SEISMIC RESILIENCE OF A WATER DISTRIBUTION NETWORK

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ABSTRACT

Water supply and distribution systems provide the (potable) water supply used by communities for drinking water, hygienic and sanitary reasons, industry and agriculture. The Re-CoDeS frameworks allows to quantify the (seismic) resilience of these systems using a compositional community demand / civil infrastructure system supply approach. The resilience is evaluated by comparing the evolution of the post-disaster water demand to the evolution of the post-disaster water supply. The application of the Re-CoDeS framework is shown for the assessment of the resilience of the water systems of the Kathmandu Valley. First, the damage suffered by the water systems after the 2015 Gorkha earthquake is described. Based on the available data and input, all the steps to evaluate the water demand and supply after an earthquake are introduced. These allow to quantify the resilience of the water distribution and supply system of the Kathmandu Valley during and after future earthquakes and to design retrofitting measures and recovery plans accordingly.

Keywords: resilience; water supply system; civil infrastructure system; recovery; vulnerability

1. INTRODUCTION

Water distribution and water supply systems are among the most ancient civil infrastructure systems of our societies. The ancient Romans built such systems to supply their urban regions with water from remote areas and sources (Gallo 2015, Monteleone et al. 2007). A reliable supply of potable water remains essential for the social and economic development of contemporary societies. Sufficient quantities of water supply are required for drinking water, hygienic and sanitary reasons, firefighting, in industry and agriculture. Service interruptions threaten, thus, the living standards of communities and can lead to high economic losses. The point-like facilities (e.g. water treatment plants, water reservoirs, pumping stations) and especially the pipes of the water supply and distributions networks are, however, susceptible to damage during seismic events. Recent earthquakes, such as the 1994 Northridge (California, USA) earthquake (moment magnitude $M_w$ 6.7), the 2010-2011 Canterbury (New Zealand) earthquake sequence, and the 2015 Gorkha (Nepal) earthquake (M$_w$ 7.8) have highlighted this vulnerability. The earthquakes caused (severe) damage to the water supply systems in the cities of Los Angeles, Christchurch and the Kathmandu Valley, respectively. In Los Angeles, damage to the raw water supply conduits, the transmission and distribution pipes, reservoirs and treatment plants was observed, leading to a decrease of the water quantity service to about 70%, a decrease of the water quality service to 0%, and a decrease of the system functionality to about 30% compared to pre-earthquake levels (Davis 2014). The quantity of service was recovered 8 days after the mainshock, the quality service needed 12 days to recover, but it took several years to recover the pre-earthquake functionality of the system (Davis 2014). A similar impact has been observed in the Kathmandu Valley.
after the 2015 Gorkha earthquake. Sources ran dry, water reservoirs were damaged, and damage to the water distribution network was observed (Didier et al. 2017b). Even 18 months after the occurrence of the 2015 Gorkha earthquake, not all of the damage was repaired. Both examples show the need for reliable recovery models of damaged components in addition to the component fragility models. Moreover, damage to the building stock and industrial facilities can lead to displacements of population, or to the interruption of production activities, having a direct impact on the post-disaster demand for water. Post-disaster water demand might increase at some locations, and decrease at others. It is, thus, essential to assess the seismic resilience of such systems in a holistic setting, considering the vulnerability and recovery of the water supply and distribution systems, as well as the vulnerability and recovery of the community demand for water. In this study, a procedure to assess the seismic resilience of the water supply and distribution system of the Kathmandu Valley using the Re-CoDeS (Resilience-Compositional Demand/Supply) resilience quantification framework (Didier et al. 2017c) is presented. Re-CoDeS permits to assess the resilience towards a disaster using a holistic community demand / civil infrastructure system supply approach. First, the resilience of the water distribution and supply system during and after the 2015 Gorkha earthquake is described. The damage and recovery data provided by various stakeholders is employed to adapt and calibrate models for the vulnerability and the recovery of the water supply and of the community demand. These models are then used within the Re-CoDeS framework to quantify the resilience of the Kathmandu Valley water systems during a scenario Mw 8.0 earthquake. The presented procedure allows system operators to identify critical components, to design retrofit measures and establish optimized recovery plans.

