

Article

# Greening Roadway Infrastructure with Vetiver Grass to Support Transportation Resilience

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**Abstract:** With flooding and other weather events intensifying, more cost-effective erosion and flood control systems are needed. Vetiver (*Chrysopogon zizanioides* (L.) Roberty), is part of an arsenal of sustainable, low cost, and green infrastructure tools to reduce the risks of erosion, landslides, and flooding. This study investigates vetiver and its broader application to transportation planning. Based on a literature review and interviews with experts, vetiver as a green infrastructure tool is summarized. An evaluation framework was devised in which the plant's effectiveness to stabilize hillsides and manage stormwater is investigated. This framework is applied to a recent highway flooding case where vetiver could have been used. While site-specific conditions and roadway requirements are critical to its effectiveness as a mitigation tool, additional pathways to understanding, acceptance, and use of vetiver to support transportation resilience requires convergence in engineering, design, and planning disciplines. Understanding barriers to the adoption of vetiver will also support efforts to increase other green infrastructure tools in transportation planning. Improvements in policies, standards, guidance and training and education on vetiver and green infrastructure will support the mitigation of transportation disruptions and community resilience.



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**Keywords:** transportation planning; resilience; flooding; green infrastructure; vetiver

## 1. Introduction

In this paper, barriers, opportunities, and benefits of vetiver grass as a form of green infrastructure and hazard mitigation tool to reduce risks of flooding and erosion on transportation infrastructure are investigated. The topic is relevant to transportation planning and engineering because of the growing interest in nature-based solutions to combat extreme events due to climate change, which have increased the disruption, costs, and impacts on transportation systems [1,2]. This research is also linked to stormwater management, low-impact development, and urban planning [3–6]. The approach may also be applied to landslide risk reduction, especially in the tropics [7]. The intent of the paper is to focus both on vetiver and its broader considerations related to transportation planning. The research contributes to understanding the barriers to adaptation in transportation agencies within the United States [8,9].

The paper is structured as follows. First, the results of the literature review are summarized. Next, insights based on interviews with experts in engineering, landscape architecture, and planning are described. Following the identification of issues and concerns from the literature review and interviews, an evaluative framework is developed. This checklist provides factors and considerations for evaluating the use of vetiver in transportation planning and engineering within the United States. The framework is then applied to a recent flooding and landslide case study to better understand the opportunities and barriers to implementation. The concluding section identifies the limitations of the study

and plan for further research, development, testing, training and education, and capacity building on the use of vetiver.

## 2. Materials and Methods

A literature review was conducted to understand vetiver's broader considerations related to transportation planning, the benefits and costs, and the barriers (physical, institutional, economic, political, and socio-cultural) preventing its usage within the United States (along with the opportunities).

The issues and concerns of using vetiver were investigated by conducting open ended interviews and interactions with biologists, engineers, planners, landscape architects, and practitioners who have used vetiver as a green infrastructure tool. Interviewees were consulted in person, by telephone, and by email in July 2021 with questions tailored to information needs and gaps in the published literature (see acknowledgements and Appendix A). Interviews were then transcribed and summarized. The purpose of the interviews is to extend the knowledge of practice and understanding of the overarching barriers and constraints to implementation of vetiver and green infrastructure in general. The literature review and feedback from the interviews were used to develop an evaluative framework for using vetiver in transportation projects. A case study of a recent flood and landslide disaster was conducted using the framework to investigate whether vetiver is an optimal solution for future disaster preparedness and risk reduction, but to also show how the framework can be applied to other case studies.

Community workshops were also used to discuss and deliberate flood disaster recovery with vetiver and other green infrastructure tools as strategies for flood risk reduction. These interactions with diverse stakeholders helped to identify issues and concerns as well as strategies for implementation. Interviewees had diverse backgrounds and experiences working on structural and non-structural mitigation projects, including the use of vetiver and other green infrastructure tools. Comments from the workshops were documented by the research team from the National Disaster Preparedness Training Center (NDPTC).

## 3. Results

### 3.1. Literature Review

#### 3.1.1. Background

Urbanization is increasing globally, destroying the natural environment, and resulting in significant land-use changes, which has reduced ecosystem services and increased the risks of flooding and its negative impacts [10]. Changes in land use include larger residential and commercial development, along with an increase in the paving of streets, sidewalks, and parking lots. The increase in impervious surfaces exacerbates the flow and volume of stormwater runoff [11], increasing coastal erosion caused by sea-level rise and weakening of natural defenses, such as beaches, dunes, and buffer zones [12,13].

Increased urbanization with greater intensity and duration of storms have also resulted in more landslides and flooding, blocked roadways, damaged bridges, and disruption to emergency services, evacuation, and mobility [14,15]. Functional transportation networks are essential for response and recovery [16]. Thus, there is an increased need for new approaches and strategies to cope with transportation disruptions [1,15] and to improve resilience in high-risk locations, such as the tropics [7].

An underused solution, especially in the United States, is the use of vetiver grass to increase transportation resilience. There are limited references to its use in transportation planning and engineering. There are also few standards, guidance, references, and training on how to plant, maintain, and use it to control erosion and flooding [8].

#### 3.1.2. What Is Vetiver?

Vetiver (*Chrysopogon zizanioides* (L.) Roberty) is a non-woody grass of the Poaceae family, native to tropical Asia. It is a large, tufted bunchgrass with thin, rigid blades that can reach heights of up to 1.5 m (five feet). The name comes from the Tamil language,

meaning “root” because of its long, fragrant roots, which can grow downwards to three meters (10 feet) (Figure 1).



