DESCRIPTIVE DESIGN STRUCTURE MATRICES FOR MODELLING INFRASTRUCTURE INTERDEPENDENCIES IN COMMUNITY RECOVERY

A Thesis

by

RAMEEZ RIYAZ QURESHI

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	David N. Ford
Committee Members,	Ali Mostafavi
	Charles M. Wolf
	Phil Lewis
Head of Department,	Robin Autenrieth

May 2020

Major Subject: Civil Engineering

ABSTRACT

Infrastructure interdependencies have significant impacts on the recovery of community sectors in the post-disaster period. The focus of this research is to identify critical community sectors and to understand how the interactions between these infrastructure sectors drive the recovery process. Descriptive Design Structure Matrix (DDSM) was used to qualitatively describe the interactions between infrastructure sectors. A 3-tier Hypothesis DDSM was developed to identify and define the interactions between community sectors, that was compared with a case-study DDSM to compare and validate the reported interactions, based on which a final DDSM was developed with 16 infrastructure sectors to qualitatively describe the interdependencies between community infrastructure sectors.

DSM Modelling analysis revealed the critical infrastructures and the critical interactions that influence the recovery of a community. The following insights were drawn from the DSM model and could constitute the core elements of a normative approach to community recovery that could be used when developing recovery strategies for an efficient and speedy recovery in the post-disaster period:

1. The 5 most ‘critical’ infrastructure sectors based on their importance for community recovery are – Commerce, Governance, Power Distribution and Generation, Road Transportation, and Workforce Population.

2. The primary focus in the recovery period should be on the restoration of infrastructure services that are required for the recovery of other infrastructures, even if they are not the metrics used to measure recovery performance.

3. To speed community recovery, infrastructures must recover in ways that build the capacity of their dependent infrastructures.

4. Recovery planning for short-term and long-term recovery should reflect the differences between the two stages of recovery.

The DDSM can be a useful tool for community leaders to understand the impact of infrastructure interdependencies in the post-disaster period and to develop strategies that consider these interactions for a speedy and resilient recovery. The tool is expected to compliment the use of proven methodologies (such as PDNA) and to provide a systematic and a structured approach to prioritize sequencing of resources and to analyze the impact of specific resource allocations to check if the recovery policies being implemented will have the required impact.

DEDICATION

"*To my parents, who walked me to school*."

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. David Ford, and my committee members, Dr. Charles Wolf, Dr. Ali Mostafavi, and Dr. Phil Lewis, for their guidance and support throughout the course of this research.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience.

Finally, thanks to my mother and father for their constant love and support.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professor David Ford, Professor Ali Mostafavi, Professor Charles Wolf of the Department of Civil Engineering and Professor Phil Lewis of the Department of Construction Science.

The data analyzed for Chapter V was provided by the officials of Jammu Tawi Flood Recovery Project in the Indian state of Jammu and Kashmir.

All other work conducted for the thesis was completed by the student independently.

Funding Sources

Graduate study was supported by a fellowship from Texas A&M University.

This work was also made possible in part by the Texas Department of Transportation under Contract Numbers 36-6XXIA001 and 601CT0000021708. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the Texas Department of Transportation.

NOMENCLATURE

CLD	Causal Loop Diagram
DRM	Disaster Risk Management
DSM	Design Structure Matrix
DDSM	Descriptive Design Structure Matrix
FEMA	Federal Emergency Management Agency
GFDRR	Global Facility for Disaster Reduction and Recovery
JTFRP	Jammu Tawi Flood Recovery Project
PDNA	Post-Disaster Needs Assessment

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION

Disaster[1] losses have quadrupled from $50 billion in 1980 to $200 billion in 2000. In the last 30 years, 2.5 million people have lost their lives and almost $4 trillion has been lost due to disasters caused by natural hazards (GFDRR 2018). With rising populations and rapid urbanization, the United Nations estimates that more than two-thirds of the world population will be living in cities by 2050. A World Bank report explains how these trends could put 1.3 billion people and $158 trillion in assets in risk from disasters due to flooding (GFDRR 2018). It is imperative that disaster risk management is incorporated in development planning to reverse the ongoing trend of rising disaster impacts (GFDRR 2018). The World Bank estimates that when communities rebuild stronger, faster and more inclusively after disasters, they can potentially decrease the impact on livelihoods and well-being of the people by as much as 31% (GFDRR 2018).

Disaster experiences are described in phases by organizations that respond to disasters. In general, the disaster management and recovery cycle described by various international agencies can be divided into following phases – Prevention, Mitigation, Disaster, Response and Recovery (National Governors' Association (NGA) 1979). The current work focusses on the community recovery phase. Recovery efforts seek to return the livelihoods of shock event victims by returning the community to conditions equal to

---

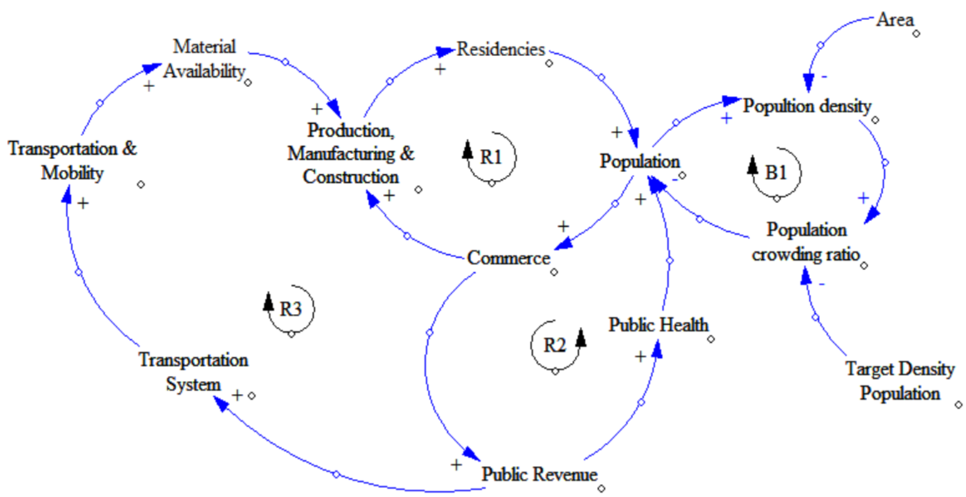
[1] Disaster is defined as a serious alteration in the normal functioning of the community due to hazardous physical events interacting with vulnerable social conditions leading to loss of lives, economy and infrastructure (IPCC 2012).

or better than those before the disaster (Ford and Keith 2016). The continuing effects of a disaster long after the event itself (such as starvation, homelessness, etc.) make time costly in terms of community health and well-being. It is therefore important that the recovery is planned and managed as effectively as possible. A lot of research has focused on agencies and tools that facilitate the processes that organizations should use to develop recovery plans, e.g. Disaster recovery guide by GFDRR (GFDRR 2015); FEMA (Lindell, et al. 2006) etc. However, little research has been done to help community leaders formulate effective recovery strategies for quick recovery to self-sufficiency, that is, the content of the recovery plan.

Consider the 2014 floods in the Indian State of Jammu and Kashmir (J&K) as an example of the challenges addressed by this research, in which 0.35 million structures suffered damages and 0.65 million hectares of crop loss was reported. In addition, extensive damage of the infrastructure including roads, telecommunication, power, health, fuel distribution and drinking water supply system was reported (Agarwal, Fulzele and Aggarwal 2014). While the Post Disaster Needs Assessment (PDNA) identified the needs within the sectors, the community leaders in the state of Jammu & Kashmir, were tasked with the development of a Recovery Management Plan for setting the priorities for allocation of limited resources and to sequence the needs within and across the sectors for post-disaster reconstruction and recovery. The limited availability of resources prevents the simultaneous rebuilding of all the damaged components of the community. For instance, the goals to restore economy are dependent on simultaneous efforts, including restoration of public infrastructure, rebuilding housing, and reopening of educational institutions. The lead agencies for community recovery, that are often the local government agencies (such as the Relief and Rehabilitation Department of J&K), face problems in deciding what sectors of the community need to be prioritized to facilitate a sustainable recovery. The answer is difficult due to the inherent interdependencies between community components and the limited availability of resources in the post-disaster period. Further, the level and scale of damage as well as pre-existing community factors can increase the complexity of community recovery projects.

The impacts of these interdependencies can be modelled with causal feedback loops. In causal loop diagrams, causal links (symbolized with arrows) describe how an increase or decrease in the value of the component at the tail of the arrow impacts the value of the component at the head of the arrow. Positive causal links ("+" at the arrowhead) indicate that the values move in the same direction and negative causal links ("-" at the arrowhead) indicate that the components move in opposite directions. Feedback loops are either balancing or reinforcing. Structures dominated by reinforcing feedback loops move component values progressively away from initial values or accelerate flows. In contrast, balancing feedback loops resist continued change in a single direction and direct systems toward a goal or equilibrium conditions. See Sterman (Sterman 2000) for details on modelling with causal loop diagrams.

Multiple feedback loops interact to drive and/or constrain recovery in the post-disaster period. Figure 1 uses a causal loop diagram (Sterman 2000) to describe a feedback-based theory of community recovery based on an economic reinforcing growth loop (Ford and Keith 2016) and adapted to our context. In the model residencies support population, that engage in commercial activities to increase the production, manufacturing, and construction capability of the community, which further increases the available residencies to meet the population needs (Figure 1, Loop R1). In addition, public revenue generated through commerce increases the available funding for developing public health and transportation infrastructure (Figure 1, Loop R2 & R3). Population growth is limited by crowding due to the community having more residents than it can support (Figure 1, Loop B1). These elements and their interactions define the community recovery (in a highly simplified form) after a disaster. For example, in the case of Jammu and Kashmir, the physical facilities such as the houses, roads, hospitals, schools, and other critical infrastructure were reported to suffer extensive damages after the floods (Agarwal, Fulzele and Aggarwal 2014). As can be seen from Figure 1, even when there is adequate housing in the community, the lack of public health infrastructure will constrain the population recovery in the community. Similarly, lack of adequate transportation system in the community will constrain the construction of residencies due to unavailability of raw material supply required for construction.



Legend of Loops:

R1: Economic Growth Loop: Residencies in a community increases the number of people that a community can support, who engage in commercial activities, therefore increasing the production, and construction capacity of the community.

R2: Public Health Infrastructure Growth Loop: Increase in Commercial activities increases the public revenue being generated, which increases the available funding for public health infrastructure in the community. Abundance of public health infrastructure in the community increases the attractiveness of the community to the immigrant population.

R3: Transportation Infrastructure Growth Loop: Population engaging in trade and commerce increases the public revenue, which increases the available funding for expanding the transportation infrastructure in the community, which further increases the number of people that can be supported in the community.

Figure 1 A Causal Loop Diagram Showing the Interactions Between Population, Transportation and Public Health Infrastructure for Community Recovery

Figure 1 shows just one example of interdependencies between infrastructure systems. In a community, there are many interdependent components such that the state of one infrastructure (e.g. whether the railroad is able to supply sufficient coal stocks to an electrical generator) directly influences the state of another infrastructure (whether the electric power plant can supply sufficient power to meet the railroad's demand). The interactions in the feedback system evolve, creating dynamic behaviors and shifts in influence. Therefore, the problem in practice is very complex, and the community leaders tasked with developing a recovery plan are forced to choose between multiple sectors that affect the recovery and it is the interactions between different feedback loops that make it difficult to sequence the needs between sectors for efficient community recovery. For example, should the leaders first rebuild the infrastructure sectors (community infrastructure, water, transport etc.) or focus on the production sectors (employment and livelihoods, agriculture etc.)? And what if the entire region is affected? What if the local community was already on a downward trend? The interactions between the sectors can have significant policy implications and need to be considered to develop resilient recovery strategies.

