

**The effects of sedimentation from unpaved roads on coral reefs: an analysis of  
St. John, USVI and Koh Tao, Thailand**

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**Abstract:** Land-based sediments pose one of the greatest threats to the destruction of coral reefs. On St. John, USVI, sedimentation from unpaved roads has been identified as the dominant source and greatest threat to its coral reefs. Local and national organizations are now using the research to develop best management practices for minimizing sedimentation rates on St. John. However, many other islands surrounded by coral reefs are unaware of the threats from unpaved roads, and use solely a marine-based approach to reef conservation. This paper analyzes and compares the geography, coral reef characteristics, and road networks of St. John and Koh Tao, Thailand to see if sedimentation from unpaved roads can be considered a threat to Koh Tao's reef. The results find road-based sedimentation a threat and argue for Koh Tao to take a land and marine-based approach to conserving its reefs, attacking the threat of sedimentation at its source.

**Keywords:** coral reefs, sedimentation, St. John, Thailand, roads, conservation

*The effects of sedimentation from unpaved roads on coral reefs: an analysis of St. John, USVI and Koh Tao, Thailand*

**Introduction**

As the tourism industry drastically expanded on St. John, US Virgin Islands, developers constructed hundreds of unpaved dirt roads to facilitate the fast-paced population growth on the island. During rain storms, the unpaved roads created runoff from the mountainous terrain of St. John, and sedimentation smothered the coral reefs surrounding the island. Due to the geography of the island, coral reef characteristics, and dirt road network, the biggest threats to coral reefs around the island was considered sedimentation from unpaved roads. Sedimentation drastically threatens the ability for reefs to survive. This study uses existing research on the sedimentation from unpaved roads on St. John to apply to the interaction between other island infrastructure systems and coral reefs around the world. For decades, individuals and organizations conducted studies in St. John on the amounts of sedimentation reaching coral reefs from unpaved road segments, and discovered what road variables contribute to highest sedimentation rates. The local St. John community and larger conservation organizations now use the research findings to develop different strategies and techniques to minimize sedimentation rates from unpaved roads. Interestingly, there remains minimal research on sedimentation from unpaved roads and runoff into the ocean besides the existing exploration on St. John. The process of conducting similar studies in new locations requires large amounts of time, money, and effort. However, a faster and less costly approach would be to use the research and findings on St. John and apply this knowledge to help other coral reef communities minimize sedimentation. However, these alternate reef communities must show consistent similarities to St. John in their geography, road structures, and coral reef systems. Without constant parallels, sedimentation from unpaved roads in other regions may not be a major threat to their coral reefs, and the mitigation techniques used in St. John may prove unsuccessful. In this paper, I want to evaluate the coral reefs, geography, and road system on the island of Koh Tao, Thailand, and determine if the findings and mitigation strategies used in St. John can be applied to the island. If many similarities exist between the development, terrain, coral reef

dynamics, soils, and weather patterns of St. John and Koh Tao, the same strategies could be used on Koh Tao to help minimize the negative effects of unpaved roads. The research can help Koh Tao and other similar islands find the best management practices to reduce sedimentation from unpaved roads and save their coral reef ecosystems.

### **Literature Review**

Many people living near coral reefs depend on reef resources for survival. Local coastal communities use the reef for the backbone of their local economy (VI CB&D, 2010). Reefs remain vulnerable environmental resources, providing necessary food, security, and safety to millions of people across the globe. Coral reefs provide ecosystem goods and services including tourism, fisheries, coastal protection, biodiversity, and carbon sequestration. According to one estimate, the yearly net benefit of the world's coral reefs is \$29.8 billion (Cesar et al., 2003). However, coral reefs may be the most globally endangered of all ecosystems (Mumby and Steneck, 2008). Threats to coral reefs include ocean acidification, ocean warming, increased levels of carbon dioxide in the air, water pollution, sedimentation, coastal development, destructive fishing practices, coral mining, careless tourism, and ozone depletion (Coral Reef Alliance, 2010). One study discovered over half of the world's coral reefs disappeared since 1980 (Mongabay, 2008).

