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A Decision Framework for Pre-disaster Risk Mitigation Planning of Interdependent Infrastructure Systems

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ABSTRACT: Implementing strategic pre-disaster risk mitigation plan to improve the resilience of the interdependent civil infrastructure systems is essential for enhancing the social security and economic prosperity of a community. Majority of the existing infrastructure risk mitigation studies or projects focus on a single infrastructure system. However, improving the resilience of a single infrastructure system under disasters may not be the most efficient and effective way to mitigate the loss and enhance the overall community disaster resilience. This is because the proper functioning of the facilities in an infrastructure system usually depends on the normal operation of facilities in several other infrastructure systems for product input and information sharing. This article presents a risk-informed decision framework which could support the pre-disaster risk mitigation planning of several interdependent infrastructure systems. The characteristics of the Interdependent Infrastructure Risk Mitigation (IIRM) decision problem, such as objective, decision makers, constraints, etc., are clearly identified. A four-stage decision framework to solve the IIRM problem is also presented. One novel contribution of this decision framework is that it considers the pre-decision processing step, which prioritizes the infrastructure facilities in different systems for risk mitigation investment and intervention. The application of the proposed IIRM decision framework is illustrated using a case study on pre-disaster risk mitigation planning for the interdependent critical infrastructure systems in Jamaica. The outcome of the IIRM problem is useful for the decision makers to allocate limited risk mitigation budget or resources to the most critical infrastructure facilities in different systems to achieve greater community disaster resilience.

KEYWORDS: community disaster resilience; decision-making; interdependency; infrastructure risk mitigation planning; priority assessment.

1. INTRODUCTION

Natural disasters such as flooding, hurricanes and earthquakes affects millions of people and cause huge socioeconomic disruptions each year. Although the occurrence of natural disasters is unavoidable, their impact to the socioeconomic system could be reduced through implementing actions on mitigating the risk and improving the resilience of the critical civil infrastructure systems.

Numerous studies and projects exist on pre-disaster risk mitigation planning of infrastructure systems (Asian Development Bank, 2013 & 2017; Briceño-Garmendia et al, 2015; Jayawardena et al, 2016; Asian Infrastructure Investment Bank, 2017; Dos Anjos Ribeiro Cordeiro et al, 2017; Shibuya & Bradshaw, 2018). However, they tend to focus on a single infrastructure system. Improving the resilience of one single infrastructure system under disasters may not be the most efficient and effective way to reduce the loss and enhance the overall community disaster resilience due to the interdependencies among different infrastructure systems. The service interruptions of one infrastructure system could set off a cascading failure across its interconnected systems after the disaster, which could pose both direct and indirect socioeconomic impacts. If an infrastructure risk mitigation plan only focuses on improving the performance of one single infrastructure system under disasters, the impact of the failure of its dependent systems to the operation of this system would be left out, which will result in inefficient and ineffective risk mitigation efforts.

This paper presents a four-stage decision framework to solve the Interdependent Infrastructure Risk Mitigation (IIRM) problem. The framework could guide the decision makers allocating limited risk mitigation budget or resources to the most critical facilities in several interdependent infrastructure systems to achieve greater community disaster resilience. One innovation of this decision framework is that it identifies the facilities that deserve priority consideration for risk mitigation investment and intervention in the pre-decision processing stage. This step is important since it could make the resulted risk mitigation plan better targeted.

The characteristics of the IIRM decision problem are first identified in section 2, followed by the four-stage decision framework to solve the IIRM problem. The framework is illustrated using a case study on pre-disaster risk mitigation planning of Jamaica infrastructure systems in section 3. Finally, the contributions and significance of this work are summarized.

2. INTERDEPENDENT INFRASTRUCTURE RISK MITIGATION PLANNING

The Interdependent Infrastructure Risk Mitigation (IIRM) problem is introduced in this section. The characteristics of the IIRM decision problem, including objective, applicable phase, decision makers and constraints are summarized in Table 1.

Table 1: Characteristics of the IIRM problem.

