# Impact of flood damaged critical infrastructure on communities and industries

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## Abstract

**Purpose** – The purpose of this paper is to assess the severity of social and economic impact of floods on the communities and industries with respect to their reliance on the flood impacted critical infrastructure. This paper illustrates a severity assessment tool to determine the reduced serviceability level of critical infrastructure after a disaster, how the change in serviceability impacts activities of associated communities and industries, and the resulting social and economic impact.

**Design/methodology/approach** – The results presented in this paper are a part of a larger research designed to develop a decision support system for disaster impact mitigation. This research evaluated the impact of floods as a natural hazard on infrastructure and the related industries and communities in terms of criticality and vulnerability of infrastructure and the severity of social and economic impact if the critical infrastructure were to be affected. The overall research focused on the 2008 Midwest floods for the required data collection (including the cities of Cedar Rapids, Iowa, Terre Haute, Indiana, St Louis, Missouri, Gulfport and Des Plaines, Illinois). Relevant data were collected through questionnaire surveys, personal interviews, and site visits.

**Findings** – The data collected through this research highlighted the importance of relationship between infrastructure, communities and industries with respect to technical, social and economic aspects. While the overall research resulted in a Decision Support System with three modules, to assess criticality, vulnerability and severity, this paper only elaborates the Severity Assessment Tool (SAT). Serviceability of an infrastructure plays an important role in post disaster recovery and response. Reduction in the serviceability of an infrastructure also affects the functionality of the activities that depend on the affected infrastructure resulting in social and economic impact. The tool presented in this paper determines the severity of social and economic impact by evaluating the reduction in the functionality of the affected activities.

**Originality/Value** – The model (SAT) presented in this paper determines the social and economic impact on communities and industries due to natural disaster when the serviceability of disaster impacted critical infrastructure is impaired. This tool can be effectively used by city managers as well as emergency planners for industries and communities in developing mitigation strategies based on the severity of social and economic impact due to the affected critical infrastructure. The results would also help the decision makers in arriving at more effective investment decisions to repair/rehabilitate certain critical infrastructure.

**Keywords** United States of America, Floods, Communities, Decision support systems, Disaster risk reduction, Social impact, Economic impact, Critical infrastructure

**Paper type** Research paper

## Introduction

The impact of natural disasters affects not only people and property but also the services and activities of industries and communities. Recently, the 2010 earthquake in Haiti caused major damage to Port-au-Prince, Jacmel, and other settlements in the region. The Haiti earthquake was neither unprecedented nor unusually large for the region and historically earthquakes have plagued the region, generally occurring in clusters. However, this earthquake was uniquely devastating because of Haiti's weak infrastructure and disruption of critical "lifeline services" after the earthquake including healthcare, transportation, telecommunications, water supply, utilities, and waste disposal (Brattberg and Sundelius, 2011).

Similarly, the 2008 Midwest floods in the USA are considered one of the worst floods that caused widespread damage in cities and towns in Iowa, Illinois, Missouri, and Indiana. While the massive floods of summer 2008 were triggered by heavy rains, one of the major reasons for the widespread damage was infrastructure failures, such as broken levees along the rivers, damage to bridges and roads, power plants, water and wastewater plants, etc. Therefore, identifying and fortifying vulnerable critical infrastructure ahead of time would significantly improve protection of communities and industrial activities.

This paper illustrates an approach to assess the severity of impact of flood damaged critical infrastructure on communities and industries with respect to social and economic aspects. For this research, severity has been defined as extent of impact on communities and industries in terms of social and economic aspects due to reduced serviceability level of infrastructure.

## Background and research

Failures of critical infrastructure are closely related to the conditions of critical infrastructure. The majority of infrastructure throughout the USA has been weakened due to age and deteriorated conditions making them vulnerable to natural disasters. The 2009 ASCE Report Card for infrastructure gives an average grade of D to US infrastructure signifying a need for urgent rehabilitation (American Society of Civil Engineers (ASCE), 2009).

The following section highlights some of the key results obtained by researchers with respect to technical, social, and economic impacts due to infrastructure failures during disasters.

## Technical impact

Leavitt and Kiefer (2006) have argued that the failure of multiple infrastructure systems escalated the impact of Hurricane Katrina in the city of New Orleans. Flood protection systems such as levee, canal systems, etc., were constructed to safeguard the city of New Orleans. However, these systems were poorly maintained and did not withstand the impact of the hurricane resulting in widespread damage to the city of New Orleans. Disasters and aging interdependent infrastructure will only lead to increase in disaster impact (Leavitt and Kiefer, 2006; Choate and Walter, 1981).

Infrastructure networks are highly integrated systems that sustain various activities and services of the communities and industries. Rinaldi *et al.* (2001) have proposed a framework that has six dimensions including, type of failure, infrastructure characteristics, state of operation, type of interdependencies, environment and coupling and response behavior to determine the interdependencies among infrastructure. However, they suggest that the defined interdependency among

infrastructure need metrics such as social and economic factors that can clearly explain the risk of failure. Osorio *et al.* (2007) have proposed a framework to assess the effect on the performance level of interdependent networks due to seismic disruption using various parameters related to the infrastructure and topology of the region.

## Economic impact

Chang *et al.* (2002) utilized a simulation approach to model the linkage between physical infrastructure system and the urban economy. They suggested an economic-loss methodology for water lifeline systems interrupted by an earthquake. Their methodology integrates engineering-damage models and an economic-loss model based on probabilistic evaluation. In addition, Chang (2003) proposed a framework for extended life cycle cost analysis to evaluate mitigation strategies for lifeline systems.

Tapsell *et al.* (2002) suggest that current research methods on assessing losses due to floods can estimate economic gains and losses but are unable to capture the degraded quality of life after floods. Burrus *et al.* (2002) and Yang *et al.* (2009) have proposed economic business models that measure the impact of disasters on businesses using parameters such as business interruption, equipment damage, building damage, workforce losses, loss of customers, etc. Okuyama (2007) has pointed out that direct loss such as physical damage to lifeline systems lead to disruption of economic functions of industries such as production, shipping, etc., that escalates regional economic loss.

## Social impact

Lindell and Prater (2003) illustrated the relationship of physical and social impacts of natural disasters on communities and emphasized the need for research to identify social and economic characteristics of communities such as type of commercial, industrial or agricultural business, etc. Cutter *et al.* (2003) have suggested that social vulnerabilities of communities are usually not considered as they are difficult to quantify. They developed a Social Vulnerability Index for the USA using 1990 census data for measuring social vulnerability of different counties against environmental hazards. With an increase in socioeconomic losses due to natural disasters more emphasis is being placed on improved risk management strategies that consider both social as well as monetary loss. Munich-Re (2007), a leading reinsurer, has developed a Social Flood Vulnerability Index consisting of three social characteristics and four financial-deprivation indicators to measure the impact of floods on communities.

## Emergency management tools

HAZUS-MH is a disaster response, GIS integrated tool developed by the Federal Emergency Management Agency that helps emergency officials to estimate social and economic losses on communities. HAZUS-MH is customized for estimating losses from earthquake, floods, and hurricanes. It provides information about physical damage to residential and commercial buildings, economic loss in terms of lost jobs, business interruptions, repair and reconstruction costs; and social impacts, including estimates of shelter requirements, displaced households, and population exposed to disasters. Furthermore, the model also helps in debris generation and shelter requirements (Scawthorn *et al.*, 2006). However, similar level of support is not available for an industry in a city to prepare against a potential disaster. Therefore, there is a need for a system that can complement support available through systems such as HAZUS and

be able to identify the state of critical infrastructure for quick recovery response such as evacuation, functioning, and sustenance of communities and industries as well as identify critical vulnerable infrastructure for long-term mitigation and rehabilitation strategies.

