in 50 years)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Public Health</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Backup of any raw sewage into buildings</td>
<td>Not acceptable (less than 1% probability of occurrence).</td>
<td>Not acceptable (less than 5% probability of occurrence).</td>
<td></td>
</tr>
<tr>
<td>Overflow of raw sewage into streets</td>
<td>Acceptable in localized areas; less than 24 hrs.</td>
<td>Acceptable (treatment plant is inundated) less than 72 hrs.</td>
<td></td>
</tr>
<tr>
<td><strong>Environmental</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discharge of raw sewage to stormwater system, ditch or stream</td>
<td>Acceptable in localized areas; less than 72 hrs.</td>
<td>Acceptable less than 7 days.</td>
<td>ALA (2004)</td>
</tr>
<tr>
<td>Discharge of raw sewage to lake or river</td>
<td>Acceptable in accordance with CSO/NPDES.</td>
<td>Acceptable less than 30 days.</td>
<td></td>
</tr>
<tr>
<td>Discharge of raw sewage to salt water</td>
<td>Acceptable in accordance with CSO/NPDES.</td>
<td>Acceptable less than 90 days.</td>
<td></td>
</tr>
<tr>
<td>Discharge of disinfected primary effluent</td>
<td>Acceptable less than 30 days.</td>
<td>Acceptable less than 180 days.</td>
<td></td>
</tr>
</tbody>
</table>
REFERENCES


ALA 2005. *Seismic Guidelines for Water Pipelines*, prepared by ASCE, FEMA and NIBS.


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