Decision objective	Reduce the socioeconomic impact when future hazard occurs through improving the resilience of the interdependent infrastructure network
Applicable phase	Pre-disaster risk mitigation planning phase
Decision makers	• Multi-national development banks (e.g. the World Bank, Asian Infrastructure Investment Bank, Inter-American Development Bank, etc.) • Emergency management departments or agencies (e.g. Department of Homeland Security, FEMA, etc.) • Disaster risk management related organizations (e.g. UNISDR, etc.) • Utility companies (e.g. Memphis Light, Gas and Water Division, CenterPoint Energy, etc.) and other multi-infrastructure system owners
Constraints	Financial budget, available resources, time

Each stage of the IIRM decision framework is explained below.

Step 1. Decision Problem Definition

The first stage of the IIRM decision framework is to define the decision problem, in which the decision objective, decision makers, constraints, study region, and hazard types are specified. Any assumptions and relevant information needed to define the situation of the IIRM problem should also be clarified in this step.

Step 2. Pre-decision Processing: Priority Assessment

Due to limited available budget, resources or time, risk mitigation practices cannot be carried out on every facility in the network. Therefore, identifying some critical facilities in the interdependent infrastructure network that deserve priority consideration for risk mitigation investment or intervention is especially important. The task of the pre-decision processing stage is to prioritize the facilities in different interdependent infrastructure systems for risk mitigation investment and intervention. There are three steps to assess the priority of individual infrastructure facilities, as shown in Figure 1.

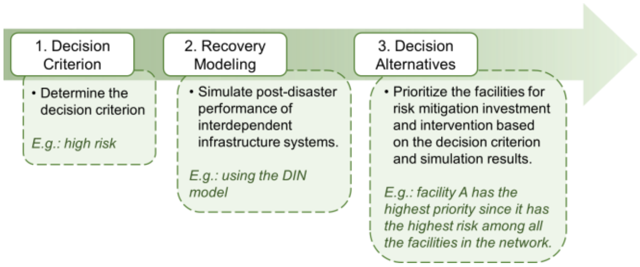


Figure 1: Three-step priority assessment framework.

In the first step, the decision criterion used to prioritize the infrastructure facilities is determined. Some example criteria include: high vulnerability, high risk, long recovery time, etc. Next, the damage and recovery of the interdependent infrastructure network under specified hazards are simulated using a recovery model with considering the dependency relationships among infrastructure facilities. Finally, the facilities are prioritized based on the decision criterion and recovery simulation results.

Step 3. Decision Alternatives

In this stage, several alternative risk mitigation plans focusing on the critical facilities that have the priority need for risk mitigation investment and intervention are proposed.

Step 4. Decision Analysis

The task of the decision analysis stage is to analyze each alternative risk mitigation plan proposed in the previous step. Different decision analysis tools and techniques, such as decision matrix, cost-benefit analysis, trade-off analysis, T-chart analysis, Pareto analysis, SWOT analysis, PEST analysis, etc. (Hall et al, 2008; Kureshi & Asghar, 2015; Caramela 2017), can be utilized in this stage.

In the end, the optimal pre-disaster risk mitigation plan(s) would be selected based on the decision analysis results.

3. RISK MITIGATION PLANNING FOR JAMAICA INFRASTRUCTURE SYSTEMS

The proposed IIRM decision framework is illustrated using a case study on risk mitigation planning for Jamaica infrastructure systems in this section.

3.1. Decision Problem Definition

The key components to define the case study IIRM problem are summarized in Table 2.

Table 2: Key components of the case study IIRM problem.

Decision objective	Reduce the service disruptions to hospitals and schools when future hurricane hazard occurs by improving the resilience of electric power, potable water and transportation (road) systems
Decision maker	The World Bank
Study region	Jamaica
Constraints	Financial budget, available resources, time

Jamaica is the fourth largest and fourth most populous island country situated in the Caribbean Sea. The geographic location and unique topography make Jamaica one of the most exposed countries in the world to natural disasters, especially hurricane hazard. The damage severity and loss of Jamaica after a hazard is also quite high due to its isolated location and socio-economic structure. Some critical infrastructure facilities in Jamaica are located in high-risk areas, not built to high standards and poorly maintained, which exacerbate their vulnerability to natural disasters and highlight the importance to implement a strategic pre-disaster risk mitigation plan to enhance the infrastructure and overall community resilience. The electric power, potable water and transportation systems considered in this case study are the three most critical infrastructure systems in Jamaica since they are essential for the public health, social welfare and the proper functioning of most other infrastructure systems. The hospitals and schools are considered as critical end-user facilities in this study since they are important for the medical care and sheltering of people after the disaster. The number of individual types of the critical facilities modeled in the network and their geospatial locations are shown in Table 3 and Figure 2, respectively.