Mantell (2005) and Moteff *et al.* (2003) have pointed out that even though abundant research is available today to measure economic losses, most of the models are highly complex. Models need to be validated before they are applied to any disaster area. There is a need to develop input-output models that provide quick estimation of loss. This would greatly help the emergency management teams to develop proper mitigation strategies.

Oh *et al.* (2010) proposed a basic cell model to assess disaster impacts based on the relationship between damaged infrastructure, communities, and industries (Figure 1). These inter-relationships mainly focussed on technical issues, such as critical infrastructure affected by floods, level of inter-relationship, and industrial distribution in the affected areas.

The available literature does not offer a method to assess the severity of social and economic impact on the communities and industries with respect to their dependency on flood affected critical infrastructure. The research presented in this paper addresses this issue.

## Research approach

The basic cell model (Figure 1) was used to analyze the impact of 2008 Midwest floods. Part of the work conducted in this research was supported by the US National Science Foundation (NSF) through small grant for exploratory research (SGER): a short-term site investigation of 2008 Midwest floods. During the NSF SGER project, the research team focussed data collection with respect to critical infrastructure and the impact
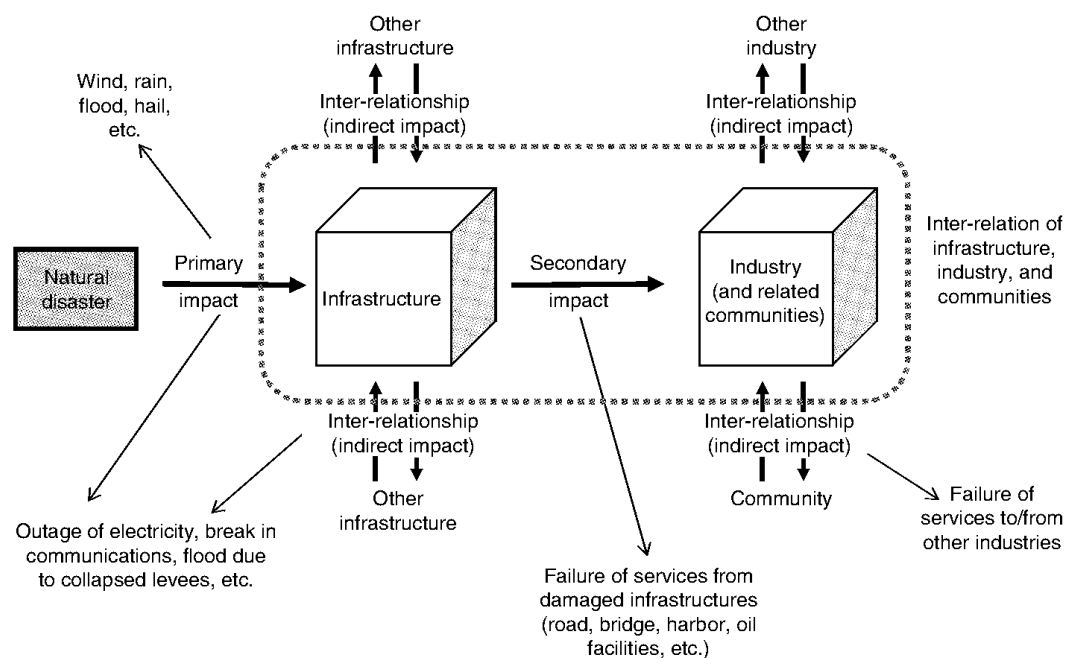
**Source:** Oh and Hastak (2008)

**Figure 1.**
Disaster impact
mechanism – basic cell
model

of floods on associated industries and communities through damaged critical infrastructure.

Three modes of data collection, i.e. interviews, site investigations, and questionnaire survey in terms of technical, social, and economic aspects were used:

(1) The site investigations were conducted for Cedar Rapids, Iowa; Terre Haute, Indiana; Gulfport, Illinois; Des Plaines, Illinois; and St Louis, Missouri and focussed on collecting information regarding flood affected infrastructure and their impact on daily activities of communities and industries.

(2) Interviews were conducted to collect technical, social, and economic data from affected communities, industrial experts as well as experts who were responsible to operate and maintain the critical infrastructure in the affected areas. A total of 15 interviews were conducted in Cedar Rapids (the city departments (7), industrial representatives (4), and community representatives (4)). Five interviews were conducted in Terre Haute, Gulfport, and St Louis.

(3) Survey questionnaire aimed at collecting social and economic data from residents in the affected areas. Data collected by survey questionnaires included demographical information (i.e. population, gender, employment, income, etc.), mental distress, physical damage faced by the communities, duration of service failure (i.e. hours, days, weeks, months, and years), impact of damaged infrastructure on daily activities, etc.

A total of 65 anonymous questionnaires were collected from affected communities in the City of Cedar Rapids, Iowa. Some of the results obtained from the questionnaire survey that are relevant to the focus of this paper are illustrated below to understand not only the impact of flooding but also the impact of damaged critical infrastructure on communities.

The results of the survey analysis indicated that residents of the devastated communities in Cedar Rapids were severely affected by the failure of infrastructure and disruption of service. The routine social and economic activities such as commuting, shopping, access to family and friends, etc., were affected by flood impacted infrastructure (Figure 2).

The results of the survey identified two types of infrastructure, i.e. electricity and roads, to have had the most economic impact on the affected communities (Figure 2). The social and economic impact is measured in terms of full and partial disruption of social and economic activities of a community or an industry as a result of the reduced
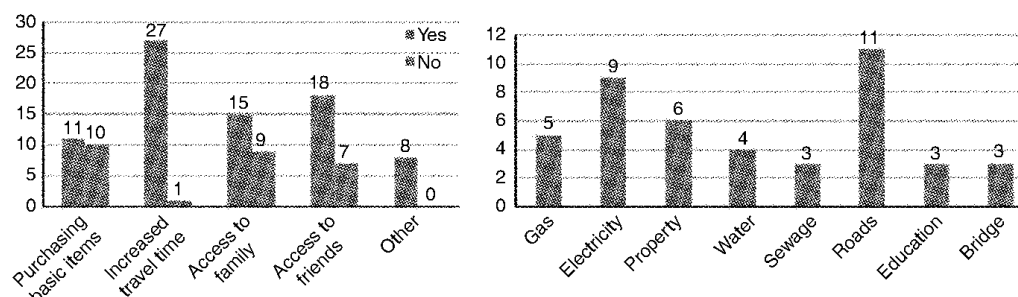