**Figure 1.** Vetiver with extensive roots for anchoring soil [17].

It has been widely grown in India and Southeast Asian countries [18–21]. With erosion control and soil conservation being one of the many reasons this plant has been used [18–20,22,23]. Other uses include agriculture to control drainage and irrigation in order to buffer crops [19]. Vetiver is a sturdy, low cost, low maintenance plant that is drought tolerant and fire-resistant [18,19]

### 3.1.3. How Vetiver Is Used and Cultivated

Vetiver has been used for ecological engineering and environmental restoration. It has been cultivated to be environmentally friendly, because it is sterile, non-aggressive, non-invasive, and can grow in a wide range of climatic conditions. The roots can secure soil at deep depths with strength, making it extremely useful for slope stabilization, as it has been widely recognized that root reinforcement is a major component for slope stability [24]. Because of these properties, it has been called the “soil nail” or “living nail” [18–20,23,25–29] (p. 13). Furthermore, the plant is also resistant to flooding and can protect agriculture during heavy rainfall [27].

### Essential Oils and Other Uses

In Asia and Africa, vetiver has been used for essential oils in medicine, cosmetics, toiletries, perfumes, soaps, soft drinks, pan masala (a mixture of herbs and seeds used to freshen breath after meals), and aromatherapy. The aromatic oils used for aromatherapy relieve stress, anxiety, and insomnia. It has also been used in India to treat various ailments, diseases, and disorders. In addition, the plant material was used to make screens, mats, baskets, and other household goods. The pulp can make paper, and the stems for brooms and roof thatching [20].

### Agricultural Applications

Vetiver is used in farming for irrigation and drainage control, erosion management, mulching, pest control, and remediation of contaminated soils [18,20–23,25,27,28]. It has also been used to improve soils, increase productivity, and support livelihoods in rural areas [22,27].

Properly installed vetiver can reduce soil erosion by approximately 90% and prevent soil slippage and landslides in hilly locations [20,26].

The stalks and roots of vetiver absorb water, increase surface areas and friction to capture, direct, and slow the velocity of stormwater runoff [27,30]. Planted in rows, vetiver hedges can reduce runoff by approximately 70% [27]. Its deep roots and thick growth can also protect grey infrastructure, such as dams or dikes [25,27,28,30]. There have also been advances in the use of biostimulants, soil amendments, and other additives to improve soil structure and reduce the impacts of rainfall, sheet, and rill erosion [31].

Beyond agricultural applications, when investigated in Hawai'i, vetiver has been found to be used for hillside stabilization in Hawai'i County, installed in projects at the Pacific Missile Range Facility on Kaua'i, and placed on golf courses in Maui [32]. Vetiver has also been used for the Kamananui Road project in Wahiawa on O'ahu through the Mālama i ka wai initiative [33].

#### 3.1.4. A Green Infrastructure Tool

Planting vetiver is a nature-based solution for protecting and restoring the environment from natural and human-induced hazards such as pollution, greenhouse gases, and urbanization [19,20,34]. It also provides multiple benefits (social, economic, and biophysical), resilience and sustainability to the effect of climate change, and low-cost for implementation [35,36]. Compared to traditional grey infrastructure (i.e., concrete and other conventional aggregate materials), vetiver is much less harmful to the environment [27]. It can also be used to protect and stabilize traditional engineered systems, prolonging their lifespan and reduce the need for new construction or extensive remediation of existing structures [27]. Green approaches in general need to be integrated with conventional engineering and construction practices to support innovative solutions for erosion control and stormwater management [27,37,38].

#### 3.1.5. Highways and Transportation Applications

Vetiver has been used for highway and transportation projects across the world [20,30,39] (Figure 2). Countries such as Australia, Brazil, Fiji, Vietnam, Ethiopia, South Africa, Malaysia, China, and Bangladesh have used the plant for highways, roads, rail, and travel corridors, erosion reduction, and mitigating hazards [20,23,25,27,28,40,41]. In Benguet Province in the Philippines, it was used for hillside stabilization to reduce landslide risk [21].

Based on interviews with transportation engineers and planners, vetiver has been sparsely used in the United States, primarily in southern and warm climate locations in flat to rolling hill sites. Cases were limited in scope and not widely used in the transportation sector for hillside stabilization, flood mitigation, nor erosion control. More often vetiver has been incorporated into small projects on an experimental basis or as a limited part of development and infrastructure projects. There have been few studies evaluating its effectiveness in protecting roadways and other critical assets within the U.S.

#### 3.1.6. Integrated with Living Shorelines and Watershed Management

Vetiver has, however, been used in ecosystem, watershed, and living shoreline projects [13]. It has been planted to conserve and restore shorelines, dunes, wetlands, tidal zones, riverbanks, and fishponds and as buffers for roadways to support filtration and flood control [22,25,27]. There are clearly greater opportunities to integrate it with natural area protection with other green tools to enhance habitat, protect flora and fauna, improve ecosystem services, and reduce hazard risk [42].



**Figure 2.** Vetiver grass stabilizing a cut slope along the Guwahati–Shillong National Highway, Meghalaya State, India as of July 2015 [20].

### 3.1.7. Benefit-Cost Analysis

While there are few detailed cost-benefit analyses of vetiver from the United States, there is useful information from other countries. In India, the yield benefits from the use of vetiver were estimated at 50% versus 30% for other field bunds and retaining walls [43] (p. 30). The initial costs of installing vetiver were estimated to be Rs 275 (USD \$3.69) per hectare. Field bunds were estimated to be Rs 932 (USD \$12.49) per hectare. The net value of using vetiver was approximately Rs 8543 (USD \$114.51) compared to normal bunding at approximately Rs 3436 (USD \$46.05). The internal return on vetiver was estimated at 95% compared to bunding at 28% [43].