Table 3: The number of individual types of the critical facilities modeled in the network.

System	Facility Type	Number
Power	Power plant	10
	Substation	25
	Transmission line	26
	Distribution line	1079
	Transmission tower	Every 320 m along transmission lines
	Distribution poles	Every 40 m along distribution lines
Water	Pumping station	11
	Treatment station	43
	Storage tank	140
	Water pipeline	1214
Transportation	Road segment	836
End-user	Hospital	50
	School	971
Total nodes		**1250**
Total links		**2309**

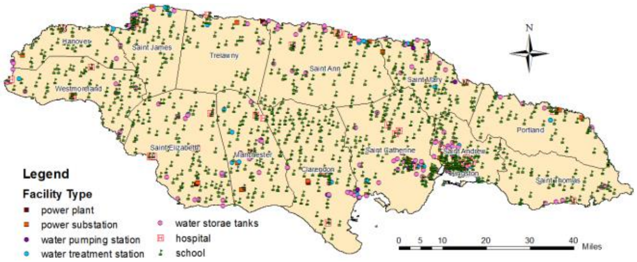


Figure 2: The geospatial locations of the critical facilities in Jamaica.

Eighteen scenario hurricane hazards with different intensities, landfall locations and approaching angles were simulated using Georgiou's model (Georgiou et al, 1984). The hurricane rainfall rate and inundation depth on the roads were modeled using Tuleya's method (Tuleya et al, 2007).

3.2. Pre-decision Processing

The facilities that have priority need for risk mitigation investment and interventions are identified using the priority assessment framework shown in Figure 1.

3.2.1. Decision criterion

In this study, *risk* is used as the criterion to prioritize the facilities, which means that the facilities with higher risk deserve priority consideration for pre-disaster risk mitigation investment. Here, the risk of an infrastructure facility is defined as the vulnerability (proportional to the probability of damage) of the facility and the impact if it is damaged.

3.2.2. Recovery modeling

The Dynamic Integrated Network (DIN) model proposed by He and Cha (2018a, b, 2019) was used to simulate the damage and recovery of the interdependent infrastructure network following scenario hurricane hazards. The DIN model was chosen since it could simulate the damage and recovery of individual facilities, systems and the integrated network over time considering the dependencies at the facility level and account for the uncertainties. The general framework of the DIN model and some example outputs are shown in Figure 3.

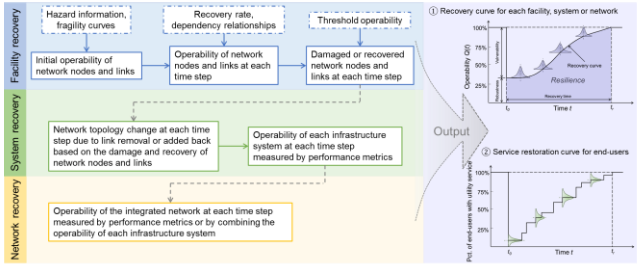


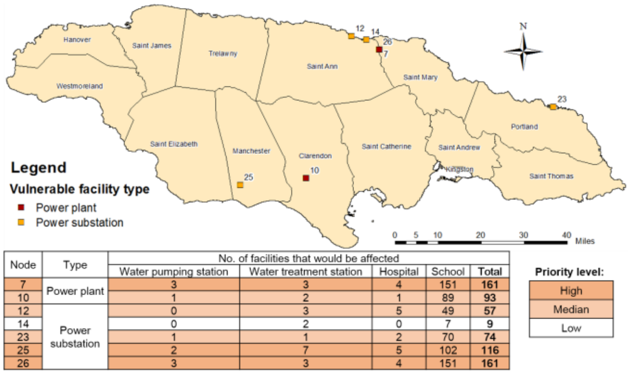
Figure 3: The general framework of the DIN model.

3.2.3. Priority assessment

Based on the DIN simulation results, the critical facilities in each infrastructure system that have priority need for risk mitigation interventions were identified as below.