**Figure 2.**
Survey results from questionnaire
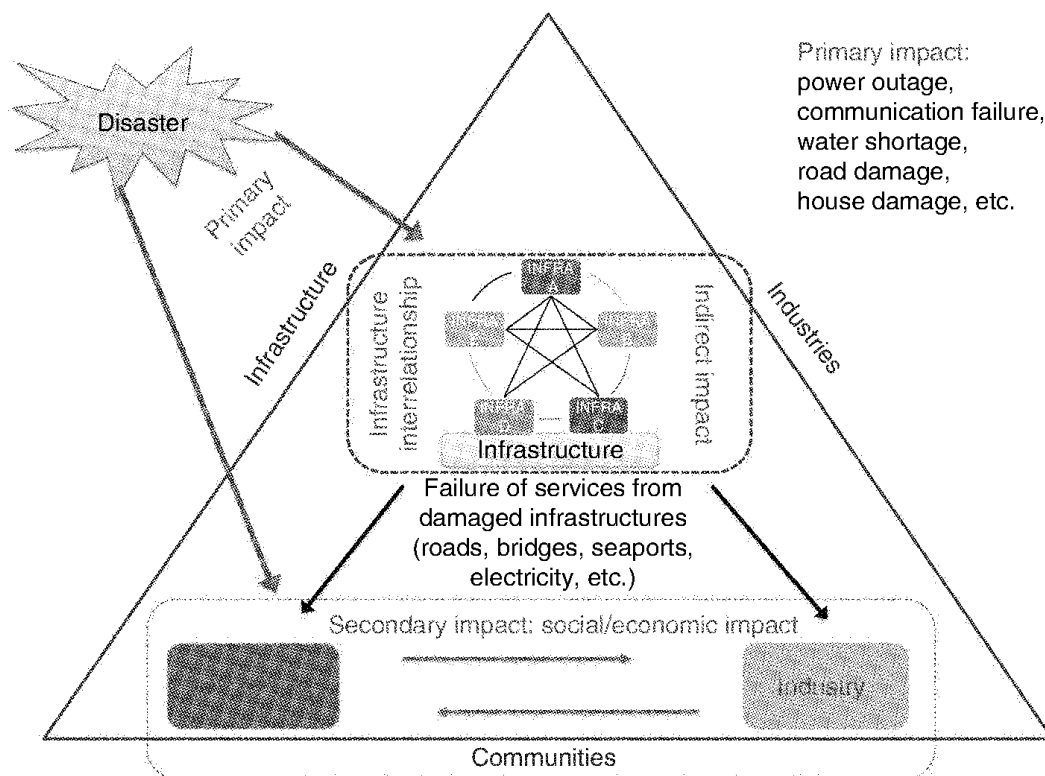
**Source:** Deshmukh (2010)

level of services offered by the supporting infrastructure affected due to the floods (Figure 3).

In this research, a conceptual framework was developed to understand the flow of impact as illustrated in Figure 3. Primary impact of a natural disaster can cause functional or structural damage to the infrastructure that could have a secondary impact on the social and economic activities supported by the affected infrastructure for the communities and industries resulting in a loss of benefits. For example, disruption of services offered by a road could result in loss of connectivity between a community and a school, or a church, or a market. Similarly, if electrical or water services were to be affected it might significantly influence the production capabilities of an industry.

## Framework of Disaster Impact Mitigation Support System (DIMSuS)

As mentioned earlier, the overall objective of this research was to develop DIMSuS for assessing the impact of floods on the infrastructure and the associated communities and industries in terms of technical, social, and economic aspects. This system enables city managers, emergency planners, as well as communities and industries to prepare better mitigation strategies. The framework consists of three metrics, i.e. criticality, vulnerability, and severity (Figure 4).
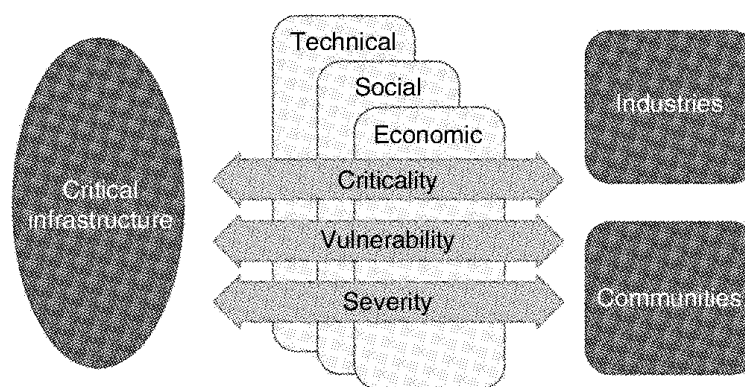
Criticality determines the relative importance of an infrastructure to a city, community, or an industry to perform their daily routine activities, i.e. activities related to the supply chain, transportation, or social activities. Vulnerability addresses the threats or real hazards to industries or communities in disaster situations and can vary



Primary impact:
power outage,
communication failure,
water shortage,
road damage,
house damage, etc.

**Figure 3.**
A conceptual framework
of disaster impact

**Source:** Deshmukh (2010)

**Figure 4.**
Metrics of inter-
relationships

**Source:** Oh *et al.* (2010)

according to the condition of infrastructure. Severity on the other hand relates to the extent of impact on communities and industries in terms of social and economic aspects due to the reduced serviceability level of infrastructure (Oh *et al.*, 2009).

The activities supported by the critical infrastructure are important for an industry to grow and to sustain their income stream and for communities to not only be economically stable but to be socially well equipped. Disasters such as floods, earthquakes, etc., lead to cascading failures of critical infrastructure, which affect relying activities that rely on those infrastructure. The social and economic activities are unable to perform efficiently resulting in losses and negative impacts on communities and industries.

This paper focusses on the severity assessment of flood damaged critical infrastructure on communities and industries. A severity assessment tool (SAT) is proposed to assess the social and economic impact on communities and industries due to reduced serviceability level of the flood damaged infrastructure (Figure 5).
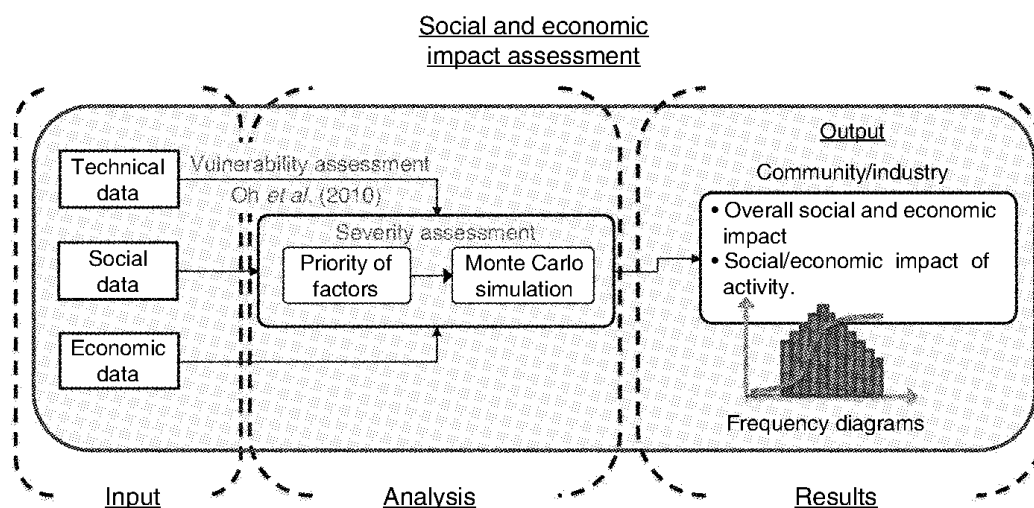


**Figure 5.**
Severity assessment tool
(SAT)

**Source:** Deshmukh (2010)

## SAT

SAT establishes the technical, social, and economic impacts due to the natural disaster (i.e. floods) under the differing vulnerability conditions of an infrastructure. The vulnerability of critical infrastructure against floods is based on the infrastructure health (i.e. state of good repair), its characteristics, and flood level. This implies that an infrastructure having a high vulnerability level is likely to achieve a low level of serviceability after a flood impact and vice versa.