In Australia, vetiver has been applied to road shoulders, with the initial cost at AUD 15.50 (USD \$11.40) per meter compared to traditional road shoulder dykes costing AUD 38.00 (USD \$28.14) per meter. The use of vetiver saved 60% in cost [40]. Given these savings, vetiver can have a high benefit and cost ratio where the costs may be up to 1/20th of a traditional engineered design [20]. China has also reported savings with vetiver of 85–90% over other approaches to slope stabilization [27].

The potential for commercial use, including the extraction of oil and use of plant materials for consumer goods, adds further value to the benefits of vetiver. Tabulation of the ecosystem and harm reduction values is challenging, but given the lower costs of material, installation, and maintenance, vetiver will generate positive returns quickly. A more detailed cost-benefit analysis would support these initial observations.

## 3.2. An Evaluation Framework Based on Expert Interviews and Literature Review

### 3.2.1. Barriers and Opportunities

Based on the literature review and interviews, the barriers comprising the physical, institutional, economic, political, and socio-cultural factors were investigated.

#### Physical Barriers

Physical challenges arise because the plant comes from and works well in tropical and sub-tropical regions with warm temperatures and humid conditions. It thrives in deep, sandy, well-drained soils with plenty of direct sunlight. It may not be appropriate in forests or areas with heavy tree cover. While it can tolerate flash flooding and occasional downpours, routine exposure to very wet conditions may undermine its growth and health. If used to anchor shorelines, salinity may also affect plant growth [27].

### Institutional Barriers

In addition to physical limitations affecting the potential use of vetiver, there are institutional barriers to its use in transportation planning, design, and construction as a form of green infrastructure. Disciplinary practices often favor the use of certain materials, construction techniques, equipment, and systems. Those using vetiver may have had specialized training, education, and practical experiences or might have been influenced by local building practices and the availability of products.

Most disaster recovery programs focus on rebuilding back roadway and infrastructure systems as they existed before a disaster. This is due, in part to federal statutes and regulations—whether for FEMA or FHWA—which encourage replacement rather than betterment and reliance on conventional engineering and design approaches [5,44]. This has resulted in less support for novel green approaches [45] (p. 43); including the use of “living nails” or systems and plants to stabilize soil or control flooding. Based on the interviews, there is not just reluctance to use green approaches, but also inadequate information on the ecological benefits and social returns using vetiver in the USA. Costs and benefits accounting, auditing, and reporting focus principally on the initial costs of materials and labor rather than the benefits, especially over the long-term of recovery projects. There is limited appreciation for green over grey systems to build and retrofit systems damaged by flooding and other hazards.

### Maintenance and Operational Barriers

Another concern raised with vetiver is the need to irrigate, fertilize, trim, weed, and care for plants. Maintenance concerns also pertain to culverts, ditches, and other grey infrastructure for flood risk reduction and water resources management [9]. Increased collaboration with the landscape and environmental design community would help support the proper siting and installation of vetiver to reduce long term maintenance costs. In addition, there is a need for more field tests and trials to increase the understanding and support of vetiver.

One landscape professional mentioned the importance of “trimming back the plants initially to encourage deeper root growth and penetration to maximize soil and water retention capabilities”. Another landscape professional mentioned that “root health has to do with planting hole preparation and pruning”. A civil engineering professional emphasized “grading plans, drainage, and site preparation for managing other species and plant life in new construction as well as during rehabilitation and recovery projects”.

Another concern among professionals and community members is the perceived increased maintenance of roadways and infrastructure corridors where vetiver would be installed. This includes the potential for more detritus from dead and decaying plants and additional organic material on roadways, in drainage ditches and other built systems necessitating additional cleaning and debris management. Areas not properly maintained could result in blockages and disruption of operations due to the accumulation of organic material or flooding, which could transport large waste onto roadways, canals, ditches, and other infrastructure [15]. Similar concerns have been raised with planting trees in urbanized areas.

While there are standard references on landscape architecture [46] and a few publications on vetiver, information on planting, maintaining, and installing it for highways and transportation projects are quite limited. There are examples of its use abroad, yet in the United States there is a lack of knowledge [47] and experience for transportation planners, engineers, and those involved in hazard mitigation. The guide prepared by the TRB task force for the AASHTO Highway Subcommittee on Design [48] is a good starting point, but more needs to be done to increase knowledge and awareness, training and education, and implementation of landscape design and transportation infrastructure system improvements.

### Ecological Impacts

Among the most significant concerns with the use of vetiver is the long-term impact of introducing a non-native species in a sensitive ecosystem under stress from urbanization and highway traffic. As an introduced plant, the effects of new grasses like vetiver on native and endangered plant and animal life must be carefully considered [31,37]. Long-term monitoring and evaluation of plantings in sensitive ecosystems should be conducted with controlled laboratory and in-situ investigations, incorporating new sensor and data collection technologies for monitoring plant growth and environmental change [42]. Some states have stringent controls and procedures for the introduction of new plant life into pristine or fragile ecosystems.

Native species may be preferable to vetiver because of the need to protect an existing habitat for indigenous flora and fauna, which could be affected by the introduction of vetiver. In Hawai'i, there are many different species of native grasses, some of which might function as well as vetiver. Further research and evaluation are needed.

