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Assessment of Infrastructure Resilience in Developing Countries: A Case Study of Water Infrastructure in the 2015 Nepalese Earthquake

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Despite the emerging literature on resilient infrastructure systems, the number of studies related to developing communities is rather limited. The majority of the existing studies focus mainly on resilience of infrastructure networks in developed countries. Infrastructure networks in developed countries are less vulnerable to the impacts of catastrophic disasters due to the existence of established design codes and management processes and the availability of financial and technological resources. Catastrophic disasters usually have more extensive impacts on infrastructure systems in developing countries. The objective of this study is to investigate the resilience of infrastructure in developing countries using a case study of water system in Kathmandu Valley in the aftermath of the 2015 Nepalese Earthquake. First, a new systemic framework for assessment of infrastructure resilience was developed. Second, data obtained from various sources including pre-disaster condition, post-disaster damage assessments, and interviews with different stakeholders were used in assessment of different components of resilience in the water system. The study investigated three dimensions of resilience in Kathmandu Valley's water system : (1) exposure ; (2) sensitivity ; and (3) adaptive capacity. Through a systemic analysis, various resilience characteristics such as coupling, response behaviors, and types of interdependencies that affect the resilience of the system were identified. The findings of the study highlight different factors that influenced the resilience of the water system in Kathmandu Valley. These results provide new insights regarding infrastructure resilience in the context of developing countries.

1 INTRODUCTION

The field of infrastructure resilience is an emerging area in science and engineering. Several studies (e.g., Rinaldi et al. 2001; O'Rourke 2007) have studied the determinants of resilience in infrastructure systems. The majority of the exiting studies in this area are related to infrastructure systems in developed countries. The extent and nature of resilience in Infrastructure systems in developed countries are different from the ones in developing countries due to the existence of established design codes and management processes, differences in social, economic, and political contexts, as well as the availability of financial and technological resources. There is a critical gap in the body of knowledge related to understanding the characteristics

of resilient lifeline systems in developing countries. In addition, among different infrastructure sectors, water supply infrastructure plays a vital role in the resilience of communities in the face of natural disasters. A better understanding of the determinants of resilience in water supply infrastructure is essential in prioritizing the allocation of limited resources in developing countries to reduce the adverse impacts of natural disasters on communities. However, the existing studies related to the resilience of water systems in developing countries are rather limited. To this end, the objective of the study presented in this paper was to investigate the factors influencing the resilience of water systems in developing countries using a case study of the 2015 earthquake in Nepal.

2 RESEARCH FRAMEWORK

Lifeline Infrastructure systems are recognized as key elements in investigating the resilience of communities in the context of disasters (Cutter et al., 2003). The National Infrastructure Advisory Council (NIAC) defined infrastructure resilience as “the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event” (NIAC, 2009).

In one stream of research, researchers have conceptualized resilience using four properties (known as 4Rs of resilience): robustness, redundancy, resourcefulness, and rapidity (Bruneau et al. 2003). In another stream of research, different studies have investigated the concepts involved in understanding system resilience. According to Gallopin (2006), the resilience of a system depends on: (1) the exposure of the system to hazard-related perturbations, (2) configuration of the system prior to a perturbation, (3) the transformation (a.k.a. sensitivity) of the system due to the perturbation, and (4) the adaptive capacity of the parts. The frameworks proposed in each of these streams of research are useful for investigation of resilience at different levels. For example, the 4Rs framework is appropriate for evaluation of resilience at facility or organizational level. On the other hand, the framework proposed by Gallopin (2006) is suitable for a system level analysis in which resilience is evaluated through the use of the concepts of exposure, sensitivity, and adaptive capacity. Hence, in this study, a framework for systemic assessment of infrastructure resilience was created to analyze the water supply system in Kathmandu Valley in 2015 Nepalese Earthquake. As shown in Figure 1, the framework includes three dimensions of analysis (i.e., exposure, sensitivity, and adaptive capacity) consistent with the resilience model proposed by Gallopin (2006). Exposure is defined as the extent to which a system is subjected to perturbations induced by hazards. The exposure of a system can be understood based on the nature of hazards and value of economic and social resources at risk. Sensitivity of infrastructure systems is dependent on system condition (Mostafavi and Abraham 2012); dependencies with other infrastructure (Rinaldi et al. 2001), human-infrastructure coupling, and the preparedness of