Marine Protected Areas (MPA) represent one of the major ways to combat coral reef decline globally. Currently, over 6,800 MPA's exist across the world's oceans, many of which protect coral reef ecosystems (IUCN, 2010). The regulations for each MPA greatly differ, but every MPA claims to help conserve the natural aquatic environment in some way. Restrictions for each MPA may include fishing practices, development, catch limits, removing marine life, mooring in certain locations, and many others. Many Marine Protected Areas continually face opposition due to their lack of enforcement and inability to preserve the reef. Many national authorities regulate Marine Protected Areas, but studies show keys to coral reef protection focus on local management and knowledge (Mumby and Steneck, 2008). Other problems with MPA's include solely focusing on the protection of the underwater reef without connecting the threats from land-based sources of pollution (Keller et al., 2009.) Understanding and attacking each threat remains an

essential part to protecting the world's coral reef systems. Successful MPA's exist in areas where local people work together to control and manage all water and land-based threats to coral reefs. Without a collaborative approach, incorporating and understanding both land and ocean-based threats, the future for coral reefs remains daunting.

A recent study found land-based sediment onto coral reefs the biggest threat to their depletion in future years (Burke et al., 2011). Some estimates indicate erosion and sedimentation represent a high threat to over 22% of the earth's coral reef ecosystems. At local scales, sedimentation and runoff can be the biggest pressure on inshore reefs and cause the most harm to their ecological balance (ISRS, 2004). Land based sources of sediment can negatively affect coral reefs in several ways. Sedimentation effects can include "1) smothering of coral colonies by excess sedimentation; 2) reducing light availability due to high turbidity of the water column potentially inducing bleaching stress responses 3) physical abrasion that cause tissue damage or loss; 4) changes in pH and salinity that may trigger bleaching stress responses; 5) eutrophication from increased nutrient loads and proliferation of undesirable species such as algae, weedy corals, etc. and 6) loss of biodiversity and ecosystem services which can affect wider interactions including fish populations" (VI CB&D, 2010). These effects kill off coral sections, reduce biodiversity in the reef, and require living organisms to expend more energy to shed the sediment, thus making the total ecosystem more vulnerable to disease and less resilient to natural resources (Rogers, 1990).

A study on St. John, USVI determined the unpaved road network as the dominant source of sedimentation onto its coral reefs. During rain storms, the unpaved roads act as pathways for dirt, clays, and pollutants to travel down the mountainous terrain of St. John and onto the reefs surrounding the island (Anderson and MacDonald, 1998). Although other islands contain similar geographic features and road networks as St. John, minimal research exists on sedimentation rates in other areas. Studies on sedimentation usually take at least one year because they evaluate each seasons unique precipitation rates (Ramos-Scharron & MacDonald, 2005). The studies also require large amounts of funding, expertise, and effort from many individuals. This research paper provides a collaboration of existing knowledge about sedimentation from unpaved roads and its effects on coral reefs. With serious declines in coral reefs from sedimentation,



communities must find fast and effective ways to manage their essential reef ecosystems and reduce sedimentation rates. Rather than conducting new research, individual islands, including Koh Tao, can use this paper and the studies of St. John to determine the best methods to help prevent sedimentation from unpaved roads. If other coastal regions contain similarities to St. John in geographic characteristics, reef structures, and unpaved road networks, they can use the information in efforts to minimize sedimentation rates on current and future development of unpaved roads.

The state of existing knowledge on coral reef sedimentation rates from unpaved roads on St. John Island remains abundant. However, very few other coastal regions have directly studied unpaved roads and their relation to sedimentation on coral reefs. In the Caribbean, many studies focus on mass wasting (Larsen and Parks, 1997; Jibson, 1989), while others relate towards surface erosion studies in general (Gumbs and Lindsay, 1982; Tirado and Lugo-Lopez, 1984) but lack the connection of unpaved roads and sediment being delivered to the ocean. Other studies across the world focused on sediment data for unpaved roads, but did not include rates entering coral reef ecosystems. Some examples include Australia (Bren and Leitch, 1985), New Zealand (Fahey and Coker, 1992) and Thailand (Ziegler et al., 2001).

