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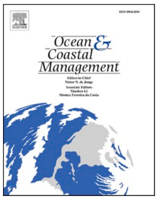

Risk-based transportation infrastructure management: An integrated framework and case study in USVI against coastal flood and sea level rise

Ruohui Zhang [a], Junyan Dai [b], Yun Bai [a,c,e,*], Daniel Barone [c], Lauren Hill-Beaton [d]

[a] Intelligent Transportation Thrust, Systems Hub, The Hong Kong University of Science and Technology, Guangzhou, 511458, China
[b] Department of Civil and Environmental Engineering, Rutgers University, Piscataway, NJ, 08854, USA
[c] Center for Advanced Infrastructure and Transportation, Rutgers University, Piscataway, NJ, 08854, USA
[d] Department of Atmospheric Science, Rutgers University, Piscataway, NJ, 08854, USA
[e] Guangdong Provincial Key Lab of Integrated Communication, Sensing and Computation for Ubiquitous Internet of Things, at Hong Kong University of Science and Technology, Guangzhou, China

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ABSTRACT

This paper develops a comprehensive analytical framework for evaluating transportation infrastructure investment strategies for asset management considering the impacts of extreme natural hazards and climate change. We integrate quantitative risk analysis (RA) and economic impact analysis (EIA) into a comprehensive assessment of the benefits and costs of infrastructure maintenance, rehabilitation and reconstruction (MR&R) strategies. Moving beyond this, the framework explicitly incorporates the bidirectional feedback/impact between asset management (in normal situations) and risk management (against extreme conditions). To illustrate the application, the framework is applied to a case study on the roadway transportation system of the United States Virgin Islands (USVI), considering flood risk and the impact of future sea level rise. The case study demonstrates quantitative measures of the agency and user cost, risk, and other economic and environmental impacts under different MR&R, coastal flood and sea level rise scenarios. The framework supports high-level decision-making that transportation agencies face such as project prioritization, resilience planning, and capital planning. It can be generalized to analyze different types of infrastructure and natural hazards.

1. Introduction

Many transportation agencies need help determining the optimal level of investment in the infrastructure assets they manage. Given limited funding and the challenging fiscal situation, agencies are, more than ever, in need of a clear and concise methodology to guide them as they prioritize assets and decide which assets are most in need of repairs and updates. They hope to understand the economic value of current suboptimal versus adequate maintenance for both normal operating conditions and against extreme natural hazards and climate change.

Transportation or Infrastructure Asset Management (TIAM) is a strategic approach that transportation managers have increasingly utilized to oversee and logically plan infrastructure at a system level, to maintain and improve all assets efficiently for the public over a long-term basis. Taking advantage of technologically enhanced data collection and analysis abilities, state and local agencies have sought to integrate an increasing amount of information in planning for the uncertainty and variability of future extreme events on assets (Office of Asset Management (OAM, 1999). Besides, with the increasing frequency and severity of climate change, the U.S. Federal Highway Administration (FHWA), many State Departments of Transportation (DOTs) and agencies recognized that effective risk-based TIAM and strategies to maintain resilient transportation systems are even more critical for system managers (OAM, 2013).

However, a more standardized, quantitative approach to risk-based assessment and analysis at a system level is still needed to mesh with existing TIAM frameworks and decision-making processes. According to OAM (2013), the state of practice planning of MR&R intervention activities under TIAM has primarily been drawn from past performance and experience. They neglect the significant impacts of severe events that are “erratic, abrupt, and almost always negative”, as well as their increasing likelihood and consequences due to climate change (McBean,

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* Corresponding author. No. 1 Duxue Road, Nansha District, Guangzhou, Guangdong Province, PR China.
E-mail addresses: rzhang856@connect.hkust-gz.edu.cn (R. Zhang), junyan.dai@rutgers.edu (J. Dai), yunbai@ust.hk, yunbai@hkust-gz.edu.cn (Y. Bai), daniel.barone@rutgers.edu (D. Barone), lkh38@scarletmail.rutgers.edu (L. Hill-Beaton).

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2004). Risk consequences can also contribute to the faster-than-expected deterioration of assets across systems (Jr, 2018; Mallick et al., 2017), meaning long-term models and planning alterations are necessary.

Specifically, we noted the connection between infrastructure conditions and the unexpected damage caused in extreme situations, corresponding to the bi-directional feedback/impacts between regular asset management and risk management. On the one hand, the pre-disaster condition of an infrastructure asset, maintained regularly in normal operating situations, is a critical factor affecting its vulnerability in extreme natural events and thus its risk values (e.g., Lei et al., 2022; Rowan et al., 2014). On the other hand, damages caused by natural disasters in extreme situations not only impact the post-disaster condition but also further accelerate the deterioration of the infrastructure if not treated timely. A good example of this bi-directional effect is the roadway pavement infrastructure under flood or storm surge hazards (Zhang et al., 2021). The surface condition of highway pavement (e.g., cracking and potholing) will allow faster and greater infiltration of rainfall and runoff to enter the base and subbase course, making the structure more vulnerable in these naturally hazardous events and possibly leading to entire structure failure (Jr, 2018), especially for the coastal infrastructures which are suffering from sea level rise and storm (Ahmed et al., 2021; Audère and Robin, 2021). Furthermore, the post-disaster damages caused by flooding, which are often underneath and invisible, will compromise the capacity to support the high-laden truck traffic and further worsen the surface condition (Jr, 2018). Therefore, proactive maintenance may enhance resilience against extreme threats, while risk reduction investments can keep recovery and continued maintenance costs low in normal conditions.

Most existing literature on TIAM methodologies focuses on either maintenance planning in a normal situation or risk/resilience planning in extreme events. So far, there is no standardized methodology integrating the two aspects into a single framework. **More importantly, to the best of the authors' knowledge, no existing studies considered the interconnection between the two types of analysis simultaneously and quantitatively, for instance, the bi-directional impacts between maintenance planning and risk planning**.

Therefore, in this study, we develop a comprehensive methodological framework that incorporates MR&R decision-making into risk analysis for transportation infrastructure to produce a systematic, quantitative evaluation of cost-effective planning and management strategies. The framework was then applied to the roadway transportation system of the USVI considering coastal and riverine flood risk. In this paper, the key contributions of this study are as follows:

- Integrate the MR&R strategies in normal conditions and quantitative risk analysis in extreme situations into a comprehensive framework.
- Evaluate the bi-directional impacts between normal and risk management under different asset/management strategies under various flooding and sea level rise scenarios.
- Develop an ArcGIS-based analytical tool supporting the MR&R decision-making in long-term planning and management.

The rest of the paper is organized as follows. Section 2 presents a detailed review of relevant literature. Section 3 provides an overview of the integrated framework, breaking down each step and introducing methodologies and quantified factors. These steps are then applied to our USVI case study in section 4. Finally, we conclude the developed framework and its applications in section 5.

2. Literature review

The literature review is conducted from two perspectives: the risk-analysis framework of TIAM and the economic impacts analysis for risk assessment.

2.1. Risk analysis frameworks of TIAM

Approaches to evaluating, adapting to, and mitigating risks to assets across multi-modal transportation systems have been formulated by different international agencies and organizations (Ahmed and Dey, 2020; FHWA, 2016; Highways England, 2016; Hughes and Healy, 2014), though they each come with limitations due to scope of individual agencies and organizations. In the U.S., national groups such as the American Society of Mechanical Engineers (ASME) and the FHWA have developed methodologies to guide the assessment and incorporation of general risk into asset management: ASME's Risk Analysis and Management for Critical Asset Protection (RAMCAP) Plus approach (Brashear and Jones, 2010) and the FHWA's Vulnerability Assessment (VA) framework (FHWA, 2012). While they provide pertinent guidance, these broad frameworks are general sets of criteria and steps and require significant adaptations for application by managers.

In addition, the practice of incorporating risk and resilience in transportation infrastructure assessments varies in each state in the U.S., where the risk-based asset management frameworks are highly specific and independently developed to focus on certain hazards or asset types (Renne et al., 2020). Besides, a survey conducted by Liu and McNeil (2020) indicated that the role of the risk analysis process was not played well and was loosely connected to the decisions in most of their frameworks. Actually, there are opportunities to reduce the vulnerability of assets and potential consequences of attacks or natural events by linking the risk analysis to the decision-making process in the TIAM (Filosa et al., 2017; Koks et al., 2019). Pairing assets and threats on Interstate 70, Colorado DOT (CDOT) examined hazards' effects on system robustness asset performance, network redundancy, and post-event network resilience and how risk, costs, and performance factor into one another, especially how costs of risk mitigation balance against costs of threat consequences for a return on investment (ROI) in a benefit-cost analysis (BCA) (Flannery, 2017).

Using a quantitative risk analysis method in the MR&R decision-making process on TIAM is most likely beneficial in normal situations and discrete hazard events. Computing and then comparing risk with the potential decision costs provides a trade-off framework between benefits and costs considering pre-event mitigation and post-event recovery. On the one hand, some studies focused on the risk of infrastructure facilities for the regular maintenance plan. For instance, a quantitative risk-based decision optimal maintenance and rehabilitation framework was presented by (Seyedshohadaie et al., 2010) to minimize the degradation risk at the network level. Alshboul et al. (2021) used the quantitative risk value to select the highway sections whose maintenance will effectively reduce the total risk within the network. Besides, the quantitative risk-based management framework is also useful for avoiding the risk of the pavement management system (Alhasan, 2021; Saha and Ksaibati, 2016). On the other hand, accurate identification and quantitative assessment of risk caused by uncertain disaster events are crucial to accurately manage the impacts and consequences of risk on the infrastructure (e.g., Inkoom and Sobanjo, 2019; Salem et al., 2020). Recently, Colorado DOT (2020) developed a quantitative risk and resilience assessment model to manage flooding, rockfall, and fire debris flow threats to roadways, bridges, culverts, and concrete structures.

2.2. Economic impact assessment for climate change

Some studies explore and identify what risk events the agencies are interested in including their risk register and data sources (Khodeir and Nabawy 2019; Nlenanya and Smadi 2021; Esmalian et al., 2022). Nlenanya and Smadi (2018) noted that the factors consistently ranked in the top three on a project level were structural condition, life cycle cost, and overall performance, which highlighted that agencies are always concerned about available funding to maintain performance levels. Also, the total additional cost of MR&R actions caused by climate change can be a considerable expense in annual fiscal expenditure (Lee et al., 2016; Alam et al., 2018).

Considering this, the selection of the MR&R strategies involves a balance between reducing risk against threats and the recovered performance under capital constraints and tolerated damage (Vugrin et al., 2010; Youn et al., 2011). The economic impact of roadway system performance during a disaster can be estimated as the user and owner costs (Aydin et al., 2018; Akiyama et al., 2020). The user cost includes increased travel time due to the road closure or detour, wear and tear cost and other impacts on the users (e.g., Soltani-Sobh et al., 2015; Gu et al., 2020). The owner cost can be measured as the capital used to recover a road functionality goal for each decision (e.g., Rose and Krausmann 2013). Cartes et al. (2021) integrated cost-saving and resilience evaluation to prioritize the recovery strategies of a road segment affected by natural hazards. Akiyama et al. (2020) studied the economic loss in road networks affected by earthquakes and tsunamis. These studies mainly focused on the economic impact of the recovery strategies in a natural hazard. However, Asadabadi and Miller-Hooks (2017a; 2017b) noted that allocating additional investment to mitigate the vulnerability of the existing infrastructures can reduce the additional recovery budget in post-disaster time. Therefore, a cost-benefit analysis, indicating the bi-direction interaction between normal maintenance and resilience to extreme events, should be discussed when comparing the TIAM project options.

In addition, many researchers have also developed guidelines or strategies to ensure climate-resilient infrastructure moving forwards (e.g., Le Xuan et al., 2022; Poo et al., 2021). For the agency, the Port Authority of New York and New Jersey (PANYNJ) and its consideration of sea level rise (SLR) for coastal highway and bridge projects based on service life and how critical the asset is, requiring adjustments to project Design Flood Elevation (PANYNJ, 2018, p. 6). Such cases are highly detailed and provide a comprehensive framework for the agencies that have developed and are using them, and they are easier to implement than the general frameworks offered by ASME and FHWA. However, they cover only certain types of assets and natural hazards and can be highly localized.

3. Analytical framework

Our holistic analytical framework (Fig. 1) for providing quantitative solutions integrates perspectives of infrastructure MR&R planning, RA and EIA. Notably, our approach considers the bidirectional feedback/impact between management under normal operating and extreme conditions. To illustrate its application, we select roadway pavement as a representative type of asset to develop our methodology and create several cases, which can be applied to other types of transportation infrastructure and scaled up to the integral infrastructure system.

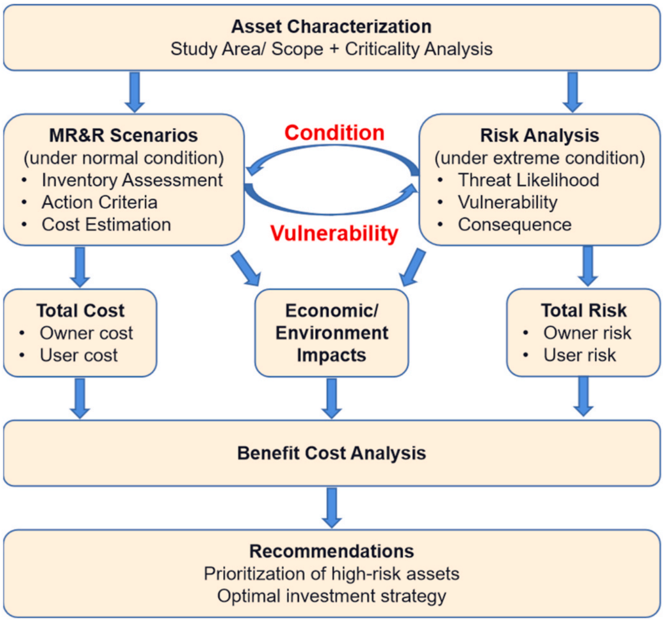


Fig. 1. Analytical framework overview.

3.1. Asset characterization

3.1.1. Define study scope

This step is to define the study scope by identifying:

1) The type of infrastructure: they are highly impactful and potentially vulnerable to natural hazard events in the study area.
2) The set of assets to study: they belong to certain categories and within a geographical or jurisdictional boundary or are on an important corridor.

When resources are limited to perform the full-scale risk analysis for all the assets in the system, a criticality analysis can be conducted to prioritize those important assets that have potentially high risk or impact on the entire infrastructure system, the community, and the economy. In addition, data availability may be a key factor that limits which assets are included in the risk-based asset management (Filosa et al., 2017). Other factors such as the assets' geographical location, representativeness, stage of life may also be considered in selecting the assets for study.

3.1.2. Criticality analysis

Once assets have been identified, criticality analysis could be used to prioritize a subset of assets for detailed analysis. According to CDOT (CDOT, 2020), criticality is a measure of the importance of an asset to the overall highway system operations. Criticality does not measure the cost of an asset, nor the likelihood of an asset's failure under a hazard, but rather the significance of the asset to the overall system's resilience. The more critical an asset is for a system, the more successful it will be in delivering its service for its users. In the case of roadway infrastructure, the more critical a road segment is to a user, the more important it is to be sufficiently resilient. In doing so, more lengthy detours or unsafe trips during and after hazardous events can be avoided, which in turn, makes it easier for users to traverse.

For highway transportation infrastructure, factors to determine criticality may include but is not limited to: Usage (e.g., traffic), Classification (e.g., the American Association of State Highway and Transportation Officials (AASHTO) classification for roadway), Freight Value, Tourism Value, System Redundancy, Location (e.g., linkage to other critical infrastructure or on emergency evacuation routes), etc. Redundancy can be measured by the number of alternative routes available for travelers on, which is, however, sometimes hard to define or quantify, especially when the network is complex. In the case of roadway, one may also use detour distance as another measure of redundancy for roadway assets, in the sense that the longer the detour, the less likely there are nearby alternative routes for a specific road segment.