organizations managing and operating these systems. The third dimension of the framework investigates a system’s adaptive capacity. The adaptive capacity of infrastructure systems depends on the social systems managing, operating, and utilizing the physical networks. Hence, infrastructure systems’ adaptive capacity can be understood based on the analysis of the capacity of organizations to respond to hazard-induced perturbations as well as public’s capacity to respond to service disruptions.

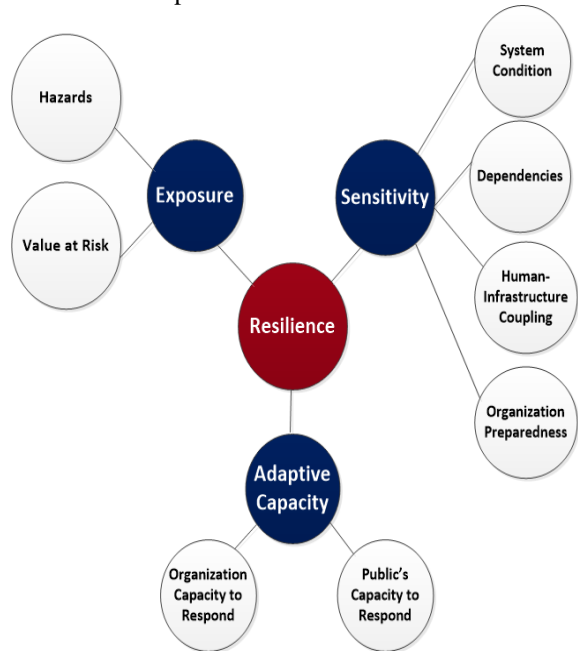


Figure 1. Framework for systemic assessment of resilience in infrastructure systems.

3 CASE STUDY

On April 25, 2015, Nepal witnessed one of the most destructive earthquakes in its history. This disaster claimed almost 8,500 lives, 22,000 people were injured, more than 800,000 houses were damaged or fully destroyed, and about 3 million inhabitants relocated. The earthquake affected 33 out of 75 districts in Nepal and various infrastructure sectors.

Among different sectors, water supply systems ranks second (after transportation systems) in terms of the value of damages caused by the earthquake. The extent of damages varies in different locations. Kathmandu Valley is among the districts that were severely

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impacted the earthquake. Kathmandu Valley is the most developed and fastest growing place in Nepal with population of 2.5 million. While other parts of Nepal are mainly rural and lack centralized water systems, Kathmandu Valley is an urbanized setting with an old water supply system. Hence, this study focused on the water supply system in Kathmandu Valley in order to investigate its resilience.

Data required for analysis of water system resilience in this study was obtained from four sources: (1) reports related to water system characteristics in Kathmandu Valley, (2) the post disaster need assessment (PDNA) report published by the government of Nepal in collaboration with international agencies such as the Asian Development Bank and Japan International Co-operative Agency (JICA), (3) the report published by the Earthquake Engineering Research Institute (EERI) Reconnaissance Team, and (4) field visits and interviews with different stakeholders. The primary method for collecting these data was in-depth interviews with elected (e.g., mayors, commissioners, and members of infrastructure agencies) and appointed public officials (e.g., public works managers and urban planners) at local and national levels, who were directly involved in water system operation, management, restoration, and response. The interviews were recorded (with permission of the interviewees) and transcribed in both Nepalese and English. The transcribed interviews were coded along with the secondary sources of information (e.g., PDNA and EERI reports) using NVIVO 11 software. The codes were refined through pattern analysis to summarize groups of codes into constructs, which will be explained in the following sections.