Serviceability level of an infrastructure has been defined as the ability of an infrastructure to support activities of a community or industry. In this research, the as-is condition of an infrastructure in a predisaster situation is equated to 100 percent serviceability level of that infrastructure. For this analysis the set of activities and the supporting infrastructure are prioritized based on the social and economic contribution of activities and the assistance offered by an infrastructure in supporting the activities.

The prioritization of activities and infrastructure is performed using the Analytic Hierarchy Process (AHP). In AHP, a relative scale ranging from (1, 9) is used as shown in Table I (Saaty, 1982, 1990). The research team has developed a web-based AHP tool to facilitate this analysis.

In this research, assistance level of an infrastructure has been defined as assistance offered by an infrastructure for sustaining the activities of a community or an industry. The level of assistance is based on the attributes of an infrastructure, for example, in a preflood situation, a local road having a lower speed limit and several intersections will offer a lower assistance level when compared to an interstate highway even though both are able to provide 100 percent serviceability. Reduction in assistance level offered is proportional to the reduction in serviceability level of the infrastructure.

## Framework of SAT

Severity assessment is performed using a three phase methodological framework (Figure 6). The working of the framework is explained using a hypothetical situation where an "industry A" in a town is impacted by a flood event.

Consider that "industry A" is supported by infrastructure as shown in Figure 7, to perform its daily activities. Severity assessment is conducted for this hypothetical situation using the framework for SAT.

*Phase 1: identification of activities of communities and functions of industries*
In this phase, economic functions of industries and social and economic activities of communities are identified in the flood-affected area. Related critical infrastructure that supports the affected communities and industries are also identified.

The activities providing major economic contribution were identified for the industry. The activities identified for "industry A" are production, storage, shipping, and finance. These activities were prioritized based on their level of economic

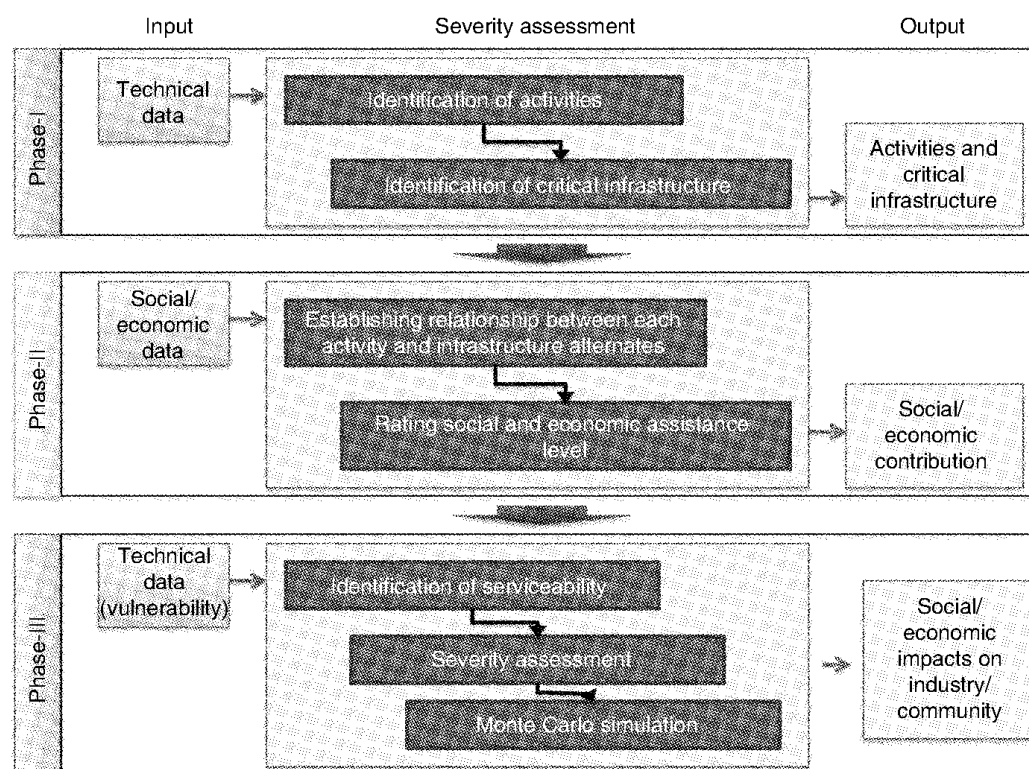| Scale | 1 | 2, 4, 6, and 8 | 3 | 5 | 7 | 9 |
| --- | --- | --- | --- | --- | --- | --- |
| Importance level | Equal importance | Intermediate response | Weak importance | Strong importance | Very strong importance | Absolute importance |

**Source:** Saaty (1982, 1990)

**Figure 6.**
Framework for severity
assessment tool (SAT)

**Source:** Deshmukh (2010)

contribution. In order to assess the social and economic contributions made by the activities, two methods could be used:

(1) *Direct input from users.* Direct input is useful when the users can provide the portion of social and economic contributions for their activities. For example, if the industry officials would have a breakdown of the economic contribution of identified activities, it would then be easy for prioritizing activities based on the level of economic contribution made.

(2) *Input using AHP for prioritization of activities based on their level of contribution through interviews.* In case, the interviewees are unable to directly establish the level of contribution, prioritization of activities can be performed using the AHP technique of pair-wise comparison. The AHP method also includes a procedure for consistency check to minimize errors due to biased ratings, overrated or underrated scores, etc.

The web-based AHP feature was used to prioritize the activities based on their level of contribution. For example, A2 "finance" when compared to A4 "commuting," is given a rating of 3 signifying weak importance of A2 over A4 (Table I and Figures 7 and 8).

Similarly, pair-wise comparison was performed for all the activities and the eigenvector corresponding to the maximum eigenvalue was computed to establish their prioritized level of economic contribution as shown in Table II.
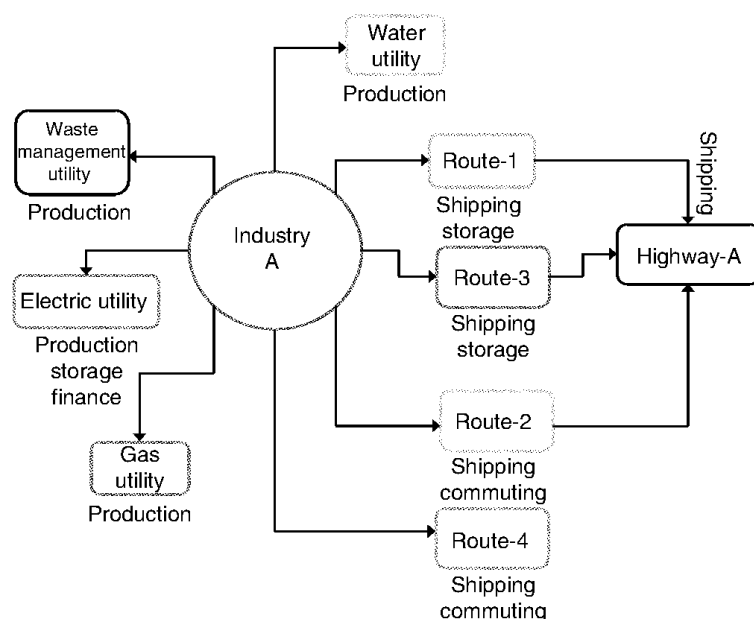
**Figure 7.**
Community and industry
relationship with critical
infrastructure



**Figure 8.**
Rating of activities using
web-based Analytic
Hierarchy Process feature
of severity assessment tool

| Activity | Economic contribution AHP scores (%) |
| --- | --- |
| Storage | 7.40 |
| Finance | 25.50 |
| Production | 40.60 |
| Commuting | 8.60 |
| Shipping | 17.90 |

**Table II.**
Economic contribution
for each activity

*Phase 2: rating the relationships between infrastructure, communities, and industries*
As shown in Figure 7, the activities of "industry A" are supported by infrastructure such as Route-1, Route-2, water utility, electric utility, waste management utility, etc. It was observed that:

• Infrastructure alternates were available for activities shipping and commuting, for example, commuting can be performed using either Route-2 or Route-4 (Figure 7).