2. RESILIENCE OF THE WATER SUPPLY AND DISTRIBUTION SYSTEM OF THE KATHMANDU VALLEY DURING AND AFTER THE 2015 GORKHA EARTHQUAKE

The resilience of the water distribution system of the Kathmandu Valley during and after the 2015 Gorkha earthquake has been evaluated by Didier et al. (2017b). The system had already a large supply deficit before it was additionally damaged during the 2015 Gorkha earthquake. The water supply provided by the network was intermittent: in some areas water supply was only available for a few hours each day (JICA and MoHA 2002b). Additional water supply was provided by water tanker trucks and by local water reservoirs to substitute a part of the supply deficit of the piped network. Before the earthquake, the maximum water supply from the water distribution system of the Kathmandu Valley (excluding distribution losses) was 144 million liters per day (ML/d) during the wet season, and 86 ML/d during the dry season (KUKL 2015). The 2015 Gorkha earthquake occurred at the end of the dry season. Damage leading to a decrease of the supply capacity of the system included damage to sources and water intakes, water pumps and storage tanks.

Similarly, the piped water distribution network of the Kathmandu Valley was already in a poor state before the earthquake: approximately 20% of the total supply capacity was being lost due to leaks in the system (KUKL 2015). During the earthquake, almost all pipes were damaged. This had a severe adverse effect on the water consumption (since the supply of water is lost through leakage of the pipes before it can be consumed by the community). Recovery of many small-diameter pipes of the distribution network was still going on more than 1.5 years after the earthquake.

Figure 1 shows the evolution of water demand, supply capacity and consumption of the Kathmandu Valley on a system level. More than a third of the water supply capacity was lost immediately after the earthquake. The consumption decreased accordingly. It took approximately 60 days to recover the supply capacity to the pre-event level. The water demand decreased as well, due to damage to the building stock and to industrial facilities, leading to disruptions in production processes. The slow recovery of the demand is caused by the slow recovery of the built environment. In fact, the building stock often takes much longer to recover than the civil infrastructure systems. After the 2015 Gorkha earthquake, recovery of the building stock has been additionally delayed by slow payouts of financial aid to the owners of damaged buildings (Dixon 2016).

The Lack of Resilience of the water supply and distribution system of the Kathmandu Valley, LoR_{sys},
is estimated in the assessment period considered by Didier et al. (2017b) (from the occurrence of the earthquake until the first 100 days after the mainshock) to $\text{LoR}_{sys} = 27166 \text{ ML}$ using the following formula:

$$\text{LoR}_{sys} = \sum_{i=1}^{I} \text{LoR}_i = \sum_{i=1}^{I} \int_{t_0}^{t_f} (D_i(t) - S_i^w(t))dt$$

$$= \sum_{i=1}^{I} \int_{t_0}^{t_f} (D_i(t) - C_i(t))dt = \int_{t_0}^{t_f} (D_{sys}(t) - C_{sys}(t))dt. \quad (1)$$

where $\text{LoR}_i$ is the Lack of Resilience at a (demand) node $i \in \{1, \ldots, I\}$, $I$ is the total number of (demand) nodes, $D_i(t)$ is the water demand at node $i$ at time $t$, $S_i^w(t)$ is the available water supply at node $i$ at time $t$, $C_i(t)$ is the water consumption at node $i$ at time $t$, $D_{sys}(t)$ is the water demand to the whole water distribution system at time $t$ and $C_{sys}(t)$ is the total water consumption in the system at time $t$. Time $t_0$ denotes the start of the resilience assessment, and time $t_f$ denotes its end.