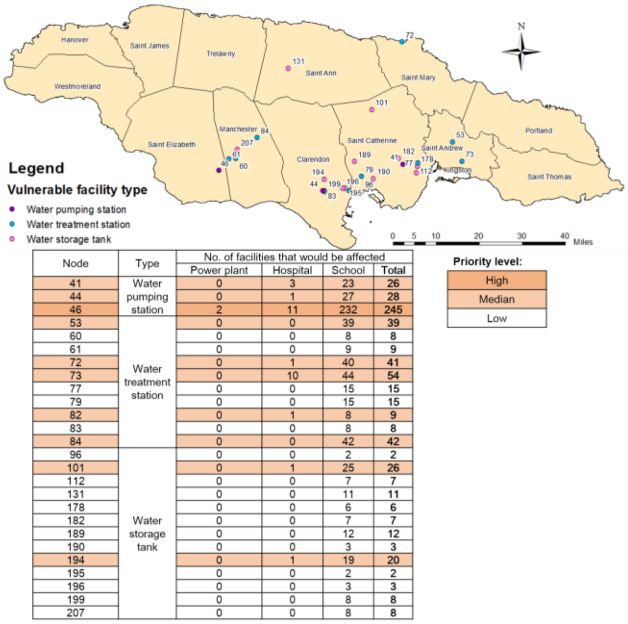
3.2.3.1. Power and water systems

The vulnerability of the power and water facilities in Jamaica was measured by the mean initial inoperability under all scenario hurricane hazards calculated using the DIN model. The power and water facilities that are both vulnerable and serve large number of end-users have high risk, thus deserve priority consideration for risk mitigation investment or intervention. The high risk power and water facilities in Jamaica are shown in Figure 4 and Figure 5, respectively. Taking water pumping station No. 46 for example, it has the highest priority among all water system facilities since it is both highly likely to be damaged after the disaster and its damage would affect the normal operation of the largest number of end-users and two power plants in Jamaica.



Node	Type	No. of facilities that would be affected				
		Water pumping station	Water treatment station	Hospital	School	Total
7	Power plant	3	3	4	151	161
10		1	2	1	89	93
12	Power substation	0	3	5	49	57
14		0	2	0	7	9
23		1	1	2	70	74
25		2	7	5	102	116
26		3	3	4	151	161

Figure 4: The high risk power facilities.

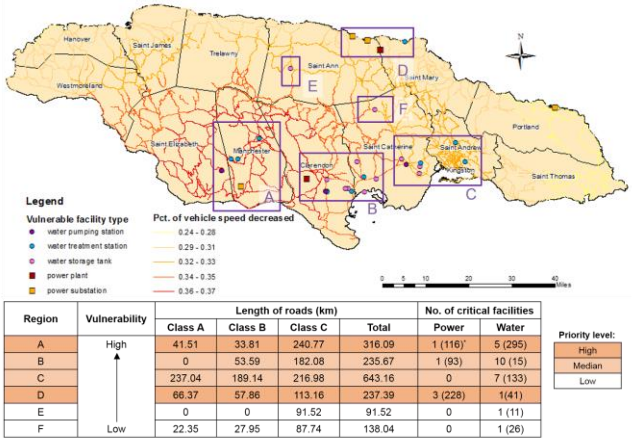


Node	Type	No. of facilities that would be affected			
		Power plant	Hospital	School	Total
41	Water pumping station	0	3	23	26
44		0	1	27	28
46		2	11	232	245
53	Water treatment station	0	0	39	39
60		0	0	8	8
61		0	0	9	9
72		0	1	40	41
73		0	10	44	54
77		0	0	15	15
79		0	0	15	15
82		0	1	8	9
83		0	0	8	8
84		0	0	42	42
96	Water storage tank	0	0	2	2
101		0	1	25	26
112		0	0	7	7
131		0	0	11	11
178		0	0	6	6
182		0	0	7	7
189		0	0	12	12
190		0	0	3	3
194		0	1	19	20
195		0	0	2	2
196		0	0	3	3
199		0	0	8	8
207		0	0	8	8

Figure 5: The high risk water facilities.

3.2.3.2. *Transportation system*

The vulnerability of the roads in Jamaica was measured by the percentage of the vehicle speed decrease on the roads due to the hurricane rainfall induced flooding, which was calculated using Pregnolato's model (Pregnolato et al, 2017). In this study, the road segments that are both vulnerable and leading to lots of vulnerable power and water system facilities are said to deserve priority consideration for risk mitigation investment. This is because the vulnerable power and water facilities are highly likely damaged after the disaster and require repair. If the repair teams couldn't reach the damaged facility sites promptly due to the damaged or blocked road network, the utility service restoration to lots of critical end-users would be delayed, thus aggravating the social disruptions.