The aim of this research is to identify and evaluate how the major infrastructure systems in a community interact with each other to constrain and drive the recovery process. This will aid recovery leaders to address 'what to do' and help design effective recovery strategies for an efficient multisectoral community recovery. The research will facilitate the development of the contents of the recovery plan that will enable recovery managers to set priorities for allocation of resources across sectors. This requires understanding of the interactions between community system elements for mapping community recovery patterns.

Problem Description

When a community is hit by a disaster, it disrupts the normal functioning of the community elements. The objective of community recovery is to restore these normal patterns of interactions among the different elements in a community in the post disaster period, to conditions that existed before the disaster struck (Lindell, et al. 2006). The recovery process begins when the immediate threat to human life and property has been resolved and the sense of urgency and uncertainty has been replaced by the thoughts about the restoration of services and infrastructure, and to return the community to normal patterns of activity (Lindell, et al. 2006). One organization that works to improve community disaster recovery is the Disaster Risk Management (DRM) group of the World Bank, which helps client countries assess disaster risks and provides technical assistance for community resilience and recovery projects (Disaster Risk Management 2018). Global Facility for Disaster Reduction and Recovery (GFDRR) is a strategic unit of the DRM that works with the disaster-prone countries before disaster events in order to enhance their readiness for post-disaster recovery. In 2014, GFDRR launched the Guide to Developing Disaster Frameworks (GFDRR 2015) to facilitate a smooth recovery process and help improve resilience for the future. The guide provides a flexible methodology that countries can adopt to their own context in order to help them rebuild and recover. The recovery guide has been divided into modules, that follow the sequence of steps required to develop and implement the framework. For developing the recovery plan and strategy, the World Bank recommends that the communities "(i) Articulate a recovery vision – to enable the government to convey its recovery priorities and build a national or sub-national consensus (ii) Formulate a policy framework - to adequately finance and implement post-disaster recovery and to achieve the recovery vision **(iii)** ***Identify the priority sectors for recovery, based on the Post Disaster Needs Assessment (PDNA) and in line with the broader recovery vision*** (GFDRR 2015)" (emphasis added).

The best entity to oversee the recovery efforts is the local community government (often referred to as the lead agency). The lead agency, such as the Relief and Rehabilitation department of Government of Jammu and Kashmir ensures coordination within the government and other stakeholders. The lead agency oversees the development of sectoral, geographic and functional details of the community recovery plan and faces a major challenge of deciding how the limited resources will be distributed across sectors in the post-disaster period. Conventionally, the allocation of resources across sectors is based on the reported damage across different sectors with an emphasis on restoration of physical infrastructure. The sectors that suffer maximum damage are primarily given priority over sectors that have suffered relatively lesser damage, and that's what decides the priority in the recovery phase (Phelps, et al. 2017). However, the most damaged sector may not be the one that should receive recovery resources first or most. For example, if the commercial sector is badly damaged but the critical entry and exit routes to the community have also been made unusable by the disaster, resources might be better allocated sequentially to first restore the critical transportation routes so as to allow the restoration of housing, water, and other critical infrastructures instead of the most damaged sector. What sectors should be resourced how much in what sequence to optimize recovery? Answering this critical question in disaster recovery requires an understanding of community sector interactions. Therefore, a major issue in the conventional development of recovery strategies is the lack of understanding of how infrastructure system interdependencies affect the execution of community recovery projects.

Moreover, in the post-disaster period, some urban development activities such as construction, finance, and the flow of information, are, optimally, compressed in time and space, something referred to as the time compression phenomenon (Olshansky, Hopkins & Johnson 2012). The time compression phenomenon with limited resources exacerbates the complexities of interdependencies of community infrastructure systems. This is because, if effective resource sequencing strategies are not adopted, the existing damage may be escalated and result in additional damage throughout the interdependent infrastructure. As an example, during the 1998 Ice Storm in Canada, several hospitals in Montreal experienced periodic power outages lasting several hours. This resulted in heat system failure in the hospitals. As a result, four people died from Hypothermia, and seven people died due to carbon monoxide poisoning while using poorly ventilated heating sources (Chang, McDaniels, et al. 2007). If the flows of information, financing of recovery, and reconstruction of the hospital’s power systems had been compressed in time the outages could have been avoided and these cascading effects due to the disruption of one infrastructure on the dependent infrastructure could have been reduced.

A comprehensive understanding of how community infrastructure systems interact during disaster recovery to drive and/or constrain recovery is needed. However, most of the research in the community recovery domain has focused on the development of plans and processes for developing the recovery framework. No community-wide models of infrastructure interactions during community recovery for strategic allocation of resources across multiple sectors are known (discussed in chapter II). Given the criticality of time in recovering the community to its pre-disaster state and the amplification of complexities in the recovery phase due to the time-compression phenomenon, the focus of this research will be to model community infrastructure interdependencies that impact the recovery phase of disaster management. This study is expected to provide the recovery planning lead agency with a scientific approach to decide on the prioritization across sectors for allocation of limited resources in the post-disaster period and to understand the impacts of specific resource allocations in the execution of community recovery projects. It will also act as a basis for the construction of more sophisticated models of community recovery, such as formal simulation models. Critically, to be useful in helping the community leaders commit to specific resource allocations, the interdependencies between community infrastructure systems must be easily understood by those community leaders, who often do not have technical expertise.

For the purposes of this research two terms will be defined: Critical infrastructure[2] and Critical interaction. A critical infrastructure is one that provides basic services for community operations and has a significant influence on the recovery of at least one other sector. A critical interaction between two infrastructures is a dependency that can

[2] Includes both physical and social infrastructure

constrain the capacity of the dependent infrastructure. Consequently, this study will address the following research questions:

- What community sectors best describe recovery from disasters?
- What are the qualitative interdependencies (physical, geographic, cyber and logical) between infrastructure systems in a community's disaster recovery period?
- How do the infrastructure interdependencies impact disaster recovery and the execution of community recovery projects?

CHAPTER II

BACKGROUND

Infrastructure interdependencies have been studied from multiple perspectives. Rinaldi (Rinaldi, Peerenboom and Kelly 2001) emphasized the role of interdependencies among infrastructure systems and their influences on the normal functioning of industries. Rinaldi proposed a 6-dimensional taxonomy to facilitate understanding of interdependencies such as the type of interdependencies, coupling and response behavior, infrastructure characteristics, types of failures, and state of operations. Oh (Oh, Deshmukh and Hastak 2013) stressed that understanding the interdependencies between infrastructure systems is an important component for understanding the impacts of a disaster. Several researchers have highlighted the importance of understanding and analyzing infrastructure interdependencies for developing disaster mitigation strategies. For example, Amin (Amin 2002) studied the interdependencies between transportation, telecommunication, and electricity with other critical infrastructures and discussed strategies for avoiding widespread network failure due to cascading and interactive effects within the infrastructure network. Similarly, Attary (Attary, et al. 2019) developed a risk-informed decision-making tool to model the interdependencies between electric power network and the impacts of the failure of the network on the physical infrastructure such as buildings to help the emergency planners in enhancing resilience of the communities, especially identifying the volume of resources needed in the recovery process.

Infrastructure interdependency models have been shown to be useful in different phases of disaster management, such as, the mitigation, response and recovery phases, for enhancing resilience of the community. In the mitigation phase, infrastructure interdependencies have been modelled to potentially identify the vulnerabilities in the community. For example, Chang (Chang, 2003) identified the infrastructure failure interdependencies of critical infrastructures due to power outages caused by the 1998 Ice Storm in Canada. They developed a conceptual framework for characterizing infrastructure failure interdependencies from the standpoint of impacts to the communities and demonstrated how the framework can be applied for pre-disaster mitigation and preparedness efforts. Choi (Choi, et al. 2019) developed a model for healthcare infrastructure systems to understand the dynamic interplay between social and technical components in the post disaster emergency room operations. The model has been used to replicate various post disaster scenarios to explore policies and strategies associated with the capacity building of healthcare system components using the functional stress-strain principle.

In the post-disaster phase, infrastructure interdependencies have been modelled to develop strategies for reducing the recovery time of the community, and therefore to increase the resilience in the community. For example, Rand (Rand and Fleming 2019) developed a theoretical framework for evaluating recovery strategies to reduce displacement duration. The study uses social science and transportation literature to describe linkages between population displacement and civil infrastructure systems and identifies key infrastructure systems required to resolve population displacement. The study highlights the significance of developing effective infrastructure recovery strategies to reduce displacement time. Similarly, Oh (Oh, Deshmukh and Hastak 2013) developed a disaster impact mitigation support system that can be helpful to the emergency managers to prepare better mitigation strategies by identifying and prioritizing activities that, when restored in a post-disaster situation, will help reduce social and economic impacts by quickly restoring livelihoods. This was done by identifying the interrelationships between infrastructure systems (highways, water, and electricity), associated industries and communities to measure the level of criticality (level of dependency) for critical infrastructure. The assessment was performed by prioritizing critical infrastructure based on the number of activities it supports and the assistance level of critical infrastructure.

Despite the significant research that has been conducted to understand the impacts of infrastructure interdependencies, most of the research is limited to mapping the interdependencies between physical infrastructure and their impacts on the community (see, (Amin 2002), (Rand and Fleming 2019), (Ouyang 2014)). Moreover, none of the previous studies analyzed the impacts of infrastructure interactions in the disaster recovery phase at a community-level. This research bridges the gap by identifying and defining a set of relevant community infrastructures, describing, and analyzing the interdependencies between those infrastructures, and investigating their impacts in the recovery phase. This has been done by modelling the dynamic interplay between infrastructure systems. Interdependencies between the systems vary widely, each having its own characteristics and effects on the infrastructure agents. For example, in this research, infrastructure interdependencies that are examined fall into the following major categories, as described by Rinaldi (Rinaldi, Peerenboom and Kelly 2001): Physical Interdependency, Cyber Interdependency, Geographic Interdependency and Logical Interdependency. A conceptual model has been developed that maps the interdependencies between community-level infrastructure systems, including physical, economic, social, and institutional infrastructures.

CHAPTER III

RESEARCH APPROACH AND METHODOLOGY

To answer the research questions, the researcher developed a five-step methodology that entails 1) Identify the community infrastructure components; 2) Hypothesis development using a Design Structure Matrix (DSM, described below), to describe the community infrastructure interactions; 3) Hypothesis testing by developing a case-study DSM; 4) Analysis & Application to practice – testing the DSM results on a case-study community recovery project to derive policy recommendations for community recovery projects, 5) Development of answers to the research questions and conclusions.

Review Community Recovery Domain and Tools

A comprehensive review of the disaster management domain was done to understand different phases of disaster management cycle with a focus on the community recovery phase. This research defines recovery as the restoration of normal patterns of household, business and government activity to exactly as they existed before in the pre-disaster phase (Lindell, et al. 2006). It is therefore, assumed that most of the infrastructures and their interdependencies that existed in the pre-disaster state will hold true in the recovery phase, with the exception that these interactions are compressed in time (Olshansky, Hopkins and & Johnson 2012) .

Design Structure Matrix (DSM) was used to model the interdependencies between community infrastructure components. A DSM is a two-dimensional matrix representation of the structural or functional interrelationships of objects, tasks or teams.

Design structure matrices (DSM) are used to identify locations of interactions in a system and to quantify the strength of those interactions (Eppinger and Browning 2012).

The application of DSM in the current research differs from typical DSM applications in at least two important ways: 1) typical DSM applications are to products or a single organization or enterprise, whereas the current application is to an entire community, and 2) typical DSM applications seek to quantify interaction strength, sometimes to mathematically simulate interactions, whereas the current application seeks to improve the understanding of a system of interactions by non-technical planners and managers using qualitative descriptors. Therefore, simple, logical descriptions of community infrastructure interactions that create rebuilding bottlenecks and thereby constrain the recovery of other components are used to create a "Descriptive Design Structure Matrix" (DDSM) that can have at least three valuable uses: 1) as a tool to identify and model community system interactions, 2) as a tool for explaining community system interactions and their impacts on recovery to community leaders, and 3) as the basis for a simple binary DSM or quantified DSM of a community that can be used in formal modelling of recovery. A preliminary descriptive design structure matrix was conceptualized based on an understanding of the community infrastructure interactions and the literature findings to identify qualitative interdependencies between infrastructure systems. The conceptual DDSM was compared and analyzed against the case-study DDSM to validate the hypothesis and to develop policy recommendations for practice.