The normalized Lack of Resilience, $\tilde{\text{LoR}}_{sys}$, and the resilience of the water supply and distribution system of the Kathmandu Valley, $R_{sys}$, have been evaluated to $\tilde{\text{LoR}}_{sys} = 0.86$ and $R_{sys} = 0.14$, respectively, using Equations (2) and (3):

$$\tilde{\text{LoR}}_{sys} = \frac{\sum_{i=1}^{I} \text{LoR}_i}{\sum_{i=1}^{I} \int_{t_0}^{t_f} D_i(t)dt} = \frac{\sum_{i=1}^{I} \int_{t_0}^{t_f} (D_i(t) - S_i^w(t))dt}{\sum_{i=1}^{I} \int_{t_0}^{t_f} D_i(t)dt} = \frac{\int_{t_0}^{t_f} (D_{sys}(t) - C_{sys}(t))dt}{\int_{t_0}^{t_f} D_{sys}(t)dt} \quad (2)$$

$$R_{sys} = 1 - \tilde{\text{LoR}}_{sys} \quad (3)$$

Figure 1. Observed Lack of Resilience of the water distribution system after the 2015 Gorkha earthquake, following Didier et al. (2017b)
3. MODELING OF THE WATER SUPPLY AND DISTRIBUTION SYSTEM OF THE KATHMANDU VALLEY

The following components are required to quantify the natural disaster resilience of a civil infrastructure system using the Re-CoDeS framework (Didier et al. 2017c):

- Evolution of the service supply, depending, among other factors, on the vulnerability and the recovery of the components of the civil infrastructure system;
- Evolution of the service demand, depending, among other factors, on the vulnerability and the recovery of the components of the community and other consumers;
- System service model, determining the distribution and allocation of the supply capacity to the different demand nodes and consumers of the civil infrastructure system.

The sum of the supply deficit (i.e. the demand that cannot be supplied due to a lack of available service supply) at the different demand nodes of the system over the resilience assessment time gives the Lack of Resilience of the civil infrastructure system (Equation 1).

In the case of a water supply and distribution system exposed to earthquake risk, the following information is, thus, required:

- The supply capacity of the components of the water supply system before the earthquake, and their evolution over time in the aftermath of the earthquake. The behavior of the supply system components is modeled in the following with component seismic fragility functions and component recovery functions.
- The demand for the water provided by the water supply and distribution system at the different nodes before the earthquake, and the evolution of the demand over time after the earthquake. The seismic performance of the building stock is used here as proxy for the evolution of the water demand and is modeled using fragility and recovery functions for the different elements of the built environment.
- The system service model of the undamaged and the damaged water supply and distribution system over the different repair steps. The system service model depends on the topology of the network and the distribution and prioritization strategy of the operator. A simplified topology of the undamaged water network of the Kathmandu Valley is used in this resilience assessment. Pipe repair rates are used to obtain the network topology at the different time steps.

Existing fragility and recovery models are adapted and/or calibrated with the damage and recovery data of the building stock and of the components of the water distribution system, obtained from various stakeholders after the 2015 Gorkha earthquake (Didier et al. 2017b). However, much of the information required to adapt sophisticated models was not recorded or saved by the operator, or it was only partly recorded and is, thus, not available for analysis purposes. Missing information is substituted in the following resilience assessment by assumptions, following closely the input provided by different experts in Kathmandu. The experts include managers and employees of the operator of the water system, KUKL (Kathmandu Upatyaka Khanepani Limited), and of the responsible government authority, DWSS (Department of Water Supply and Sewerage). The models can, then, be used to evaluate the resilience of the water supply and distribution system of the Kathmandu Valley if the systems are subjected to a future earthquake.