### Opportunities

Effective planning and design, proper installation, and maintenance plans are necessary for green and traditionally engineered systems. This requires training and education, and capacity building for construction and maintenance crews, designers, planners, and engineers who work on transportation projects. More collaboration across disciplines, including biology, ecology, geology, hydrology, engineering, planning, and landscape design is needed, along with stronger education and outreach with professional and community organizations (including vulnerable socio-economic communities) involved in environmental stewardship, and collective action to improve the resilience and sustainability is also needed. Holistic, integrative, collaborative approaches to planning, design, engineering, and construction are needed to improve fairness, equity, and justice across and within communities [3,49–56]. In addition to the inherent complexities and challenges of introducing green technologies in transportation planning, there is a need for stronger advocacy [35]. Transportation planning can be used to identify where and how vetiver can be applied to improve flood control, environmental quality, and strengthen communities.

#### 3.2.2. Framework for Evaluation

Table 1 titled “Key Factors and Considerations for Implementing Vetiver as a Green Infrastructure Tool”, provides a checklist of what is needed to implement vetiver in transportation projects. It is divided into key functions and site variables.

Implementation of vetiver begins with understanding its key functional uses. The most important function is to stabilize soils by covering and anchoring to prevent erosion, slippage, and runoff. This supports drainage and flood risk reduction. The plants absorb water and maneuver channel flows when incorporated into engineered and natural drainage for ponding, sedimentation, detention, and retention functions [42,57]. The effectiveness may also depend on planting strategies, as vetiver can be planted in rows, hedges, or bunds. In addition to holding water and soils, vetiver can buffer and remediate polluted areas trapping heavy metals, pesticides, and other hazardous materials. Toxic pollutants can be removed from the site by harvesting, processing, and properly disposing the plants.

Site-specific factors including soil types, slope, placement, climatic and weather conditions, and other environmental factors such as shade and salinity tolerances need to be considered when implementing vetiver. Project size and dimensions also need to be considered when planning and designing vetiver with other stormwater management, flood detention, and water quality treatments [7,42].

Other factors concerning the use of vetiver have been identified. One of the most important is wildfire risk, particularly in sites affected by drought or fire. While vetiver is resistant to fire, according to one key informant [58], other vegetation and combustible materials in the area need to be considered, along with suppression assets and prevention measures to limit the ignition and spread of wildfire. Wildfire risk is influenced by

seasonal and climate change, precipitation levels, temperature, dryness, and the growth of vegetation.

Several sources have indicated the importance of timing to avoid, for example, problems with planting and the plant establishment under conditions of heavy runoff during rainy seasons. Flooding, erosion, landslides, wildfires, and other events could disrupt the plant growth and functionality. Each site will need to be assessed and possibly rehabilitated or re-planted depending on the extent of the damage. Other tactics, treatments, and additives increase soil strength, density, and productivity following fires and flood events [37]. It is important to note that vetiver can be considered with other green infrastructure designs to increase permeable surfaces and treat surfaces subject to heavy rainfall and runoff loadings [38].

Vetiver has the lowest rating on the invasive species scale with a  $-8$  on the scale ranging between  $-8$  and  $+8$  [58]. As stated previously, while the plant spreads minimally into other areas, its impact on native flora and fauna needs to be considered as well as habitat and other ecosystem interactions. There is growing interest in the use of native grasses to control erosion on steep terrain [31]. However, because of vetiver's versatility in mountainous and coastal locations, unlike some native grasses, it can be used for episodic events such as heavy rainfall and adapt to global warming and climate change. Yet, planting and maintenance takes approximately two years with sufficient sunlight, watering, and drainage to allow rapid growth and establishment. In areas with poor soils and inadequate precipitation, irrigation solutions may be needed to establish vetiver grass. Considerations such as site access affects not only the initial establishment but also long-term care and management.

The approximate initial cost is USD \$3 for each vetiver plant plug, with the average initial installation costs ranging from USD \$10 to \$30 per linear foot [58]. Depending on precipitation and the need for watering, the maintenance and care after the initial establishment period of two years can be minimal. Unfortunately, no studies have been found showing cost comparison over time between traditional methods and vetiver.

**Table 1.** Key Factors and Considerations for Implementing Vetiver as a Green Infrastructure Tool.

| Key Functions           | Considerations   |
|-------------------------|--|
| Soil Stabilization      | <ul style="list-style-type: none"> <li>• Stabilize soil up to 3 m deep</li> <li>• Protects soils from rainfall, runoff, slippage</li> <li>• Functions in hilly and flat terrains</li> </ul>  |
| Drainage and Flooding   | <ul style="list-style-type: none"> <li>• Can be planted on steep gradients</li> <li>• Absorbs and retains water</li> <li>• Channel flows towards natural and engineered drainage</li> <li>• Consider accumulation</li> <li>• Reduces flow velocity</li> <li>• Resistant to high-velocity flows</li> <li>• Edges, streambanks, embankments</li> <li>• Buffer and protect assets</li> <li>• Implement rows of hedges to maximize bunding</li> <li>• Can survive months in water</li> </ul> |
| Pollution Control       | <ul style="list-style-type: none"> <li>• Mitigate on-site and offsite pollution</li> <li>• Buffer tailing ponds and other hazardous material sites</li> <li>• Traps pesticides, heavy metals, herbicides, and pollutants</li> </ul>  |
| Carbon Sequestration    | <ul style="list-style-type: none"> <li>• Can sequester 2 kg of carbon dioxide per year per plant</li> </ul>  |
| Site-Specific Variables |  |
| Soil Type               | <ul style="list-style-type: none"> <li>• Best with deep sandy, well-drained soils</li> <li>• Can be placed in shallow or deep soils</li> <li>• Works with different soils</li> </ul>   |
| Precipitation           | <ul style="list-style-type: none"> <li>• 250–5000 mm</li> </ul>  |
| Temperature/Humidity    | <ul style="list-style-type: none"> <li>• <math>-22\text{ }^{\circ}\text{C}/55\text{ }^{\circ}\text{C} = -7.6\text{ }^{\circ}\text{F}/131\text{ }^{\circ}\text{F}</math></li> </ul>   |