A 1998 study on St. John linked the connection of unpaved road sedimentation and its delivery to different bays containing coral reef ecosystems (Anderson and MacDonald, 1998). Using an empirical road erosion model (ROADMOD), the authors found the unpaved road network to be the dominant source of sediment, causing sedimentation yields to the reefs four times higher compared to areas without roads (Anderson and MacDonald, 1998). The ROADMOD system contained limited data and lacked important factors controlling road erosion rates, like precipitation or frequency of grading. While the study presented initial estimates of sediment delivery rates from unpaved roads, the research contained no field data measurements to determine the primary factors controlling runoff and sediment delivery during individual storms. The deficiencies in the research made assessing the larger-scale impacts of current and proposed roadways in St. John impossible.

A later study aimed to collect field data and measure the exact amounts of runoff and sediment production from vegetated plots and unpaved roads on St. John

(MacDonald et al., 2001). The study used three different areas across the island to test sedimentation rates in relation to precipitation and slope of terrain. The findings showed road surface runoff could best be predicted by storm precipitation and road size, as sedimentation rates were significantly correlated with runoff, intensity, and precipitation. Unlike unpaved roads, the undisturbed vegetated hill slopes only generated runoff during the largest storms, with minimal sedimentation. However, unpaved roads in the study generated runoff when rainfall exceeded anything more than 6 mm. The research also documented several basic mitigation strategies, including paving the roads and creating inslopes, but still needed additional information to determine key factors of sedimentation from unpaved roads (mitigation techniques described in detail in analysis). Ramos-Scharron and MacDonald (2005) found minimizing the frequency of grading and improving road drainage as the best means to reduce erosion. Their study aimed to not only measure sediment production at different unpaved sites and evaluate precipitation, but also looked into evaluating sedimentation effects determined by the traffic and grading of each road. By evaluating 21 road segments on St. John, the study found regrading to significantly increase sediment production rates. Figure 1 (Ramos-Scharron and MacDonald, 2005) illustrates the process of grading a road, where a bulldozer flattens all gullies and dips in the road, originally created from erosion. This process improves the road condition for automobile access.



Figure 1: Grading a road segment in St. John, USVI.

The annual erosion rate for ungraded roads was 41 percent lower than roads graded at least once during the year. Once grading the road, loose dirt can easily waste away during rainfall. Figure 2 (Ramos-Scharron and MacDonald, 2005) shows the relationship between sediment production and time since grading an unpaved road.

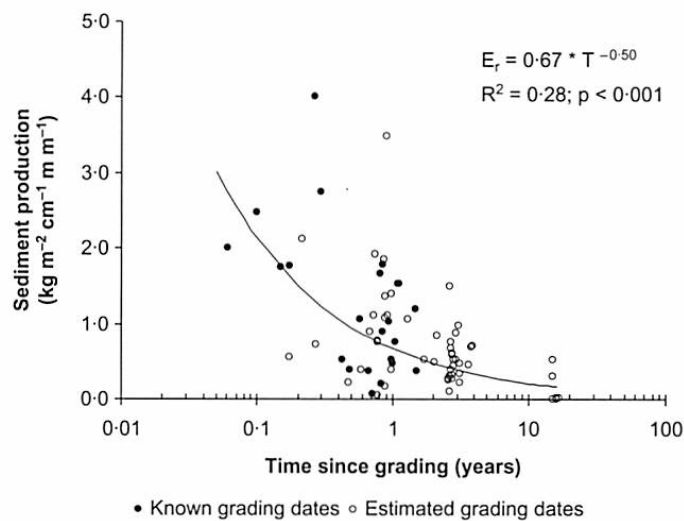


Figure 2: Relationship between sediment production rates and time since grading. The data was normalized by precipitation and slope.

Several studies also looked into the differences of slopes for unpaved roads and its effects on sedimentation rates. Measured sediment production rates for unpaved roads “ranged from 5.7 Mg ha/yr for a road with a slope of 2% to 580 Mg ha/yr for a road with a slope of 21%” (Ramos-Scharron and MacDonald, 2007). An earlier study found road segment slope as an important control on sediment production, and argued sedimentation from unpaved roads drastically increases with the slope of the terrain (Ramos-Scharron and MacDonald, 2005).