Hypothesis Development

Infrastructure interdependencies are varied in nature. For the purpose of our research, Rinaldi's classification of infrastructure interdependencies (Rinaldi, Peerenboom and Kelly 2001) was used and adopted to identify and analyze interdependencies.

- "Physical interdependency – A physical interdependency arises when each infrastructure is dependent on the material output of the other" (Rinaldi, Peerenboom and Kelly 2001). For example, functional road networks are required in the recovery phase for the supply and reconstruction of power stations whereas, electric power is required for normal transportation operations.
- "Geographic Interdependency – Infrastructures are geographically interdependent when elements of one are in close spatial proximity of each other such that the shock events could create correlated damages in geographically interdependent infrastructures" (Rinaldi, Peerenboom and Kelly 2001). For example, people in a community engage in commercial activities which in turn supports the population in the community.
- "Cyber Interdependency – Infrastructure has a cyber interdependency if the state of one depends on the information transmitted through the information infrastructure" (Rinaldi, Peerenboom and Kelly 2001). For example, electric power stations require communication networks for operation and management of grid units in the recovery phase, which in turn provides electricity for the operation of communication infrastructure system components.

- “Logical Interdependency – Infrastructures are logically dependent if an infrastructure agent is linked to an agent in the other infrastructure without any physical, geographic or cyber connection” (Rinaldi, Peerenboom and Kelly 2001). For example, resident population in the community increases the attractiveness of the community to the workforce population.

A descriptive design structure matrix (DDSM) was conceptualized based on a literature review of various World Bank case studies (GFDRR 2017) and other literature to identify and describe the interactions between community infrastructure components. The DDSM consists of three parallel 2-dimensional matrices. The first (Level 1 or primary or non-technical) DDSM describes the interactions in text that can be easily understood by community leaders who often do not have the technical expertise e.g. the mayor of the community. The second matrix (Level 2 or technical) provides detailed explanation of interdependencies between infrastructure agents to elaborate on the reported interactions in the primary matrix. The level 2 matrix will be useful for experts who have the technical knowledge of different sectors, e.g. the heads of department of transportation, public health etc. The third (Level 3) matrix provides literature support for each of the reported infrastructure interactions in Level 1 and Level 2.

In developing the Level 1 matrix, community infrastructure systems that are essential for housing, population, and economic recovery were identified and examined for interdependencies. The areas considered sectors for intersectoral prioritization by the World Bank was used to initially identify community infrastructure components including, social sectors (housing, land and settlements, population); production sectors (employment and livelihoods, agriculture, commerce and trade, and industry); infrastructure sectors (community infrastructure, water, sanitation and hygiene, transport and telecommunications, and energy and electricity). The focus of the current work is on the built infrastructures and their related social infrastructures in disaster recovery. Therefore, potential sectors that use relatively little built infrastructure or play relatively smaller roles in disaster recovery are beyond the scope of this research. Examples include, gender equality, culture and heritage, politics, etc. The sectors were aggregated at the community level to describe 16 distinct community infrastructure systems that represent the major community sectors, in line with the typical breakdown of programmatic recovery as outlined by the World Bank (GFDRR 2015).

Level 2 DDSM provides a detailed explanation of the community infrastructure interactions reported in Level 1. Community infrastructure systems are disaggregated into system agents in each cell to describe what and how the elements of driving infrastructure interact with the elements of the driven infrastructure. The interaction described in each cell is assumed to hold true for all communities that are on the path to a self-sufficient and sustainable recovery. This is because the interdependencies described between infrastructure systems are inherent for the normal operations, maintenance and reconstruction of the physical infrastructure system. The interdependencies reported in each cell is backed by literature research as given in Level 3 matrix.

Hypothesis Testing with Case-Study DDSM

To test the validity of reported interactions in the hypothesis, the Indian state of Jammu and Kashmir was chosen as the case-study to compare and analyze the community infrastructure system interactions. The state of Jammu and Kashmir has a high exposure to natural hazards with a low development index due to the region's fragile status (GFDRR 2020). Two cases of disruptions to the normal community functioning were selected to identify the infrastructure interactions, one natural and one man-made. The natural disaster case is that of the massive floods that hit the region of Jammu and Kashmir in September 2014. The floods caused massive damage, killing more than 300 people and destroyed houses, educational institutes, agricultural crops, government establishments, businesses etc (Tabish and Nabil 2014). Consequently, a community recovery project, funded by the World Bank, was started in the year 2015 to support and increase the disaster resilience in Jammu and Kashmir, while restoring damaged infrastructure in the community (The World Bank 2015). The second (manmade) case was the disruptions caused due to the 2019 political unrest in Jammu and Kashmir. On 5 August 2019, the Indian government repealed provisions established by the Article 370 of Indian constitution that guaranteed special status to Jammu and Kashmir. Post the revocation of the special provisions, the Indian government discontinued the internet services in the state and shut down the communication network. Economic losses to the tune of $1 billion were reported with significant disruptions caused in the education and public health sector (Siddiqui 2019). This study chose both a natural disaster and a manmade disruption to compare the model results. Both incidents caused extensive disruptions in the normal functioning of the community, which have been reported in multiple news reporting and other scholarly literature publications.

News articles and other scholarly articles published between September 2014 and December 2019, that reported the impacts of disruptions on the community infrastructures were selected to identify how the lack of one infrastructure affected the normal operation of the other. The reported case-study infrastructure interactions were modelled as 3-layered descriptive design structure matrices (DDSM). Level 1 of case-study DDSM qualitatively describes the identified community infrastructure interactions. Level 2 of case-study DDSM elaborates on the interdependencies described in Level 1 to explain how the driving infrastructure drives the normal operations of the dependent infrastructure in the community. These interactions are supported by published news articles, interview data collected from the case-study (attached in appendix), and scholarly publications documented in Level 3.

To test the validity of the proposed model and to build confidence in usability of the model, multiple validation tests were conducted by the researchers to compare the results of the Hypothesis DDSM with that of the case-study DDSM. Model validation tests as described by Sterman (Sterman 2000) were used and adapted in our context to assess the overall suitability of the model to our purpose, its conformance to fundamental formulation principles and the integrity of the modelling process. This was done by designing the validation tests in a way that uncover flaws and hidden assumptions, challenge preconceptions, and expose assumptions for critique and improvement. Table 1 summarizes the main tests that were used to validate the modelling results.

Table 1 Model Validation Tests (adapted from Sterman 2000)

Test	Purpose of Test	Tools and Procedures
Boundary Adequacy	Are all the sectors important for community recovery included in the model? Are they mutually exclusive?	Using Interviews, literature and case-study recovery project documents.
Structure Assessment	Is the hypothesis model structure consistent with relevant descriptive knowledge of the infrastructure systems in the community?	Using Interviews, literature and case-study recovery project documents to compare the differences, if any.
	Is the level of aggregation for different sectors appropriate and consistent with the actual community system?	
Behavior Reproduction	Does the model reproduce the behavior of interest in the system (qualitatively)?	Compare expected modes of hypothesis behavior with that of the actual case-study modes of behavior
	Does the model generate the right behavior for the right reasons as observed in the real system?	

CHAPTER IV

RESULTS

The research methodology described in Chapter III was applied to identify community infrastructure sectors, both physical and social, and to describe the interactions in the form of a DDSM to generate the critical community sectors for recovery. This was compared with a case-study DDSM and the differences were analyzed to develop confidence in our model. It was found that 93% of interactions in the Hypothesis DDSM were reported in the Case-Study DDSM. Interactions not reported in the case-study were mainly due to case-study specific disaster and other socio-economic conditions. The results of the modelling process are discussed below.

Sector Descriptions

The sixteen community sectors identified are: Housing, Population, Road Transportation, Other modes of Transportation, Power generation and distribution, Fuel supply and distribution, Water supply and Wastewater Treatment, Drainage and Sanitation, Public Health, Commerce, Food, Information and Communications Technology, Tourism, Governance, and Education. These broad infrastructure categories were used as the rows and columns for the DDSM. Figure 2 shows a snapshot taken from the tool. Each sector has distinct characteristics and is mutually exclusive to other sectors. For example, in given figure, resident population includes only the non-working population of the community. Even though, workforce population are residents in a community they are included in the workforce population and not the resident population.

The complete description of all the sectors, along with their source is given under 'Sector Definitions' tab in the attached Excel file.

Infrastructure	Definition	Notes
Population - Resident	Includes all the non-working people of the community who live in a given geographical location at a given date and time, excluding the workforce.	
Population - Worforce	Includes the employed labour pool of the commmunity who live in a given geographical location at a given time. Includes both formal and informal sectors	Includes all skilled and unskilled workforce of the community, including doctors, engineers, planners, management executives, government officials, labor workforce, clerks and other workforce employed by NGO, private and public agencies
Transportation -Road Transportation	Road transportation infrastructure includes all activities essential for the construction, operation and maintenance of road networks and other supporting infrastructure such traffic lights, control centers in a community. Supports transportation of goods and personnel from one place to the other.	Includes public transportation systems, supporting infrastructure such as traffic control and monitoring equipment. Private-owned vehicles are also included in road transportation. Includes only the built infrastructure and does not include business operational aspect of the infrastructure.
Energy - Electric Power Generation & distribution	Includes all the activities essential for the construction, operation and maintaince of electric power production and distribution infrastructure. Supports delivery of electricity services in the community	Includes all the transmission lines, power transformers, metering equipment, and electric generation control systems. Includes the built infrastructure but does not include business operational aspect of the infrastructure.

Figure 2 Sector Definitions

Hypothesis DDSM

The qualitative interaction given in the DDSM describes the causal relationship between the driving and the driven infrastructure. In a DSM, elements in the row drives the elements in the column (driven infrastructure). For example, in Figure 3 infrastructure sectors in Row 1 drive the sectors in column A. As an example, road transportation (driving infrastructure) is required for normal operation of sanitation services (driven infrastructure). Similarly, effective drainage infrastructure is required for the normal operation of road transportation. Interdependencies between these sectors were identified based on the available literature and modeler's understanding of the requirements (in terms of goods and services) for the normal operation and physical reconstruction of the infrastructure system. Figure 3 shows a snapshot of Level 1 DDSM (for non-technical managers). Complete Level 1 DDSM is given under the tab 'Hypothesis DDSM – level 1' in the attached Excel file.

	A	B	C	D
1	Driving Sector Driven Sector	**Road Transportation**	**Drainage & Sanitation**	**Governance**
2	**Road Transportation**		Creates demand for road infrastructure for clearing debris and trash removal. Effective drainage systems are required for clearing water off the roads.	Governance ensure proper instituional capacity for the execution and operation of transportation projects. E.g., State Department of Transportation
3	**Drainage & Sanitation**	Requires functional road networks for collection and disposal of solid waste		Governance ensure proper instituional capacity for the execution of drainage and sanitation projects and the operation of sanitation plants
4	**Governance**	Supports the government to deliver its services and information effectively in the community	Supports the normal operation of governmnet establishments	

Figure 3 Level 1 Hypothesis DDSM

Level 2 DDSM (for technical managers) provides a detailed description of the interaction reported in Level 1. This is intended for the recovery managers with technical expertise to aid them in a detailed understanding as to how the driving infrastructure interacts with the driven infrastructure. A snapshot of Level 2 matrix showing the interdependencies between community sectors is shown in Figure 4. As can be seen in Figure 4, the description provides a more detailed explanation of how the elements of driving infrastructure (in row) drives the elements of the driven infrastructure (in column). For example, effective drainage systems need to be in place to ensure that surface rainwater is drained off without disrupting the normal operations of road networks. Complete Level 2 DDSM is given under the tab 'Hypothesis DDSM – level 2' in the attached Excel file. Level 3 provides the source of the reported interactions. Level 3 DDSM is provided in the tab 'Hypothesis DDSM – Level 3' in the attached Excel file.