Table 1. Cont.

| Key Functions            | Considerations  |
|--------------------------|---|
| Incline                  | <ul style="list-style-type: none"> <li>• &gt;up to 56° slopes</li> </ul>  |
| Tree Cover               | <ul style="list-style-type: none"> <li>• Avoid heavily shaded locations</li> <li>• Consider trees and other vegetation in the planting area</li> </ul>  |
| Saltwater Tolerance      | <ul style="list-style-type: none"> <li>• High tolerance of salinity</li> <li>• Can tolerate up to 8 dS/m</li> </ul>   |
| Area for treatment       | <ul style="list-style-type: none"> <li>• Size and dimensions of the project</li> <li>• Geological/meteorological and factors affecting earthquake, landslide, flooding, and other hazard risks</li> </ul>   |
| Other Factors            |   |
| Wildfire Risk            | <ul style="list-style-type: none"> <li>• Resistant to fire</li> <li>• Consider other vegetation and land use in an area</li> <li>• Fire suppression assets</li> </ul>   |
| Invasive Species         | <ul style="list-style-type: none"> <li>• Considered non-invasive</li> <li>• Rated −8 on invasive scale (−8 to 8)</li> <li>• Potential impacts on other species in the area</li> </ul>   |
| Planting and Maintenance | <ul style="list-style-type: none"> <li>• Average is USD \$10–30 per linear foot installed</li> <li>• Initial cost is USD \$3/plug</li> <li>• Two years to establish</li> <li>• Initial maintenance period</li> <li>• Low or no maintenance after establishment</li> <li>• Avoid hard, infertile soils</li> <li>• Will require irrigation in the first few months of planting (for dry weather, it must be watered every day during the first two weeks and every second day afterward until mature. Watering is not required for matured plants. It is drought tolerant.)</li> <li>• Fertilization can come from organic manure or Ca-Mg-P. Must fertilize 1–2 times per year.</li> <li>• Plant hedges 3 feet apart</li> <li>• Plants should be 6 inches apart</li> </ul> |
| Other Concerns           | <ul style="list-style-type: none"> <li>• Potential for other commercial uses</li> <li>• Access, harvesting, processing of oils</li> </ul>   |
| SOURCES:                 | [19,20,27,28,43,57,59]<br>See Appendix A for a list of interviewees   |

### 3.3. Case Study: 2018 Flooding, Kuhio Highway, Kaua'i

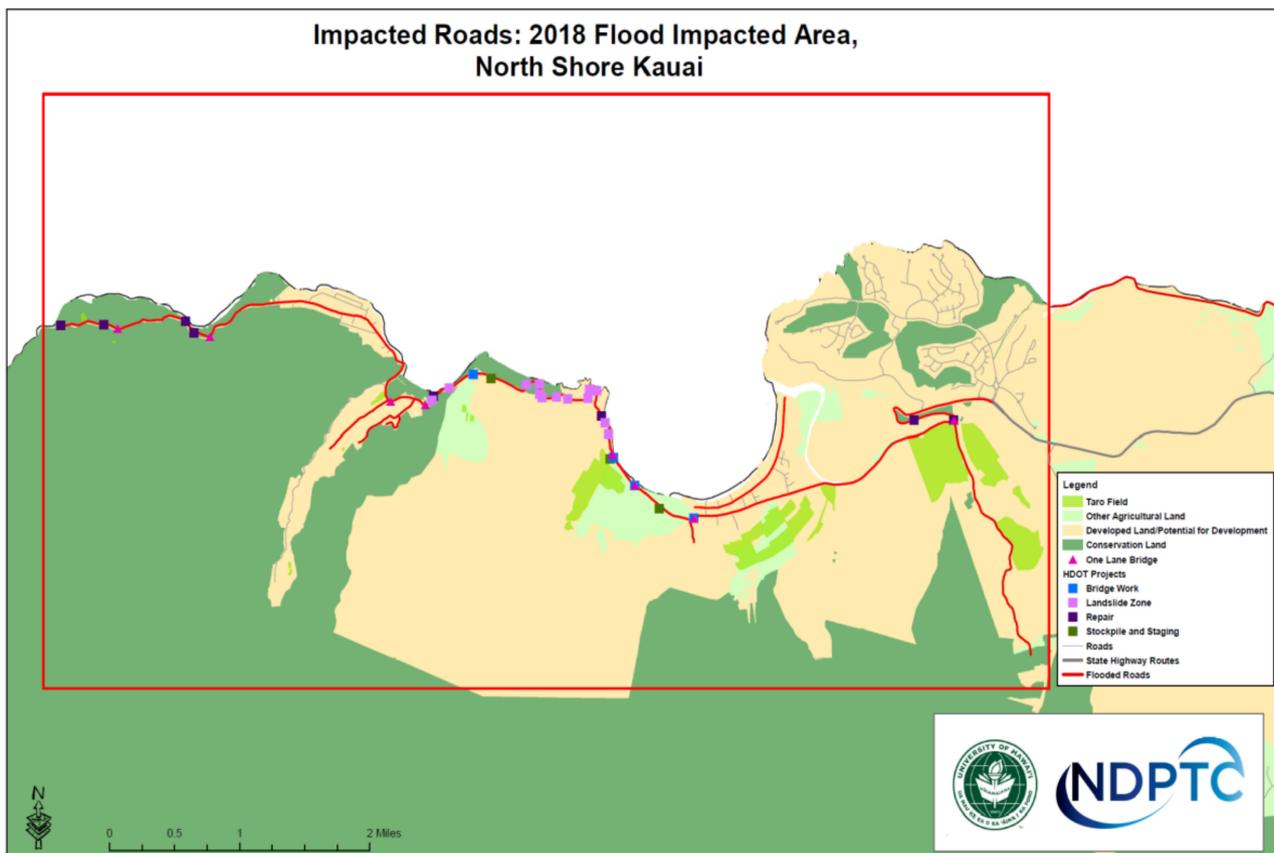
In this section, the evaluative framework is applied to a recent disaster case in Hawai'i. While there have been other recent disasters where vetiver could have been used in the recovery of damaged areas, the 2018 flood on Kaua'i was selected because of the extent of damage and the potential for the use of vetiver. Authors were part of a study team to investigate the recovery from this disaster [15,60]. While this paper focuses on the 2018 flooding, it is worth noting that in early 2021, the same area in Kaua'i experienced heavy rainfall and landslides, and a repeat of transportation infrastructure damage to Kuhio Highway.