3.1 Modeling of the Community Water Demand

The seismic performance and the post-disaster recovery of the built environment (composed by the residential building stock, the commercial and industrial buildings, the hospitals and schools) are used as proxies to determine the evolution of the water demand. In fact, it is supposed that the performance of the building stock is closely linked to the water demand of the community: if residential buildings are damaged or collapsed, the access to appliances like taps, showers and toilets in the buildings is restricted or hindered; if an industrial facility is damaged, the production is often impacted, and the water needed for the production process decreases (BPN paper). The building stock in the Kathmandu Valley is mostly
composed by low and mid-rise constructions (Didier et al. 2017a), housing approximately 2.5 million people (The World Bank 2013). The buildings are classified by use and construction types (e.g. brick in mud, brick in cement, reinforced concrete frame, etc). To evaluate the seismic performance of the building stock, the fragility functions suggested by Didier et al. (2017e) for the different building types in Nepal, or those updated by Didier et al. (2017a) using the observed damage after the 2015 Gorkha earthquake can be employed to model the vulnerability of the building stock (Table 1). The suggested fragility functions distinguish 3 damage states: undamaged (i.e. damage state 1, DS1); slight to moderate damage (i.e. damage state 2, DS2); and collapsed (i.e. damage state 3, DS3), and are evaluated using the peak ground acceleration (PGA) as intensity measure.

Table 1. Lognormal fragility function parameters, with median $\lambda$ and standard deviation $\zeta$ for the building types in Nepal, from Didier et al. (2017a).

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Fragility Function DS2</th>
<th>Fragility Function DS3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\lambda$</td>
<td>$\zeta$</td>
</tr>
<tr>
<td>Adobe (AH)</td>
<td>-2.0509</td>
<td>1.3591</td>
</tr>
<tr>
<td>Brick in mud (BM)</td>
<td>-1.9947</td>
<td>1.9280</td>
</tr>
<tr>
<td>Brick in cement (BC)</td>
<td>-0.2656</td>
<td>1.8383</td>
</tr>
<tr>
<td>RC frame (RC3)</td>
<td>0.5118</td>
<td>1.7274</td>
</tr>
</tbody>
</table>

Lognormal component recovery functions, conditioned on the initial post-disaster damage state and on the time elapsed since the disaster, are employed for the recovery of the elements of the building stock (Didier et al. 2015). At the time of this study, no long-term data was available for the recovery of the building stock in Kathmandu. In fact, the recovery of the building stock after the 2015 Gorkha earthquake was delayed multiple times (Dixon 2016). Therefore, the recovery functions generated from the data of the 2005 Cashmere earthquake, adapted to the Nepalese building stock, are used in this case study (Didier et al. 2017e, ERRA 2009, 2010, 2015). The parameters of the recovery functions are given in Table 2.

Table 2. Recovery function parameters for the building types considered in the resilience assessment, with mean $\mu$ and standard deviation $\sigma$ from Didier et al. 2017e.

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Recovery from DS2</th>
<th>Recovery from DS3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu$ [months]</td>
<td>$\sigma$ [months]</td>
</tr>
<tr>
<td>Adobe (AH)</td>
<td>11.943</td>
<td>10.589</td>
</tr>
<tr>
<td>Brick in mud (BM)</td>
<td>11.943</td>
<td>10.589</td>
</tr>
<tr>
<td>Brick in cement (BC)</td>
<td>11.943</td>
<td>10.589</td>
</tr>
<tr>
<td>RC frame (RC3)</td>
<td>25.119</td>
<td>8.33</td>
</tr>
</tbody>
</table>

Finally, the pre- and post-disaster water demand associated to the different buildings is determined. For the water demand, only an aggregated total value for the whole Kathmandu Valley is available, and no detailed information could be obtained. The mean water demand for the different building types is, thus, estimated from other available demographic data (Didier et al. 2017b). The domestic water consumption in Kathmandu is 73 l/capita/d, and the average size of a household is 5.6 persons (Joshi et al. 2003). The water demand of a household can, therefore, be estimated to 408 L/d/household. Considering the 447'000 households in the study area, this would sum up to a total water demand associated to the residential building stock of 182.5 ML/d. An average water demand of 862 L/d is, finally, determined for each individual building, considering the total number of residential buildings in the Kathmandu Valley (note that due to the lack of more precise data, no distinction is made between single and multifamily buildings). The remaining of the 370 ML/d of water demand of the Kathmandu Valley
(KUKL 2015) are associated with the industrial facilities, offices, schools and hospitals as indicated in Table 3.