Driving Sector / Driven Sector	**Road Transportation**	**Drainage and Sanitation**	**Governance**
Road Transportation		Effective drainage systems are required to be in place to ensure that surface water such as rainwater is drained off without disrupting the normal oprations of road networks. Further, availability of sanitation infrastructure services in the community require functional road networks for the garbage trucks to ply on in order to collect the waste from houses to be disposed off in the treatment plants and/or landfills. This creates demand for the availability of road infrastructure in the community.	Governance is important to regulate the normal operations of transportation infrastructure services in the community. For example, managing public highways, airports etc. Government regulates the transportation construction activities in the community. For example, funding, permitting, environmental and other legal issues are all regulated by the government. Governance is also important to avoid conflicts and for resolution of issues such as environmental, financial etc.
Drainage and Sanitation	Operational transportation infrastructure system facilitate the supply of construction material such as steel, aggregates, pipes, cables; transportation of construction teams, equipments and other materials that are required for the physical construction of sanitation infrastructure system components. Furthermore, functional networks allow the transportation of waste to landfills through the use of garbage trucks etc. Lack of availability of transportation infrastructure services such as road transportation interfere with effective execution of WWTP (re)construction projects leading to delays and may eventually delay the recovery projects.		Governance is important to regulate the normal operations of sanitation services in the community. For example, regulations for treatment plants, regulations for landfills etc.. Government regulates the sanitation plant construction activities in the community. For example, funding, permitting, environmental and other legal activities are all regulated by the government. Governance is also important to avoid conflicts and for resolution of issues such as environmental, financial etc.
Governance	Availability of transportation infrastructure services facilitates distribution of information and services in the community. E.g. emergency response teams require road transportation networks or helicopters in order to implement rescue operations etc.	Government institutions and offices require solid waste disposal services to carry out the daily operations of government institutions. Available of sanitary infrastructure services support the government instituitions to carry out community projects	

Figure 4 Level 2 Hypothesis DDSM

Case-Study DDSM

Three levels of case-study DDSM were developed, consistent with the Hypothesis DDSM. This was done by identifying the case-study specific interactions reported due to natural and man-made disruptions. Figure 5 shows a snapshot of 3*3 Level 1 DDSM with the description of the interactions reported. Case-Study Level 1 matrix is similar to Hypothesis Level 1 Matrix with the exception that the description of the interaction is based on the actual interactions as reported in case-study literature. For example, as can be seen in Figure 5, the government of Jammu and Kashmir manages the operation of road transportation in the community. Similarly, functional road transportation is required by the government to deliver the government services and for dissemination of information in the community. Complete case-study level 1 DDSM is provided under the tab 'Case-Study DDSM – Level 1' in the attached Excel file.

Driving Sector / Driven Sector	**Road Transportation**	**Drainage & Sanitation**	**Governance**
Road Transportation		Effective sanitation infrastructure services are required to drain off the rain water that may otherwise cause waterlogging on the roads. Creates demand for road infrastructure for clearing debris and trash removal	Government controls the operations and management of the transportation systems such as public road transportation etc.
Drainage & Sanitation	Functional road networks are required for the collection and disposal of solid waste Also creates a demand for the availability of effective stormwater management system		Government is responsible for managing and operating the sanitation infrastructure services
Governance	Supports the government to deliver its services and information effectively in the community	Supports the normal operation of governmnet establishments	

Figure 5 Level 1 Case-Study DDSM

Level 2 matrix of the case-study DDSM elaborates on the reported interaction. Figure 6 shows a snapshot of 3*3 Level 2 matrix with the details of how the driving infrastructure interacts with the driven infrastructure. Level 2 DDSM matrix is like the Hypothesis Level 2 matrix with the exception that the description of the interaction is specific to the case-study in hand. For example, in Figure 6 Government manages sanitation in Kashmir through city municipal corporations. Therefore, lack of effective governance will have an impact on sanitation recovery projects, which was observed in Kashmir in the post-disaster recovery period. Level 3 DDSM provides references to various news sources and other scholarly articles that were referred to for identifying interaction in the case-study example. Case-study Level 2 and Level 3 DDSM are given in the attached Excel file.

Driving Sector → Driven Sector	Road Transportation	Drainage & Sanitation	Governance
Road Transportation		Inefficient drainage system in Kashmir led to waterlogging that disrupted the normal operation of road transportation.	Government controls the operations and management of the transportation systems such as Airports, Railroads etc. As an example, train operations and services in Kashmir were stopped due to security reasons by the government. Following the 2019 political unrest in Kashmir, the train services were resumed only after the government issued security clearance.
Drainage & Sanitation	Functional road networks are required for the collection and disposal of solid waste Also creates a demand for the availability of effective stormwater management system		Government of Jammu and Kashmir manages the municipal corporation in the community that looks after the drainage and sanitation in the community
Governance	Supports the government to deliver its services and information effectively in the community	Supports the normal operation of governmnet establishments	

Figure 6 Level 2 Case-Study DDSM

Preliminary Comparison Results

In addition to comparing the number of interactions reported in Hypothesis and Case-Study DDSM, the location of interactions was also compared. Table 2 shows the results of the comparison between interactions reported in Hypothesis and Case-study DDSM.

Table 2 Comparison Between Hypothesis DDSM and Case-Study DDSM

Category of interaction	**Comparison count (Count of cells in the matrix)**	**Percent of Total reported interactions**	**Percent of Total possible interactions**
Interaction reported in both Hypothesis and Case Study DDSM	180	93%	71%
Interactions reported in Hypothesis DDSM but not in Case-Study DDSM	12	6%	5%
Interactions reported in Case Study DDSM but not in Hypothesis DDSM	1	1%	0%
No interactions reported in either Hypothesis or Case Study	47	NA*	18%
Intradependencies (internal infrastructure dependencies) – diagonal cells	16	NA*	6%
Total Possible Interactions	**256**	**100%**	**100%**

**Total reported interactions do not include cells with no reported interactions and cells with intradependencies*

Table 3 Qualitative Description of Missing Interactions in Either the Hypothesis or Case-Study DDSM

Driving Infrastructure	**Driven Infrastructure**	**Reported in Hypothesis**	**Reported in Case Study**	**Reason**	**Notes**
Other Transportation	Communication	Yes	No	Road transportation is the major source of transportation in Kashmir. Lack of other modes of transportation does not create any demand for communication infrastructure.	Interaction missing due to Case-Study Specific context
Other Transportation	Food	Yes	No	Road transportation is the major source of transportation in Kashmir. Lack of other modes of transportation means that food is primarily distributed using road transportation.	Interaction missing due to Case-Study Specific context

Table 3 Continued

Driving Infrastructure	Driven Infrastructure	Reported in Hypothesis	Reported in Case Study	Reason	Notes
Food	Other Transportation	Yes	No	Road transportation is the major source of transportation in Kashmir. Lack of other modes of transportation does not create any demand for other transportation.	Interaction missing due to Case-Study Specific context
Road Transportation	Communication	Yes	No	Traffic management in Kashmir is done manually by the traffic police and does not require communication infrastructure for managing the road transportation.	Interaction missing due to Case-Study Specific context

Table 3 Continued

Driving Infrastructure	Driven Infrastructure	Reported in Hypothesis	Reported in Case Study	Reason	Notes
Electric Power	Road Transportation	Yes	No	Traffic in Kashmir does not really depend on the traffic lights for its operation and management etc.	Interaction missing due to Case-Study Specific context
Water Supply & Treatment	Food	Yes	No	Food production is mainly local in Kashmir and due to abundance of natural water resources, the industry does not rely on Water Supply and Treatment services.	Interaction missing due to Case-Study Specific context
Drainage & Sanitation	Food	Yes	No	Local means of production in Kashmir do not rely on the drainage and sanitations services for their normal operations.	Interaction missing due to Case-Study Specific context

Table 3 Continued

Driving Infrastructure	Driven Infrastructure	Reported in Hypothesis	Reported in Case Study	Reason	Notes
Food	Water Supply & Treatment	Yes	No	Food production is mainly local in Kashmir and due to abundance of natural water resources, the industry does not rely on Water Supply and Treatment services.	Interaction missing due to Case-Study Specific context
Food	Drainage & Sanitation	Yes	No	Local means of production in Kashmir do not rely on the drainage and sanitations services for their normal operations.	Interaction missing due to Case-Study Specific context

Table 3 Continued

Driving Infrastructure	Driven Infrastructure	Reported in Hypothesis	Reported in Case Study	Reason	Notes
Communication	Road Transportation	Yes	No	Traffic management in Kashmir is done manually by the traffic police and does not require communication infrastructure for managing the road transportation.	Interaction missing due to Case-Study Specific context
Communication	Other Transportation	Yes	No	Road transportation is the major source of transportation in Kashmir. Lack of other modes of transportation does not create any demand for communication infrastructure.	Interaction missing due to Case-Study Specific context

Table 3 Continued

Driving Infrastructure	Driven Infrastructure	Reported in Hypothesis	Reported in Case Study	Reason	Notes
Communication	Food	No	Yes	Communication infrastructure is required for normal coordination and operation of food production units in the community. For example, phone services need to be available for coordination of food processing activities.	Interaction updated in Final DDSM

Table 3 gives a qualitative description of the interactions that are reported in either the Hypothesis or the case-study but not in both. 12 interactions were found missing in the case-study DDSM that are reported in the Hypothesis DDSM. This is because of the case-study specific cultural and economic contexts. As such, interactions not reported in the case-study are still assumed to hold true in other communities with different contexts. One interaction was found missing in the hypothesis DDSM that was reported in the case-study DDSM. The same was updated in the modified final DDSM. The modified DDSM has been attached in an excel file with this document.

CHAPTER V

ANALYSIS OF DDSM FOR RECOVERY PLANNING

For the purposes of this analysis two terms will be defined: critical infrastructure and critical interaction. A critical infrastructure[3] is one that provides basic services for community operations and has a significant influence on the recovery of at least one other sector. A critical interaction between two infrastructures is a dependency that can constrain the capacity of the dependent infrastructure. For example, road transportation required for supply of materials and equipment for power generation is a critical interaction between the road infrastructure and the power generation and distribution infrastructure because power stations need raw materials such as coal, etc. for the generation of electricity and power generation may get impacted without continuous supply of materials. The terms critical infrastructure and critical interaction will be used in the analysis below.

Critical Infrastructures for Community Recovery

The final 16*16 descriptive design structure matrix (DDSM) was analyzed using Cambridge Advanced Modeler (CAM), a software tool used for modelling and analyzing flows and dependencies in a complex system (Wynn, 2010). CAM allows the user to construct and visualize linkage models using DSMs. In a DSM, each element being displayed corresponds to a row and a column of the matrix, while connections between two elements are shown as marks in the requisite matrix cells. The structure of the system

[3] Includes both physical and social infrastructures

was analyzed using the Structural Profiling option in CAM. When applied to the community recovery DSM, the structural profiling analysis allows the model to be summarized as a set of numbers using different metrics to characterize individual community sectors (nodes) with respect to other sectors in the system. The following metrics were used for the analysis: Betweenness Centrality, In-Degree Centrality, and Out-Degree Centrality (Golbeck, 2015).