The research performed on St. John provides vital information on sedimentation from unpaved roads and its effects on coral reefs, and the research can be used by organizations to develop ways to reduce sedimentation. Sedimentation from unpaved roads on St. John results in rates four orders of magnitude higher than undisturbed hillslopes (Ramos-Scharron and Macdonald, 2007). Aside from St. John, only a few studies look at the delivery of sediment from unpaved roads to the ocean. One study in Puerto Rico aimed to measure the sediment rates from abandoned unpaved roads and evaluate the effects from precipitation, slope, plot size, and vegetation cover. Similar to research on St. John, the study found larger runoff rates for roads with steeper slopes and larger areas (Ramos-Scharron, 2010). The study also revealed vegetation as an important role in sedimentation rates. During the two-year study period, sedimentation rates for each of the nine abandoned roads became smaller, and these differences can be attributed partially to re-grown vegetation on the abandoned roads. Communities in St. John and Puerto Rico currently use this vital information to develop strategies fighting against sedimentation from unpaved roads. These different techniques will be discussed later in the paper.

While existing studies show unpaved roads as the leading cause of sedimentation onto coral reefs in St. John, no similar studies exist for other coral reef regions in the world. Several studies look at sedimentation rates on coral reefs in Thailand, but none focus on the major impacts from unpaved roads. Examples of such studies in Thailand include the effect of sedimentation from coastal mining in Phuket (Chansang et al., 1981) and the effects of sedimentation and climatic patterns on coral reef biodiversity in Phuket (Brown et al., 2002). Using the studies conducted on St. John, I will see if islands with coral reefs in Thailand appear vulnerable to large amounts of sedimentation from

unpaved roads. By looking at the geography of the islands, lithology, characteristics of the reefs, climate, road structures, and many other factors, I hope to compare St. John and Thailand's coral reef system and its threats. The comparisons will also enable me to make predictions on future developments and road building on less inhabited coral reef islands in Thailand. If the Thailand islands contain similar features as St. John, this paper can be used to show the proper techniques to help mitigate sedimentation from unpaved roads on Thailand. Other developing coastal regions can use the information contained in this research paper to make smart decisions about future road building near valuable coral reef ecosystems. The combined aesthetic, economic, environmental, and cultural value of the earth's reefs should make protection a global priority. As more and more coastal regions develop, unpaved roads will inevitably be constructed for transportation purposes. Without understanding the effects of sedimentation on coral reefs and the causes of runoff from unpaved roads, many undeveloped regions will face the same problems occurring on St. John. Rather than wait to see the coral reefs suffer from sedimentation off of poorly designed unpaved roads, coral reef islands experiencing expansion can use the knowledge and significant research from St. John and this paper to make more informed decisions about development and road building.

## **Theory**

Coral reef organizations on Koh Tao, including Save Koh Tao and Eco Koh Tao, use a marine biology approach to preserve and protect the reefs surrounding the island. Conservation efforts focus on the coral reefs themselves, including dive site cleanups, boat anchoring regulations, and the installment of artificial reefs (Save Koh Tao, 2012 and Eco Koh Tao, 2012). Although these conservation organizations understand some threats to coral reefs originate from the land, their marine approach focuses on dealing with the threat once it reaches the reefs, rather than preventing the threat from ever entering the reef ecosystem (Save Koh Tao, 2012). On St. John, however, coral reef conservation efforts focus on land and sea, and aim to eliminate a coral reef threat before it actually enters a reef (VI RC&D, 2010). After several studies revealed sedimentation from unpaved roads as the most dangerous threat to St. John's coral reefs, organizations

including *Coral Reef Alliance* and the *US Coral Reef Task Force* quickly developed and implemented erosion control strategies on the island (Division of Environmental Protection, 2010). In this paper, I use a geographic and historical framework to compare the two islands, their road system, and its coral reefs. If the islands possess many similarities, I will argue Koh Tao can use the same erosion control plans as St. John to reduce the threat of sedimentation on its coral reefs. I will be taking Thailand's marine-based conservation efforts and incorporating land-based conservation strategies related to unpaved roads to help better protect the valuable reefs surrounding Koh Tao.