#### The 2018 Flood

Heavy rainfall and severe flooding occurred on the islands of O'ahu and Kaua'i from 13 to 15 April 2018. Many residences, businesses, and facilities were heavily damaged. Flooding and landslides closed major highways and roads networks. An automated rain gauge in Waipa on Kaua'i recorded 49.69 inches in a 24-h period ending at 12:45 p.m. on 15 April 2018 [2,15]. While there were no fatalities directly attributable to the flood disaster, their estimated public spending to respond to and recover from the disaster exceeds USD \$100 million, with approximately USD \$70 million spent (funded by the

FHWA) on highway and roadway repairs. For a small county with a resident population of just over 70,000 people, the 2018 flooding was a large, expensive disaster. The study team conducted several site visits to document and catalog repair work.

The team conducted focus group meetings with state and county officials on 25 October 2019, to review damages and investigate recovery activities. The group included personnel from emergency management, public works, transportation agencies, fire and first responders, and residents from the impacted community (See Appendix A for details) These meetings provided additional data on the damage to roadways, critical infrastructure, the impact on services including emergency response, waste management, and lifeline services as well as the impacts on the community. The main highway connecting the North Shore to the rest of the island was cut off by landslides in 11 different locations (Figure 3).

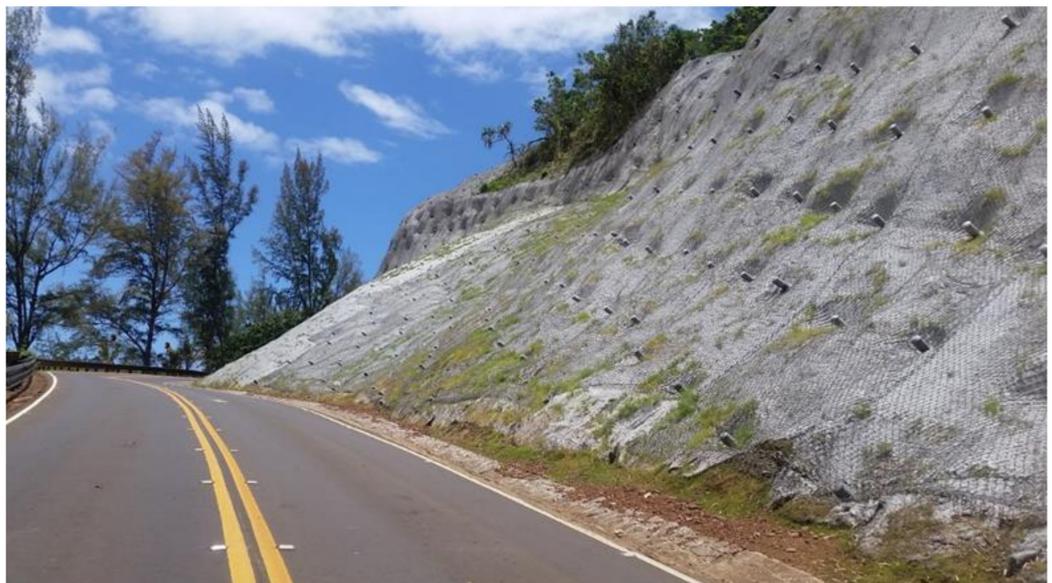


**Figure 3.** Flood damage locations, North Shore, Kaua'i, 2018 [60].

ArcGIS Storyboard and a visual platform using Google StreetView imagery were used to document the damage and repairs. These platforms were also used to visualize, track, monitor and characterize the recovery of the flood disaster. In some sections, the highway was covered by landslide debris, while in other areas, the roadway was washed away or collapsed because of severe erosion of the cliffs. There was also damage to bridges, culverts, and drainage systems caused by flooding and accumulated debris. Because of the remote location and the extensive damage, the main highway was closed for repairs for more than a year (Figures 4 and 5) [61–63]. While significant progress has been made towards recovery, it is evident that conventional approaches to hillside stabilization, erosion control and damage recovery were used.



**Figure 4.** Landslide stabilization with metal soil nails. Source: Authors.



**Figure 5.** Conventional hillside stabilization following the landslide, Kaua'i. Source: Authors.

Many site variables (hillside slope incline and tree cover) in Table 1 have been reviewed in the case study site. Based on imagery and visits to damage sites, tree coverage is moderate to heavy in many locations. However, in other locations, the vegetation has been cut back to accommodate roadways, residential properties, agriculture and near streams, and ditch locations. Within the case study site, many trees were damaged by the storm and landslides, and many were removed as part of the recovery work. Clear cutting of forests was necessary for both installation of hillside stabilization hardware and for equipment and supplies (i.e., gray infrastructure) to access project sites. Therefore, areas where trees were either damaged and/or cut back intentionally, are suitable places for vetiver.