- **Betweenness Centrality**: Betweenness centrality measures the number of times a node (sector) lies on the shortest path between other nodes. This measure shows which nodes are 'bridges' between nodes in a network. It does this by identifying all the shortest paths and then counting how many times each node falls on one.
- **In-Degree Centrality**: Number of in-bound links to the node. In our model, in-degree implies the number of infrastructure services that feed into an infrastructure sector.
- **Out- Degree Centrality**: Number of out-bound links from the node. In our model, out-degree implies the number of infrastructures that are driven by an infrastructure sector.

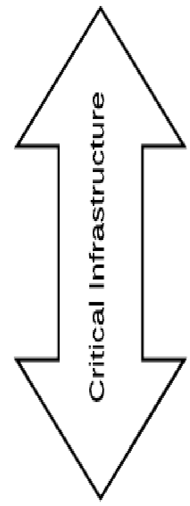
Sectors with higher values for any of these metrics are in some sense 'important', 'central', or 'critical' to the community recovery system being modelled (Wynn 2010). Table 4 shows the centrality values of the community infrastructure sectors in the final DDSM, categorized as critical and non-critical infrastructure based on their centrality values.

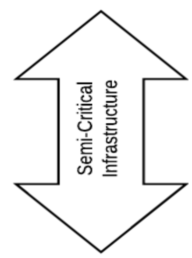
Sectors that provide services to all the other 15 infrastructures (Out-Degree Centrality =15) OR those that lie on the most number of shortest paths between sectors (Betweenness Centrality >5), were identified as the most 'critical' infrastructure sectors for community recovery. Based on their centrality values, the top 5 critical infrastructures are: Commerce, Road transportation, Power generation and distribution, Workforce Population, & Governance (Table 4). Although having low betweenness centrality, Governance was added to the list primarily because it provides service to all the other sectors with the maximum value of out-degree centrality (driving all the other sectors) with relatively lesser value of in-degree centrality (driven by other sectors). Further, government is an important driver of community recovery in the post-disaster period given that it requires effective governance to initiate and coordinate recovery efforts in a community (GFDRR 2015).

It is important to note that this analysis does not suggest that the other community sectors are not important, only that they are less critical to fast and efficient recovery than the sectors assessed to be critical or semi-critical. Some of these other sectors (.e.g, Tourism, Resident Population, Education) are classified as such because they are primarily performance measures of recovery. Others (e.g., gasoline) are classified as such because, while important, they interact as part of relatively long causal chains and therefore have relatively low centrality measures. Alternative analyses such as causal loop diagram analysis may provide additional insight about the relative criticality and importance of sectors but is beyond the scope of the current work.

Table 4 Centrality Values of Community Infrastructure Sectors

S.No.	Sector	Betweenness Centrality	In-Degree Centrality (Driven by other sectors)	Out-Degree Centrality (Drives other sectors)
1	Commerce	6.37	15	15
2	Workforce Population	6.19	15	14
3	Road Transportation	5.23	13	15
4	Power Generation and Distribution	5.03	14	14
5	Governance	2.70	10	15
6	Gasoline	3.13	12	14
7	Water Supply & Wastewater Treatment	3.30	13	11
8	Public Health	2.64	14	12
9	Food	1.95	13	11
10	Tourism	1.73	12	12
11	Communication	1.54	11	11
12	Drainage and Sanitation	1.24	10	10
13	Education	1.09	10	10
14	Other Transportation	0.69	10	10
15	Residential Housing	0.17	8	6
16	Resident Population	5.01	13	13





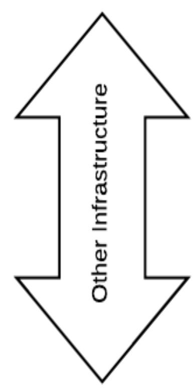


Figure 7 shows a 5*5 DSM displaying the interactions between critical infrastructure sectors. As can be seen in the figure, all the sectors are interdependent, making it a very tightly coupled system. This means that all the sectors provide services that feed directly into each other and each is required for the recovery of the other. This indicates that each of these sectors can constrain the recovery of the others, suggesting that speedy recovery requires that all five sectors must generate, or recover to generate capacity in parallel.

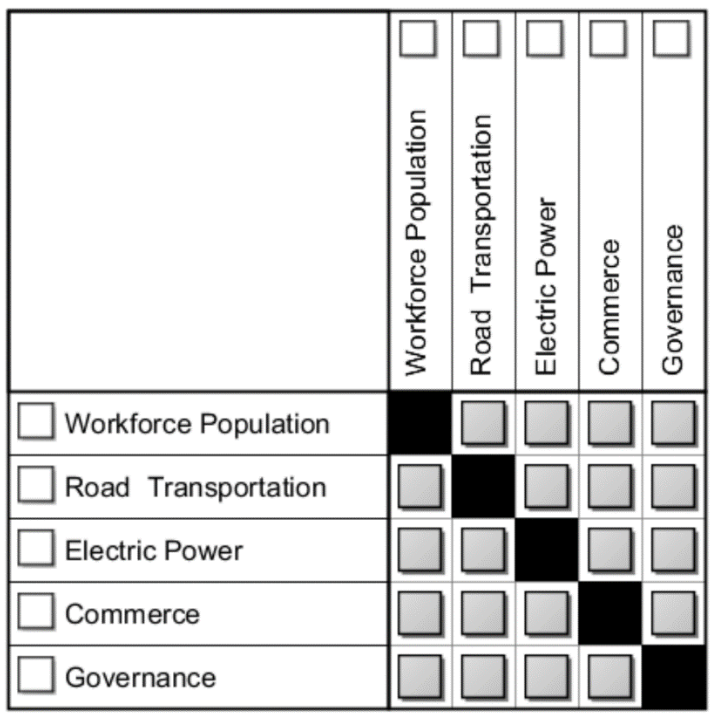


Figure 7 DSM of Critical Sectors for Recovery

Figure 8 shows the same information as shown in Figure 7 in the form of a partial causal loop diagram (CLD). In CLD variables indicate system components and arrows indicate the direction of causality. Reinforcing feedback loops (R) amplify effects and

Balancing (B) feedback loops generate goal-seeking behavior. CLD clearly show the feedback structure in the system. Figure 8 is only a partial CLD because all the community elements that impact the system elements in Figure 8 have not been included in the diagram for the sake of simplicity. For example, growth of physical facilities is limited by crowding due to a lack of land for further construction is not shown in the CLD

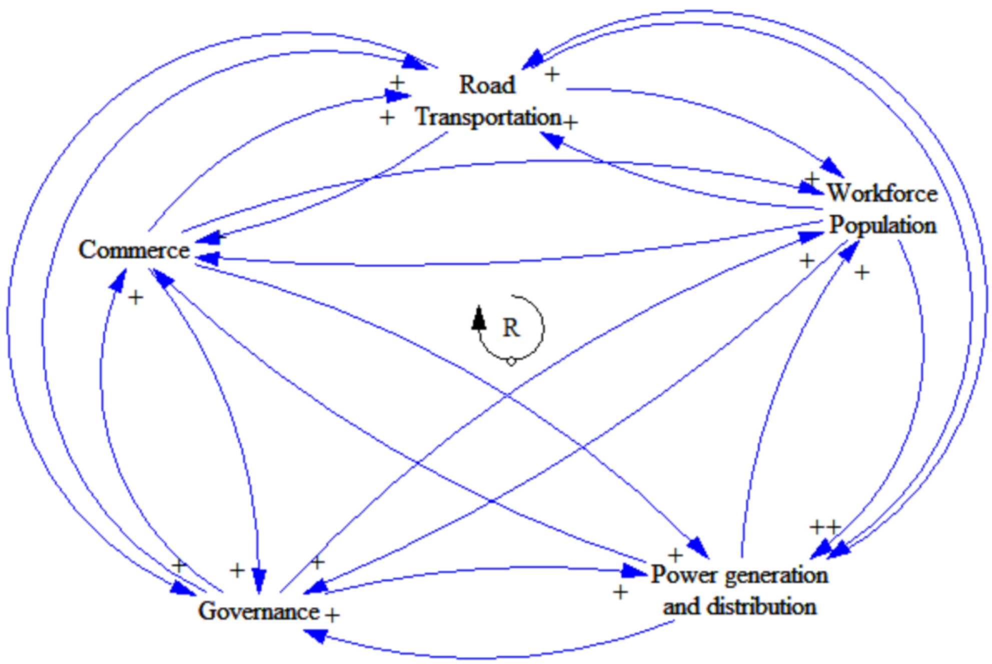


Figure 8 DSM Based Causal Loop Diagram of Critical Sectors for Recovery

Critical Infrastructures for Short Term Versus Long Term Recovery

The types of services provided by one infrastructure for the recovery of another infrastructure varies in different stages of recovery. For example, during the short-term recovery phase, where the major focus is on the reconstruction of physical infrastructure, road transportation is required for power generation mainly for the supply of materials, labor, and equipment required for reconstruction of power plants and distribution stations.

However, during the long-term recovery phase, where the focus is on the overall restoration of services, road transportation is required for power generation and distribution mainly for the supply and distribution of raw materials required for power generation.

The DDSM of critical infrastructures was disaggregated into two DDSMs, one reflecting short-term recovery interactions and a second DDSM reflecting long term recovery interactions based on modeler evaluation of the second (technical) level of the final DDSM. Figures 9 and Figure 10 show the interactions between the critical infrastructure sectors in the short-term and long-term recovery phase. Although the interactions (connections) do not differ much in the short-term and long-term recovery phase, the description of the dependencies varies and can have significant policy implications. See attachment with this document for short-term and long-term DDSMs with all three levels (non-technical, technical, references).

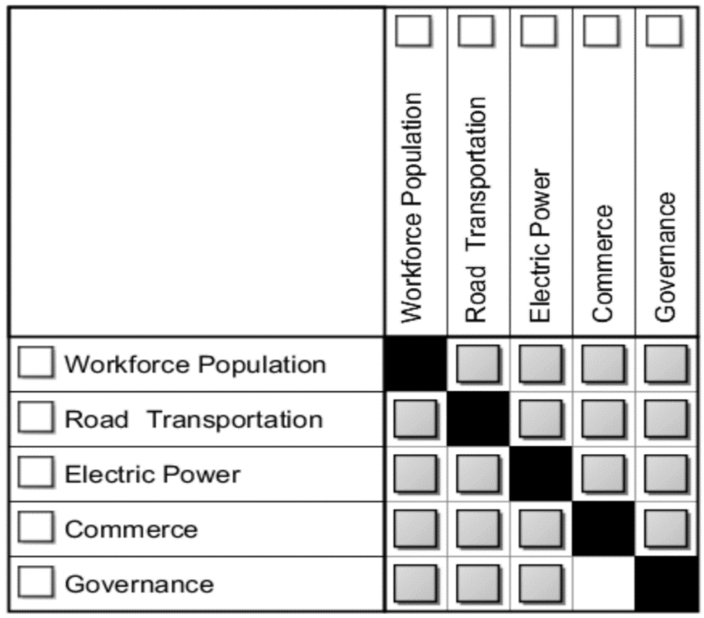


Figure 9 DSM of Critical Sectors for Short-Term Recovery

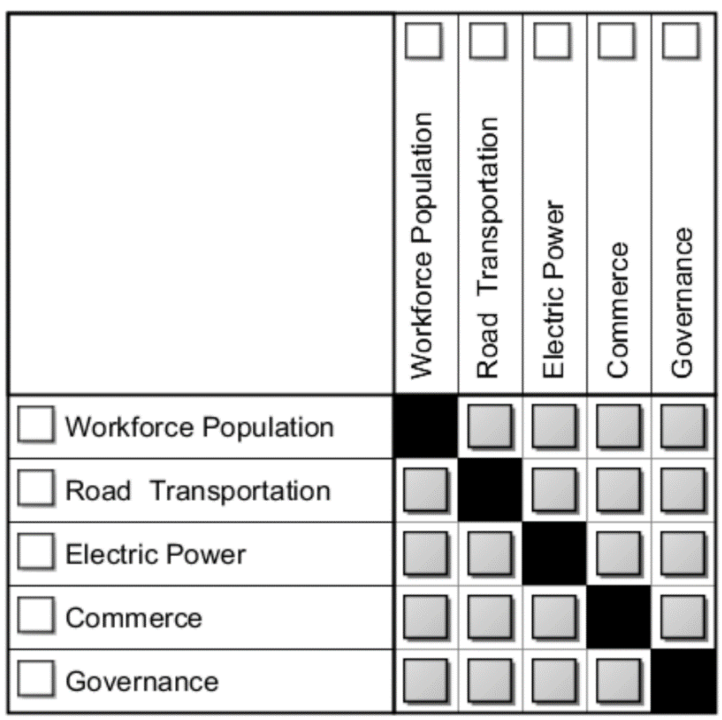


Figure 10 DSM of Critical Sectors for Long-Term Recovery

To test the criticality of infrastructures, the list of sectors was expanded to include 3 ‘semi-critical’ infrastructure systems based on the centrality measures given in Table 4. Sectors with Betweenness centrality >2, or an out-degree centrality of >14 are considered as semi-critical infrastructure. The basic idea is that as the list of critical infrastructures is expanded to include semi-critical infrastructures, the interdependencies between the sectors starts to thin out with lesser number of reported interactions. The final list of critical and ‘semi-critical’ infrastructure sectors along with their dependencies are shown in the DSM in Figure 11. Resident Population, although having high centrality values was not included in this list because recovery of dislocated resident population in the community is often used as a performance metric that is based on the recovery and restoration of other services in the community.