• Electric utility, water utility, waste management utility, and gas utility did not have any alternates to support depending activities.

The procedure for establishing the relationship between infrastructure and the activities of "industry A" is explained through activity "shipping." Shipping can be performed through four infrastructure alternates (Figure 9):

(1) Option-1: Route-1 + Highway A

(2) Option-2: Route-2 + Highway A

(3) Option-3: Route-3 + Highway A

(4) Option-4: Route-4

In a predisaster situation, each infrastructure alternate is capable of supporting shipping but at a different assistance level. As discussed earlier, assistance level of an infrastructure has been defined as assistance offered by an infrastructure for sustaining an activity of a community and/or an industry.

*Rating social and economic assistance level*
Activity "shipping" is supported by Route-1, Route-2, Route-3, and Route-4, where Route-1, Route-2, and Route-3 connect to Highway-A, while Route-4 independently supports shipping. However, the economic assistance provided by each route would be different; for example, Route-1 might be an interstate highway whereas Route-2 might be a less maintained state road.

Using AHP, all infrastructure alternates are prioritized based on the level of economic assistance offered to support activity "shipping." The infrastructure alternates are rated for their assistance offered to a specific activity and are normalized with respect to the best score. For example, as shown in Table III, Option-3 (49 percent) was ranked as the best option, therefore the normalized level of assistance offered by
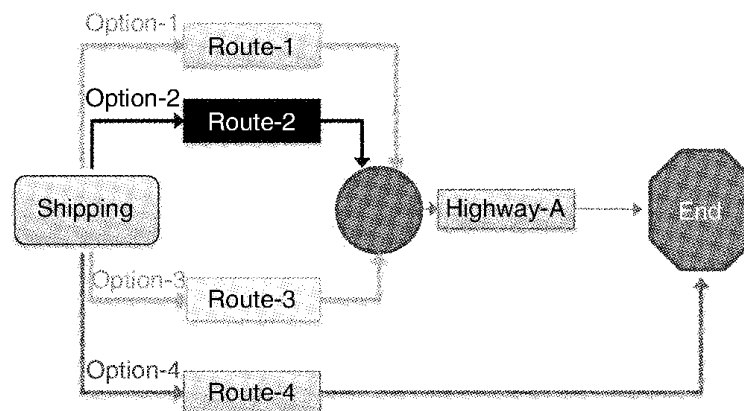


**Figure 9.**
Infrastructure options for activity "shipping"

Option-2 is determined to be 42 percent by dividing its AHP score, i.e. 25 percent by the best score, i.e. 49 percent.

Thus, in predisaster situation, the assistance level of Option-3 acts as a benchmark for comparison of assistance of infrastructure alternates (Table III). This also establishes that the assistance offered by Option-3 was the best among all the options.

*Phase 3: serviceability assessment*
The serviceability level of an infrastructure for supporting an activity is considered as 100 percent during the predisaster situation. This also establishes a benchmark for comparing the drop in serviceability level during and after a disaster.

Moreover, it is considered that the serviceability level of an infrastructure is directly proportional to the social and economic assistance offered to support an activity. For example, the serviceability level of 100 percent for Option-1 in the predisaster situation is proportional to 21 percent economic assistance offered by Option-1 for the activity "shipping." Any drop in the serviceability level would then proportionally affect the feasible economic assistance in the postdisaster situation that Option-1 would be able to offer (Figure 10).

| Infrastructure | Assistance level AHP scores (%) | Normalized level of assistance (%) |
| --- | --- | --- |
| Option-1 | 11 | 21 |
| Option-2 | 25 | 42 |
| Option-3 | 49 | 100 |
| Option-4 | 15 | 71 |

Table III.
Normalized level of assistance for infrastructure alternates
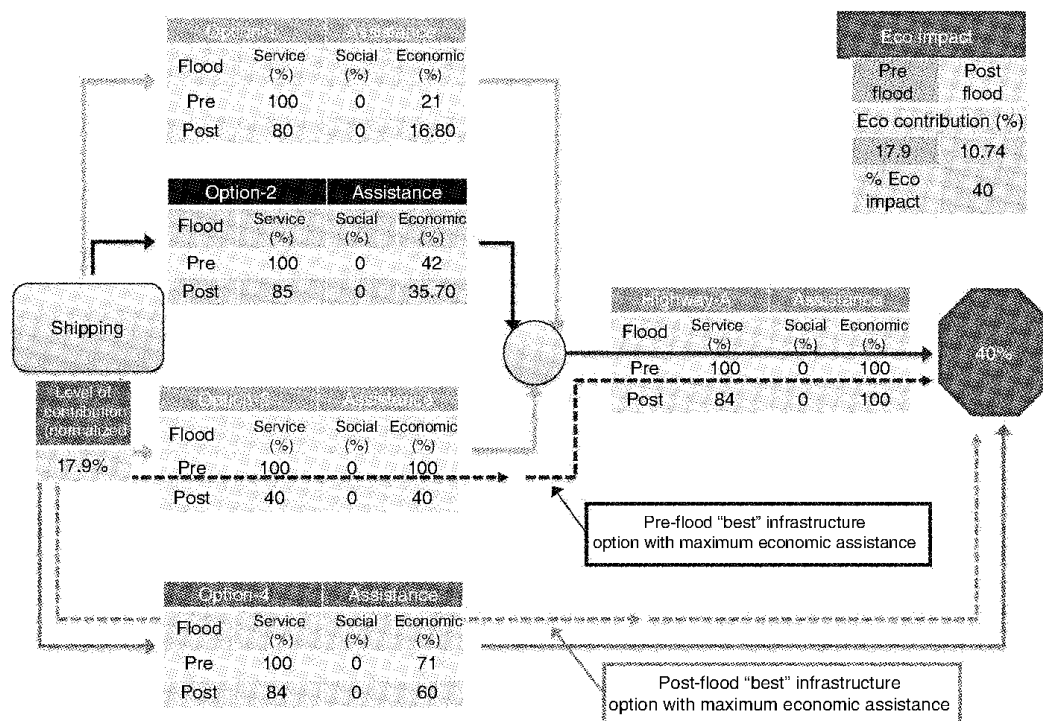


Figure 10.
Sample impact assessment

Therefore, the infrastructure offering the highest economic assistance to support activity "shipping" will be the best infrastructure in a preflood situation among the infrastructure options available. In the example shown in Figure 10, Option-3 provides 100 percent economic assistance (normalized level of assistance, refer to Table III). Thus, when Option-3 is used for supporting shipping, it can be expected that shipping will be able to generate 17.9 percent economic contribution to the industry (refer to Table II and Figure 10).

*Severity assessment*
In a flood situation, it is quite possible that a critical infrastructure gets damaged and as a result of which its level of serviceability is also reduced. This reduction in serviceability directly influences the economic contribution expected from the activities of "industry A."