Different countries, cities, and communities surrounded by coral reefs create their own regulations and guidelines to protect the future of their valuable coral reef ecosystem. Each coral reef remains unique, and a serious threat to one reef could be minimally damaging towards another. For example, several off-shore reefs face a serious threat from overfishing, yet seem unaffected from careless tourism practices. However, reefs located near heavily populated tourist areas can be constantly destroyed from careless boating, diving, and snorkeling (Coral Reef Alliance, 2010). A 2011 study (Burke et al., 2011) found local threats to coral reefs the most severe in Southeast Asia and least severe in Australia, and further emphasized the different threats for each coral reef location.

Although many communities seem aware of the decline in coral reefs, their efforts to protect their reefs prove unsuccessful. Reasons for failure can range anywhere from poor management and regulation to incorrect conservation planning. Only fifteen percent of the world's Marine Protected Areas (MPA) qualify as being "effective" (Burke et al., 2011). The MPA approach to protect coral reefs continues to be unsuccessful and full of flaws, and other techniques must be used in order to provide a future for coral reef ecosystems (Burke et al., 2011).

On the island of Koh Tao, Thailand, several local, national, and global organizations continue to work together to help preserve the coral reefs around the island. Two of the largest conservation programs include Save Koh Tao and Eco Koh Tao. Established in 2000, Save Koh Tao's goal involves strengthening the community, improving the usage of the coral reefs, being a leader of sustainable and eco-friendly development, and helping to provide a sustainable living island for future generations

(Save Koh Tao, 2012). Save Koh Tao works with tourism agencies, dive companies, business owners, and local people to find the best ways at protecting the rich coral reef ecosystems surrounding the island. Eco Koh Tao's "aim is for the preservation and conservation of marine environments through education, awareness, and action" (Eco Koh Tao, 2012). Eco Koh Tao works with several international partners, including *United Nations Environment Program* and *Coral Reef Alliance*, to protect the reefs. Through education, action, and research, Eco Koh Tao hopes to provide a positive influence on the future for Koh Tao and its coral reefs.

To date, NGO's in Koh Tao have used a marine conservation approach to minimize the threats on coral reefs. However, this may prove insufficient because many land-based threats can be devastating once entering the reef ecosystems. Both Save Koh Tao and Eco Koh Tao have several ongoing marine conservation projects, yet lack projects based on the land. Current projects from Eco Koh Tao include a reef check and ecological monitoring program, Buoyancy World, artificial reefs, BioRock, beach and dive site clean ups, mooring buoy projects, coral nurseries, a giant clam nursery, and whale shark and turtle sighting databases (Eco Koh Tao, 2012). These projects focus around a marine biology framework consisting of direct reef rebuilding and cleanup, thus minimizing reef threats. For example, Buoyancy World, Save Koh Tao's major project for 2009, created an artificial underwater playground for novice divers to practice buoyancy before heading off to actual reefs. Rather than divers touching and destroying actual sections of a coral reef, Buoyancy World provides an alternate area for divers to become comfortable with being underwater before accessing reef ecosystems. Save Koh Tao also set up artificial reefs around the island from household appliances and furniture, and the reefs now welcome many species of fish. The artificial reefs also help spread out the number of divers at each site on a daily basis and reduce the risk of over-diving on authentic coral reef sites. The Mooring Buoy Project created several proper boat mooring systems around the island, and significantly reduced reef damage from anchoring and improper mooring installation (Eco Koh Tao, 2012).

Save Koh Tao uses similar marine biology based projects to protect the coral reef systems around the island. BioRock remains one of their biggest accomplishments over the previous years. BioRock, an artificial reef structure placed near living reef systems,

uses low voltage electrical current to improve the growing conditions for corals and reef organisms (Save Koh Tao, 2012). BioRock establishments around Koh Tao increase coral health, biodiversity, and fish abundance dramatically (Marine Conservation Koh Tao, 2012). Save Koh Tao also works with local dive schools to organize underwater and beach clean ups from rubbish on the island. Between 2008 and 2010, Save Koh Tao organized 29 clean-ups which helped protect the reefs from structural damage and improved the appearance of beaches and dive sites. Save Koh Tao's Ecological Monitoring Program collects detailed information on the biodiversity and abundance of fish and coral species on the reefs. Combining this information with water quality tests, Save Koh Tao can follow the trends in the health of reefs around the island (Marine Conservation Koh Tao, 2012).