<table>
<thead>
<tr>
<th>Occupancy Type</th>
<th>Water demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>862 l/d</td>
</tr>
<tr>
<td>Small industry</td>
<td>7862 l/d</td>
</tr>
<tr>
<td>Heavy industry</td>
<td>78620 l/d</td>
</tr>
<tr>
<td>Offices/Commercial</td>
<td>862 l/d</td>
</tr>
<tr>
<td>Hospitals</td>
<td>78620 l/d</td>
</tr>
<tr>
<td>Schools</td>
<td>7862 l/d</td>
</tr>
</tbody>
</table>

Table 3. Water demand associated with each building before the earthquake per occupancy type.

To estimate the post-disaster water demand associated to the different elements of the building stock that are potentially damaged, the simplified procedure proposed by Didier et al. (2017d) is used. Buildings that remain in DS1 have the same post-disaster water demand as before the earthquake. Buildings in DS3 have no water demand anymore (since they collapsed or are evaluated as unsafe to enter). For residential buildings and industrial facilities in DS2, the demand reduction factors given by Didier et al. (2017f) are employed to interpolate between the pre-disaster water demand (DS1) and no water demand (DS3). The post-disaster demand of critical buildings in DS2 is assumed to remain unchanged. In fact, these buildings often see an increase in demand for their services after a major disaster: schools are used as emergency shelters, hospitals are faced with an increase in the numbers of injured people that need treatment. This increase in operations should compensate for a potential restricted use of parts of the building due to damage.

The aggregated community water demand at each demand node depends, finally, on the number of buildings connected (via a local distribution system) to each demand node. In the simplified topology of the network considered for this case study (see Section 3.2), demand nodes are junctions between water mains and local distribution networks that deliver the water via small pipes to the service connection of each building. The number of buildings connected to a demand node is estimated using the total number of buildings (CBS 2012, MoHA et al. 2015), the population density and the distribution of the building/occupancy types in that area (JICA and MoHA 2002a,c).

Note that in this case study, the water demand of temporary shelters, and the variations of the water demand at certain demand nodes due to population movements are neglected. Such situations can, however, lead to an increased water demand at some locations.

### 3.2 Modeling of the Water Supply and Distribution System of the Kathmandu Valley

A simplified water supply and distribution network is used for the following resilience assessment (Figure 2). It comprises the 246 pipes with the largest diameters in the original network, 70 wells and water intakes, 10 pumping plants, 15 treatment plants, 29 storage tanks, and 93 demand nodes (Didier et al. 2017b). The Kathmandu Valley is delimited by the dashed border in Figure 2. Note that many water intakes and wells are located outside of this area. Based on the varying degree of detail of the available data (for some components very detailed information is available, for others basic specification, like the material or the pipe diameter are missing), the topology of the network is simplified. The simplifications consist of: (i) replacement of co-located or redundant pipes with only one pipe; (ii) disregarding small-diameter pipes; and (iii) agglomeration of buildings into demand nodes (Didier et al. 2017b).
Vulnerability and recovery of the point-like facilities of the system (pumping stations, water treatment plants, water storage tanks, wells and water intake sources) are modeled using component fragility functions and lognormal component recovery functions, respectively. The available data from the 2015 Gorkha earthquake is not sufficient to compute fragility functions for the different components of the water supply system in Kathmandu that are based on the observed damage. Due to the low resolution of the available shake-map (USGS 2015) and the limited data on and description of the damage of the different components, there are not enough data points available for such a computation. The fragility of the point-like facilities of the water supply and distribution system of the Kathmandu Valley is, therefore, modeled using existing fragility functions from FEMA (2013), returning the probability of observing a certain (or more severe) damage state of a component for a given peak ground acceleration (PGA) value.