3.2. MR&R scenarios

The investment levels or management strategies for MR&R decisions are expected to affect both the infrastructure's resilience response to natural events and the long-term performance of the infrastructure system. Therefore, it is essential to conduct the analysis under a specific investment scenario to quantify the benefit and cost in terms of risk, cost, condition improvement, and the associated broader economic value.

3.2.1. Inventory and condition assessment

The first and foremost component before any analysis is asset inventory and condition assessment, in which a wide range of relevant data on the infrastructure network is collected, such as size, type, material, age, design standard, descriptive information, etc. In addition, GIS- formatted data and visualizations (e.g., graphics, tables) may be integrated to support search, display, and statistical analysis in a consistent digital format.

3.2.2. *Action criteria*

An infrastructure MR&R scenario should regularly define the following three aspects for each of the assets in the study scope:

1) **Type of action.** It should include at least one type of action besides the do-nothing option. The type of actions could be either one or more main categories, either strategic level analysis or specific treatment options with detailed, fine resolution analysis.
2) **Timing of action.** It should include when each action will be performed, based on a fixed frequency or the condition (i.e., trigger point).
3) **Applicable asset.** This could be decision rules or policies applied to specific assets or categories of assets. For example, maintenance may be applied to major and minor roadway sections at different frequencies.

For roadway pavement, the state-of-practice of many state agencies follows a treatment decision tree (Fig. 2) to select treatment actions (Table 1) based on the condition rating, such as Pavement Condition Index (PCI) to identify which pavement treatment is appropriate on a given section.

3.2.3. *Costs associated with MR&R actions*

Currently, much infrastructure maintenance is performed on an as-needed, reactionary basis. Infrastructure budget and purchase order information can be used to understand the average unit costs of MR&R actions based on the type of intervention. These unit costs will be used to calculate the total budget necessary to improve the condition of each asset to a higher level or renew to the best condition state.

3.3. *Risk analysis*

Our risk analysis framework is adapted specifically for transportation infrastructure based on the ASME's Risk Analysis and RAMCAP Plus Approach (Brashear and Jones, 2010) and a general procedure developed by CDOT (CDOT, 2020).

3.3.1. *Threat characterization and assessment*

First step is to identify threats relevant to the critical asset for analysis, ranging from probable threats that have consistently occurred over the past and the worst possible consequences that could occur. The likelihood of each extreme event occurring on each asset is estimated with data of climate and natural hazard. The likelihood L_e of a certain type of natural hazard event e is quantified as a probability metric between 0 and 1, corresponding to the magnitude of the event. For example, the likelihood of a 100-year magnitude flood happening in a year is 0.01/year.

Table 1
Sample treatment types defined in treatment families for pavement.

Treatment actions	Description
Do-Nothing	Those pavement sections do not have sufficient distress level to warrant expenditure of funds.
Pavement Preservation	Those pavement sections that require minimal treatments to seal the pavement surface to prevent moisture from entering the pavement structure.
Minor Pavement Rehabilitation	Those pavement sections that require a functional overlay treatment to improve pavement ride quality, skid resistance, or rutting.
Major Pavement Rehabilitation	Those pavement sections that require a structural overlay treatment to improve the pavement structure and pavement ride quality, skid resistance, or rutting.
Reconstruction	Those pavement sections that require a partial or complete reconstruction due to extensive pavement deterioration.

3.3.2. *Vulnerability analysis*

Vulnerability $V_{i,e}$ for asset i represents the probability of the worst possible circumstances that will occur to that asset in extreme event e. According to Argyroudis et al. (2019), vulnerability of a transportation asset is affected by structural characteristics, protection and condition, thus MR&R decisions have a direct impact on it. Vulnerability analysis is conducted through consultation with experts, usage of Vulnerability Logic Diagrams (VLD), usage of Event Trees, or some combination of methods.

3.3.3. *Consequence analysis*

An analysis of the worst consequences, including owner consequence $OC_{i,e}$ and user consequence $UC_{i,e}$ for asset i, considering the repercussions that come with the worst scenario in extreme event e. Examples of consequences include fatalities, serious injuries, and financial losses to the owner and user. Please see Appendix A for detailed calculation of the user consequence and owner consequence suggested in the CDOT (CDOT, 2020).

3.3.4. *Risk assessment*

The monetized risk measures ($/year) are defined as the total expected losses to the owner and the users considering all possible extreme events $e \in E$. The total system owner TOR and user risks TUR:

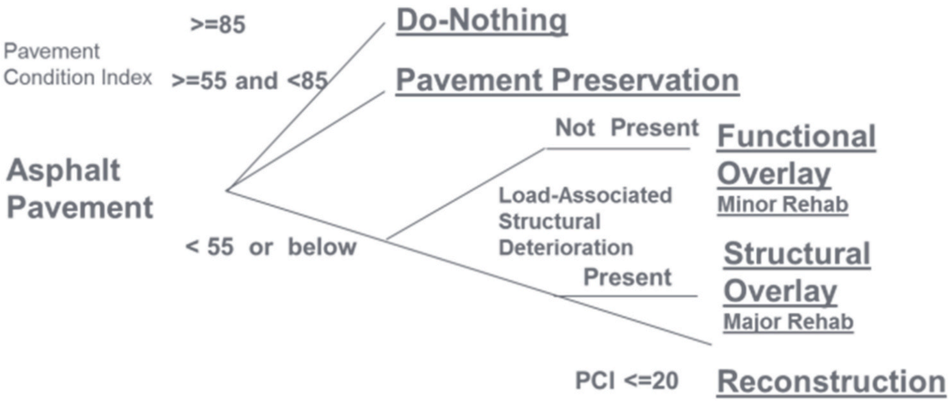


Fig. 2. An example of treatment decision trees for pavement.

$$TOR = \sum_{i \in I} \sum_{e \in E} L_e \times V_{i,e} \times OC_{i,e} \tag{1}$$

$$TUR = \sum_{i \in I} \sum_{e \in E} L_e \times V_{i,e} \times UC_{i,e} \tag{2}$$

3.4. Economic and environmental impact analysis

Before further analysis to support risk management decision making, it is necessary to understand the full benefits and costs of each of the intervention/investment scenarios for the public, government, and the overall macroeconomic economy, relative to a baseline scenario, such as a "do nothing" or status quo scenario. We identify the following economic impacts of transportation infrastructure failure.

3.4.1. User costs associated with poor transportation infrastructure

Poor conditioned or damaged infrastructure results in increased delays and detours from slowing traffic, compromised level of service, and temporary closures. Based on data on the average traffic and additional time due to detours, the following measures will be estimated:

1) **Wear and tear on vehicles.** In the case of roadway pavement, previous study (e.g. Islam and Buttlar 2012) finds that any road segment with a present serviceability index (PSI) rating of less than 3.5 will result in additional per-mile maintenance costs in terms of increased maintenance, repairs, tires, and depreciation costs. These costs will be estimated based on road usage and infrastructure condition rating for personal vehicles and trucks.
2) **Lost time/productivity due to traffic and detours.** Because peak hour traffic usually occurs during commute times, the productivity loss estimation will be based on the morning commute delays of workers using the roadways. In addition to lost time for the individual delayed due to roadwork or poor infrastructure, others who are dependent on them are idle as well. This loss would be greater with the variance of the delay. These losses can be estimated based on avoidable annual time delays and the median average wage of the region.
3) **Gas and pollution costs.** Extra time in traffic increases the time commuters are idling in their vehicles. This idling time increases gas costs and pollution. Our estimates will use data from INRIX and the Environmental Protection Agency to estimate the amount the gas and CO_2 emissions expended by this traffic.
4) **Safety implications.** Poorly maintained roads and added congestion due to insufficient roadways or detours, can increase frequency and severity of accidents. Based on the correlation analysis of accident severity and frequency by Zaloshnja and Miller (2009), our analysis will calculate the added costs of accidents due to subpar roadway conditions.

3.4.2. Macroeconomic constraints for poor infrastructure

The gains associated with improved maintenance directly affect citizens but also have real economic implications. A common macroeconomic indicator of economic growth is real GDP per capita. Investment in infrastructure is a form of growth of an economy's public capital stock and can directly lead to an increase in labor productivity in the private sector, leading to an overall increase in real GDP growth. Recent literature has found strong linkages between public sector capital stock investment and private sector productivity. A 10% increase in an economy's public capital stock would lead to private sector output/GDP of 1.5%–2% (Bom et al., 2009; Rioja, 2013).

3.5. Decision analysis and recommendations

The quantitative results of the above steps were used for supporting investment and management decisions through standard BCA. By comparing the benefit cost ratio or ROI of all proposed scenarios, insights about a good MR&R strategy could be drawn from the most cost effect scenarios. The BCA will be useful for further prioritization of projects and optimization of planning decisions.

4. USVI case study

In this section, we apply the entire analytical framework to conduct a comprehensive case study analyzing the roadway network in the USVI territory, in which we demonstrate how to pull and utilize data to quantify risk and economic impact of MR&R scenarios on infrastructure.

4.1. Study asset characterization

4.1.1. Study scope

The scope of this case study is limited to transportation infrastructure for three main islands of the USVI territory: St. Croix, St. Thomas, and St. John. Given the scope of this study and the availability of data, we focus on the major roadway pavement network, which is among the most critical types of highway transportation infrastructure. The natural hazard event we focus on is coastal and riverine flooding and the impact of future sea level rise, as it is one of the predominant natural threats in the coastal environment of USVI.

4.1.2. Data sources

Most roadway infrastructure data was provided the University of Virgin Islands (UVI) and USVI Department of Public Works (DPW), including the ArcGIS roadway network dataset, and roadway characteristics by segment (such as class, length, slope, number of lanes, traffic, pavement type, condition rating). DPW also provided cost data for roadway works from which we estimate the cost for pavement MR&R for each roadway segment. Furthermore, we have referred to other public reports (e.g. Virgin Islands Office of Highway, 2019) for more infrastructure and cost data. Natural hazard data public sources include the flood plain map layer from FEMA National Flood Hazard Layer (NFHL) and the sea level rise scenario layers from NOAA Sea Level Rise Viewer (NOAA, n.d.). Geo-spatial information is also collected from the ArcGIS database and integrated into one tabular dataset in formats that are ready for input into the analysis (Fig. 3). Even though the framework support multiple event scenarios, considering data availability, only 100-year magnitude flood event scenario is analyzed in the case study.

4.1.3. Critical asset identification

Based on above data sources, as discussed in the section 3.1, we used the road usage, including Annual Average Daily Traffic (AADT) and Annual Average Daily Truck Traffic (AADTT). Table 2 presents the criticality criteria examples used to determine the level of criticality for transportation infrastructure. Considering the St. Croix, USVI as an example, Fig. 4 shows the network map views of the criticality levels of the transportation infrastructures.

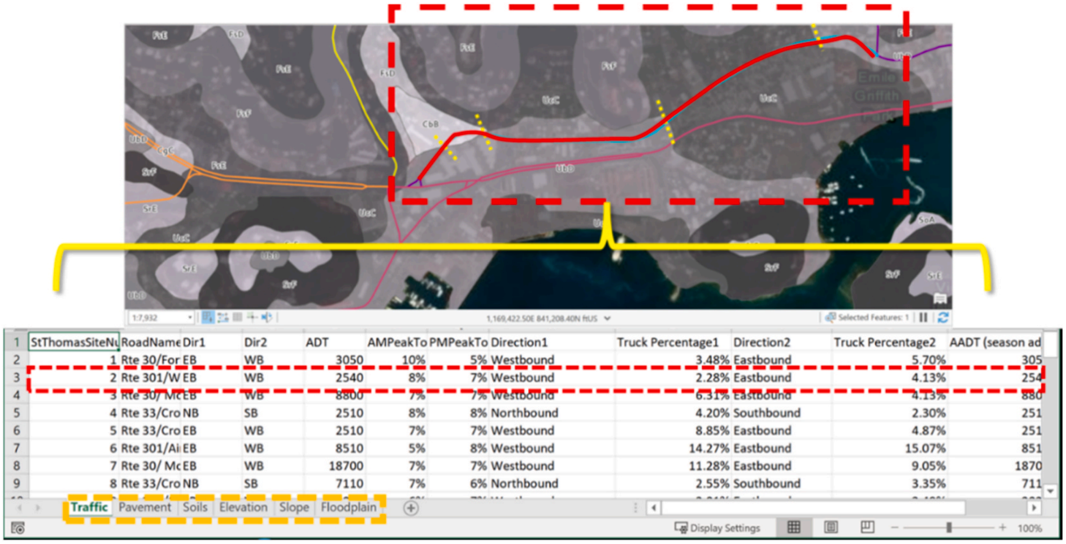
4.2. Roadway pavement MR&R scenarios

4.2.1. Inventory and condition assessment

According to the 2040 USVI Comprehensive Transportation Master Plan, the condition of most of the roads in the Territory is fair to good in St. Croix (Parsons Brinckerhoff). The roadway pavement inventory condition map produced based on the 2017 ArcGIS dataset (Fig. 5). The PSI is based on the original AASHO Road Test Pavement Serviceability Rating (PSR), ranging from 5 (very good) to 0 (very poor).

4.2.2. Roadway intervention scenarios

Six pavement intervention scenarios including a baseline "do-nothing" scenario are defined based on the a pavement treatment tree (Fig. 2) that identify ranges of pavement condition levels to trigger pavement preservation, minor rehabilitation, major rehabilitation, and reconstruction treatments (Table 3). Scenario 5 is a special one in which



1	StThomasSiteNu	RoadName	Dir1	Dir2	ADT	AMPeakTo	PMPeakTo	Direction1	Truck Percentage1	Direction2	Truck Percentage2	AADT (season ad
2	1	Rte 30/For	EB	WB	3050	10%	5%	Westbound	3.48%	Eastbound	5.70%	305
3	2	Rte 301/W	EB	WB	2540	8%	7%	Westbound	2.28%	Eastbound	4.13%	254
4	3	Rte 30/ Mc	EB	WB	8800	7%	7%	Westbound	6.31%	Eastbound	4.13%	880
5	4	Rte 33/Cro	NB	SB	2510	8%	8%	Northbound	4.20%	Southbound	2.30%	251
6	5	Rte 33/Cro	EB	WB	2510	7%	7%	Westbound	8.85%	Eastbound	4.87%	251
7	6	Rte 301/Ai	EB	WB	8510	5%	8%	Westbound	14.27%	Eastbound	15.07%	851
8	7	Rte 30/ Mc	EB	WB	18700	7%	7%	Westbound	11.28%	Eastbound	9.05%	1870
9	8	Rte 33/Cro	NB	SB	7110	7%	6%	Northbound	2.55%	Southbound	3.35%	711

Fig. 3. Illustration of the segmentation and aggregation of line features and the integrated tabular dataset with multiple attributes for roadway segments.

Table 2
The criticality criteria of transportation infrastructure.

Criteria	Level (Vehicle/day)		
	Low	Moderate	High
AADT	0–5000	5000–10,000	>10,000
AADTT	0–1000	1000–2000	>2000

MR&R actions are only applied to those major roadway segments with PSI 3 or less and AADT above the average value of all roadway segments in the island. Please see Appendix B for detailed description of each of the five scenarios. Typically, a road with a PSI of 0–1 is regarded as failed and would have to be reconstructed completely. A road with a PSI between 1 and 4 would raise the PSI level above 4.5 after MR&R actions.

Note that in this analysis we will consider only short-term treatment activities and economic effects of the MR&R plans. We will ignore long-term cost and economic impacts due to data limitation and to maintain simplicity in this illustrative case study.

4.3. *Risk analysis*

In this case, the two road segments, Route 30 (Veterans Drive) and Route 32 (Turnpike), were selected as representative examples for illustrating our risk assessment procedures in section 3.3, followed by the network level results for all six scenarios defined in section 4.2. Detailed information about the two segments is included in Appendix B.

4.3.1. *Facility-level risk assessment*

4.3.1.1. (1) threat characterization. The threat scenario is a 100-year coastal flood (1% probability) for both road segments. Based on the chosen segments in the FEMA NFHL, 1.4 miles of Route 30 and 0.61 miles of Road 32 lie within the affected areas of this hazard, showing in the Fig. 6 and Fig. 7, respectively.