3.1 Exposure of Water System

Hazards: Kathmandu Valley is located in a seismic zone. Prior to the 2015 earthquake, the 1934 AD Bihar-Nepal Earthquake produced strong shaking in Kathmandu Valley. The seismic record of the region suggests that catastrophic earthquakes are expected approximately every 75 years (Dixit et al. 2000). In fact, the earthquake occurred in April 2015 had an epicenter in the east part of the district of Lamjung and was not the expected seismic activity in Kathmandu Valley. If the epicenter was closer to the valley, the earthquake would have more severe damages.

Value at risk: Another factor affecting the exposure of Kathmandu Valley is its population growth, uncontrolled development, and poverty (Dixit et al. 2000). Nepal is urbanizing rapidly, and Kathmandu Valley as a major urban setting in the country has a population growth of approximately 7%. Population growth increases the demand for water supply and requires increased development of water supply system in Kathmandu valley. With increased development in water supply systems, there was more value of water utilities and facilities at risk. In addition, the population growth increased the adversity of the impacts due to water supply disruption on the people living in the region. Also, uncontrolled development led to improper connection of water mainlines to houses which caused damages and service disconnections due to the earthquake.

3.2 Sensitivity of Water System

System condition: Kathmandu Upatyaka Khanepani Limited (KUKL) operates and maintains the water supply and sewerage systems in most of Kathmandu Valley. Water services are provided by KUKL through six branch offices inside Kathmandu and four municipalities in Lalitpur and Bhaktapur. Kathmandu Valley's water supply system was built approximately 120 years ago. There are 2.7 million people and 200,000 connections in its service area. Fig. 2 depicts components of water system in Kathmandu Valley. The system is composed of eight subsystems, each with a different source and treatment plant (EERI 2015). There are about 45 water reservoirs supplying water to the valley. The water system source also includes 70 tube wells in the North part of the valley that provide about 30% of water in the region. The system was in a poor condition due to lack of periodic maintenance and rehabilitation causing water leakage in the system. The reason for the poor system condition can be attributed in part to insufficient management of operation and maintenance due to lack of technicians, lack of accurate information about registered users, and lack of maintenance funding (EERI 2015). KUKL faces two major challenges in supplying water to the valley: a huge gap between supply and demand and ground water depletion. Due to the existing supply and demand gap, not all households have private connections and many use wells and taps in the commu-

nity. In addition KUKL provides water through tankers to areas that do not have service connection. For households with private connection, the supply of water is limited to few hours during every week requiring the households to store water in their houses. To this end, the use of in-house water tanks is ubiquitous in the valley. In addition, due to the uncertainty in the water supply, households dig wells in their property for water access. The increased use of ground water has led to decline of water tables causing challenges to KUKL for management of ground water. An immediate consequence of ground water depletion is that the connected wells and pumps will no longer be able to provide water.

In Kathmandu Valley, various modes of failure happened. Due to the 2015 earthquake. One of the eight water subsystems (in the South part) experienced damage due to a landslide in the Arniko Highway. The sub-system in the North part of the valley was disrupted due to power outage causing disruptions to the pumps extracting water from ground wells. The power outage lasted for two days during which the water supply was completely disrupted in Gonbaga area. Another major damage to the water system was house connection breaks. Due to loose connections, the seismic force led to connection breaks at the end point of the supply system causing increased water leakage.

There were no damages reported for the storage tanks used for supplying water through water tankers. In fact, the storage tanks had full storage when the earthquake occurred. Thus, KUKL were able to mobilize tankers to supply water to different affected regions.

KUKL was able to restore the water supply system in 21 days after the earthquake. Despite the information presented above regarding water system disruptions, the complete extent of damages and service disruptions were not completely understood at the time of data collection for this study (five months after the earthquake). The reason for the lack of accurate information regarding the damages and service disruptions in the water system of Kathmandu Valley was the lack of service disruption reported by the customers due to: (1) damages to buildings; and (2) inconsistent quality of service prior to the earthquake.