According to the observations made by the authors during several field trips to Nepal, and as a conservative approach, pumps are assumed to be medium-sized with unanchored components. Due to the low quality of the water supplied by the water network already before the disaster, water quality is not considered in this assessment (Didier et al. 2017b). The fragility of the water treatment plants can, nevertheless, be modeled with the respective fragility functions. Fragility functions for unanchored components, depending on the volume of the treatment plants (i.e. their size), are proposed by FEMA (2013). Water storage tanks in Kathmandu include above ground (overhead) tanks made of steel, and on-ground (or underground) reinforced concrete tanks. Their capacity ranges from 40 m$^3$ to 15000 m$^3$. Water storage tanks are modelled in the following as concrete tanks, if they are on- or underground, and as steel tanks if they are above-ground. The damage states defined by FEMA (2013) are used in the following assessment (i.e. DS1, none; DS2, slight/minor; DS3, moderate; DS4 extensive; DS5, complete). The undamaged pre-earthquake capacities of most point-like facilities in the considered water network were provided by KUKL. Note that the pre-disaster capacities are not available for all the point-like facilities. The capacities of the facilities for which no data is available are estimated, based on the characteristics provided for other similar facilities. If no information on the exact decrease of the supply capacity of the damaged facility is available, the decrease in supply capacity is estimated according to the damage description (if available).

The recovery of the point-like facilities of the water supply and distribution system is modeled using lognormal component recovery functions, conditioned on the initial post-disaster damage state of the component and on the time since the occurrence of the disaster (Didier et al. 2015). The lognormal
distribution allows accounting for different sources of uncertainty in the recovery process (e.g. a possible lack of financial or human resources, lack of replacement or spare parts). To obtain the parameters of the recovery curves for the different components, a lognormal curve is fit to the available recovery data of the 2015 Gorkha earthquake for each damage state of the different types of point-like facilities by maximizing the likelihood function, using the procedure described by Baker (2011). Due to the lack of exact damage descriptions in the obtained data, it is assumed that the reported downtime is directly correlated to the extent of damage of the component. The observed recovery time of damaged point-like facilities and the assigned damage states are given in Table 4. For the damage states of the components for which no data is available, the recovery functions are inter- and/or extrapolated. Note that recovery is considered here as recovery back to a full operational service state and not back to a full functionality with the complete initial redundancy restored. For example, a well that is inoperable due to the unavailability of electric power to run the pumps can resume its service once the electric power connection of its pumps has been restored, even if the backup power system remains damaged. Such practice can often be observed after major disasters, and especially in Nepal, where resources are limited and where a quick recovery of the service operability is crucial to limit (indirect) costs related to service blackouts.

Table 4. Lognormal recovery function parameters, with mean $\mu$ and standard deviation $\sigma$ for the components of the water supply and distribution system of the Kathmandu Valley observed after the 2015 Gorkha earthquake.

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Damage state</th>
<th>$\mu$ [months]</th>
<th>$\sigma$ [months]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wells</td>
<td>DS2</td>
<td>3.00</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>DS3</td>
<td>15.50</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>DS4</td>
<td>57.84</td>
<td>2.92</td>
</tr>
<tr>
<td></td>
<td>DS5</td>
<td>143.23</td>
<td>7.24</td>
</tr>
<tr>
<td>Treatment Plants</td>
<td>DS2</td>
<td>1.50</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>DS3</td>
<td>15.11</td>
<td>3.00</td>
</tr>
<tr>
<td></td>
<td>DS4</td>
<td>45.08</td>
<td>2.75</td>
</tr>
<tr>
<td></td>
<td>DS5</td>
<td>227.39</td>
<td>20.71</td>
</tr>
<tr>
<td>Water Tanks</td>
<td>DS2</td>
<td>2.00</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>DS3</td>
<td>15.44</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>DS4</td>
<td>46.56</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td>DS5</td>
<td>579.60</td>
<td>31.66</td>
</tr>
<tr>
<td>Pumping stations</td>
<td>DS2</td>
<td>2.07</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>DS3</td>
<td>7.14</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>DS4</td>
<td>31.09</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td>DS5</td>
<td>80.61</td>
<td>4.54</td>
</tr>
</tbody>
</table>