For instance, in preflood situation, the serviceability level of Option-1 is 100 percent and it offers 21 percent assistance level to sustain activity shipping (Table III). In postflood situation, the serviceability level of Option-1 reduces to 80 percent due to flood impacts which in turn reduces the assistance level to 16.8 percent, i.e. $21 \times 80$ percent $= 16.80$ percent (Figure 10).

Thus, it is likely that the infrastructure providing the maximum economic assistance in preflood situation would be unable to provide the same level of economic assistance in postflood situation due to reduction in their respective serviceability level.

In case of "industry A", Option-4 offers the highest assistance level, i.e. 60 percent, which becomes the "best" infrastructure option in postflood situation (Figure 10). This reduction in assistance level influences the economic contribution offered by the activity shipping.

Thus, in postflood situation, the activity "shipping" when performed using Option-4, which offers the highest economic assistance, i.e. 60 percent can provide 10.74 percent ($17.9 \times 60$ percent $= 10.74$ percent) economic contribution (Figure 10).

The reduction in economic contribution due to reduced level of serviceability for critical infrastructure is considered as economic impact for the activity. The economic impact on activity "shipping" is calculated as 40 percent, i.e. $(17.9-10.74$ percent$)/17.9$ percent $= 40$ percent due to reduction in serviceability level of critical infrastructure. Similarly, the economic impact for other activities such as production, storage, etc., can be evaluated.

*Simulation of results*
The social and economic impact on communities and industries will vary according to the changing level of serviceability of associated infrastructure and the resulting impact on the level of assistance offered. It is difficult to obtain the serviceability level of infrastructure in postdisaster situation since it is likely to change during and after a flood situation. Therefore, Monte Carlo simulation technique will be helpful to generate potential results over a large range, i.e. 0-100 percent of serviceability level of critical infrastructure.

The changing level of serviceability is obtained as a randomly generated value from a uniform distribution. Monte Carlo simulation technique is helpful in generating results in case of sparse and missing data (Simpson *et al.*, 2005). Monte Carlo simulation was performed 1,000 times, each cycle providing a unique level of serviceability for the related critical infrastructure. The maximum assistance level obtained from the infrastructure alternate was used for assessing the respective

impact. Based on this simulation, a cumulative distribution curve was prepared (Figure 11). Simulation results of economic impact, the cumulative distribution function, indicates, for example that there is 54 percent probability that activity shipping would have a 51.60 percent or less economic impact due to reduced level of serviceability of related critical infrastructure. Figure 12 shows a conceptual virtual map of severity assessment for industry A with respect to various activities.

## Introduction to case study: Oakhill Jackson community, Cedar Rapids, Iowa
Cedar Rapids is the second largest city in Iowa and lies on the banks of the Cedar River. The city experienced major flooding during the 2008 Midwest floods and many industries and residential neighborhoods were completely inundated in water, which led to displacement of population, closure of local businesses, and huge property and
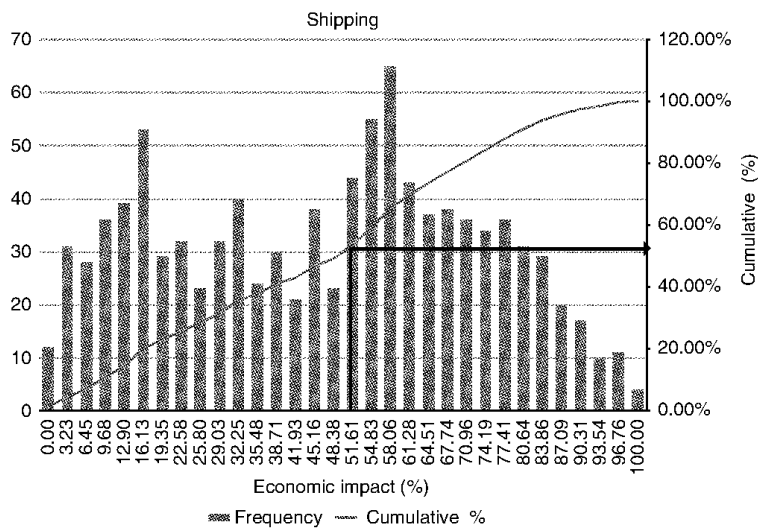


Figure 11.
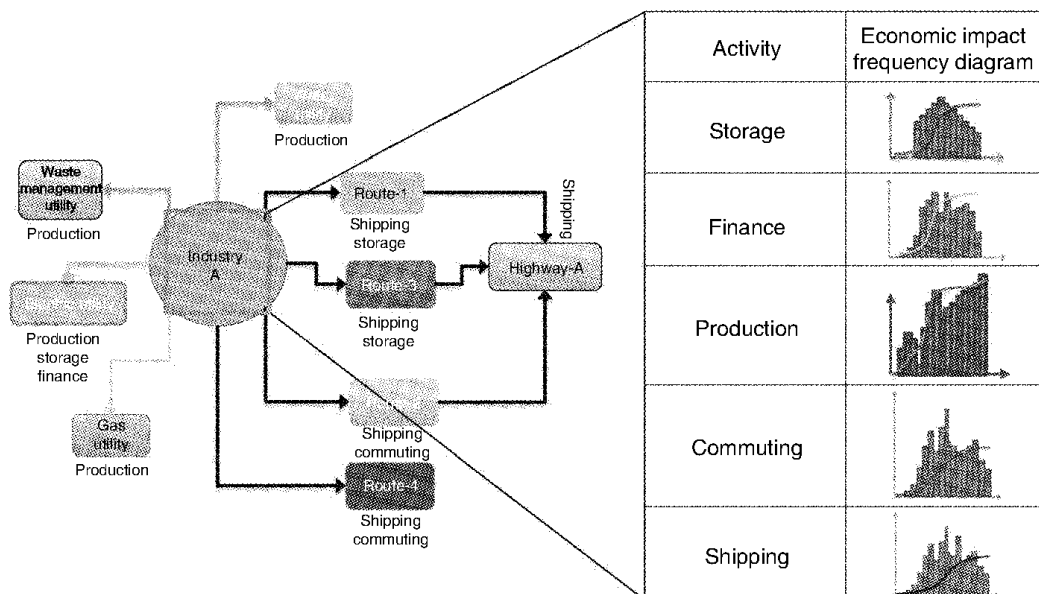Simulation result of economic impact for shipping



Figure 12.
Conceptual virtual map of severity assessment of industry A

personal losses. The impact was escalated due to the failure of critical infrastructure in the geographical location.

Severity assessment was performed to assess the social and economic impact on Oakhill Jackson neighborhood, Cedar Rapids, Iowa, which was completely destroyed during the 2008 Midwest floods.

The three phase methodological framework of SAT was used to assess the social and economic impact on the Oakhill Jackson community due to flood damaged infrastructure as explained in the following paragraphs.

*Phase 1: identification of activities of communities and functions of industries*
Major activities of the community that contribute both socially and economically were identified through interview with the community leader. The identified activities were commuting, access to livelihood, shopping, access to medical services, and access to local business. These activities were prioritized for social and economic contribution. The interviewee provided direct input for establishing the relative social and economic contribution of each activity (Table IV).

The social and economic contribution of the activities were separately normalized, for example, the normalized social contribution for activity commuting was determined to be 15.63 percent, i.e. is 50/320 percent = 15.63 percent (Table IV).