System dependencies: The types of dependencies identified between water system and other infrastructure were geographic or physical. According to Rinaldi et al. (2001), physical dependencies exist when state of one infrastructure is dependent on the output of the other infrastructure. In the water supply system in Kathmandu Valley, two physical dependencies caused service disruptions. First, in the north part of the valley, failures in the power supply system caused the pump stations to stop working, and hence,

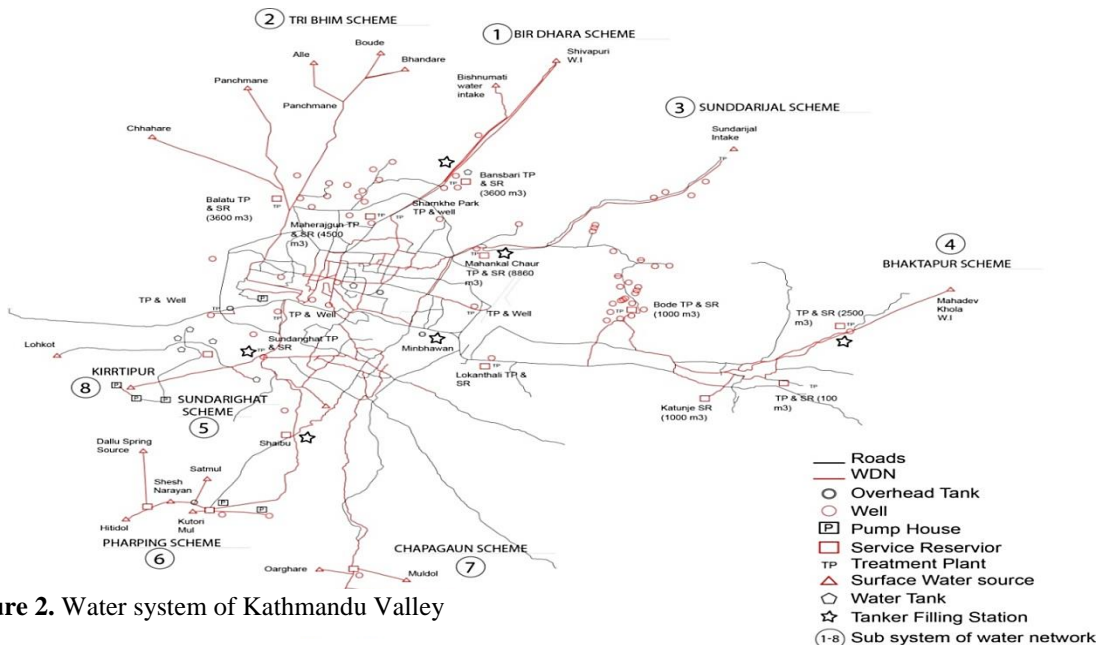


Figure 2. Water system of Kathmandu Valley

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water supply from ground water sources was disrupted. The power supply system was restored after two days, and hence, water supply was also restored. The water supply system in other areas (such as Chitwan plant) also uses ground water sources. Fortunately, however, the power supply systems in those areas were not disrupted. The second physical dependency was between water supply and roads. This is a unique type of physical dependency that usually does not exist in infrastructure systems in developed countries. This dependency was unique to Kathmandu Valley since a considerable portion of water supply was delivered through water trucks. KUKL developed capacities over time to supply water by trucks in response to the supply and demand gap in the system. KUKL has six tanker stations for filling the water trucks, and fortunately, none of these stations were damaged by the earthquake. Also, the tankers had full storage capacity when the earthquake occurred. Hence, KUKL was able to deploy its truck fleets immediately after the earthquake; however, the closure of roads due to landslides or blockage due to building collapses caused difficulties for the water trucks to access certain areas.

The second type of dependencies identified in Kathmandu Valley's water supply system is geographic dependencies. Geographic dependencies exist when a local hazard can create state changes in different infrastructure (Rinaldi et al. 2001). In Kathmandu Valley, the majority of water utility lines delivering water from the source to plants or storage tanks were constructed along the major roads. Hence, landslides in roads caused breaks in the water trunks passing through the roads. One major incident in the aftermath of 2015 earthquake was the breakage of a 35 cm water trunk line due to a land slide along the Arniko highway causing service disruptions in Patan area. This incident caused one of the eight sub-systems of KUKL to be disrupted for more than two weeks.