The pipe system of the water supply and distribution system of the Kathmandu Valley features a broad spectrum of materials, including cast iron, ductile iron, galvanized iron, steel, high density polyethylene (HDPE) and polyvinyl chloride (PVC). Most major pipes of the system are cast iron or ductile iron pipes. Pipes may be damaged due to permanent ground deformation (PGD) hazards (e.g. lateral spreading, seismic settlement or landslides) or transient ground deformation (TGD). The damage caused by PGD typically results in breaks, while TGD hazard is considered to be more likely to produce leaks (FEMA 2003). It is assumed that 80% of the damage induced by PGD result in breaks and 20% in leaks, and for TGD, 80% of the damage is assumed to result in leaks and 20% in breaks (FEMA 2003).

The damage (i.e. leaks and breaks) of the pipes can then be estimated evaluating pipe repair rates
provided by ALA (2001). ALA (2001) provides repair rates as function of PGD and peak ground velocity (PGV) intensities, depending on the material, the diameter, the connection type and the age of the pipe. The damage analysis of the pipes is run on sections of 1000m pipe length. A section is considered as broken if it contains at least one break or 5 leaks (Bellagamba 2015).

According to KUKL water system managers, the repair time to fix a leak is between 1 and 3 days, and to fix a break requires between 3 days and 3 weeks. The exact repair duration depends on the impact of the considered earthquake and on the availability of replacement parts and human resources. A random repair sequence is assumed for the following resilience assessment with a maximum of 5 pipes being repaired at the same time. The distribution losses are assumed to remain at 20% of the supply capacity throughout the recovery process.

The Floyd-Warshall algorithm is, finally, employed to determine the available connections between the different source, supply and demand nodes in the damaged network (Adachi and Ellingwood 2008). The supply of water is, then, distributed on a connectivity basis. In fact, due to the large supply deficit, it can be assumed that all the available supply is used somewhere in the network.

3.3 Ground Motion Characterization

To estimate the seismic damage of the point-like facilities, of the building stock, and of the distributed pipe network, the ground motion intensity measures have to be computed. The fragility functions of the point-like facilities are expressed in terms of PGA, while the repair rate relationship are expressed in terms of PGV and PGD. The PGA and PGV can be obtained for the different locations of the Kathmandu Valley using the attenuation relationships given for Nepal by Aman et al. (1995), depending on moment magnitude and the epicentral distance. Aman et al (1995) does not provide any relationships to estimate the PGD, which is, however, important to estimate the potential damage to the piped system that is especially susceptible to damage due to liquefaction or landslides, and, thus, influenced by the ground characteristics (e.g. soil class, groundwater depth, etc.). To estimate the PGD, the procedure outlined by Bellagamba (2015), Eicher (2015) and Baumberger and Tobler (2016) is adapted to the specific situation of the Kathmandu Valley.

A grid with 1500mx1000m cells is defined (corresponding to the cell size of the original network maps provided by KUKL, used to obtain the simplified water network, Figure 2). In each parcel of the grid, the soil parameters need to be characterized. The soil type of each parcel of the grid is classified into: type A: rock; B: gravel/sand; and C: silt/clay, according to FEMA (2013) and JICA and MoHA (2002a). JICA and MoHA (2002c) provide data on the groundwater level. The groundwater level of the Kathmandu Valley varies strongly between the dry and the rainy season, during which the groundwater level rises considerably. The 2015 Gorkha earthquake occurred at the end of the dry season (September to May). For the subsequent computations, the groundwater level of the wet season is assumed, leading to a conservative approach for the liquefaction and the landslide potential. The liquefaction susceptibility for the Kathmandu Valley is provided by JICA and MoHA (2002b). The liquefaction probability can, then, be estimated for each cell of the grid by applying the methodology given by FEMA (2013), using the soil type, the depth of the groundwater, the liquefaction susceptibility and the level of ground shaking obtained from the attenuation relationship. The component of the PGD associated to lateral spreading and ground settlement due to liquefaction is, finally, computed following FEMA (2013).