The North Shore of Kaua'i receives 1270 mm precipitation annually with a warm tropical climate with temperature and humidity ideal for growing vetiver. The soils in Kaua'i are rich in iron, which may hinder the growth of vetiver. In addition, according to several informants, the introduction of vetiver would not increase wildfire risk over existing conditions and planting strategies and integration of landscaping and other plant species.

Vetiver could have been used to stabilize sloped hillsides above and below Kuhio Highway. It could have also been incorporated into culverts and drainage structures along the main highway and on minor roads damaged by landslides and flooding. In discussing repair projects that were implemented, it is evident planners and engineers relied on conventional tactics and systems previously used for hillside stabilization and road repair. Interviews with planners and engineers involved with recovery indicated uncertainties as to the effectiveness of vetiver in terms of its soil stabilization and retention capabilities. Concerns included the two years needed for the establishment of root systems, and whether the soils and environmental conditions would support the successful implementation and performance of vetiver. Other hesitations with vetiver had to do with the ecological impacts on forested and nearshore environments with the introduction of a non-native plant species. Informants claimed that there was not enough data nor credible studies to support the implementation of vetiver given the urgency from the disaster and long-standing community concerns regarding invasive species. They reported that vetiver and other natural systems for anchoring and retaining soils were not widely used in Hawai'i and the principal approach (Figures 4 and 5) was clearing debris, removing vegetation, drilling long screws or metal nails into the side of the mountain, and erecting metal mesh screens anchored by the screws covered with concrete and soil. These methods were approved by federal and state authorities and reported by project managers to be the best approach. According to informants, while the approach was expensive and required specialized equipment, materials, and labor to be imported from outside the state, the projects were likely to be approved and funded by Federal Highway Administration (FHWA), Hawai'i Department of Transportation (HDOT), and the Federal Emergency Management Agency (FEMA). Given the importance of the highway and the need to repair and reopen it as quickly as possible, the decision was to go with conventional engineering and repair approaches rather than risk further delay with the implementation of novel, green approaches. There was concern that green approaches would not be reimbursed by FHWA Emergency Relief or Federal Emergency Management Agency (FEMA) Public Assistance programs. It was easier and more practical to adopt conventional approaches to hillside stabilization and highway reconstruction. Informants suggested that the Hawai'i Department of Transportation should expand research and testing of vetiver and other green infrastructure to support further development and implementation. Stronger collaboration across disciplines and professional organizations could promote innovation, resilience, and sustainability solutions to mitigate the impacts of hazard events.

Growers and landscape designers using vetiver reported that they were not contacted nor consulted regarding the potential of using it for the highway recovery project. Yet, there have been projects on Kaua'i that have used vetiver for other purposes outside of transportation resiliency. Outside of these projects that have used vetiver it is important to point out that it could have been tested in sites along major and minor roads in upland and coastal areas, to evaluate concerns. One of the first concerns relates to landscapes and areas for growing vetiver. Many of the landslide areas are forested, with too much shade or other plant life, which could impact growing and maintenance over time. A second concern was the need for watering, maintenance, care, and upkeep of vetiver and the responsibilities across state and local authorities, and community groups. In addition, the presence of highway traffic and the abutment of roadways against private properties raise concerns as to land ownership, liabilities and access for infrastructure installation and maintenance. There are shared responsibilities and costs borne by different stakeholders concerned with reducing flood and landslide risk. A third concern is that while engineers and planners recognize the additional benefits of pollution control, carbon sequestration,

and the potential savings of mitigation through vetiver and green infrastructure in general, attention is focused more on immediate repair, restoration, and recovery. Longer-term adaptation and resilience to climate change and future hazards and threats are lower priorities than restoring essential services immediately. A final concern emerging from the investigation as to why vetiver was not used in the recovery efforts arises from growing interests in the use of native Hawaiian plants as part of larger ecosystem restoration initiatives. Native species, as an alternative to vetiver for erosion and flood, such as Lovegrass (*Eragrostis atropioides*), Pili grass, Pala'ā (*Sphenomeris chinensis*), and Makaloa (*Cyperus laevigatus*) were mentioned as being viable and more appropriate for projects in Hawai'i [64,65].

There were missed opportunities to integrate vetiver for soil retention, buffer, and highway asset protection against flooding and landslides. There were also missed opportunities to enumerate the co-benefits of pollution remediation, carbon sequestration, and the commercial value of vetiver oil in project evaluations. Greater collaboration between the professions of agriculture, environmental biology, landscape architecture, civil and environmental engineering, and transportation planning will support not just increased resilience but also lower costs and increased benefits of green over gray systems.

#### 4. Discussion

The use of vetiver has not been adopted into the local guidance, regulation, standards, and codes in the state. According to informants, the lack of guidance and experience with it prevented its use on the upslope and downslope shoulders of Kuhio Highway. It also could have been used to repair minor road sedges, riverbanks, streams, and ditches to increase soil retention and control flooding in the watersheds of Haena, Wainiha, and Hanalei. While the focus on urgency and quick repair actions is understandable, the need to include cost-savings and ecosystem benefits of green infrastructure in environmental accounting and auditing of costs and benefits is apparent in the case study. Life cycle analysis and transportation costs of shipping concrete, materials, equipment, supplies, and labor to remote locations such as the North Shore of Kaua'i must also be factored into analyses.

There are special challenges to landslide risk reduction in tropical regions, which may require phased stabilization and restoration due to seasonal weather variations and longer travel distances for materials, equipment, and personnel. There are also aesthetic and cultural values with green infrastructure [52]. Compared to pouring and installing more concrete, conventional roadside protection, there are advantages with the use of green infrastructure in scenic natural areas such as the North Shore Kaua'i. Significant concerns, however, with introducing new plant species and as well as the potential for wildfire, need to be addressed in implementation plans.