Region	Vulnerability	Length of roads (km)				No. of critical facilities	
		Class A	Class B	Class C	Total	Power	Water
A	High	41.51	33.81	240.77	316.09	1 (116)*	5 (295)
B	↑	0	53.59	182.08	235.67	1 (93)	10 (15)
C		237.04	189.14	216.98	643.16	0	7 (133)
D		66.37	57.86	113.16	237.39	3 (228)	1(41)
E		0	0	91.52	91.52	0	1 (11)
F	Low	22.35	27.95	87.74	138.04	0	1 (26)

Note: The value in parenthesis shows the number of end-users (e.g. hospitals and schools) whose service would be affected if the power or water system facilities are not recovered quickly due to the damage of the road network.

Figure 6: The high risk road segments.

Figure 6 highlights six regions of the road network in Jamaica which are of high risk and require priority consideration for investment or intervention. Taking the road segments in region A for example, they have the highest priority since they are most vulnerable and their failure would cause the most severe socioeconomic consequences compare to the roads in other regions. The service restoration work to one vulnerable power facility which serves 116 critical end-users, and five vulnerable water facilities which serve 295 critical end-users would be affected if the roads in region A fails.

3.3. *Decision Alternatives*

Some common practices during the pre-disaster infrastructure risk mitigation phase includes: (i) frequent maintenance of the existing facilities; (ii) upgrading or retrofitting the existing facilities or (iii) building new facilities. Based on these common practices, example risk mitigation strategies for the power, water and transportation systems are proposed and listed in Table 4. Although these strategies can be applied to any facilities in a system, the high risk facilities identified in section 3.2.3 deserve priority consideration for investment if only limited budget is available. If possible, the budget is better distributed among facilities in different infrastructure systems, rather than investing in one single infrastructure system. This is because the normal operation of an end-user or infrastructure facility usually depends on the functioning of several infrastructure systems. It's only when all the infrastructure systems serving a facility function properly after the disaster could the facility be used to realize its intended function.

Table 4: Risk mitigation strategies for power, water and transportation systems.

System	Risk mitigation strategies
Power & water systems	• Having backup batteries, backup power generators and/or backup water tanks at the critical facility sites; • Increasing the frequency of maintenance; • Replacing the aged components in facilities; • Increasing the elevation of the critical components of the power and water facilities.
Road network	• Improving the capacity of the drainage system along the road network to ensure that more rain water could be drained away; • Building more greenbelts along the roads so that more rain water could be penetrated into the ground; • Increasing the frequency of maintenance such as cleaning drainages and reinforcing slopes; • Adding more lanes or building new roads to increase the redundancy of the road network; • Upgrading the roads such as raising the grade of the roads, switching from unpaved to paved roads or increasing the elevation of the roads; • Implementing traffic rules to make sure the most important vehicles can go through while others take an alternative route during the post-disaster recovery phase.

The risk mitigation plans could be proposed by implementing risk mitigation strategies in Table 4 to different set of critical facilities identified in section 3.2.3. In this study, four alternative risk mitigation plans were proposed and the corresponding improvements of the infrastructure performance were assumed for illustration purpose, which are summarized in Table 5.

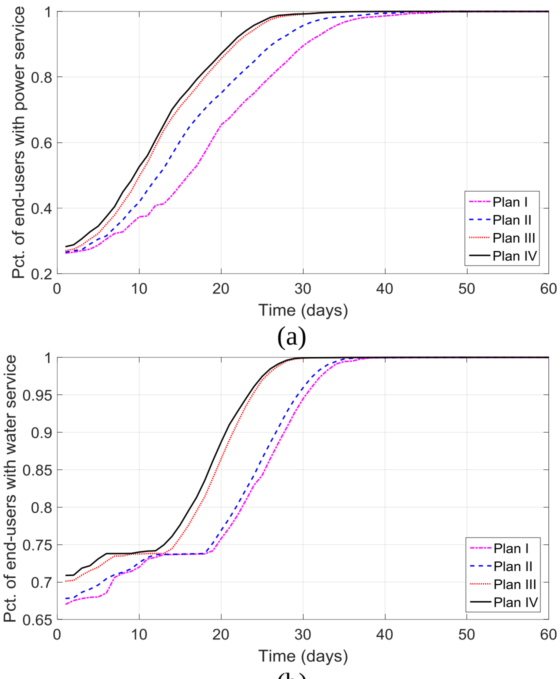
Table 5: Alternative risk mitigation plans.