Although conservation organizations on Koh Tao understand and acknowledge coral reef threats from wastewater and runoff, their approaches to minimizing reef destruction around the island rely on working and studying the reef itself, rather than solving proximate causes and drivers of destruction. In this paper, I want to use an alternative framework in solving problems related with coral reef decline on Koh Tao. Both organizations make note on their respective websites about the negative impacts development and deforestation have on the coral reefs on Koh Tao, and also note the negative impacts from sedimentation. However, their efforts to solve the problem involve working directly in the water and on the reef, rather than on the land itself. By waiting for the problem to reach the reefs, the ability to solve the problem remains impossible. Although efforts like BioRock, Buoyancy World, ecological monitoring programs, and artificial reefs help preserve the existence of reefs around Koh Tao, they do not directly solve the threats from coral reef decline or eliminate any of the sedimentation. A reef conservation framework for Koh Tao must include attacking land-based threats at its root before reaching the reefs.

As mentioned earlier in this paper, a study found sedimentation on St. John the major threat to its coral reef ecosystems and the main reason for the reefs deterioration. The study further explained unpaved road networks to be the dominant source of sedimentation (Anderson and MacDonald, 1998). Reef conservation efforts now use a marine and land based approach to mitigate reef threats. Conservation strategies include



marine-based efforts like those found in Koh Tao, but also emphasize an importance on developing and implementing erosion control plans. Several organizations have already used these different strategies to greatly reduce the sedimentation threat to coral reefs on St. John (UVI, 2010).

One study found sedimentation and wastewater pollution associated with rapid coastal development to be a major threat to coral reefs in the gulf of Thailand, including the island of Koh Tao (Yeemin et al., 2006). However, no studies exist in Thailand explaining the dominant sources of sedimentation onto the coral reefs. Although conservation organizations understand sedimentation kills the reefs and leads to major declines in biodiversity and reef health, they have no ability to stop the problem before it reaches the reefs simply because there remains no available information about sedimentation sources on Koh Tao. Instead, the organizations work in the water with a marine biology approach and help preserve the reefs once sedimentation has already settled onto the reefs.

From personal experiences on Koh Tao and St. John, I have seen several similarities in the landscape of the islands and the formation of the coral reefs around the island. I spent over a week on Koh Tao, earning my PADI scuba-diving license and diving at several dive sights around the island. I used a Buoyancy World site on my first dive, saw coral reef destruction at other sites, and witnessed the impacts on reefs from large diving group lessons. I rented a motorbike for several days and traveled around the island's dirt roads and up into the mountains, and could see the impacts from rain on the fallout of road sections. Figure 15 provides an example of a road section after heavy precipitation. I have also spent time scuba diving on the reefs around St. John and hiking on sections of the island. Although I saw several similarities in the roads and reefs of Koh Tao and St. John, these were only personal observations with no rigorous fieldwork or substantive geographic information or analysis.

In this study, I use geographic information on the landscape of both islands to see if similarities truly exist. This includes information on rock type, precipitation patterns, climate, and road design. I also want to look into details of reef sites, including size, depth, and distance to shoreline and unpaved roads. By using a geographic approach to understand similarities and differences in Koh Tao and St. John, I will be able to predict

if runoff from unpaved roads can be considered a serious threat to the coral reefs in Koh Tao. Methods will include comparing quantitative and qualitative data on the geography of the islands, analyzing pictures and images from Google earth, and comparing coral reef data for Koh Tao and St. John. The paper will also include a historical framework for both islands, looking at development and future growth.

This paper does not solve the issue of coral reef decline on Koh Tao or St. John. Unpaved roads can only be considered one of several sources of sedimentation on coral reefs, and sedimentation can be considered only one of the several threats to coral reef ecosystems. However, the ability to preserve the coral reef systems on Koh Tao for future generations may not be possible without finding solutions to prevent unpaved road runoff. The numerous studies on St. John provide experts vital information on sedimentation sources, and several implementation plans are now used in St. John to minimize runoff (UVI, 2010). If enough similarities exist between the geography, road networks, and reefs of both islands, conservation organizations on Koh Tao may find the same strategies useful to help prevent runoff. Additionally, if the analysis proves the islands to be very similar, sedimentation from unpaved roads can also be considered a high threat to Koh Tao's reefs.