4.3.1.2. (2) vulnerability analysis. Vulnerability of roadway to flood hazard is generally affected by magnitude of the flood event, soil type, terrain, frost action, and pavement ratings of road segments. Since the temperature in USVI is consistently above freezing, frost action for this region is ignored. Based on CDOT study (CDOT, 2020) and expert opinion, we incorporated pavement condition rating and soil type in determining embankment erodibility. The soil data we obtained is USDA classification. We further developed a conversion table to convert based on the composition of sand, silt and clay into three main AASHTO classes: A1-A3, A4-A8 (Davis, 2002) and Unknown (Table 4).

Segment 1, Route 30 has USDA UbD UcC (Urban Land) soil, and thus is classified as unknown category with no information about the soil characteristics of this type; with a PSI condition rating 3, its embankment erodibility is moderate. Segment 2, Route 32 has USDA SrD soil,

(a) (b)

Fig. 4. Criticality levels of St. Croix, USVI roadway network based on (a) AADT (b) AADTT.

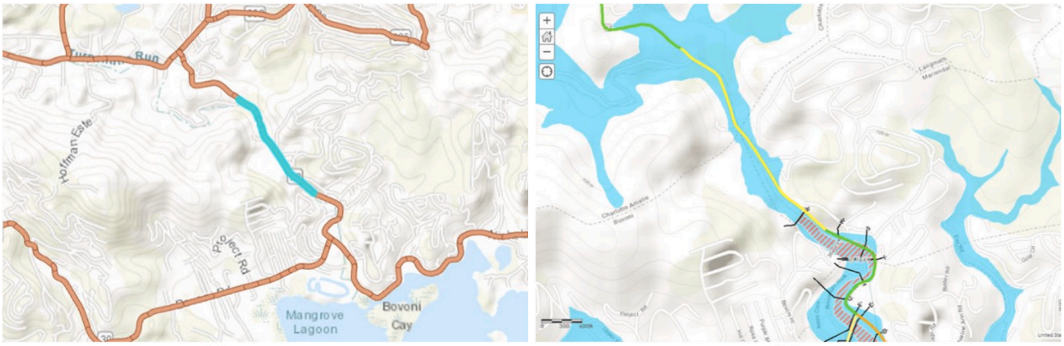
Fig. 5. Colored pavement PSI rating of major roads in St. Croix, USVI.

Table 3
Relationship between PSI, types of maintenance, and scenarios.

PSI	Type of MR&R Action	Scenarios (#)				
0 & 0.5	Pavement Reconstruction	Scenario #1	Scenario #2	Scenario #3	Scenario #4	Scenario #5
1 & 1.5	Major Pavement Rehabilitation					
2 & 2.5	Minor Pavement Rehabilitation					
3 & 3.5 & 4	Pavement Preservation					
4.5 & 5	Do Nothing					

(a) (b)

Fig. 6. Segment 1, Route 30: (a) highlighted on road map and (b) overlayed on FEMA NFHL map.



(a) (b)

Fig. 7. Segment 2, Route 32: (a) highlighted on road map and (b) overlayed on FEMA NFHL map.

which is classified as A4-A8 AASHTO category based on USVI soil survey report (Davis, 2002); with a PSI condition rating 2, its embankment erodibility is high.

Then the vulnerability index, indicating the probability of roadway damage when a flood event occurs, can be estimated based on the Table 5 which was developed in the CDOT manual.

4.3.1.3. (3) consequences. Table 6 presents the calculated values of user

Table 4
Embankment erodibility table.

Soil Class		A1-A3	A4-A8	Unknown
Pavement Condition Rating	5	Very Low	Moderate	Low
	4.5	Very Low	Moderate	Low
	4	Very Low	Moderate	Low
	3.5	Low	High	Moderate
	3	Low	High	Moderate
	2.5	Low	High	Moderate
	2	Low	High	Moderate
	1.5	Moderate	Very High	High
	1	Moderate	Very High	High
	0.5	Moderate	Very High	High
	0	Moderate	Very High	High

Table 5
Roadway prism vulnerability for 100-year and 500-year flood events (CDOT, 2020).

Flood Event	Terrain	Embankment Erodibility Potential				
		Very Low	Low	Moderate	High	Very High
100-yr	Level	0.22	0.23	0.25	0.31	0.33
	Rolling	0.26	0.28	0.3	0.36	0.39
	Mountainous	0.35	0.37	0.4	0.48	0.52
500-yr	Level	0.55	0.59	0.63	0.77	0.83
	Rolling	0.66	0.7	0.75	0.91	0.99
	Mountainous	0.88	0.93	0.99	0.99	0.99

The terrain for both road segments (based on the slope) is “Level”. With the embankment erodibility and 100-year flood category, the vulnerability values for the two segments are 0.25 and 0.31 respectively.

and owner consequences (costs) on our case study segments 1 and 2, factoring in the equations in section 3.3. Please see Appendix B for parameter values and detailed calculations of these two segments. The major parameters that differ between these two segments are traffic (pc and truck) as well as detour distance when unavailable. Comparing these two road segments, the result of the consequence indicated that the owner consequence of Route 30 is higher, but the user consequence of Route 32 is higher.

4.3.1.4. (4) risk assessment. Table 7 presents full calculations of owner and user risk values (costs) on the case study segments 1 and 2, factoring in the equations and considerations determined for consequences and vulnerability of these roadways in section 3.3.

4.3.2. Network-level risk assessment

Network-level analysis lets us apply the risk values to develop a more holistic understanding of similar transportation assets in that area. As discussed in section 4.2, upon calculation of the following specific treatments for each action, five pavement MR&R scenarios with different combinations of treatment actions are compared (Table 8). Note that we estimate the miles-weighted average network PSI level by multiplying the length of each pavement section by the PSI level for all sections and then divide the total number by the total area, before and after the MR&R treatments are applied in the five defined scenarios.

Compared with the baseline scenario, the owner risk profile in scenario 1 does not show an apparent improvement. It implies that although all pavement segments in the worst condition (about 5% of the total segments) are reconstructed and renewed to the PSI rating 5 in scenario 1, these actions do not significantly improve the owner risk values of those segments whose risk levels are probably already low.

Table 6
CDOT method user and owner consequence result for USVI segments.

Consequences	Route 30 (Veterans Drive)	Route 32(Turpentine Run Rd)
Vehicle Operating Cost (VOC)	$188,734	$286,874
Lost Wage (LW)	$194,279	$275,778
User Consequence (UC)	$383,013	$562,652
Owner Consequence (OC)	$ 11,934,039	$ 2,599,916

Table 7
CDOT method annual owner and user risk calculations for USVI segments.

Risk Terms	Route 30 (Veterans Drive)	Route 32(Turpentine Run Rd)
Threat Likelihood	0.01 (100-Year Flood)	0.01 (100-Year Flood)
Vulnerability	0.25	0.31
Consequence	OC = $11,934,039 UC = $383,013	OC = $2,599,916 UC = $562,652
Annual Owner Risk (expected owner cost)	$30,845/Year	$8332/Year
Annual User Risk	$958/Year	$1744/Year

4.3.3. Impact of sea level rise

Sea level rise scenarios are projected in specific heights for future years in the NOAA data. Three sea level rise scenarios are considered in the risk analysis:

Scenario A (Benchmark): 100-year flood without considering sea level rise.

Scenario B: 100-year flood under projected intermediate low 2050 sea level rise.

Scenario C: 100-year flood under projected intermediate low 2100 sea level rise.

We utilized ArcGIS geoprocessing to update the flood zones, considering the elevating the coastal flooding plains by the corresponding SLR height for each SLR scenario. The flood zone and risk maps and the total risk values of the three scenarios are shown in Fig. 8 and Table 9, respectively.

It is of no surprise that the total risks considering SLR in the two scenarios are higher than that of the scenario without SLR, and they increase with SLR heights. The failure risks of some pavement sections near coastlines may go up to a higher level due to SLR. Therefore, the quantitative results show that climate change may make a significant impact on natural hazard risk and consequently infrastructure management strategies.

4.4. Economic impact analysis and benefit cost analysis

We conduct an EIA for the six pavement intervention scenarios. In order to understand how routine infrastructure maintenance can improve the Territory’s overall resilience and economic growth, a set of data is analyzed that includes the annual average daily traffic split into trucks and passenger vehicles, peak hour volume, detour routes, and redundancy, and the quality of each road on each island will be assessed using PSI.

4.4.1. Roadway baseline costs

The baseline costs associated with subpar roadway maintenance must be estimated to determine the current economic costs. The direct economic consequences of not conducting roadway maintenance, include wear and tear on vehicles–such as tires, and springs, detour costs (which include user costs, the value of time, emissions, and gas), and crash costs. Table 10 demonstrates the broken-down baseline costs and total loss for the USVI Islands.

This estimation allows us to assess the economic impact of properly managed infrastructure based on crash savings and wear and tear savings from this baseline scenario. Crash savings consist of how often accidents occur and include the cost for fatalities, injuries, and property damage. Through correlation analysis of accident severity and frequency with subpar road conditions by Zaloshnja and Miller (2009), the

Table 8

Measures for five alternative MR&R scenarios of st. Croix.

St. Croix	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Investment	–	\$70.9M	\$82.2M	\$129.7M	\$158.6M	\$32.2M
Miles Weighted Avg Network PSI Rating	2.81	3.37	3.57	4.37	4.99	3.35
Annual Owner Risk	\$374,442	\$369,559	\$364,485	\$342,759	\$324,136	\$363,340
Owner Risk Reduction	–	\$4883	\$9957	\$31,683	\$50,306	\$11,102

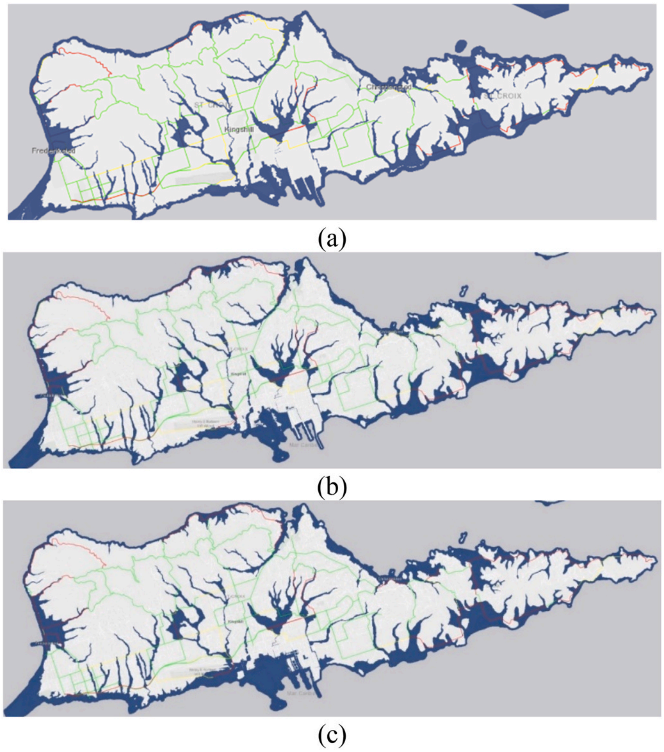


Fig. 8. Flood zone and colored risk scales of the three SLR scenarios: (a) no SLR, (b) projected intermediate low 2050 SLR, and (c) projected intermediate low 2100 SLR.

Table 9

Risk analysis result summary of the three SLR scenarios for St. Croix in USVI.

Summary of risk analysis result	Scenario A	Scenario B	Scenario C
Total Annual Owner Risk	\$374,442	\$400,914	\$464,721
Total Annual User Risk	\$11,657	\$13,671	\$15,186
Total Annual Risk	\$386,009	\$414,585	\$479,907
# of High Risk Road Segments	24	26	32
# of Medium Risk Road Segments	20	22	17
# of Low Risk Road Segments	118	114	113

Table 10

Baseline estimates of total costs associated with subpar USVI roadways.

Items	St. Croix	St. Thomas	St. John	Total
Wear and Tear	\$9.46M	\$3.60M	\$0.19M	\$13.25M
User Cost	\$9369	\$14,220	\$1041	\$24,630
Value of Time	\$16,837	\$18,995	\$1485	\$37,317
Emission	3.64	4.01	0.31	7.96
Gas	\$1482	\$1632	\$128	\$3242
Crash Costs	\$45.46M	\$35.50M	\$0.97M	\$81.93M
Total Costs	\$54.94M	\$39.14M	\$1.16M	\$95.24M

added costs of accidents can be calculated due to subpar roadway conditions in the USVI.

4.4.2. Roadway intervention scenario costs and savings

The crash costs due to subpar roadway condition is calculated as following Equation (3):

$$C_{crash} = P_{sr} \times P_{cf} \times C_{ta} \tag{3}$$

Where C_{crash} = crash cost caused by subpar roadways; P_{sr} = percentage of subpar roadway; P_{cf} = percentage of costs in which roadway condition was a contributing factor to increased costs; C_{ta} = total annual cost associated with death, injuries, and vehicle damage per island.

Wear and tear savings are composed of the costs associated with damage done on the pavement by vehicles. The wear and tear costs are calculated as following Equation (4) suggested in CDOT (CDOT, 2020):

$$C_{wt} = AF_{PSI} \times [(AnnualVMT_{cars} \times UC_{cars}) + (AnnualVMT_{trucks} \times UC_{trucks})]$$

Where

$$F_{PSI} = \begin{cases} 0.25 \ if \ AF_{PSI} \leq 2 \\ 0.15 \ if \ AF_{PSI} = 2.5 \\ 0.05 \ if \ AF_{PSI} = 3 \end{cases} \tag{4}$$

Where C_{wt} = the wear and tear costs due to subpar roadways condition (\$); AF_{PSI} = PSI Adjustment Factor determined by the PSI level; $AnnualVMT_{cars}$ = the total of the annual vehicle miles traveled for cars (miles); UC_{cars} = the unit cost of cars traveling (\$/miles), here is 0.30; $AnnualVMT_{trucks}$ = the total of the annual vehicle miles traveled for trucks (miles); UC_{trucks} = the unit cost of trucks traveling (\$/miles), here is 0.33. Please see Appendix D for detailed cost saving information of each scenario.

4.5. Analysis of results

Before and after MR&R interventions, the pavement condition distribution of St. Croix by PSI rating across all scenarios can be obtained, shown in Fig. 9. From the modeled scenario 1 to 4, the intervention strategy focuses on the current "fix worst first", while the strategy of scenario 5 allows a selection of priority roadway segments in the presented analytical framework. Compared to the baseline, the pavement

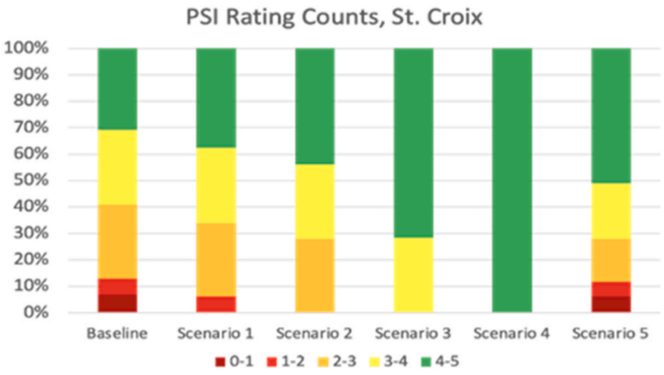


Fig. 9. Pavement condition distribution by PSI rating compared across all scenarios, St. Croix.

condition of the different MR&R scenarios has been improved on the whole. In the following subsection, considering St. Croix as an instance, the results of the presented five scenarios are analyzed further.

4.5.1. Impact of critical asset risk reduction

As discussed in section 4.3, the results presented in Table 8 demonstrate that scenarios 1 and 4 represent the lowest and highest owner risk reduction profiles, respectively. These scenarios serve as the boundary points of risk reduction in the analysis. Compared to the baseline, the actions of scenario 1 do not have an obvious improvement at the network level. Besides, the owner risk reduction of scenario 5 is $11,102, which is larger than that of scenario 2 with $9,957, which indicates that prioritizing the current “fix worst first” may not be the optimal decision-making to mitigate the risk of infrastructure. In order to analyze further, the results of specific MR&R interventions are visualized straightforwardly by the PSI rating road network maps, and four out of the six scenarios are shown in Fig. 10.