*Phase 2: establishing relationships between activity and related critical infrastructure*
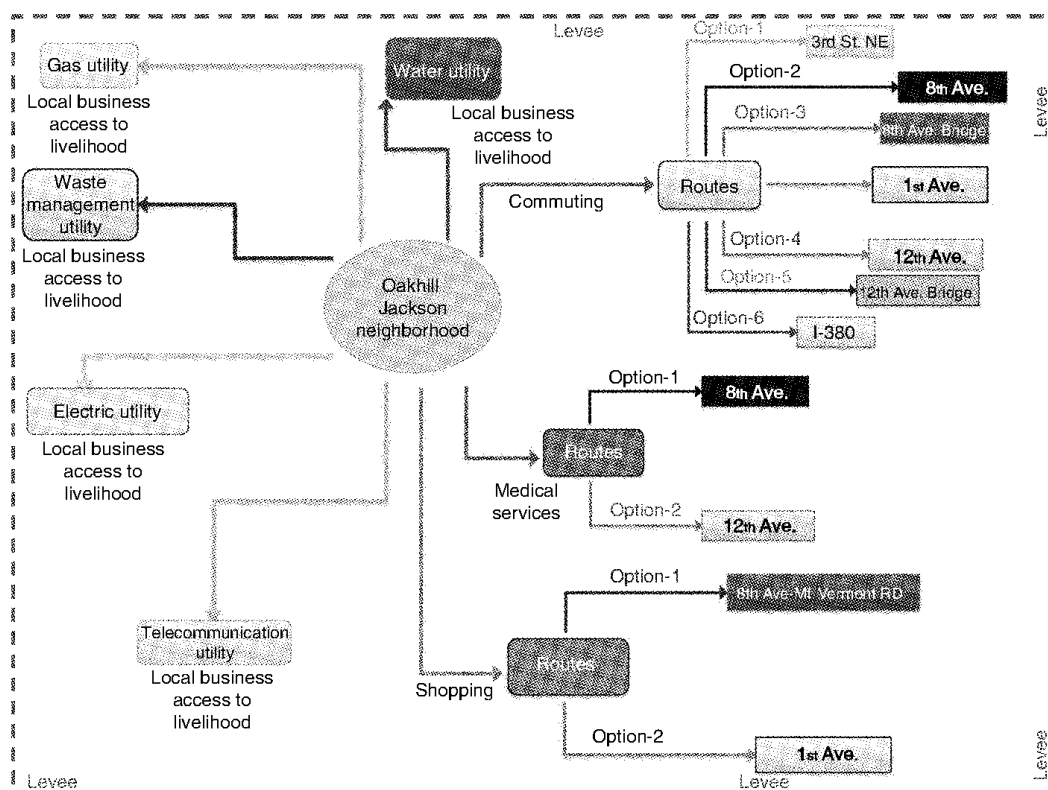The critical infrastructure supporting major activities of Oakhill Jackson community were identified through the interview (Figure 13). As shown in Figure 13, medical services, commuting, and shopping are supported by various routes. Oakhill Jackson community is protected by the levee system. Levee is a critical infrastructure that helps sustain not only the community but also the nearby infrastructure. During the 2008 Midwest floods, water overflowed the levee, which impacted the adjacent infrastructure resulting in loss of their serviceability.

*Phase 3: identification of serviceability of infrastructure and severity assessment*
As discussed earlier, the serviceability level of infrastructure in predisaster situation is considered to be 100 percent. The subsequent phases of the SAT are explained through the inter-relationship existing between infrastructure and activity "local business". Activity "local business" requires electric utility, gas utility, waste management utility, and water utility at the same time (Figure 14). In a preflood situation, with 100 percent

| Activity | Social contribution | Social contribution (normalized score %) | Economic contribution | Economic contribution (normalized score %) |
| --- | --- | --- | --- | --- |
| Commuting | 0.50 | 15.63 | 0.50 | 27.78 |
| Local business | 0.50 | 15.63 | 0.50 | 27.78 |
| Shopping | 0.80 | 25.00 | 0.20 | 11.11 |
| Medical services | 0.50 | 15.60 | 0.50 | 27.78 |
| Access to livelihood | 0.90 | 28.13 | 0.10 | 5.56 |
| Total contribution | 320% | | 180% | |
| Maximum contribution | 500% | | 500% | |

**Table IV.**
Prioritization of activities of Oakhill Jackson

**Source:** Deshmukh (2010)

| Electricity | | Assistance | |
|---|---|---|---|
| Flood | Service (%) | Social | Economic |
| Pre | 100 | 0 | 100 |
| Post | 25 | 0 | 25 |

| Water supply | | Assistance | |
|---|---|---|---|
| Flood | Service (%) | Social | Economic |
| Pre | 100 | 0 | 100 |
| Post | 85 | 0 | 85 |

| Sewer | | Assistance | |
|---|---|---|---|
| Flood | Service (%) | Social | Economic |
| Pre | 100 | 0 | 100 |
| Post | 70 | 0 | 70 |

| Gas | | Assistance | |
|---|---|---|---|
| Flood | Service (%) | Social | Economic |
| Pre | 100 | 0 | 100 |
| Post | 50 | 0 | 50 |

| Telecommunication | | Assistance | |
|---|---|---|---|
| Flood | Service (%) | Social | Economic |
| Pre | 100 | 0 | 100 |
| Post | 80 | 0 | 80 |

Local business

Level of economic contribution (normalized)
27.78%

Electricity

Water supply

Sewer

Gas

Telecommunication

Post flood "worst" infrastructure with minimum economic assistance

% Economic impact

75%

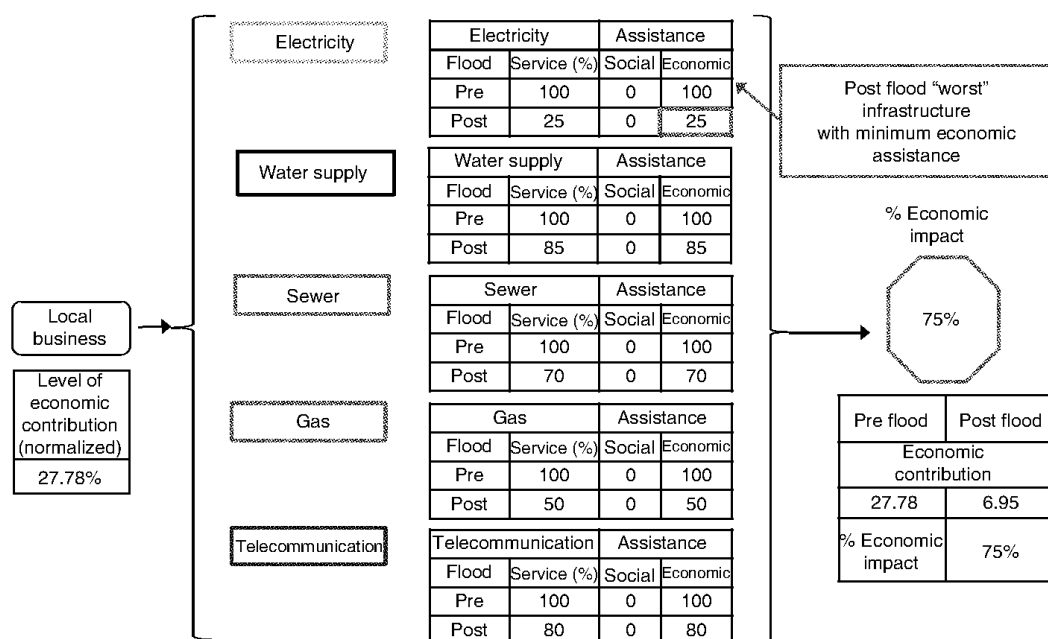| Pre flood | Post flood |
|---|---|
| Economic contribution | |
| 27.78 | 6.95 |
| % Economic impact | 75% |

**Figure 14.**
Economic impact
assessment for activity
"local business"

serviceability level, each infrastructure offers a 100 percent assistance level for supporting related activity. Thus, in preflood situation, activity local business receives a 100 percent assistance level from related critical infrastructure and can provide the expected 27.78 percent economic contribution to the community (Table IV and Figure 14).