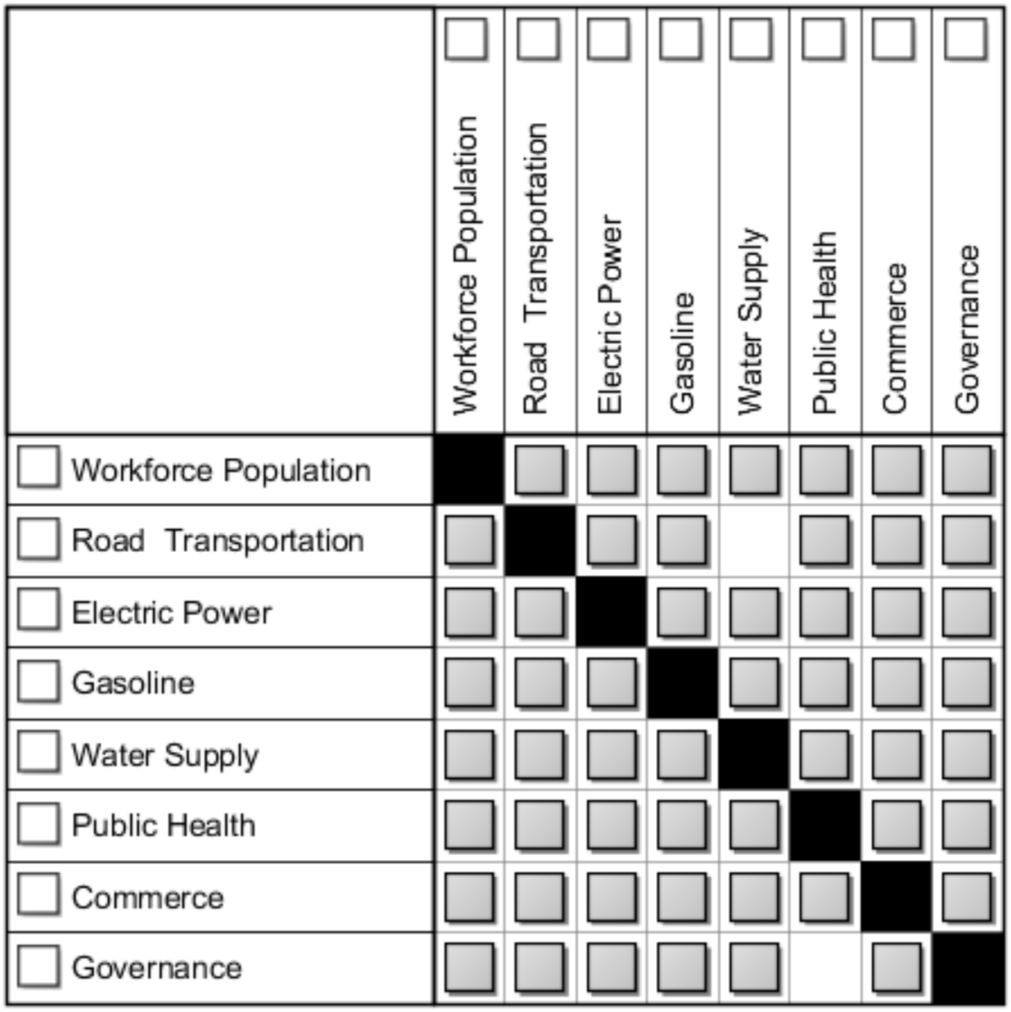


Figure 11 DSM of Critical and Semi-Critical Sectors for Recovery

Insights for Recovery Planners

- **The 5 most 'critical' infrastructure sectors based on their importance for community recovery are – Commerce, Governance, Power Distribution and Generation, Road Transportation, and Workforce Population**. These critical infrastructure sectors form the 'core' loop for recovery. In other words, irrespective of the reported damage in different sectors and the final performance metrics for recovery, it is important that these core sectors are restored and that they keep reinforcing each other since they provide the basic services required for the recovery of all other infrastructure sectors.

- **The primary focus in the recovery period should be on restoration of infrastructure services that are required for the recovery of other infrastructures,** even if they are not the infrastructures that are used to measure recovery performance. These can be considered as "foundation" infrastructures because they create and sustain the structures upon which other infrastructures and the recovery are built. In other words, recovery strategies should consider the impact of infrastructure interdependencies in the recovery of the community. For example, in the case of road transportation, the aim should be to restore road services required for reconstruction of power station and distribution stations. Similarly, it is important that workforce population required for the reconstruction and long-term operation of the road transportation is available in the community.
- **To speed community recovery, infrastructures must recover in ways that build the capacity of their dependent infrastructures**. Not all infrastructure recovery actions help build capacity in other infrastructures. For example, rebuilding damaged roads in remote areas may count as part of transportation recovery, but it does not help build capacity in other critical sectors such as commerce. Community recovery planners should target recovery efforts that restore and support dependent infrastructures.

- **Short-term and long-term recovery are different stages in recovery planning and recoveries should be planned and managed to reflect those differences**. The kind of dependencies between different infrastructure sectors are often different in the two stages. It is important that while developing recovery strategies, both short-term and long-term recovery needs are taken into consideration and planned for. For example, workforce requirement for road transportation are different in the two stages of recovery. In the short-term recovery stage, workforce requirement primarily corresponds to the construction workforce required for the reconstruction of the transportation infrastructure, whereas in the long-term recovery stage, workforce requirement may correspond to the staff required for managing and operations of road infrastructure.

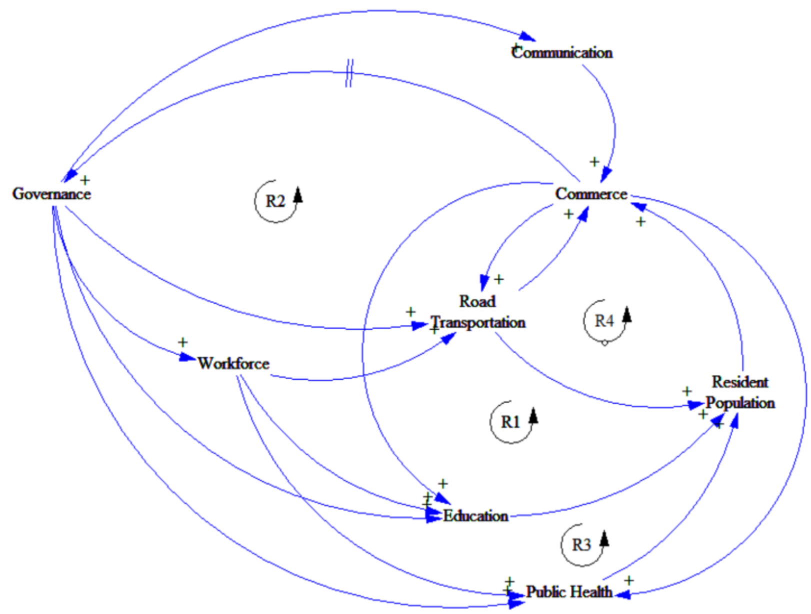
Application to Practice: Case-Study Example

After the 2014 Floods in the Indian state of Jammu and Kashmir, the Government of India requested assistance from the World Bank and an emergency project worth $250 million, "Jhelum and Tawi Flood Recovery Project (JTFRP)", was commissioned (The World Bank, 2015). The major objective of the project is to support the recovery of damaged infrastructures and build resilience in the community. Consequently, the project involves seven components, which is comprised of 4 components for reconstruction of infrastructure and 3 for building resilience in the community. The projects identified for reconstruction and restoration are (Jammu and Tawi Flood Recovery Project 2020):

- Public building such as schools and colleges.
- Hospitals and other public health related infrastructure
- Roads and Bridges.

- Non-farm livelihoods such as business centers.

The project was started in 2015 with a targeted completion date of June 2020. With the 5th year in progress, the project has been delayed multiple times and the project is likely to exceed the scheduled deadline (Malik 2020). Semi-structured interviews were conducted with recovery managers involved in the project. The aim of the interviews was to understand their perception of the constraints in the recovery of the community in general, and the execution of the project in specific. Several causes were identified for the delay in the completion of the project. The identified causes were mapped in the form of a Causal Loop Diagram (CLD) to visualize how the emergency planners perceive the recovery process of different sectors (Figure 12). The CLD is based on the mental models of officials involved in the planning and execution of the said JTFRP. Figure 13 shows these interactions based on the mental models of recovery managers in Kashmir in the form of a DSM.



R1 – Case Study Education Recovery Loop
R2 – Case Study Transportation Recovery Loop
R3 – Case Study Public Health Growth Loop
R4 – Population Growth Loop

**Only the loops identified in the Interviews have been included in the CLD*

Figure 12 Causal Loop Diagram Based on Mental Models of Recovery Managers for Post-Disaster Recovery in Kashmir

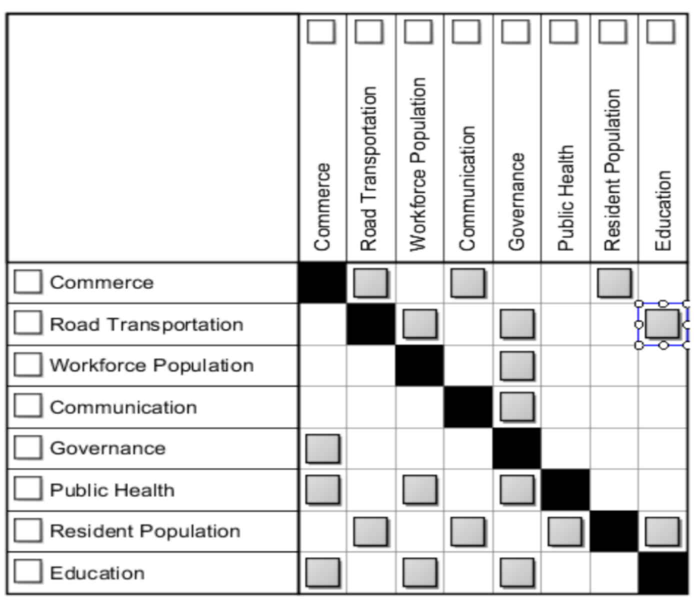


Figure 13 DDSM Based on Mental Models of Recovery Managers for Post-Disaster Recovery in Kashmir

To validate the usefulness of the research tool, DSM based mental models of Education recovery in Kashmir (Figure 13) was compared with that of actual DDSM model. Figure 14 shows the actual DDSM for the recovery of education sector in a community. This was done by rearranging the DDSM elements in CAM in a way that all the services that education recovery depends on are placed above the education infrastructure element in the matrix.