From the perspective of critical asset analysis, the current worst or second-worst pavement of roadway in St. Croix shown in Fig. 10 (a) baseline scenario is not the most criticality asset shown in Fig. 4 due to less AADT, AADTT. Although all these poor-condition pavement segments are rehabilitated and reconstructed to the PSI rating 5 in scenario 2 (Fig. 10 (b)), the treatment strategy does not show any advantage in enhancing the risk reduction compared to scenario 5, where applied the major roadway segments with PSI 3 or less and AADT above the average value of all roadway segments in the island. As shown in Fig. 4, the roads improved in scenario 5 lie in critical links in the roadway network and almost all of them are not pavement segments with PSI rating of 2 or less. Comparing scenarios 2 and 5 indicated the significant essential role of the critical asset in network vulnerability mitigation and risk reduction strategy. It also indicated that the more critical a road segment, the more important it is to be sufficiently maintained. Instead of focusing on the “fix worst first”, the critical corridors with higher volumes of traffic or access to key locations (e.g., hospitals or airports) will help mitigate the risk of the system and the communities in a network level that depend on them.

In scenario 3 shown in Fig. 10 (c), all the pavement segments with PSI rating of 3 or less are renewed to the PSI 5, nearly 40% of the total segments. It extends the range of scenario 5 from the critical area to the whole roadway network, and the reduced owner risk has been improved markedly from $11,102 in scenario 5 to $31,683. The treatment taken in scenario 3 is an ideal situation, the whole roadway network can provide a satisficed and efficient service level. In fact, focusing the limited spending and resources, the investment in MR&R strategies should be distributed in a cost-effective way.

In addition, the owner risk reduction is also influenced by the risk level of pavement segments, as discussed in section 4.3. Fig. 11 shows four of six scenarios of owner risk maps of St. Croix. As shown in Figs. 10 (a) and Fig. 11 (a), the worst condition segments in scenario 1 are at a lower risk value so that the effort is not obvious compared to the baseline. And the high-risk level pavement segments are along the coastal line, even though their PSI rating is 3 or more. This also explained the risk reduction performance of treatment actions in scenario 2, shown in Fig. 11 (b), are not as well as in scenario 5, shown in Fig. 11 (d), where the owner risks of the segments in red circles are reduced to a lower level. Compared to scenario 5, the scope of road pavement improvement in scenario 3 is larger and the results are more significant, as shown in Fig. 11 (c), the owner risks of the segments in green circles are reduced to a lower level. Please note that many of the segments have reduced risk values in scenario 3 and 5, although the reductions are not significant enough to show on a lower scale in the maps.

4.5.2. EIA comparison of intervention scenarios

The ROI is a simple metric to evaluate how cost-effective or efficient an investment is. Cost savings totals for pavement intervention Scenarios 1 through 5 can be obtained and compared to the baseline scenario and its costs (Table 11).

For each of the above roadway intervention scenarios, the ROI was calculated by dividing the total savings by the investments or intervention costs.

- Scenario 1. The ROI was 0.08, which is extremely low because these roads are in the worst condition and need to be heavily invested in while the reduction of risk and economic benefits are trivial.
- Scenario 2. The ROI is 0.09, which is only marginally higher than Scenario 1.
- Scenario 3. The ROI is 0.35, which is significantly higher than Scenarios 2 and 1 because far more roads are in fair condition (see Fig. 10 and Fig. 11), so it shows that not much money needs to be invested for lower-intensity treatments on much more roadway, producing significantly more savings from crashes and wear and tear per mile.
- Scenario 4. The ROI is 0.40 since the roads are in adequate condition, resulting in the use of less-costly preservation treatments on top of previous investments to minimize any costs due to roadway condition.
- Scenario 5. The ROI is 1.14, which is much greater than the ROIs for all previous scenarios and even predicts a net economic gain from crash and wear and tear savings alone. Scenario 5 has the highest return on investment because it applies treatments to the most necessary roads (i.e., low PSI but high traffic), instead of applying it to all the roads regardless of actual use or savings from less frequent accidents.

By choosing which roads actually or direly need treatments, Scenario 5 is the most efficient in terms of EIA. Despite an investment level lower than the “fix-the-worst” approach as modeled by Scenario 1, Scenario 5’s targeted interventions on the most critical subpar roadway segments produced over 11 times as much overall savings as Scenario 1, while achieving a full ROI of 1.14 across the Territory. Not only was this the highest ROI estimate obtained out of the five scenarios, but it was also produced from the lowest level of investment (roughly $56.4 million) out of the five strategies, including the current “fix worst first” approach that solely involves the absolutely necessary end-of-life reconstruction of pavement, as modeled by Scenario 1 (about $75.8 million). While more data is needed and may affect the relative economic impacts of each maintenance or intervention scenario, the data utilized paints a clear comparative look that favors prioritization of critical assets over more costly “fix worst first” or even fix-everything approaches.

Furthermore, the savings estimated to produce this full ROI were limited to cost savings from reduced vehicular wear and tear, detour costs, and accidents, thus omitting other economic impacts avoided, such as losses in productivity, idling time and pollution, and ripple effects in local safety and economies. The EIA and BCA performed for USVI pavement interventions thus demonstrate how just from certain or limited quantifiable values and risk analysis, an analytical procedure for identifying a more optimal management strategy can still be achieved for cost-effectiveness and risk mitigation.

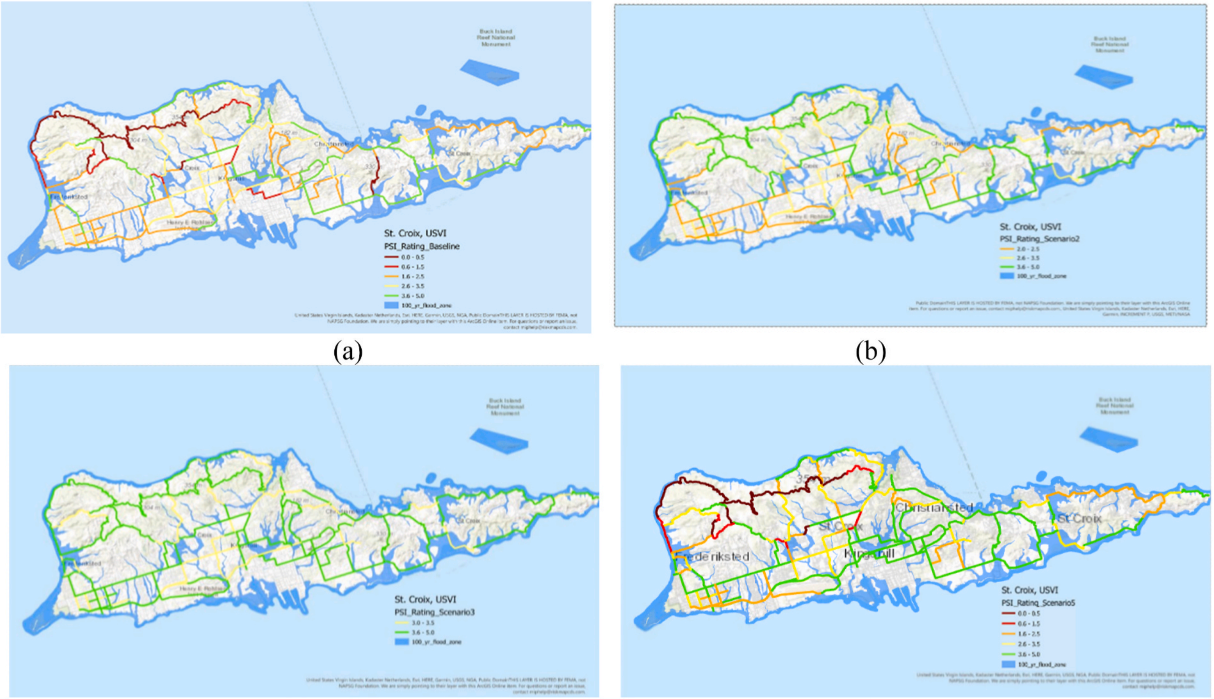
5. Discussion

In this section, the results of the risk-integrated TIAM framework implementation are discussed under the insufficient data and the limited resources. Meanwhile, how these limitations can impact the results of the research is also discussed. Besides, several challenges are identified and discussed in this section. Finally, recommendations and lessons for risk-based TIAM in the USVI are discussed. Note that due to a lack of comparable studies, it is not possible to compare in depth the results of this research and benchmark these against other studies, methods, or assumptions.

As discussed in section 4.5, it is necessary to clarify the impact of other key aspects on the research results to determine which further

Table 11
Cost saving totals of pavement intervention scenarios.

PSI	DPW Unit Cost			Treatment	Scenario				
	United States	St. Croix	St. Thomas & St. John						
0–0.5	$30.07	$282	$300	Reconstruction	Scenario #1	Scenario #2	Scenario #3	Scenario #4	Scenario #5
1–1.5	$28.50	$100	$194	Major Rehabilitation					
2–2.5	$19.25	$73	$150	Minor Rehabilitation					
3–4	$2.52	$31	$50	Preservation					
4.5–5	$0.00	$0	$0	Do Nothing					
Investment					$75.84M	$89.64M	$168.58M	$237.00M	$56.41M
Savings (Risk & Cost Reduction)					$5.72M	$8.19M	$58.18M	$95.17M	$64.31M
ROI					**0.08**	**0.09**	**0.35**	**0.4**	**1.14**
Percent of Budget					6.00%	7.10%	13.40%	18.90%	4.5%



(a) (b)

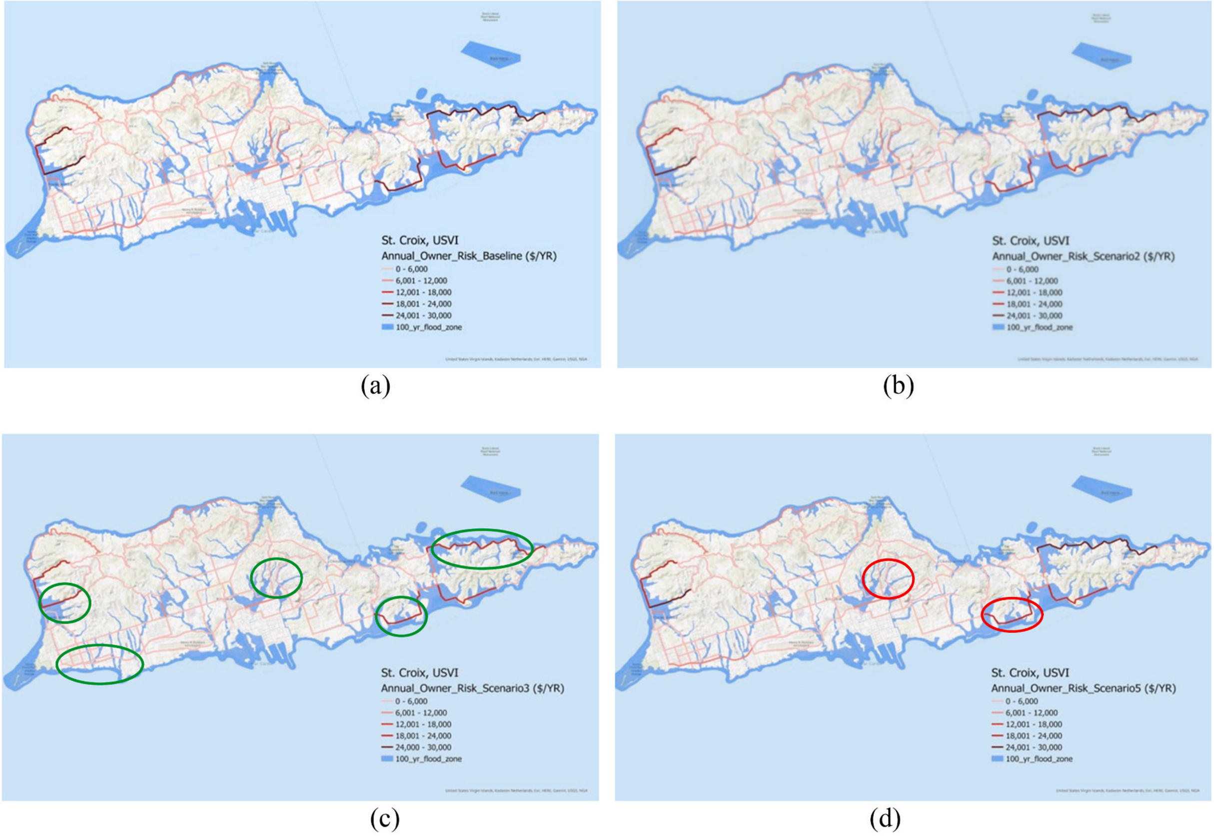
(c) (d)

Fig. 10. St. Croix PSI rating maps: (a) baseline scenario (b) scenario 2 (c) scenario 3 (d) scenario 5.

research is feasible and needed. In executing the TIAM framework, assumptions based on the CDOT procedure (CDOT, 2020) for agency risk cost data and user data, such as truck speed, vehicle occupancy and running cost, may affect the accuracy of EIA and BCA results. Besides, being unable to quantitatively account for enough factors, such as the reduced stiffness and strength of saturated pavement layers based on severe rain events, means that the results of the EIA and BCA could be improved further. In addition, a long-term life cycle cost analysis (LCCA) and pavement deterioration modeling were not considered in the study due to a substantial lack of data, including information on long-term structure deterioration, and soil and flood protection for roadways. Overall, collecting and incorporating enough relevant data on asset and management practice can support further research for an accurate and reliable long-term LCCA, prediction modeling, and planning.

The risk-integrated TIAM framework developed in this research provides an initial quantitative evaluation of EIA/BCA for various MR&R intervention strategies aiming at managing. coastal flood disasters. The framework was applied in a case study of the U.S. Virgin Islands, revealing a challenging fiscal situation heavily reliant on the FHAW funding and other federal special grants. Without sufficient funds, staff, and equipment to fully sustain and operate the transportation system in normal conditions, transportation agencies like the DPW in USVI face significant obstacles to executing major infrastructure projects, post-natural hazard recoveries, and risk mitigation or resiliency measures. Similar economic challenges have been observed in other studies, such as Alhasan (2021); Vugrin et al. (2010). Besides, the research shows that interventions conducted in a "fix worst first" approach are greater costly with stretched resources, due to intensive reconstruction treatments on the most deteriorated assets. Hinkel et al. (2018) also reached a similar conclusion. Furthermore, The BCA results highlight that a significant risk reduction/cost saving can be reached by selecting the optimal strategy, with aligns with the finding of Das Neves et al. (2023). Distinguishing itself from previous studies, this research highlights the pivotal conclusion that agencies can enhance their investment decisions by quantitatively evaluating the reciprocal relationship between normal maintenance planning and risk reduction management.

The methodology proposed in this research provides insight into how operational and capital spending can be best directed through BCA by quantifying the bi-directional impacts between asset MR&R and risk management, even with limited data in the analytical methodology. As demonstrated in the USVI case study, not only do the risk-reduction can



(a) (b)

(c) (d)

Fig. 11. St. Croix owner risk maps: (a) baseline scenario (b) scenario 2 (c) scenario 3 (d) scenario 5.

be assessed for coastal flood risks either at the individual facility or network level, but it also emerges from the research that the cost-effective approach can be selected by comparing alternative MR&R strategies. Specifically, the coastal flood risk was identified and analyzed to quantitatively illustrate the significant impact of the natural hazards on coastal infrastructure maintenance in normal conditions. Note that the vulnerability of the coastal infrastructure will gradually increase affected by other factors including extreme wind, heavy storms, and erosion on low-lying shores (Jr, 2018). In addition, it concludes from the research that coastal areas will be further affected by sea level rise, contributing to flooding and erosion and coastal flood zones will expand. The similar conclusion can be drown from Le Xuan et al. (2022). It means that the agencies like USVI have much work ahead to reduce the vulnerability and risk of its transportation system. The output of the applied framework shows that it can support maintenance decision-makers in operational planning and capital investment. The ROI indicates, in addition, that the bidirectional impacts between normal and extreme conditions must be accounted for when mitigating risk and maintaining assets, especially with more frequent events and recoveries expected in the future.