Plan	Infrastructure performance improvement
I	• The vehicle speed on the following road segments is increased by 30%: region A~D in Figure 6.
II	• The vulnerability of the following high-risk power and water facilities is decreased by 20%: node 7, 25, 26 in Figure 4, & node 46 in Figure 5. • The vehicle speed on the following road segments is increased by 20%: region A and D in Figure 6.
III	• The vulnerability of the following high-risk power and water facilities is decreased by 20%: node 7, 10, 12, 23, 25, 26 in Figure 4, & node 41, 44, 46, 53, 72, 73, 82, 84, 101, 194 in Figure 5. • The vehicle speed on the following road segments is increased by 20%: region A~D in Figure 6.
IV	• The vulnerability of the following high-risk power and water facilities is decreased by 40%: node 7, 10, 12, 23, 25, 26 in Figure 4, & node 41, 44, 46, 53, 72, 73, 82, 84, 101, 194 in Figure 5. • The vehicle speed on the following road segments is increased by 40%: region A~D in Figure 6.

3.4. Decision Analysis

The risk mitigation benefit from each plan was analyzed for decision-making. For the analysis, the service restoration curve for all critical end-user facilities (hospitals and schools) in Jamaica under each scenario hurricane hazard for each risk mitigation plan was simulated using the DIN model. The mean power and water service restoration curves under all simulated scenario hurricane hazards for each risk mitigation plan are shown in Figure 7 (a) and (b), respectively.

Two resilience-based metrics to evaluate the performance of the infrastructure network following a disruptive event are used to compare different risk mitigation plans in this study. The first metric is the total service restoration time (TSRT), T_s, after which the service to all the end-users are restored. It measures the efficiency of the infrastructure service restoration. The second metric is the skewness of the service restoration trajectory (SSRT), S_s, defined as the centroid of the area below the service restoration curve given a certain time period. The skewness of the service restoration trajectory could capture the effectiveness of the service restoration work, with lower value representing more effective restoration. The TSRT and SSRT for power and water systems under each alternative risk mitigation plan are summarized in Table 6. The SSRT was calculated using a time period of 60 days in this study.



(a)

(b)

Figure 7: Mean (a) power and (b) water service restoration curves for each risk mitigation plan.

Table 6: The TSRT (in days) and SSRT (in days) for power and water systems under each plan.

Plan	Power system		Water system	
	T_s	S_s	T_s	S_s
I	57	36.30	54	32.89
II	53	35.46	53	32.80
III	45	34.72	45	32.44
IV	43	34.50	43	32.37

The results in Figure 7 and Table 6 indicate that in general, the efficiency and effectiveness of the utility service restoration improve from plan I to plan IV as the investment increases. By comparing plan I and II, it can be learned that allocating the risk mitigation budget and efforts on several infrastructure systems (as is in plan II) could yield better result compared to focusing on a single infrastructure system (as is in plan I). If cost-benefit analysis was used, the decision makers need to carefully weigh the cost and benefit of each risk mitigation plan before selecting the optimal one. For example, if plan IV cost far more than plan III, then the decision makers need to decide whether the 2 days' reduce of the utility service restoration time deserves this amount of extra budget spend. If not, then plan III could be the optimal risk mitigation plan in this case.

4. CONCLUSIONS

This paper presents the four-stage Interdependent Infrastructure Risk Mitigation (IIRM) decision framework to support the pre-disaster infrastructure risk mitigation planning with considering the interdependencies between different infrastructure systems. One important step of solving the IIRM problem is to identify the critical facilities in each infrastructure system which deserve priority consideration for investment and intervention. The solution of the IIRM problem is useful for the decision makers from multinational development banks, emergency management departments or agencies, disaster risk management related organizations, utility companies and other multi-infrastructure owners to allocate limited available risk mitigation budget or resources on the most critical facilities in several infrastructure systems in order to achieve greater community disaster resilience.

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