The component of the PGD associated to landslides is also computed following the methodology proposed by FEMA (2013). For each cell, the landslide susceptibility category is determined, based on the slope angle, and the geological and hydrological conditions, to obtain the critical acceleration of the slope stability. The slope angles for the Kathmandu Valley are estimated based on relief maps of the Kathmandu Valley. In a next step, the displacement induced by landslides is computed with the empirical model proposed by Saygilli and Rath (2008) using the critical acceleration and the PGA (at the surface) as input. Finally, the resulting PGD is the maximum value out of the component of the PGD associated to liquefaction and the component of the PGD associated to landslides.
4. RESILIENCE OF THE WATER SYSTEMS OF THE KATHMANDU VALLEY DURING A SCENARIO EARTHQUAKE

Kathmandu Valley has been hit by multiple large earthquakes in the past, including at least 6 earthquakes with moment magnitudes between 7.4 and 8.4 that occurred close to Kathmandu (Galetzka et al. 2015). The resilience assessment with the Re-CoDeS framework, using the proposed vulnerability and recovery models of the supply system components and of the demand, is demonstrated considering a scenario earthquake with an epicenter southwest of Kathmandu and $M_W$ 8.0. The mean results for the given earthquake scenario are shown in Figure 3.

![Figure 3. Water supply capacity, demand, consumption and Lack of Resilience of the water systems of the Kathmandu Valley considering a $M_W$ 8.0 scenario earthquake with epicenter close to Kathmandu](image)

As expected, system supply capacity, consumption and demand decrease in the aftermath of the scenario earthquake due to damage to the water systems and the building stock. This corresponds to a classical resilience-related configuration (Didier et al. 2017c). Water supply capacity, and consequently consumption, decrease to almost 0. Only a small part of the demand, which decreased significantly as well, can be supplied after the scenario earthquake. The LoR in this scenario is, therefore, quite large and is quantified as $L_oR_{SYS} = 0.97$. Consequently, the resilience of the water supply and distribution system towards this scenario earthquake is $R = 0.03$ over the assessment period of 100 days. The low resilience is not only due to the high vulnerability of the community and of the civil infrastructure system to the considered event, but as well related to the slow recovery process. The supply capacity of the system recovers slowly, and barely reaches the pre-event capacity after 100 days. Due to the high damage to the piped distribution system, the consumption does not recover at the same pace and stays low over the entire assessment period.

5. CONCLUSIONS

Water service interruptions threaten the living standards of communities and can lead to high economic losses. The point-like facilities (e.g. water treatment plants, water reservoirs, pumping stations) and especially the pipes of the water supply and distributions networks are vulnerable to earthquakes. The disaster resilience of water distribution and supply systems can be evaluated using the Re-CoDeS framework. The framework considers different components, including the service supply capacity of a civil infrastructure system and the service demand of a community. The allocation of the supply is defined by a system service model. A Lack of Resilience is observed if not all of the service demand can be supplied. Different modules have been introduced and adapted to estimate the vulnerability and recovery of components of the demand and supply layers of the water supply and distribution system of...
the Kathmandu Valley, based on the damage observed after the 2015 Gorkha earthquake. The proposed models can be used to model the impact on the water system during a scenario earthquake. It is shown that the considered scenario will have a major impact on the resilience of the water systems in Kathmandu Valley. The proposed methodology can be used by stakeholders and system operators to assess resilience of their systems considering different disaster scenarios.

6. REFERENCES


Earthquake Reconstruction & Rehabilitation Authority Pakistan (2009). ERRA Sectoral Update.

Earthquake Reconstruction & Rehabilitation Authority Pakistan (2010). ERRA Sectoral Update.