6. Conclusion

In this study, we incorporated asset management, risk assessment, and EIA, studying broader effects on user and agency savings and spending, into a holistic methodological framework for comprehensive assessment of the benefit and cost of proposed infrastructure management strategies. More importantly, the framework attempts to quantify the bi-directional impacts between asset MR&R and risk management that are not considered in most existing literature, i.e., subpar maintenance will contribute to worse damage and costlier recovery, while hazard damage and post-event vulnerability will contribute to faster deterioration and reduced resilience. The risk-integrated analytical framework was applied to a case for USVI which incorporates a wide variety of quantified factors, involving roadway inventory characteristics and their conditions, the analysis of flood and SLR risk, geographical characteristics, and the proposal of specific maintenance approaches. As we demonstrated, existing risk/resilience analysis processes can be quantitatively integrated with asset management and EIA methodologies to produce useful, more comprehensive information for agencies, for both individual assets and the whole system. The outputs of our applied framework can then support risk-conscious decisions in day-to-day operational planning and capital project investment.

As we outlined and demonstrated via the USVI case, we can quantify and incorporate risk values and EIA into BCA to better study and compare investment scenarios or strategies, but there is a significant number of factors and variables that play a role in both normal condition and extreme condition that need to be considered. Extensive studies to quantify other factors - such as the reduced stiffness and strength of saturated pavement layers based on flood events and incorporation into long-term deterioration models.

Furthermore, as noted above, we did not conduct a LCCA modeling for pavement. Our analysis focuses on a direct, timely impact in the short term that notable improvement of roadway condition requires significant investment. Therefore, as a future research direction, long term analysis when infrastructure deterioration and life cycle cost are of concern, more sophisticated asset management analysis can predict the infrastructure condition applying realistic deterioration models under different long-term intervention and investment scenarios and optimization models to determine the best strategy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Algorithm to Calculate the Consequence

The algorithm to calculate the user consequence and owner consequence:

User consequence $UC_{i,e}$ is the sum of vehicle operating costs and lost wage or truck revenue due to travel on detour, as shown in Eq. (A.1) suggested:

$$UC_{i,e} = VOC_{i,e} + LW_{i,e} \tag{A.1}$$

Where $UC_{i,e}$ = vehicle operating costs incurred due the asset i clouse caused by event e; $LW_{i,e}$ = lost wages or truck revenue incurred due to the asset i clouse caused by event e.

Vehicle operating costs are calculated with the following Eq. (A.2):

$$VOC_{i,e} = \left(RC^{i}_{vehicle} \times AADT^{i}_{vehicle} + RC^{i}_{truck} \times AADT^{i}_{truck}\right) \times d^{i,e}_{FC} \times \left(RL^{i}_{d} - RL^{i}_{o}\right) \tag{A.2}$$

Where $RC^{i}_{vehicle}$ = vehicle running cost ($/vehicle-mile) of the asset i; $AADT^{i}_{vehicle}$ = average annual daily traffic(non-truck) (vehicles/days) on the asset i; RC^{i}_{truck} = truck running cost ($/truck-mile) of the asset i; $AADT^{i}_{truck}$ = average annual daily truck traffic (trucks/days) on the asset i; $d^{i,e}_{FC}$ = number of full closure days (days) of the asset i caused by event e; RL^{i}_{d} = detour route length (miles) responding to the asset i; RL^{i}_{o} = original route length (miles) related to the asset i.

Lost wage costs are calculated with the following Eq. (A.3):

$$LW_{i,e} = \left(AT^{i}_{vehicle} \times AO \times AADT^{i}_{vehicle} + AT^{i}_{truck} \times AADT^{i}_{truck}\right) \times d^{i,e}_{FC} \times Dt_{i,e} \tag{A.3}$$

Where $AT^{i}_{vehicle}$ = average value of time ($/people-hour) on asset i; AO = average occupancy (people/vehicle); AT^{i}_{truck} = average value of freight time ($/truck-hour) on asset i; $Dt_{i,e}$ = extra travel time on detour (hour) on asset i due to event e.

Owner Consequence, which is also the replacement cost $REC_{i,e}$, is calculated with the following Eq. (A.4):

$$OC_{i,e} = REC_{i,e} = C^{i,e}_{owner} \times RA_{i,e} \times RL_{i,e} + C^{i,e}_{clean} \tag{A.4}$$

Where $C^{i,e}_{owner}$ = owner unit cost ($/yard^2) of the asset i impacted by event e; $RA_{i,e}$ = rode surface area (yard^2/mile) of the asset i impacted by event e; $RL_{i,e}$ = road length (miles) of the asset i impacted by event e; $C^{i,e}_{clean}$ = clean-up cost of the replacement strategies.

Appendix B. MR&R scenario definition

A map and bar chart displaying the distribution of pavement condition by PSI rating for the baseline scenario (Do Nothing) in St. Croix is presented as follows in Fig. B. 1. This represents the status quo scenario, which will be used later to compute the net cost and benefit of each treatment scenario across all islands of the USVI.

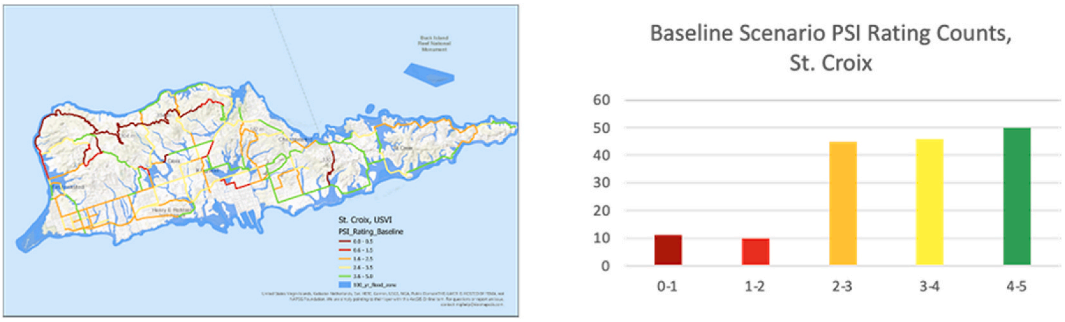


Fig. B1. Pavement condition map and distribution for baseline scenario, St. Croix.

We now define each of our five intervention scenarios by treatment type and triggering pavement condition thresholds, with maps and bar charts provided for each in Fig. B. 2 through Fig. B. 6.

- **Scenario 1**

Perform only reconstruction for all pavements below PSI rating 1 (0 and 0.5) to raise PSI to 5.

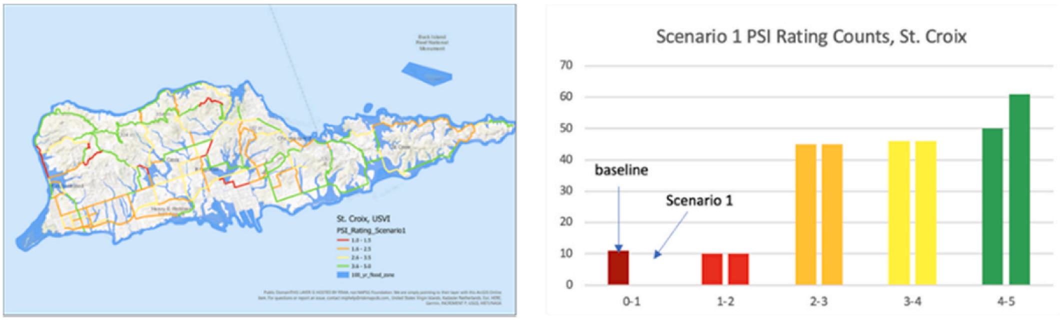


Fig. B2. Pavement condition map and distributions for Scenario 1 compared to baseline, St. Croix.

- **Scenario 2**

Perform reconstruction for all pavements below PSI rating 1 (0 and 0.5) to raise PSI to 5.
Major rehabilitation for all pavement between PSI rating 1–2 (1 and 1.5) to raise PSI to 5.

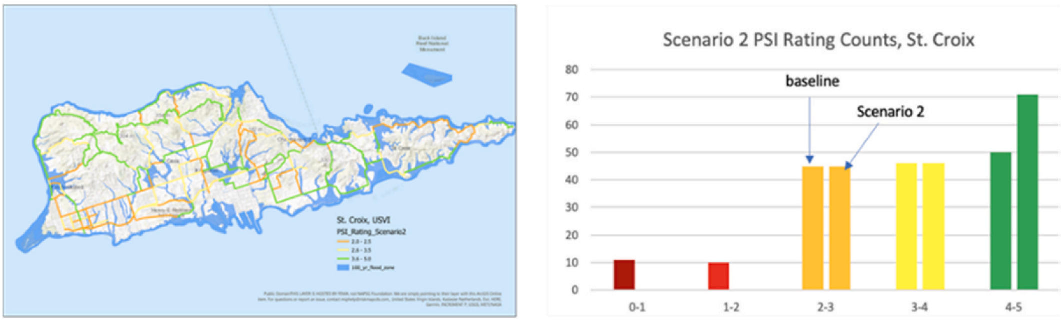


Fig. B3. Pavement condition map and distributions for Scenario 2 compared to baseline, St. Croix.

- **Scenario 3**

Perform reconstruction for all pavements below PSI rating 1 (0 and 0.5) to raise PSI to 5.
Major rehabilitation for all pavement between PSI rating 1–2 (1 and 1.5) to raise PSI to 5.
Minor rehabilitation for all pavement between PSI rating 2–3 (2 and 2.5) to raise PSI to 5.

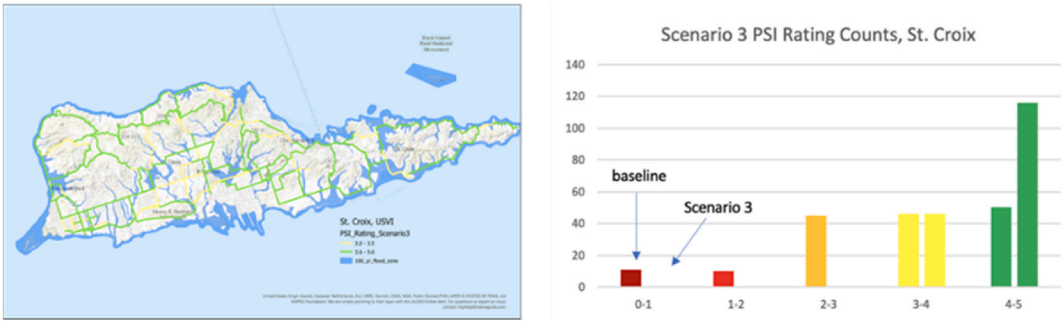


Fig. B4. Pavement condition map and distributions for Scenario 3 compared to baseline, St. Croix.

- **Scenario 4**

Perform reconstruction for all pavements below PSI rating 1 (0 and 0.5) to raise PSI to 5.
Major rehabilitation for all pavement between PSI rating 1–2 (1 and 1.5) to raise PSI to 5.
Minor rehabilitation for all pavement between PSI rating 2–3 (2 and 2.5) to raise PSI to 5.
Preservation for all pavement between PSI rating 3–4 (3, 3.5 and 4) to raise PSI to 5.

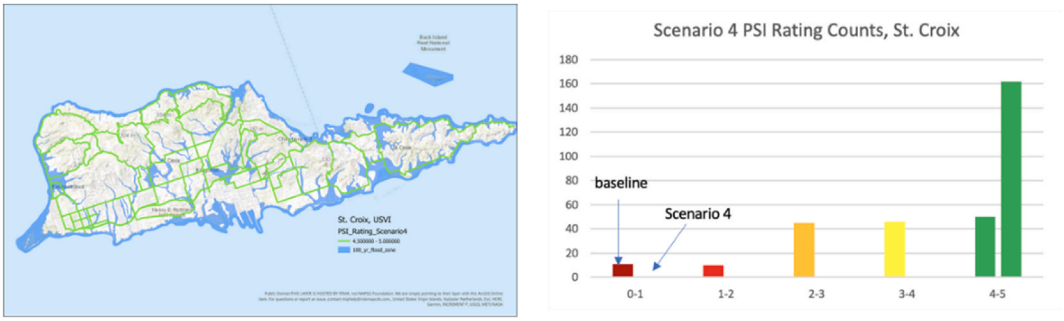


Fig. B5. Pavement condition map and distributions for Scenario 4 compared to baseline, St. Croix.

- **Scenario 5**

Perform reconstruction for select priority pavements below PSI rating 1 (0 and 0.5) to raise PSI to 5.
Major rehabilitation for select priority pavement between PSI rating 1–2 (1 and 1.5) to raise PSI to 5.
Minor rehabilitation for select priority pavement between PSI rating 2–3 (2 and 2.5) to raise PSI to 5.

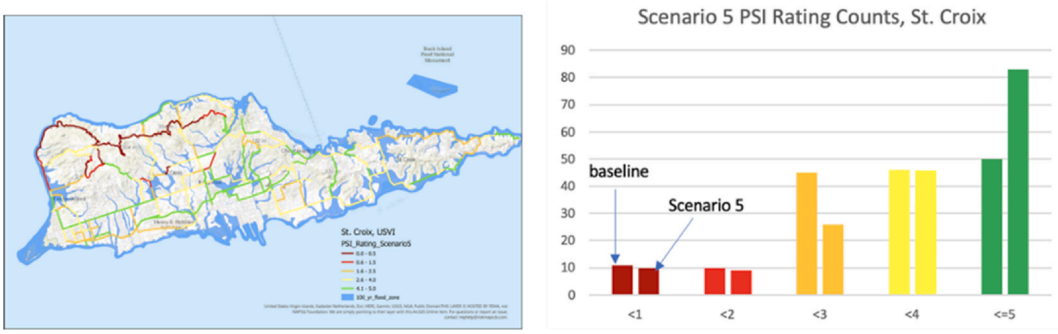
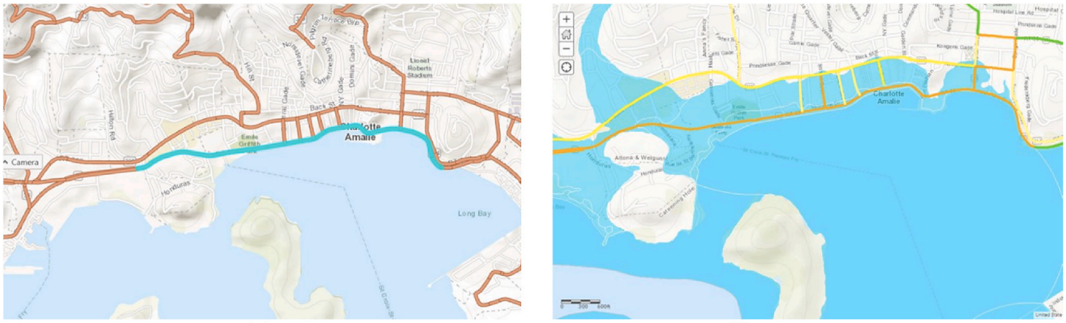


Fig. B6. Pavement condition map and distributions for Scenario 5 compared to baseline, St. Croix.

Two Example Road Segments

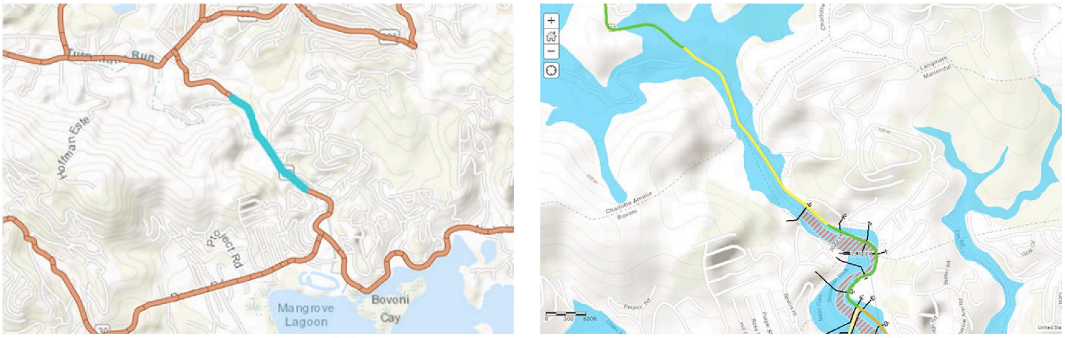
Segment 1, USVI Route 30 (Veterans Drive), lies close to the coast of Charlotte Amalie, St. Thomas. It is 1.4 miles stretch of 4-lane highway that runs between an international airport and a medical center. Its AADT for vehicles is 16,230 (vehicles/day) and AADT for trucks are 2160 (trucks/day). Thus, this segment of Route 30 is a crucial, highly trafficked roadway. Since nearly all of Segment 1 lies within the 100-year FEMA National Flood Hazard Layer (NFHL) flood zone, it is at high risk for coastal flooding. Its Soil Type is USDA UbD UcC (Urban Land), short for Urban Land-Cinnamon Bay Complex (0–12% slopes), and its Average Elevation is 1.58 m, both of which mean that the chosen road segment is occasionally flooded. Its pavement condition rating PSI was 3.0 (good).