However, in postflood situation, the serviceability level of critical infrastructure is likely to get reduced due to flood impact. As shown in Figure 14, the reduced serviceability level of the critical infrastructure further reduces the economic assistance level of the activity in postflood situation.

Even though, other related infrastructure had a higher serviceability level (Figure 14), the serviceability level of electric utility, which is the minimum governed the economic contribution of activity "local business." Electric utility was considered as the "worst" infrastructure providing the minimum serviceability level to support the activity "local business." This led to a reduction in the contribution offered by the activity. Here, the serviceability level of electric utility is considered to reduce to 25 percent in postflood situation. Thus, the economic contribution of activity "local business" reduced to 6.95 percent, i.e. 27.78 × 25 percent = 6.95 percent. The economic impact on local business was calculated to be 75 percent, i.e. (27.78–6.95 percent)/27.78 percent = 75 percent.

As explained earlier, the serviceability level of related infrastructure was simulated using Monte Carlo simulation technique and social and economic impacts for each activity were obtained. Figure 15 illustrates the social impact on each activity due to changing level of serviceability of related critical infrastructure.

## Discussion of results and conclusion

This research illustrated two types of inter-relationships between infrastructure and activities:

(1) *Infrastructure alternates available for supporting activities.* Activities such as commuting and shopping can be performed through many infrastructure alternates (Figure 13). As explained earlier, in predisaster situation, each infrastructure alternative can provide service to depending activity but with a different assistance level. The infrastructure which provides the maximum assistance level in predisaster situation is the "best" option. Similarly, in postdisaster situation, the infrastructure providing the maximum assistance level is considered the "best" option available.

(2) *Absence of infrastructure alternates available for supporting activities.* Electricity, water supply, sewer, gas, telecommunications, and postal services did not have any alternates. Moreover, activities that depend on these infrastructure such as access to livelihood and businesses require them at the same time. If one of the infrastructure (without any alternate) fail, i.e. the serviceability level reduces to 0 percent, the activity will not be able to perform.

## Development of better mitigation strategies using SAT

The results obtained from severity assessment will help the city managers, emergency response personnel from communities, and industries to strategically prepare mitigation strategies in pre- and postdisaster situation in the following ways:

• Identification and prioritization of activities based on their level of social and economic contribution.
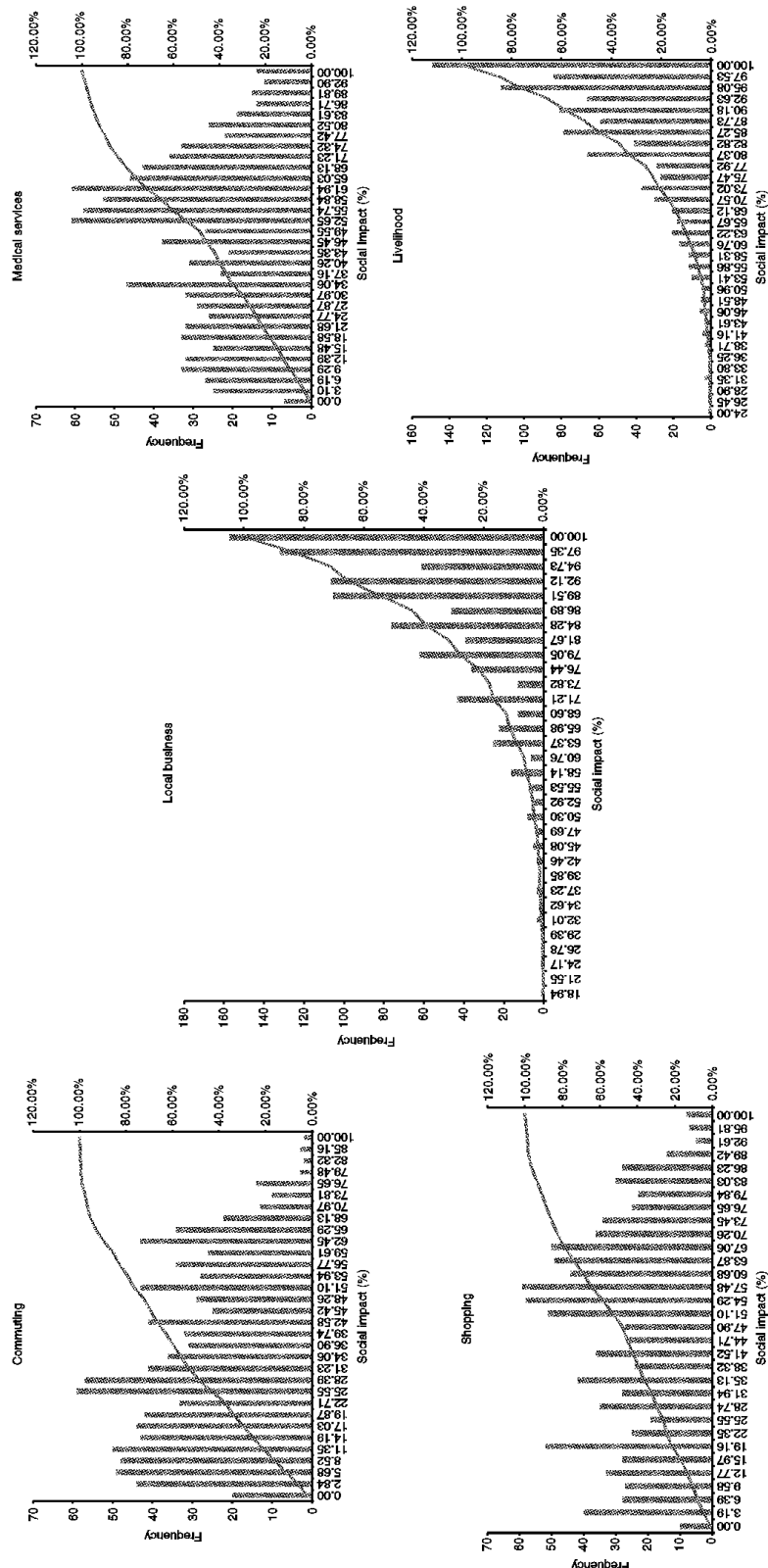
- Allocation of resources to fully utilize and safeguard critical infrastructure in the preparedness stage as well as during a disaster thereby significantly reducing the technical, social, and economic impact.

- Criticality and severity assessment will help the communities and industries to identify some of their most important social and economic activities and the associated critical infrastructure. This will not only help in restoring livelihoods of victims but also create and restore jobs after disaster. This is only possible if the most critical infrastructure are rehabilitated and restored immediately after disasters.

Severity assessment will help industry, community, and city mangers to develop strategies for minimizing impact based on the serviceability level of critical infrastructure. Infrastructure alternates having better serviceability level can be identified in postflood situation which will play an important role in not only minimizing impacts by sustaining associated activities and functions but also help in delivery of aid and relief to disaster stricken areas quickly. The analysis is based on the inter-relationship between activities of communities and industries and critical infrastructure. The SAT was designed and developed based on the ephemeral data collected during this research with respect to technical, social, and economic aspects. Furthermore, the research emphasizes that activities are an important factor in assessing social and economic impacts.

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