Human-infrastructure coupling is the extent to which the public is reliant on the services provided by a system. The supply-demand gap in the water system of Kathmandu Valley had reduced the public's reliance on the system for their water supply and storage. The use of on-site wells and purchase of water from private water trucks as well as on-site storage of water were the substitute solutions that the public had adopted to cope with the discontinuity of service in the

water system. These substitutions, to some extent, reduced the human-infrastructure coupling, and hence, reduced the sensitivity of water system to the impacts of the earthquake. If the system had been able to supply 100% of the demand consistently, the impacts of the earthquake on the system and public would have been more deleterious.

Preparedness of organization: In the case of water supply system in Kathmandu Valley, KUKL did not have an established disaster management processes in place at the time of the earthquake in 2015. As mentioned earlier, the supply-demand disparity in the water system of Kathmandu Valley had created a chronic stress on the agency. Meeting the day-to-day water needs of the customers along with limitations in the agency's resources had reduced the capability of the agency to establish disaster management processes. Despite the lack of disaster management process, KUKL was able to respond to the service disruptions caused by the earthquake with the help of WASH Cluster. First, the agency prioritized the customers based on their urgency for receiving water supply. For example, hospitals and public buildings were prioritized for immediate service restoration. Another priority for KUKL was to provide water to government-established shelter camps.

The second component of KUKL's response activities included damage assessment. In the aftermath of the earthquake, KUKL did not know the extent of damages because a large portion of population had left Kathmandu Valley and many buildings were damaged. The KUKL's response was to deploy its personnel to facilities (e.g., treatment plants, storage tanks, reservoirs, pipelines, and pump stations) to collect information about the damages to water system component. The KUKL's capacity to monitor and assess the condition of underground utility conditions was very limited. Hence, the agency was collecting information about damages based on customers' complaints such as service disruptions or water leakage in the streets. However, there were many damages and leakages that were identified late since KUKL did not receive any complaints from the customers.

3.3 Adaptive Capacity

Two determinants of social system's adaptive capacity in infrastructure include: (1) adaptive capacity of administering agency; and (2) the adaptive capacity

of general public. As mentioned earlier, the water supply system in Kathmandu Valley suffers from a significant supply-demand disparity. This supply-demand disparity created a chronic stress on the system, KUKL, and general public. The chronic stress caused both the agency and the public to develop adaptive capacity through enhancing redundancy. As for the agency, KUKL developed water trucking capacity to supply water to households during times of load shedding in the network. This additional capacity had not been developed for earthquake emergency management; as for KUKL, every day was an emergency situation to supply water to the people.

As for the general public, the chronic stress caused by water supply shortage caused the household to adopt in-house storage tanks. Almost every household in Kathmandu Valley had a storage tank to store water during the scheduled supply time and usage during load shedding periods. In addition, though it was illegal, many households had their own shallow wells as a backup source. Through these alternative solutions developed under chronic stress of water supply shortage, households built redundancy overtime. Hence, in the aftermath of the earthquake, service disruptions in KUKL water supply did not cause major problems to water access since households already had substitutions.

4 CONCLUSION

The findings of this study highlights the significant role of the social systems' adaptive capacity developed under chronic stressors (i.e., supply-demand gap) in enhancing the resilience of the water system. While the water system was very sensitive to hazards, its adaptive capacity reduced the negative impacts caused by service disruptions. In addition, the findings identify the extent of human-infrastructure coupling as an important component influencing the resilience of infrastructure systems. In the case of Kathmandu Valley, the coupling was not strong due to supply-demand disparity. Hence, the system disruptions did not have as extensive impacts. Finally, the findings of this study highlight the type of dependencies between the water system and other infrastructure. For example, the KUKL's use of water trucks for water supply had created an emergent dependency between water and road

infrastructure. These findings highlights new dimensions of analysis in the emerging field of infrastructure resilience and also provide information for decision-makers in order to better understand the various factors influencing the resilience of infrastructure systems in the context of developing countries.

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