(a) (b)

Fig. B7. Segment 1, Route 30 (Veterans Drive) (a) highlighted on road map and (b) overlayed on FEMA NFHL map.

Segment 2 is Route 32/Turpentine Run Road, St. Thomas, 0.61 miles stretch of 2-lane highway that also lies in Charlotte Amalie, specifically northwest of Compass Point Marina. The AADT for vehicles is 8400 (vehicles/day), and the AADT for trucks is 6300 (trucks/day). Similar to Segment 1 (Veterans Drive), all of the chosen segment of Route 32 lies within the FEMA NFHL 100-year flood zone, so it is also at high risk for coastal flooding. Its Soil Type is USDA SrD, short for Southgate-Rock outcrop complex (12–20% slopes), and its Average Elevation is 17.5 m, both of which mean that they are occasionally flooded. Its Pavement Condition rating is 2.0 (fair) given its measurements.



(a)   (b)

Fig. B8. Segment 2, Route 32 (Turpentine Road) (a) highlighted on road map and (b) overlayed on FEMA NFHL map.

Parameters and results of the two example road segments

Table B1
CDOT Method User and Owner Consequence Result for USVI Segments

	Route 30 (Veterans Drive)	Route 32 (Turpentine Road)
User Consequence parameters	Number of Full Closure Days: 3 (days) $AADT_{Vehicle}$ = 16,230 (vehicle/day) $AADT_{Truck}$ = 2161 (truck/day) Detour Distance = 6.8 miles, 27 min Truck Speed = 30 (mi/hour) Average Vehicle Occupancy = 1.77 (people/vehicle) Car Running Cost = 0.59 ($/vehicle-mile) Truck Running Cost = 0.96 ($/truck-mile) Average Value of Time = 10.62 ($/Adult-Hour) Average Value of Freight Driver Cost = 25.31 ($/Truck-Hour)	Number of Full Closure Days: 3 (days) $AADT_{Vehicle}$ = 8400 (vehicle/day) $AADT_{Truck}$ = 6300 (truck/day) Detour Distance = 9.3 miles, 26 min Truck Speed = 30 (mi/hour)
User Consequence 1 - Vehicle Operating Cost (VOC)	(Car Running Cost x $AADT_{Vehicle}$ + Truck Running Cost x $AADT_{Truck}$)x Number of Full Closure Days x (Detour Route Length - Original Route Length) = $188,734	(Car Running Cost x $AADT_{Vehicle}$ + Truck Running Cost x $AADT_{Truck}$)x Number of Full Closure Days x (Detour Route Length - Original Route Length) = $286,874
User Consequence 2 – Lost Wage (LW)	(Average Value of Time * Average Occupancy * AADT +Average Value of Freight Time * AADTT) * Number of Full Closure Days * Extra Travel Time = $194,279	(Average Value of Time * Average Occupancy * AADT +Average Value of Freight Time * AADTT) * Number of Full Closure Days * Extra Travel Time = $275,778
Owner Consequence Parameters	Number of Lanes: 4 Inundated Length = 1.4 (mile) Road Surface Area: 28,160 ($yard^2$/mile) Owner Unit Cost: 300 ($/$yard^2$) in St. Thomas * Clean Up Cost: 2.71 ($/$yard^2$) in St. Thomas * Roadway area per lane mile: 7040 (SY/lane-mile)	Number of Lanes: 2 Inundated Length = 0.61 (mile) Road Surface Area: 14,080 ($yard^2$/mile)
Owner Consequence	= Replacement Cost = (Owner Unit Cost + Clean Up Cost) * Road Area per Mile * Inundated Road Length (miles) = $ 11,934,039	= Replacement Cost = (Owner Unit Cost + Clean Up Cost)* Road Area per Mile * Inundated Length (miles) = $ 2,599,916

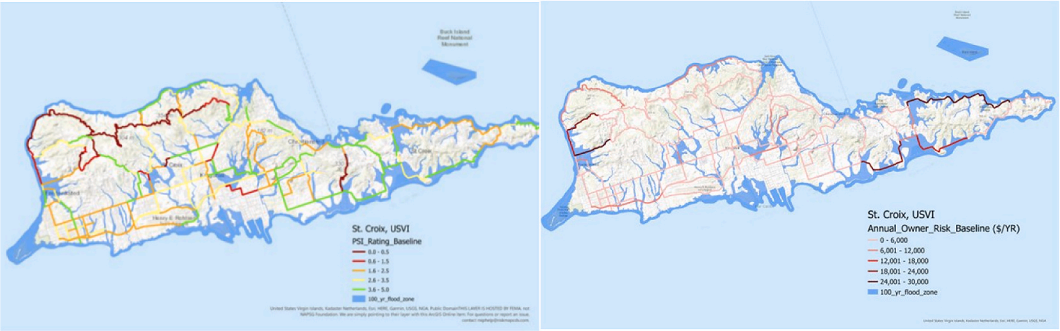
Appendix C. Network Level Risk Analysis Results for All Scenarios

Baseline

The baseline is used as a status quo to compare to other intervention or investment scenarios. Baseline miles-weighted average PSI rating and total annual owner risk are presented for each island and across the USVI in Table. C. 1 and Fig. C. 1 shows pavement condition and annual owner risk maps of the pavement system across St. Croix as an illustrative example. For each alternative maintenance scenario, the difference in annual owner risk from the baseline risk-savings from mitigating risk in each scenario compared to the status quo-is calculated as part of risk assessment for the USVI and individual islands' networks. Average network PSI ratings and pavement condition maps show the impacts of maintenance scenarios compared to this baseline.

Table C1
USVI Pavement Baseline for Alternative Maintenance Scenarios

	St. Croix	St. Thomas	St. John	USVI Total
Miles-Weighted Avg Network PSI Rating	2.81	3.45	3.86	3.12
Total Annual Owner Risk	$374,442	$204,725	$41,814	$616,981



(a) (b)

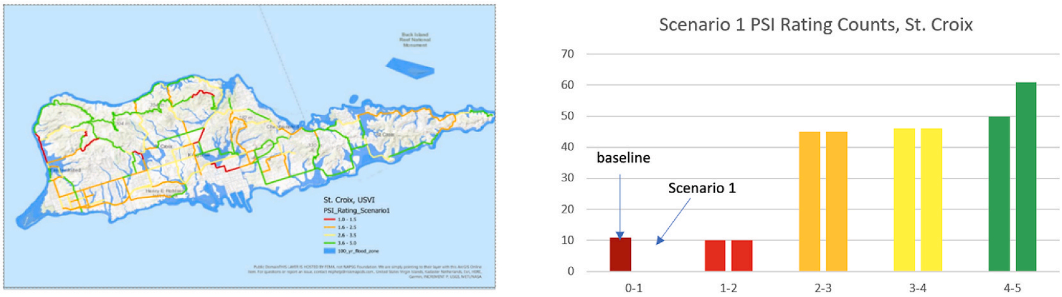
Fig. C1. St. Croix pavement baseline scenario maps: (a) PSI rating distribution and (b) annual owner risk.

Scenario 1

Scenario 1 states to perform only reconstruction for all pavements under PSI rating 1 (0 and 0.5) to raise the PSI to 5.

Table C2
USVI Pavement Alternative Scenario 1 Network Condition and Owner Risk

	St. Croix	St. Thomas	St. John	USVI Total
Investment	$70,285,837	$3,617,062	$1,939,036	$75,841,934
Miles-Weighted Avg Network PSI Rating	3.37	3.51	3.93	3.48
Total Annual Owner Risk	$369,559	$204,725	$41,814	$616,098
Annual Owner Risk Reduction	$4883	$0	$0	$4883



(a) (b)

Fig. C2. St. Croix pavement Scenario 1 PSI rating (a) distribution map and (b) distribution chart compared to baseline.

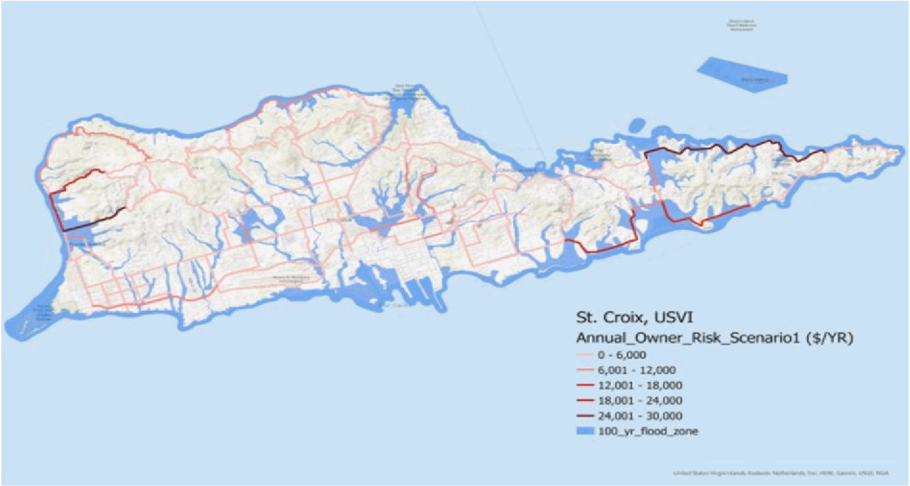


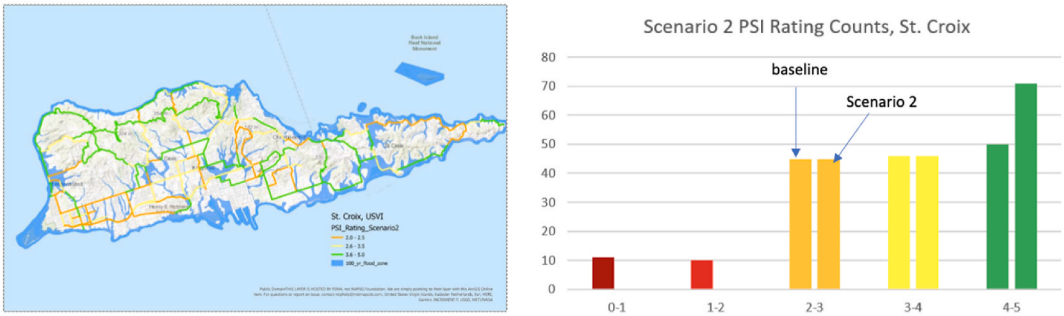
Fig. C3. St. Croix pavement Scenario 1 annual owner risk map.

Scenario 2

Scenario 2 states to perform reconstruction for all pavements under PSI rating 1 (0 and 0.5) to raise the PSI to 5 and conduct major rehabilitation for all pavements between PSI ratings 1–2 (1 and 1.5) to raise the PSI to 5.

Table C3
USVI Pavement Alternative Scenario 2 Network Condition and Owner Risk

	St. Croix	St. Thomas	St. John	USVI Total
Investment	$82,218,711	$5,479,655	$1,939,036	$89,637,402
Miles-Weighted Avg Network PSI Rating	3.57	3.54	3.93	3.61
Total Annual Owner Risk	$364,485	$204,290	$41,814	$610,588
Annual Owner Risk Reduction	$9957	$436	$0	$10,393



(a) (b)

Fig. C4. St. Croix pavement Scenario 2 PSI rating (a) distribution map and (b) distribution chart compared to baseline.

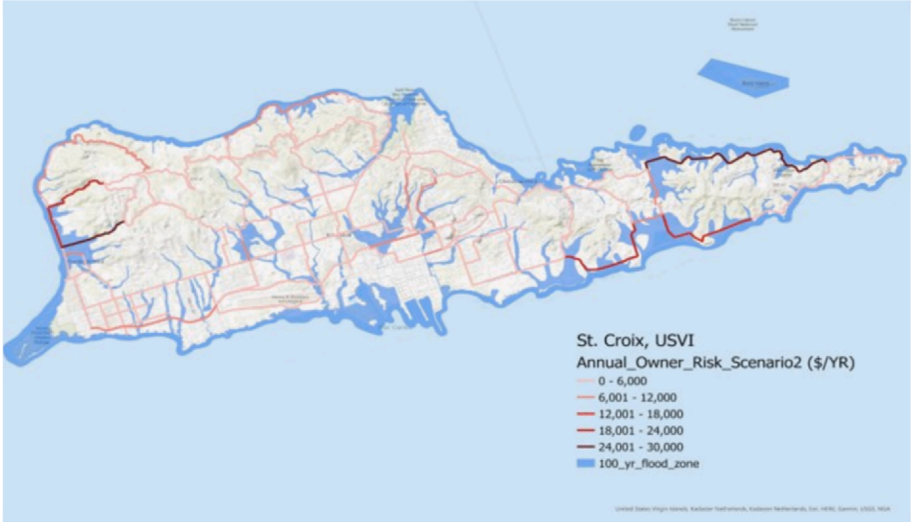


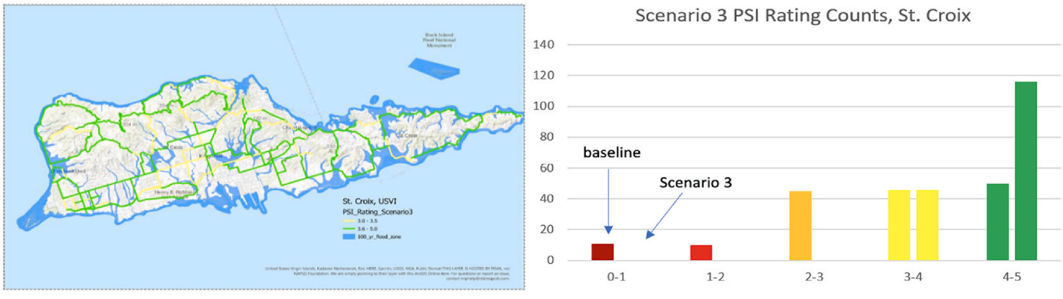
Fig. C5. St. Croix pavement Scenario 2 annual owner risk map.

Scenario 3

Scenario 3 states to perform reconstruction for all pavements under PSI rating 1 (0 and 0.5) to raise the PSI to 5, major rehabilitation for all pavements between PSI ratings 1–2 (1 and 1.5) to raise the PSI to 5, and minor rehabilitation for all pavements between PSI Ratings 2–3 (2 and 2.5) to raise the PSI to 5.

Table C4
USVI Pavement Alternative Scenario 3 Network Condition and Owner Risk

	St. Croix	St. Thomas	St. John	USVI Total
Investment	$129,771,038	$31,944,768	$6,857,996	$168,573,802
Miles-Weighted Avg Network PSI Rating	4.37	4.02	4.13	4.25
Total Annual Owner Risk	$342,759	$200,788	$40,897	$584,444
Annual Owner Risk Reduction	$31,683	$3938	$917	$36,537



(a) (b)

Fig. C6. St. Croix pavement Scenario 3 PSI rating (a) distribution map and (b) distribution chart compared to baseline.