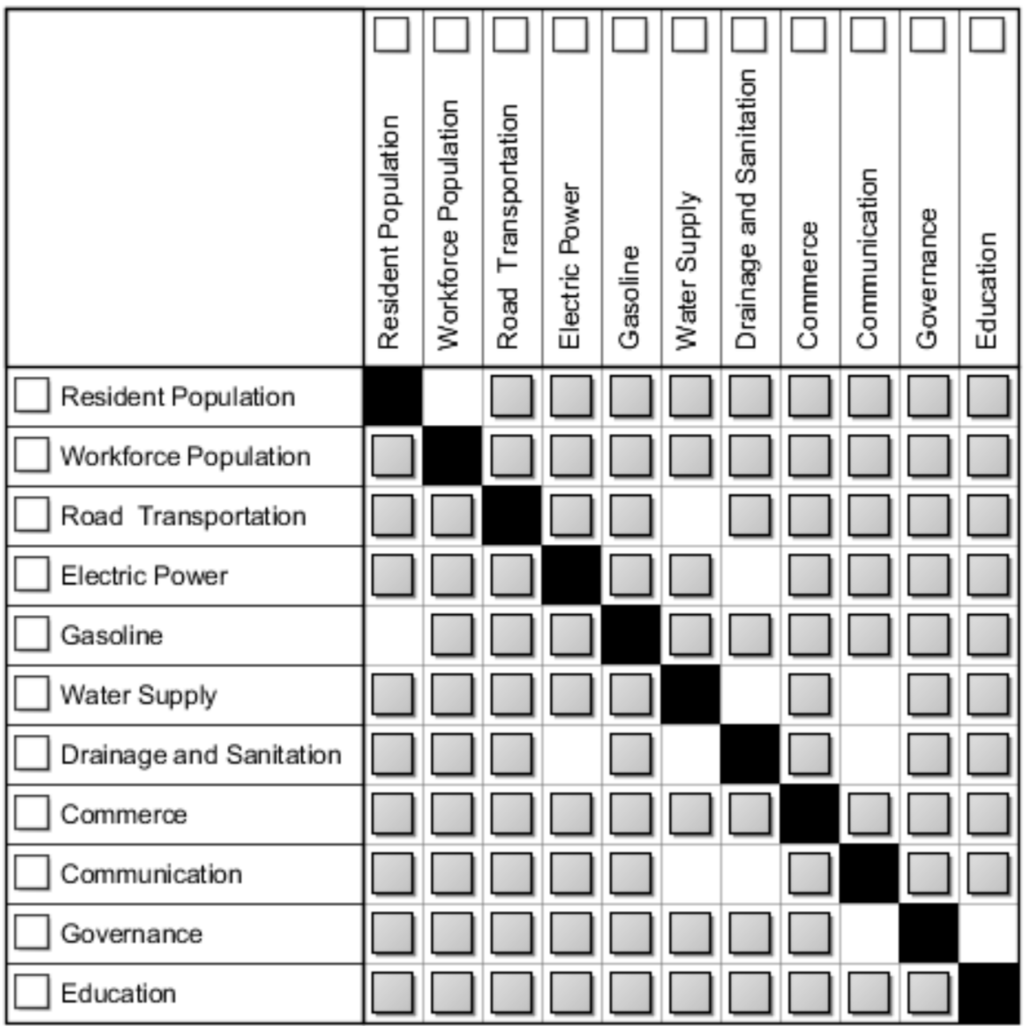
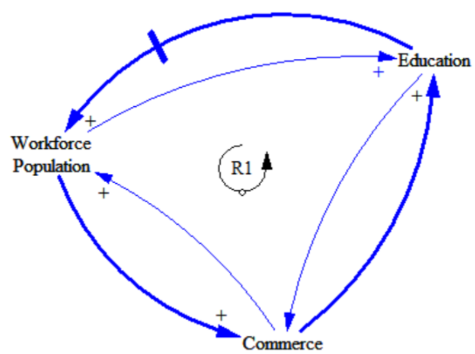


Figure 14 DDSM for Education Recovery

- The major constraints identified for Education Recovery in Kashmir by the community informants (planners and recovery managers) are: Lack of Workforce Population for planning and construction of educational institutes, Lack of Road Transportation for material supply (Road Transportation), Lack of effective implementation (Governance), and Lack of bidders for procurement and construction contracts (Commerce). This mental model includes 4 of the 5 critical infrastructures for recovery and therefore is consistent with the most critical sectors identified for recovery in this research. Electric power generation and distribution was not impacted by the floods and therefore, was not a constraining factor. Critical Sectors form the core loop that can potentially constrain or drive recovery. This suggests that the community informants are aware of the critical role of the five critical infrastructures in recovery.
- The shortage of skilled Workforce in the community can be attributed to a lot of factors. For example, the state of Jammu & Kashmir had a low development-index prior to the floods of 2014, owing to its fragile status (GFDRR 2020). This negatively impacted the level of skilled workforce available in the community. Lower level of skilled workforce entering the businesses negatively impacted the availability of private sector companies such as contractors, planning and consulting firms etc. Therefore, loop R1 (Figure 15), based on the reported interactions as given in Figure 14, is a negatively reinforcing loop which means that all the elements in the system move in the same direction that is acting to degrade conditions, thus resulting in decay of the loop. This created a bottleneck in the recovery of education sector in the post-disaster period by causing a delay in the reconstruction of schools and colleges. This suggests that the

community informants did not factor for the dependencies between education and workforce while developing recovery strategies. Use of DDSM tool can help the community leaders qualitatively describe these interactions that may otherwise go unnoticed and may constrain or delay community recovery in the post-disaster period.

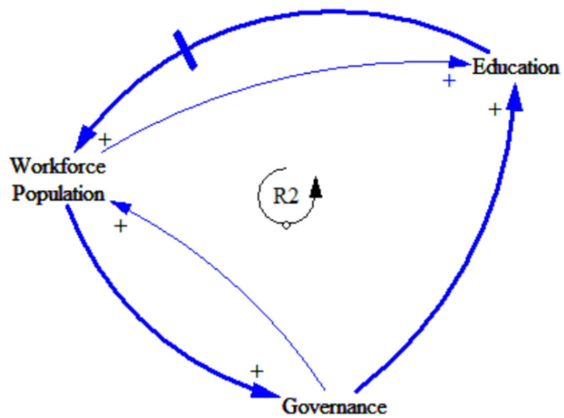


R1 – Commerce Growth Loop

Figure 15 DDSM Based CLD of Commerce for Education Recovery

- The Jhelum and Tawi River Flood Recovery Project identified road construction as one of the important elements for recovery (The World Bank, 2015). Road Transportation is needed for the supply of materials and equipment required for the reconstruction of education infrastructure. However, the selection of roads critical for the reconstruction were not identified properly (see insights above). The National Highway connecting Kashmir with Jammu is prone to landslides and road closures for maintenance is a common phenomenon (Peerzada, A., 2020). Functional National Highway is important for transfer of goods, labor, materials and equipment for reconstruction projects. However, no resource was allocated to increase the capacity of national highway. This created a major constraint in the supply and delivery of materials and equipment for reconstruction from outside Kashmir causing a delay in the recovery of education sector. This reinforces the insights drawn above that in order to speed community recovery, infrastructures must recover in ways that build the capacity of their dependent infrastructures. Consequently, the DDSM tool can be helpful in identifying the interactions that can potentially constrain or drive the capacity building of dependent infrastructure in the post-disaster period.

- Lack of effective governance was identified as one of the other important factors for the delay in reconstruction (Malik 2020). Lack of technical capacity for the execution of projects impacted planning and coordination of construction activities. This can be attributed to the fact that the workforce entering the local government is not very aware with the modern resilient construction practices (pre-requisite for World Bank funded projects) due to lower level of education and training available in the community. This impacted the institutional capacity of the government in the post-disaster period causing a delay in effective planning and mobilization of resources important for an efficient recovery planning (loop R2, Figure 16) (Malik 2020). The DDSM tool can help in understanding the feedback loops that may be already on negative growth trend, and therefore can be useful in identifying vulnerabilities that can potentially constrain the recovery efforts in the post-disaster period.



R2 – Governance Growth Loop

Figure 16 DDSM Based CLD of Governance for Education Recovery

In summary, the sectors identified for recovery in the state of Jammu and Kashmir are consistent with the critical infrastructure sectors identified in the DDSM. However, the interactions between sectors was not considered while allocating resources between sectors. For example, no resources were allocated for road transportation critical for the supply of materials and equipment required for reconstruction of infrastructure sectors. This caused delay in the execution of reconstruction projects. Consequently, the interdependencies between multiple sectors caused constraints in timely recovery of the community. The case study indicates that the community leaders had a good understanding of which infrastructures were critical to recovery but a poor understanding of how infrastructures interacted to drive or constrain recovery.

Discussion

The DDSM based community recovery model can be an effective tool in efficient allocation of resources for a resilient recovery. The tool can be used to identify the critical sectors for the recovery of community infrastructure sectors. The tool can also be used to identify interactions between different infrastructure sectors, to make sure that the recovery strategies are based on the interactions between sectors and to allocate resources to increase capacity in dependent sectors. Consequently, a guideline aimed at helping the recovery managers to develop the content of the recovery strategies is given below:

- Read the DDSM to contextualize the community infrastructure sectors and to verify the applicability of the model based on the context of disaster, reported damage, and other cultural and community specific contexts.
- Use this to identify the community-disaster-specific infrastructures that are critical for recovery. Check whether the sectors identified for recovery are consistent with the critical infrastructures important for community recovery in the DDSM.
- Use the DDSM and community-disaster information to identify and understand the interactions between critical sectors. Identify the critical interactions, i.e. those that drive or constrain recovery of dependent infrastructures.
- Allocate resources based on the criticality of infrastructures
- Allocate resources to critical interactions between the sectors, those that increase the capacity in the dependent sectors.

CHAPTER VI

CONCLUSIONS

Infrastructure Interdependencies can have significant impacts on the recovery of community sectors in the post-disaster period. Community leaders tasked with recovery planning are faced with a difficult challenge of deciding how to allocate the limited resources for an effective and an efficient recovery. Infrastructure interactions can potentially constrain and/or drive the recovery process of a community. The focus of this research was to identify the critical infrastructure systems and to understand how the interactions between these community sectors drives the recovery process. A 3-tier Hypothesis Descriptive Design Structure Matrix (DDSM) was developed to define and identify the connections (interactions) between community sectors. The Hypothesis DDSM was compared with a case-study DDSM to validate the reported interactions, based on which a final DDSM was developed with 16 infrastructure sectors to qualitatively describe the interdependencies between community sector elements.

DSM Modelling analysis revealed the critical infrastructures and the critical interactions that influence the recovery of a community. The following insights were drawn from the DSM model and could constitute the core elements of a normative approach to community recovery that could be used when developing recovery strategies for a resilient and speedy recovery in the post-disaster period:

1. The 5 most ‘critical’ infrastructure sectors based on their importance for community recovery are – Commerce, Governance, Power Distribution and Generation, Road Transportation, and Workforce Population. Restoration of critical infrastructures

services in the recovery period is essential for recovery of other infrastructure sectors in the community, irrespective of the reported damage and final performance metrics for recovery.

2. The primary focus in the recovery period should be on the restoration of infrastructure services that are required for the recovery of other infrastructures, even if they are not the metrics used to measure recovery performance.

3. To speed community recovery, infrastructures must recover in ways that build the capacity of their dependent infrastructures. Recovery managers should focus on restoration of infrastructure services that support recovery of dependent infrastructure.

4. Recovery planning for short-term and long-term recovery should reflect the differences between the two stages of recovery.