The missed opportunities include development of test sites and in-situ evaluation of vetivers, but also integration of green with conventional engineering, design, and planning capabilities. The ability to grow "living nails" or find other cost-effective alternatives as opposed to using imported conventional materials and technologies can be more feasible with green versus concrete systems. Especially on Kaua'i, with its dependence on tourism and the decline of plantation agriculture, the need for new approaches to governance [55] in supporting innovative green industries is apparent. While Hawai'i conjures images of white sandy beaches and swaying palm trees at the base of steep mountains, the reality is more complicated, with a need to better study, develop, test, and implement green, affordable solutions to the pressing problems of extreme weather, climate change, and damage to the built and natural environments.

#### 5. Conclusions

While there are limitations to this study, as it was largely literature-based and limited to the United States, there are clear takeaways. First and foremost, despite the increasing demand for green infrastructure driven both by climate change and disasters, there is limited awareness and understanding of how specific tools such as vetiver can be used

more widely in transportation projects. The barriers to adaptation identified by Dowds and Aultman-Hall (2015), including the management of uncertainties and the need for vulnerability assessment tools and metrics for asset criticality, are just as relevant to Kaua'i as other states [66,67]. Second, there is more appreciation and experience with green approaches in developing countries, which provide valuable experience to integrate it with conventional approaches. This was evident from the literature review and interviews. The research team plans to be involved in more engagement, information sharing, site visits, and other exchanges with international researchers and practitioners working on green infrastructure. A study tour with visits to transportation projects would be useful to practitioners and decision-makers interested in low-cost, high-return green infrastructure. Third, training and educational needs include coursework on green infrastructure, transportation planning, hazard mitigation, and adaptation to climate change. The National Disaster Preparedness Training Center ([ndptc.hawaii.edu](http://ndptc.hawaii.edu)) and the Pacific Urban Resilience Lab at the University of Hawai'i will continue to integrate green infrastructure in training for emergency managers, responders, and those involved in disaster recovery. Fourth, changes in policies, funding, priorities, and evaluation of recovery and reimbursement of federal and other funds to support building back greener and faster should be initiated. There is a need for more investigation and documentation of recovery and a stronger advocacy for greener, more cost-effective, and beneficial approaches to disaster management.

Other promising directions emerge from this research. For example, in terms of the preparedness and maintenance of highway slopes, and levee and dam slopes on problematic soil, vetiver can be a transformative technique due to its ease of use, cost-effectiveness, and adaptability in adverse climates. Performing a comprehensive study on soil strength and stiffness could also help with preparedness [68].

There is a need for greater interdisciplinary, transdisciplinary convergence to support understanding, technology transfer, and a better accounting of the costs and benefits of vetiver and other green infrastructure tools [69]. There is demand for local knowledge and integration of social, cultural, and environmental assets to manage risk and to address not only damage repair, but to build more just, sustainable, and resilient communities. Planning must consider needs, capabilities, and opportunities for growth and improved quality of life in disaster relief and reduction, especially for underrepresented populations [49]. Expanding choice, promoting inclusiveness and diversity, and striving for greater participation in the planning, design, and engineering of transportation systems and the communities they serve are all part of the calculus for success.

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## Appendix A

### *Interviewees and Subject Matter Experts Consulted with on Green Infrastructure and Flood Disaster Recovery*

The Hawai'i Disaster Recovery Workgroup (Hi-DRAW) is a research project funded by the State of Hawai'i, based at the University of Hawai'i. The project was created to study the recovery from the flood disasters in 2018. Team members conducted community workshops in Waimanalo, O'ahu, and in the County of Kaua'i. Team members collected data on flooding impacts, response and rescue efforts, and repair and recovery projects. They focused on stormwater and flood control infrastructure and improvements to mitigate impacts of flooding and landslides. In addition to conventional engineering approaches, the team also investigated green infrastructure, maintenance and renovation of existing systems, and community-based watershed management to reduce flood risk. As part of the HI-DRAW project, many site visits and interviews with experts in engineering, landscaping, planning, and hazard mitigation were conducted and interviewed. The following individuals provided information support to understanding of the opportunities and challenges with green infrastructure, including vetiver, to support transportation system resilience: Jason Fox (Vetiver Farms Hawai'i, Papaikou, HI, USA); Brad Granley (Leacheate Management Specialists, LLC, USA); Eric Wiedger (Leacheate Management Specialists, LLC); Warren Sullivan (Mosquito Hawk Farms LLC, Anahuac, TX, USA); Wendy Meguro, Michael Hamnett, Robert Paull (University of Hawai'i, Honolulu, HI, USA); Yekang Ko (University of Oregon, Eugene, OR, USA); James Yamamoto (R.M. Towill Corporation, Honolulu, HI, USA); David Takeyama (Oceanit, Inc., Honolulu, HI, USA); Larry Dill (Hawai'i Department of Transportation, Honolulu, HI, USA); Elton Ushio (Kaua'i Emergency Management Agency, Lihue, HI, USA); Wade Lord (Kaua'i Public Works, Kaua'i, HI, USA); Solomon Kanoho and Gary Hudson (Kaua'i Fire Department, Lihue, HI, USA). Residents and members of the public impacted by the flood disaster also contributed information and perspectives on hazard mitigation and recovery.



**Figure A1.** (a) Left: Physical model used to collect damage information and feedback on mitigation strategies; (b) Right: Stakeholder workshop at held at Kaua'i Emergency Operations Center. Source: Authors.

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