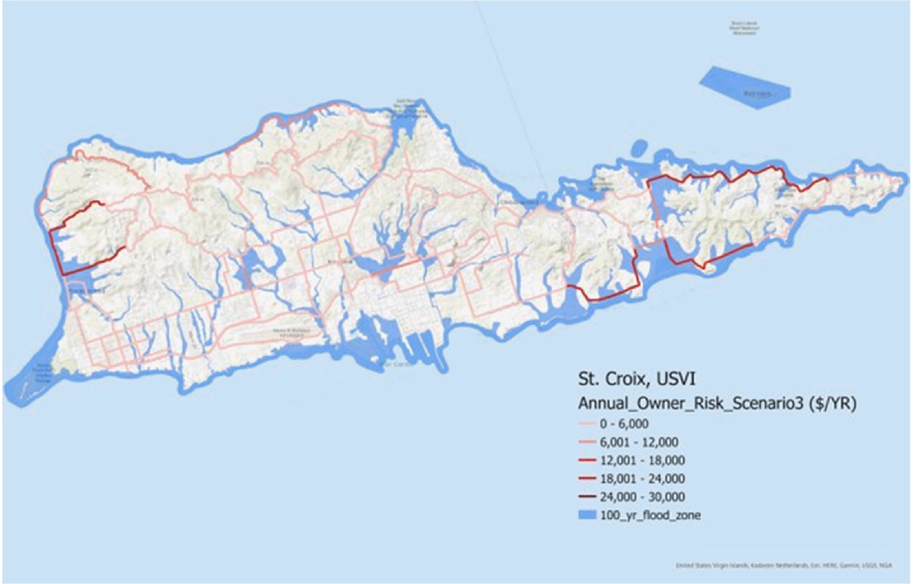


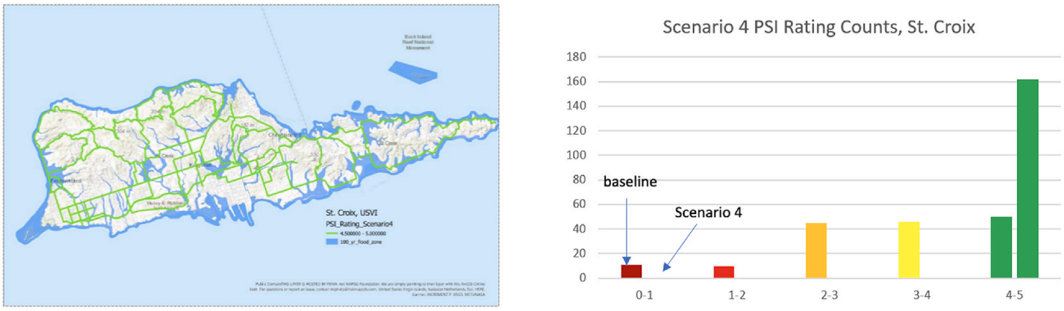
Fig. C7. St. Croix pavement Scenario 3 annual owner risk map.

Scenario 4

Scenario 4 states to perform reconstruction for all pavements under PSI rating 1 (0 and 0.5) to raise the PSI to 5, major rehabilitation for all pavements between PSI ratings 1–2 (1 and 1.5) to raise the PSI to 5, minor rehabilitation for all pavements between PSI Ratings 2–3 (2 and 2.5) to raise the PSI to 5, and preservation for all pavement between PSI rating 3–4.5 (3, 3.5 and 4) to raise PSI to 5.

Table C5
USVI Pavement Alternative Scenario 4 Network Condition and Owner Risk

	St. Croix	St. Thomas	St. John	USVI Total
Investment	$158,256,200	$61,559,342	$17,158,965	$236,974,507
Miles-Weighted Avg Network PSI Rating	4.99	4.93	4.94	4.96
Total Annual Owner Risk	$324,136	$188,295	$37,686	$550,116
Annual Owner Risk Reduction	$50,306	$16,431	$4128	$70,865



(a) (b)

Fig. C8. St. Croix pavement Scenario 4 PSI rating (a) distribution map and (b) distribution chart compared to baseline.

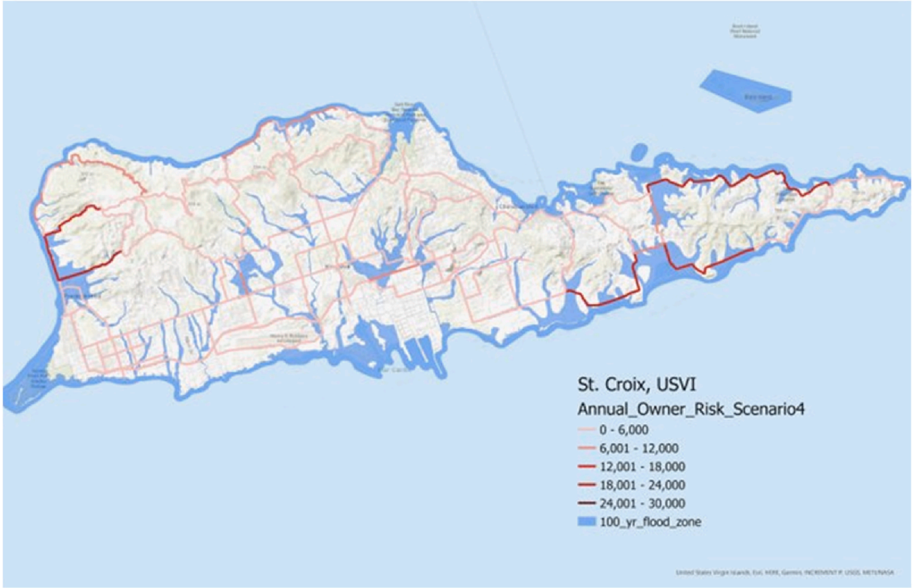


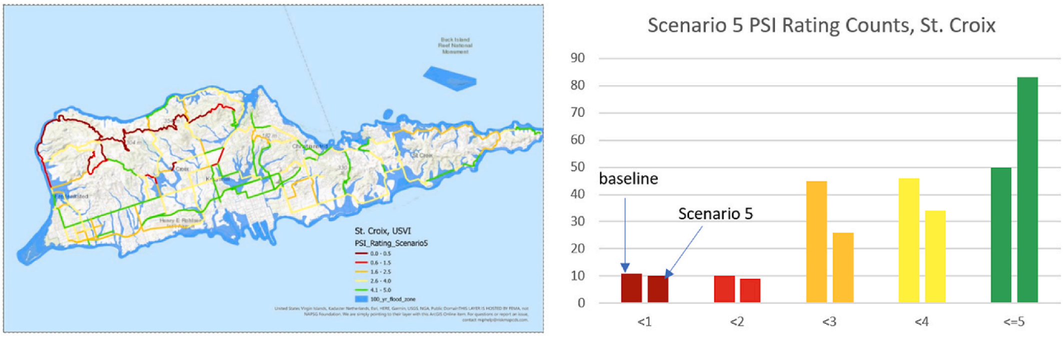
Fig. C9. St. Croix pavement Scenario 4 annual owner risk map.

Scenario 5

Scenario 5 states to perform reconstruction for selected pavements under PSI rating 1 (0 and 0.5) to raise PSI to 5, major rehabilitation for selected pavement between PSI ratings 1–2 (1 and 1.5) to raise the PSI to 5, and minor rehabilitation for selected pavements between PSI ratings 2–3 (2 and 2.5) to raise the PSI to 5.

Table C6
USVI Pavement Alternative Scenario 5 Network Condition and Owner Risk

	St. Croix	St. Thomas	St. John	USVI Total
Investment	$32,112,363	$21,509,553	$3,125,288	$56,757,145
Miles-Weighted Avg Network PSI Rating	3.35	3.99	4.14	3.62
Total Annual Owner Risk	$363,340	$196,948	$41,814	$602,102
Annual Owner Risk Reduction	$11,102	$7777	$0	$18,879



(a) (b)

Fig. C10. St. Croix pavement Scenario 5 PSI rating (a) distribution map and (b) distribution chart compared to baseline.

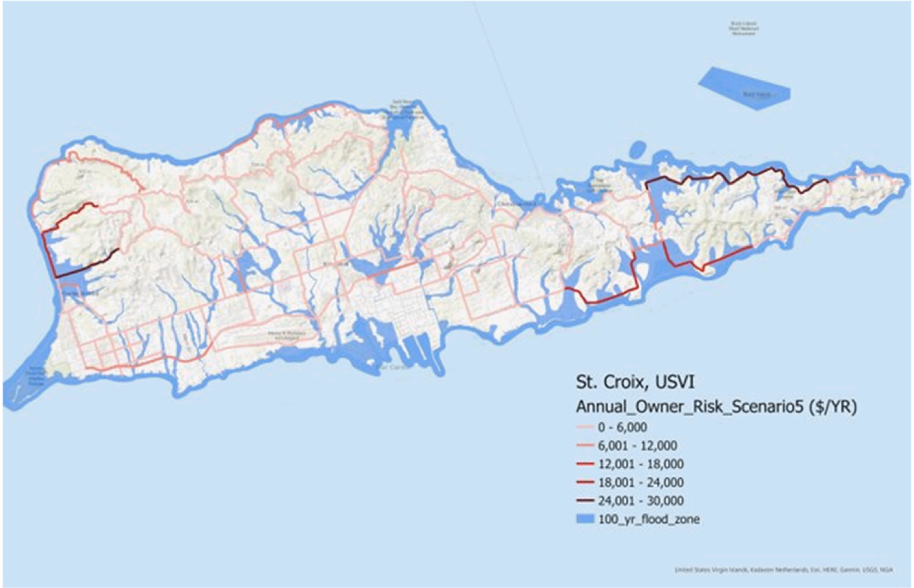


Fig. C11. St. Croix pavement Scenario 5 annual owner risk map.

Appendix D. Economic Impact Analysis Results for All Scenarios

Scenario 1

Scenario 1 consists of pavement reconstruction for roads with a PSI of 0–0.5. Table D. 1 shows the breakdown for crash savings and Table D. 2 shows the breakdown for wear and tear savings for St. Croix, St. Thomas, and St. John.

Table D1
Roadway Intervention Scenario 1 Crash Savings Breakdown

Items	St. Croix	St. Thomas	St. John	USVI Total	Savings
Fatalities	$16,776,454	$11,025,425	$0	$27,801,879	$1,687,088
Injuries	$23,765,138	$22,389,089	$898,305	$47,052,532	$2,508,947
Private Property	$1,149,822	$1,547,372	$56,506	$2,753,700	$127,858
Total Crash Costs	$41,691,006	$34,961,886	$954,811	**$77,608,111**	**$4,323,893**

Table D2
Roadway Intervention Scenario 1 Wear and Tear Savings Breakdown

PSI	St. Croix		St. Thomas		St. John		Total additional Wear and Tear Cost
	Percent of Daily Vehicle miles traveled	Additional Wear and Tear Cost	Percent of Daily Vehicle miles traveled	Additional Wear and Tear Cost	Percent of Daily Vehicle miles traveled	Additional Wear and Tear Cost	
0–2	16%	$4,102,043	12%	$1,927,966	3%	$51,777	$6,081,786
2.5	20%	$3,117,909	7%	$716,279	3%	$25,784	$3,859,972
3	18%	$954,635	26%	$842,006	36%	$110,919	$1,907,560
3.5–5	46%	$0	55%	$0	58%	$0	$0
Total cost	100%	$8,174,587	100%	$3,486,251	100%	$188,480	$11,849,318
Saving cost	–	$1,275,624	–	$112,399	–	$3054	**$1,391,077**

For Scenario 1, the total savings from crashes are $4,323,893 and wear and tear are $1,391,077. This makes the overall savings $$5,714,970. Because $75,841,938 is the amount invested when scenario 1 occurs, the ROI (return on investment) is 0.08 in total, with the ROI for crash and wear and tear being 0.02 and 0.06 respectively.

Scenario 2

Scenario 2 consists of major pavement rehabilitation for roads with a PSI of 1.0–1.5, in addition to scenario 1 (reconstruction of roads with a PSI 0–0.5). Table D. 3 shows the breakdown for crash savings and Table D. 4 shows the breakdown for wear and tear savings for St. Croix, St. Thomas, and St. John.

Table D3
Roadway Intervention Scenario 2 Crash Savings Breakdown

Items	St. Croix	St. Thomas	St. John	USVI Total	Savings
Fatalities	$16,315,822	$10,781,208	$0	$27,097,030	$2,391,937
Injuries	$23,112,617	$21,893,164	$898,305	$45,904,086	$3,657,393
Private Property	$1,118,251	$1,513,097	$55,609	$2,686,958	$194,600
Total Crash Costs	$40,546,690	$34,187,469	$953,914	**$75,688,074**	**$6,243,930**

Table D4
Roadway Intervention Scenario 2 Wear and Tear Savings Breakdown

PSI	St. Croix		St. Thomas		St. John		Total additional Wear and Tear Cost
	Percent of Daily Vehicle miles traveled	Additional Wear and Tear Cost	Percent of Daily Vehicle miles traveled	Additional Wear and Tear Cost	Percent of Daily Vehicle miles traveled	Additional Wear and Tear Cost	
0–2	14%	$3,714,146	11%	$1,765,842	3%	$51,777	$5,531,765
2.5	20%	$3,117,909	7%	$716,279	3%	$25,784	$3,859,972
3	18%	$954,635	26%	$842,006	36%	$110,919	$1,907,560
3.5–5	47%	$0	56%	$0	58%	$0	$0
Total cost	99%	$7,786,690	100%	$3,324,127	100%	$188,480	$11,299,297
Saving cost	–	$1,663,521	–	$274,523	–	$3054	**$1,941,098**

For Scenario 2, the total savings from crashes are $6,243,93046,851,323 and wear and tear are $1,941,098. This makes the overall savings $8,185,02858,184,157. Because $89,637,403168,573,804 is the amount invested for scenario 2, the ROI (return on investment) is 0.09 in total, with the ROI for crash and wear and tear being 0.07 and 0.02 respectively.

Scenario 3

Scenario 3 consists of minor pavement rehabilitation for roads with a PSI of 2–2.5, in addition to scenario 2.

Table D. 5 shows the breakdown for crash savings and Table D. 6 shows the breakdown for wear and tear savings for St. Croix, St. Thomas, and St. John.

Table D5
Roadway Intervention Scenario 3 Crash Savings Breakdown

Items	St. Croix	St. Thomas	St. John	USVI Total	Savings
Fatalities	$5,690,775	$6,346,272	$0	$12,037,047	$17,451,920
Injuries	$8,061,421	$12,887,236	$766,803	$21,715,460	$27,846,020
Private Property	$390,033	$890,673	$47,469	$1,328,175	$1,553,383
Total Crash Costs	$14,142,229	$20,124,181	$814,272	**$35,080,682**	**$46,851,323**

Table D6
Roadway Intervention Scenario 3 Wear and Tear Savings Breakdown

PSI	St. Croix		St. Thomas		St. John		Total additional Wear and Tear Cost
	Percent of Daily Vehicle miles traveled	Additional Wear and Tear Cost	Percent of Daily Vehicle miles traveled	Additional Wear and Tear Cost	Percent of Daily Vehicle miles traveled	Additional Wear and Tear Cost	
0–2	0%	$0	0%	$0	0%	$0	$0
2.5	0%	$0	0%	$0	0%	$0	$0
3	18%	$954,635	26%	$842,006	36%	$110,919	$1,907,560
3.5–5	82%	$0	74%	$0	64%	$0	$0
Total cost	100%	$954,635	100%	$842,006	100%	$110,919	$1,907,560
Saving cost	–	$8,495,576	–	$2,756,644	–	$80,614	**$11,332,834**

For Scenario 3, the total savings from crashes are $ 46,851,323 and wear and tear are $11,332,834. This makes the overall savings $ 58,184,157. Because $168,573,804 is the amount invested for scenario 3, the ROI (return on investment) is 0.35 in total, with the ROI for crash and wear and tear being 0.28 and 0.07 respectively.

Scenario 4

Scenario 4 consists of pavement preservation for roads with a PSI of 3–4, in addition to scenario 3. Table D. 7 shows the breakdown for crash savings and Table D. 8 shows the breakdown for wear and tear savings for St. Croix, St. Thomas, and St. John.