The DDSM can be a useful tool for emergency planners and recovery managers to understand the impact of infrastructure interdependencies in the post-disaster period and to develop strategies that consider these interactions for a speedy and resilient recovery. The DDSM tool is not intended to replace other resource allocation methodologies, which are conventionally based on the reported damage to infrastructure sectors, such as PDNA (GFDRR 2015). The tool is expected to compliment the use of proven methodologies and to provide a systematic and a structured approach to prioritize sequencing of resources and to analyze the impact of specific resource allocations to check if the recovery policies being implemented will have the required impact. Further, the tool can help in identifying the pre-disaster vulnerabilities that may impact recovery of infrastructure sectors in the post-disaster period, and therefore aid in developing policies that are aimed at building self-sustaining and resilient communities. The tool can also be used for disaster mitigation planning to identify the vulnerabilities in a community and to qualitatively describe the primary, secondary, and tertiary impacts of infrastructure service disruptions for resilient infrastructure investment decisions. Consequently, guidelines were developed for helping the emergency planning managers in the application of DDSM tool in a community.

The results and insights discussed above were validated by the case-study of Indian state of Jammu and Kashmir. However, in retrospect, the results of the research are limited by a few factors which also paves the way for future research. First, the Hypothesis was tested with only one case-study with specific disaster and cultural contexts. Future research can develop and validate the DDSM with more diverse case-studies across different contexts to build confidence in the model. Moreover, the DDSM is a binary DDSM and does not describe relative strength of dependencies. The model is useful in sequencing the resources but cannot be used to determine the quantity of resources required for each sector. Quantifying strengths of interactions by collecting data from various case-studies to determine the impact of specific sectoral recovery on the overall recovery of the community can be used to determine dominant loops and therefore high impact policies. Further, the model doesn't describe how to increase the capacity in the dependent infrastructure. External constraints not included in the model include quantity & flow of money, good will capital, social capital incentives etc. Also, the model does not include other factors that may impact recovery. For example, social sectors such as politics, gender equality, environment etc. have not been included in the model.

REFERENCES

Agarwal, S., T. Fulzele, and G. Aggarwal. 2014. Flood Recovery Management in Jammu And Kashmir: A Tool for Resiliene. New Delhi: *Asian Journal of Environment and Disaster Management*, 6(3), 215–229.

Amin, M. 2002. "Toward Secure and Resilient Interdependent Infrastructures." *Journal of Infrastructure Systems*, 8(3), 67-75.

Attary, N., J. Lindt, H. Mahmoud, and S. Smith. 2019. "Hindcasting Community-Level Damage to the Interdependent Buildings and Electric Power Network after the 2011 Joplin, Missouri, Tornado." *Natural Hazards Review*. doi.org/10.1061/(ASCE)NH.1527-6996.0000317

Cantrell, C.; Lewis, R. 2010. *Food System Infrastructure: Michigan Good Food Work Group Report*. C.S. Mott Group for Sustainable Food Systems at Michigan State University, Michigan.

Chang, S. 2003. "Evaluating Disaster Mitigations: Methodology for Urban Infrastructure Systems." *Natural Hazards Review*, 10.1061/(ASCE) 1527-6988 (2003), 186-196

Chang, S., T. McDaniels, J. Mikwoz, and K. Peterson. 2007. "Infrastructure Failure Interdependencies in Extreme Events: Power Outage Consequences in The 1998 Ice Storm." *Nat. Hazards* 41**,** 337–358 (2007).

Choi, J., N. Naderpajouh, D. Yu, and M. Hastak. 2019. "Capacity Building for an Infrastructure System in Case of Disaster Using the System's Associated Social and Technical Components." *Journal of Management in Engineering*, 35(4): 04019013

Disaster Risk Management. 2018. Overview of Disaster Risk Management Group. <https://www.worldbank.org/en/topic/disasterriskmanagement/overview#1> (March 16, 2019)

Eppinger, S., and T. Browning. 2012. *Design Structure Matrix Methods and Applications.* The MIT Press, Cambridge, Massachusetts.

Ford, D., and B. Keith. 2016. "A Dynamic Feedback Theory of Community Recovery from Shock Events: Testing the role of social capital." *System Dynamics Conference*, Delft, The Netherlands.

GFDRR. 2018. Aftershocks: Remodelling the past for a resilient future. <https://www.gfdrr.org/en/feature-story/aftershocks-remodeling-past-resilient-future> (March 16, 2019)

GFDRR. 2020. Building Regulations For Resilience In India. <https://www.gfdrr.org/en/feature-story/building-regulations-resilience-india> (Accessed March 16, 2019)

GFDRR. 2015. *Developing Disaster Recovery Frameworks - Sendai Conference version.* GFDRR, World Bank Group, Washington D.C.

GFDRR. 2018. "Overview of Global Facility for Disaster Risk and Recovery". <https://www.gfdrr.org/en> (March 16, 2019)

Golbeck, J. 2015. *Introduction to Social Media Investigation: A Hands on Approach*. Syngress, Elsevier, Waltham, MA.

GKNN. 2018. "JTFRP integrated with ERA to fast pace projects". Greater Kashmir, October 5.

IPCC. 2012. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.* IPCC Cambridge University Press, Cambridge, England.

Jammu and Tawi Flood Recovery Project. 2020. Project Development Objectives. <http://jtfrp.in/jehlum-tawi-flood-recovery-project/> (Accessed February 11, 2020)

Johnston, E. 2010. “Governance Infrastructure in 2020”. *Public Administration Review*, (70), 122 - 128.

Lindell, M. K., R. W. Perry, C. Prater, and W. C. Nicholson. 2006. *Fundamentals of Emergency Management*. FEMA Emergency Management Institute, Emmitsburg, Maryland.

Malik, S. 2020. “Govt to Speed Up Work on Jhelum - Tawi Flood Recovery Project”. *Greater Kashmir*, October 10.

McClurg, and C. Josiah. 2012. “Electricity Production and Distribution Infrastructure”. University of Iowa. <https://wiki.uiowa.edu/display/greenergy/Electricity+Production+and+Distribution+Infrastructure> (February 10, 2020)

Morgan, B. 2015. *QER Report: Energy Transmission, Storage, and Distribution Infrastructure.* Department of Energy, Washington D.C.

National Governors' Assosiation (NGA). 1979. *Comprehensive Emergency Management - A Governors' Guide.* Centre for Policy Research, Washington D.C.

Oh, E., A. Deshmukh, and M. Hastak. 2013. “Criticality Assessment of Lifeline Infrastructure for Enhancing Disaster Response.” *Nat. Hazards Review*, http://dx.doi.org/10.1061/(ASCE)NH.1527-6996.0000084

Olshansky, R. B., L. D. Hopkins, and L. A. & Johnson. 2012. “Disaster and recovery: Processes compressed in time”. *Natural Hazards Review*, 13(3) 173-178.

Ouyang, M. 2014. “Review on modeling and simulation of interdependent critical infrastructure systems”. *Reliability Engineering and System Safety*, (121) 43-60.

Peerzada, A. 2019. “Closure of National Highway causes problems in Kashmir Valley”. *The Hindu*, April 6.

Phelps, P., T. Akbar, J. Mercadante, M. Mortlock, M. Mung'oni, J. Fernandez, and K. Vatsa. 2017. *Process for Preparing Disaster Recovery Frameworks*. GDFRR, Washington, DC.

Phelps, P.; Akbar, T.; Mercadante. 2017. *Disaster Recovery Guidance Series: Housing and Settlements Recovery*. GFDRR, Washington D.C.

Phoenix, L.; Atkins, W. 2019. Sciences and Issues: Water Encyclopedia; Water Supply Infrastructure. <http://www.waterencyclopedia.com/Hy-La/Infrastructure-Water-Supply.html> (February 10, 2020)

Rand, K., and C. Fleming. 2019. “An Interdisciplinary review to develop guidelines for modeling population displacement as a function of infrastructure reconstruction decisions”. *Transportation Research Interdisciplinary Perspectives*, 3(2019) 100072.

Rinaldi, S., J. Peerenboom, and T. Kelly. 2001. "Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies". *IEEE Control Systems Magazine* 21 11-25.

Siddiqui, Z. 2019. "Kashmir Shutdown Caused Losses of More Than $1 Billion, Trade Body Says". *Reuters,* November 19.

Sterman, J. 2000. *Business Dynamics : Systems Thinking and Modeling for a Complex World.* McGraw Hill, Chennai, India.

Tabish, S., and S. Nabil. 2014. "Epic Tragedy: Jammu & Kashmir Floods: A Clarion Call." *Emergency Medicine, 5:1 (1000233).*

The World Bank. 2015. "Jhelum and Tawi Flood Recovery Project". <https://projects.worldbank.org/en/projects-operations/project-detail/P154990?lang=en&tab=procurement> (December 12, 2019).

The World Bank. 2018. *Disaster Recovery Guidance Series - Transport Sector Recovery: Opportunities to Build Resilience.* GFDRR, Washington D.C.

Wynn, D., Wyatt, D., Nair, S., & Clarkson, P. 2010. "An Introduction to the Cambridge Advanced Modeller." *Proceedings of MMEP 2010,* Cambridge, UK.

APPENDIX A

CASE-STUDY BACKGROUND AND INTERVIEW DETAILS

In September of 2014, the Indian state of Jammu and Kashmir experienced continuous spell of monsoon rains coupled with poor urban planning prior caused disastrous floods that impacted more than a million households and significant damage of agriculture, infrastructure sectors, including roads, communication, livelihood, public health, water supply, and fuel distribution was reported. In response, the Government of India requested World Bank for assistance to help recover the community. Jammu Tawi Flood Recovery Project (JTFRP) was sanctioned in 2015 by the World Bank to support the recovery and reconstruction efforts in the Indian state of Jammu and Kashmir, following the disastrous floods of 2014. With a total project cost of $250 million, the aim of the project is to strengthen the critical infrastructure in the state of Jammu and Kashmir (Jammu and Tawi Flood Recovery Project 2020). The local government body, Relief and rehabilitation department of Jammu and Kashmir, constituted a Project Steering Committee (PSC) for the overall strategic guidance and monitoring of JTFP, headed by the chief secretary, the administrative head of the state and comprising of associated government departments including, Housing and Urban Development Department, Public Health Engineering (PHE), Planning & Coordination, Irrigation and Flood Control. PSC oversees the Project Management Unit (PMU), which is directly responsible for the implementation of the recovery project. As of beginning of 2019, less than 10% of the total estimated expenditure had been achieved with many of the project components still under bidding stage (Malik 2020). In March 2019, the Project Steering Committee (PSC) of JTFRP ratified the proposal for extension of project deadline from June 2020 to December 2021, which was submitted to the Department of Economic Affairs, and the World Bank (Jammu and Tawi Flood Recovery Project 2020). Further details about the project can be found on the JTFRP website: http://jtfrp.in/.

To understand the constraints in the implementation and execution of JTFRP, in-person interviews were conducted with the representatives of Project Management Unit (PMU) to understand the constraints in timely execution of JTFRP. The aim of the interview was to understand how the recovery planning managers of PMU perceive the multisectoral community recovery in Kashmir. The constraints were casually mapped in the form of a Causal Loop Diagram to visualize the perceived community recovery (mental models) of Jammu and Kashmir. The following officials from PMU were interviewed:

1. Ms. Avni Lavasa, CEO JTFRP
2. Mr. Iftikhar Ahmad Hakim, Director Planning and Coordination
3. Mr. Iftikhar Ahmad Kakroo, Director Technical Projects
4. Mr. Tasawuf Amin, Chief Accounts Officer
5. Mr. Muhibul Hassan Mirza, Project Manager (Civil)

The medium of conversation for the Interviews was English, Urdu, and Kashmiri. The interviews were recorded with the permission of the PMU officials. Audio recordings of the interview in .mp3 format have been attached with this document.