Table D7
Roadway Intervention Scenario 4 Crash Savings Breakdown*

	St. Croix	St. Thomas	St. John	USVI Total	Savings
Fatalities	$0	$0	$0	$0	$29,488,967
Injuries	$0	$0	$0	$0	$49,561,479
Private Property	$0	$0	$0	$0	$2,881,558
Total Crash Costs	$0	$0	$0	$0	**$81,932,004**

Table D8
Roadway Intervention Scenario 4 Wear and Tear Savings Breakdown*

PSI	St. Croix		St. Thomas		St. John		Total additional Wear and Tear Cost
	Percent of Daily Vehicle miles traveled	Additional Wear and Tear Cost	Percent of Daily Vehicle miles traveled	Additional Wear and Tear Cost	Percent of Daily Vehicle miles traveled	Additional Wear and Tear Cost	
0–2	0%	$0	0%	$0	0%	$0	$0
2.5	0%	$0	0%	$0	0%	$0	$0
3	0%	$0	0%	$0	0%	$0	$0
3.5–5	100%	$0	100%	$0	100%	$0	$0
Total cost	100%	$0	100%	$0	100%	$0	$0
Saving cost	–	$9,450,211	–	$3,598,650	–	$191,534	**$13,240,395**

For Scenario 4, the total savings from crashes are $81,932,004 and wear and tear are $13,240,394. This makes the overall savings $95,172,399. Because $236,974,508 is the amount invested for scenario 4, the ROI (return on investment) is 0.40 in total, with the ROI for crash and wear and tear being 0.35 and 0.06 respectively.

*Note: The crash savings and wear and tear savings are $0 given that this scenario is the best case for crashes and wear and tear (all pavement is brought to PSI level of 5), so we can assume that the agency has already done everything it can to improve the pavement to the best condition possible. Therefore, these costs cannot be reduced any further through maintenance, and are effectively zero.

Scenario 5

Scenario 5 consists of targeted pavement prioritization for roads with a PSI of 3 or less and above average usage. Table D. 9 shows the breakdown for crash savings and Table D. 10 shows the breakdown for wear and tear savings for St. Croix, St. Thomas, and St. John.

Table D9
Roadway Intervention Scenario 5 Crash Savings Breakdown

	St. Croix	St. Thomas	St. John	USVI Total	Savings
Fatalities	$5,758,719	$3,630,252	$0	$9,388,972	$20,099,995
Injuries	$8,157,669	$7,371,874	$356,375	$15,885,918	$33,675,561
Private Property	$394,690	$509,491	$22,061	$926,242	$1,955,316
Total Crash Costs	$14,311,079	$11,511,617	$378,436	$26,201,132	**$55,730,872**

Table D10
Roadway Intervention Scenario 5 Wear and Tear Savings Breakdown

PSI	St. Croix		St. Thomas		St. John		Total additional Wear and Tear Cost
	Percent of Daily Vehicle miles traveled	Additional Wear and Tear Cost	Percent of Daily Vehicle miles traveled	Additional Wear and Tear Cost	Percent of Daily Vehicle miles traveled	Additional Wear and Tear Cost	
0–2	7%	$1,936,675	4%	$675,142	4%	$54,830	$2,666,647
2.5	7%	$1,151,236	3%	$339,345	3%	$25,784	$1,516,365
3	4%	$193,455	7%	$254,209	10%	$31,759	$479,423
3.5–5	82%	$0	86%	$0	83%	$0	$0
Total cost	100%	$3,281,366	100%	$1,268,696	100%	$112,373	$4,662,435
Saving cost	–	$6,168,846	–	$2,329,954	–	$79,160	**$8,577,960**

For Scenario 5, the total savings from crashes are $ 55,730,872 and wear and tear are $8,577,960. This makes the overall savings $ 64,308,832. Because $56,408,684 is the amount invested for scenario 5, the ROI (return on investment) is 1.14 in total, with the ROI for crash and wear and tear being 0.99 and 0.15 respectively.

References

Ahmed, S., Dey, K., 2020. Resilience modeling concepts in transportation systems: a comprehensive review based on mode, and modeling techniques. J. Infrastruct. Preserv. Resil. 1, 8. https://doi.org/10.1186/s43065-020-00008-9.

Ahmed, N., Howlader, N., Hoque, M.A.-A., Pradhan, B., 2021. Coastal erosion vulnerability assessment along the eastern coast of Bangladesh using geospatial techniques. Ocean Coast Manag. 199, 105408 https://doi.org/10.1016/j.ocecoaman.2020.105408.

Akiyama, M., Frangopol, D.M., Ishibashi, H., 2020. Toward life-cycle reliability-, risk-and resilience-based design and assessment of bridges and bridge networks under independent and interacting hazards: emphasis on earthquake, tsunami and corrosion. Struct. Infrastruct. Eng. 16, 26–50.

Alam, F., Ofli, F., Imran, M., Aupetit, M., 2018. A Twitter Tale of Three Hurricanes: Harvey, Irma, and Maria. ArXiv Prepr. ArXiv180505144.

Alhasan, A.A., 2021. Investment strategies under uncertainty for transportation asset management. In: International Conference on Transportation and Development 2021. Presented at the International Conference on Transportation and Development 2021. American Society of Civil Engineers, Virtual Conference, pp. 133–144. https://doi.org/10.1061/9780784483541.013.

Alshboul, O., Shehadeh, A., Hamedat, O., 2021. Development of integrated asset management model for highway facilities based on risk evaluation. Int. J. Constr. Manag. 1–10.

Argyroudis, S.A., Mitoulis, S.A., Winter, M.G., Kaynia, A.M., 2019. Fragility of transport assets exposed to multiple hazards: state-of-the-art review toward infrastructural resilience. Reliab. Eng. Syst. Saf. 191, 106567.

Asadabadi, A., Miller-Hooks, E., 2017a. Assessing strategies for protecting transportation infrastructure from an uncertain climate future. Transport. Res. Part Policy Pract. 105, 27–41.

Asadabadi, A., Miller-Hooks, E., 2017b. Optimal transportation and shoreline infrastructure investment planning under a stochastic climate future. Transp. Res. Part B Methodol. 100, 156–174.

Audère, M., Robin, M., 2021. Assessment of the vulnerability of sandy coasts to erosion (short and medium term) for coastal risk mapping (Vendée, W France). Ocean Coast Manag. 201, 105452 https://doi.org/10.1016/j.ocecoaman.2020.105452.

Aydin, N.Y., Duzgun, H.S., Heinimann, H.R., Wenzel, F., Gnyawali, K.R., 2018. Framework for improving the resilience and recovery of transportation networks under geohazard risks. Int. J. Disaster Risk Reduc. 31, 832–843.

Bom, P.R., Ligthart, J.E., others, 2009. How Productive Is Public Capital? A Meta-regression Analysis (Georgia State Univ., Andrew Young School of Policy Studies).

Brashear, J.P., Jones, J.W., 2010. Risk analysis and management for critical asset protection (RAMCAP plus). Wiley Handb. Sci. Technol. Homel. Secur. 2, 1–15.

Cartes, P., Echaveguren Navarro, T., Giné, A.C., Binet, E.A., 2021. A cost-benefit approach to recover the performance of roads affected by natural disasters. Int. J. Disaster Risk Reduc. 53, 102014 https://doi.org/10.1016/j.ijdrr.2020.102014.

Das Neves, L., Bolle, A., De Nocker, L., 2023. Cost-benefit-analysis of coastal adaptation strategies and pathways. A case study in West Africa. Ocean Coast Manag. 239, 106576 https://doi.org/10.1016/j.ocecoaman.2023.106576.

Davis, J.R., 2002. Soil Survey of the United States Virgin Islands.

Department of Transportation, Colorado, 2020. Risk and Resilience Analysis Procedure: A Manual for Calculating Risk to CDOT Assets from Flooding, Rockfall, and Fire Debris Flow. Colorado Department of Transportation.

England, Highways, 2016. Climate Adaptation Risk Assessment Progress Update-2016. Highways England.

Esmalian, A., Yuan, F., Rajput, A.A., Farahmand, H., Dong, S., Li, Q., Gao, X., Fan, C., Lee, C.-C., Hsu, C.-W., others, 2022. Operationalizing resilience practices in transportation infrastructure planning and project development. Transport. Res. Part Transp. Environ. 104, 103214.

Fhwa, 2012. Climate Change and Extreme Weather Vulnerability Assessment Framework. Federal Highway Administration, US Department of Transportation.

Fhwa, 2016. Asset management plans and periodic evaluations of facilities repeatedly requiring repair and reconstruction due to emergency events. Fed. Regist. 81, 73196–73268.

Filosa, G., Plovnick, A., Stahl, L., Miller, R., Pickrell, D.H., 2017. Vulnerability Assessment and Adaptation Framework, third ed.

Flannery, A., 2017. I-70 Corridor Risk & Resilience Pilot: Final Report. Colorado Department of Transportation.

Gu, Y., Fu, X., Liu, Z., Xu, X., Chen, A., 2020. Performance of transportation network under perturbations: reliability, vulnerability, and resilience. Transport. Res. Part E Logist. Transp. Rev. 133, 101809 https://doi.org/10.1016/j.tre.2019.11.003.

Hinkel, J., Aerts, J.C.J.H., Brown, S., Jiménez, J.A., Lincke, D., Nicholls, R.J., Scussolini, P., Sanchez-Arcilla, A., Vafeidis, A., Addo, K.A., 2018. The ability of societies to adapt to twenty-first-century sea-level rise. Nat. Clim. Change 8, 570–578. https://doi.org/10.1038/s41558-018-0176-z.

Hughes, J.F., Healy, K., 2014. Measuring the Resilience of Transport Infrastructure.

Inkoom, S., Sobanjo, J.O., 2019. Competing risks models for the deterioration of highway pavement subject to hurricane events. Struct. Infrastruct. Eng. 15, 837–850. https://doi.org/10.1080/15732479.2019.1581229.

Islam, S., Buttlar, W.G., 2012. Effect of pavement roughness on user costs. Transp. Res. Rec. J. Transp. Res. Board 2285, 47–55. https://doi.org/10.3141/2285-06.

Jr, N.P., 2018. Investigation of Causes and Extent of Storm Damage to Roads Due to Hurricanes Irma and Maria and Recommendations for Repair.

Khodeir, L.M., Nabawy, M., 2019. Identifying key risks in infrastructure projects – case study of Cairo Festival City project in Egypt. Ain Shams Eng. J. 10, 613–621. https://doi.org/10.1016/j.asej.2018.11.003.

Koks, E.E., Rozenberg, J., Zorn, C., Tariverdi, M., Vousdoukas, M., Fraser, S., Hall, J., Hallegatte, S., 2019. A global multi-hazard risk analysis of road and railway infrastructure assets. Nat. Commun. 10, 1–11.

Le Xuan, T., Ba, H.T., Thanh, V.Q., Wright, D.P., Hasan Tanim, A., Tran Anh, D., 2022. Evaluation of coastal protection strategies and proposing multiple lines of defense under climate change in the Mekong Delta for sustainable shoreline protection. Ocean Coast Manag. 228, 106301 https://doi.org/10.1016/j.ocecoaman.2022.106301.

Lee, J., Noya, L., Ramanujam, J., 2016. Pavement treatments and lessons learnt from the flood reconstruction work in the Transport Network Reconstruction Program (TNRP) in Queensland. In: ARRB Conference, 27th, 2016 (Melbourne, Victoria, Australia).

Lei, X., Xia, Y., Dong, Y., Sun, L., 2022. Multi-level time-variant vulnerability assessment of deteriorating bridge networks with structural condition records. Eng. Struct. 266, 114581 https://doi.org/10.1016/j.engstruct.2022.114581.

Liu, Y., McNeil, S., 2020. Using resilience in risk-based asset management plans. Transp. Res. Rec. J. Transp. Res. Board 2674, 178–192. https://doi.org/10.1177/0361198120912239.

Mallick, R.B., Tao, M., Daniel, J.S., Jacobs, J., Veeraragavan, A., 2017. Development of a methodology and a tool for the assessment of vulnerability of roadways to flood-induced damage: vulnerability of roadways to flood-induced damage. J. Flood Risk Manag. 10, 301–313. https://doi.org/10.1111/jfr3.12135.

McBean, G., 2004. Climate change and extreme weather: a basis for action. Nat. Hazards 31, 177–190. https://doi.org/10.1023/B:NHAZ.0000020259.58716.0d.

Nlenanya, I., Smadi, O., 2018. Risk management and data needs: a state of the practice survey of state highway agencies. Transport. Res. Rec. 2672, 55–61.

Nlenanya, I., Smadi, O., 2021. A risk management database framework implementation for transportation asset management. CivilEng 2, 193–213.

Noaa, n.d. Sea Level Rise Viewer [WWW Document]. Sea Level Rise Viewer. URL. https://coast.noaa.gov/slr/.

Office of Asset Management, 1999. Risk-Asset Management Primer. Office of Asset Management, U.S. Department of Transportation, Federal Highway Administration.

Office of Asset Management, 2013. Risk-Based Transportation Asset Management: Building Resilience into Transportation Assets: Report 5: Managing External Threats through Risk-Based Asset Management. Office of Asset Management, U.S. Department of Transportation, Federal Highway Administration.

Poo, M.C.-P., Yang, Z., Dimitriu, D., Qu, Z., Jin, Z., Feng, X., 2021. Climate change risk indicators (CCRI) for seaports in the United Kingdom. Ocean Coast Manag. 205, 105580 https://doi.org/10.1016/j.ocecoaman.2021.105580.

Renne, J., Wolshon, B., Murray-Tuite, P., Pande, A., 2020. Emergence of resilience as a framework for state Departments of Transportation (DOTs) in the United States. Transport. Res. Part Transp. Environ. 82, 102178 https://doi.org/10.1016/j.trd.2019.11.007.

Rioja, F., 2013. What is the value of Infrastructure Maintenance? A Survey. Infrastruct. Land Policies 13, 347–365.

Rose, A., Krausmann, E., 2013. An economic framework for the development of a resilience index for business recovery. Int. J. Disaster Risk Reduc. 5, 73–83.

Rowan, E., Snow, C., Choate, A., Rodehorst, B., Asam, S., Hyman, R., Kafalenos, R., Gye, A., 2014. Indicator approach for assessing climate change vulnerability in transportation infrastructure. Transp. Res. Rec. J. Transp. Res. Board 2459, 18–28. https://doi.org/10.3141/2459-03.

Saha, P., Ksaibati, K., 2016. A risk-based optimisation methodology for pavement management system of county roads. Int. J. Pavement Eng. 17, 913–923.

Salem, S., Siam, A., El-Dakhakhni, W., Tait, M., 2020. Probabilistic resilience-guided infrastructure risk management. J. Manag. Eng. 36, 04020073 https://doi.org/10.1061/(ASCE)ME.1943-5479.0000818.

Seyedshohadaie, S.R., Damnjanovic, I., Butenko, S., 2010. Risk-based maintenance and rehabilitation decisions for transportation infrastructure networks. Transport. Res. Part Policy Pract. 44, 236–248.

Soltani-Sobh, A., Heaslip, K., El Khoury, J., 2015. Estimation of road network reliability on resiliency: an uncertain based model. Int. J. Disaster Risk Reduc. 14, 536–544.

The Port Authority of New York and New Jersey, 2018. Climate Resilience Design Guidelines.

Virgin Islands Office of Highway, 2019. Safety Fiscal Year 2019 Annual Report (Virgin Islands Office of Highway).

Vugrin, E.D., Warren, D.E., Ehlen, M.A., Camphouse, R.C., 2010. A framework for assessing the resilience of infrastructure and economic systems. In: Sustainable and Resilient Critical Infrastructure Systems. Springer, pp. 77–116.

Youn, B.D., Hu, C., Wang, P., 2011. Resilience-driven System Design of Complex Engineered Systems.

Zaloshnja, E., Miller, T.R., 2009. Cost of crashes related to road conditions, United States, 2006. In: Annals of Advances in Automotive Medicine/Annual Scientific Conference. Association for the Advancement of Automotive Medicine, p. 141.

Zhang, C., Yin, K., Shi, X., Yan, X., 2021. Risk assessment for typhoon storm surges using geospatial techniques for the coastal areas of Guangdong, China. Ocean Coast Manag. 213, 105880 https://doi.org/10.1016/j.ocecoaman.2021.105880.