The preservation of coral reef ecosystems requires a collaboration of efforts from multiple sources. Save Koh Tao and Eco Koh Tao already use several important marine biology approaches to protect the reefs around the island. However, their efforts must also focus on preventing land-based pollution sources from reaching the reefs. This paper uses an environmental impact assessment approach, analyzing both terrestrial and marine components and road networks over space and time to compare the islands and determine if Koh Tao can use the same runoff mitigation strategies as St. John for unpaved roads. Other management practices remain necessary to provide the best conservation to coral reefs, but if results show constant similarities, sedimentation from unpaved roads may be the biggest threat to coral reefs in Koh Tao. The paper will then provide the best strategies to alter Koh Tao's marine-based approach to preserving its coral reefs and include emphasis on mitigating runoff from unpaved roads before it reaches and harms the valuable reefs.

## **Methodology**

Increased sedimentation from unpaved roads and the associated decline of coral reefs remains a critical environmental issue for St. John, USVI and other tropical coral reef areas. The studies on St. John provide excellent information on the causes of increased sedimentation, and give detail on unpaved roads and its effects (Macdonald et al., 2001, Ramos-Scharron, 2010, Ramos-Scharron and MacDonald, 2005). As stated earlier, the studies reveal unpaved roads to be the biggest reason for large sedimentation inputs onto the coral reefs surrounding the island (Anderson and Macdonald, 1998). Further, the studies identified what forms of roads (slope, grade, location) produce the most sediment and runoff into the reef ecosystems. Today, NGO's, local organizations and communities, and individuals use this information to implement sediment and erosion control techniques on the island. The information proves to be useful for future development and road planning on the island as well.

To transfer this knowledge and valuable information to the island of Koh Tao, Thailand, the geographic characteristics, road networks, and coral reef features of both islands must be similar. If the islands do not take after one another, the sedimentation control techniques on St. John may not be useful for the island of Koh Tao. Several methodologies and sources will be used to identify similarities and differences between the islands and their coral reef ecosystems.

The first step of analysis in this paper will compare the geography and landforms for both islands with qualitative and quantitative information. Using maps, statistical information, and images of both islands, I will compare information on island size, location, slope, soil, precipitation, and climate. A comparison between the coral reefs for both islands will include information on bays, coral reef depths, dive site locations, water fluidity, and distance from land. The effects of sedimentation on coral reefs depend on individual reef characteristics including depth, distance to shore, and location (VI RC & D, 2010). Road networks and development will also be compared between the islands using historical data, satellite imagery, personal descriptions from locals and tourism websites, and images of road segments. The geographic characteristics of the islands and their road systems play a vital role in the amount of sedimentation reaching a reef. A case study in Coral Bay, St. John will then be used to evaluate the above information and

determine whether or not Koh Tao can use similar techniques to minimize sedimentation onto its reefs.

Due to the significant and chronic impacts sediments have on coral reefs, the USVI Department of Planning and Natural Resources Division of Coastal Zone Management developed a watershed management plan for the bay and its surrounding area. The report presents a framework for managing the Coral Bay watershed in St. John, and puts emphasis on developing strategies to reduce sedimentation from unpaved roads. The report acknowledges major reductions in sedimentation can be achieved through local applications of watershed-based management and use of Best Management Practices (BMP's) (VI RC &D, 2010). If the methodologies used in this paper show similarities between the two islands, then the control techniques and BMP's for unpaved road sedimentation can be applied towards the island of Koh Tao. The case study will also help determine what areas and bays on Koh Tao face the highest risk of sedimentation onto its coral reefs.

The paper contains no numerical data on actual sedimentation rates for Koh Tao. Although the lack of data may be seen as a drawback in the analysis, such studies require substantial amounts of time, effort, and money. Rather than investing energy into individual studies on Koh Tao, money and efforts could be used to construct sediment and erosion control sites on the island. The paper also lacks detailed scientific information on individual road slope and size for Koh Tao. An analysis using GIS would provide statistical numbers for Koh Tao and should be considered for future studies on the island. However, the methodologies used in this paper should provide enough information to determine whether Koh Tao faces great risks from sedimentation on current and future developments, and discuss the best methods to prevent high sedimentation rates from unpaved roads on coral reefs. This paper provides a simple and cost-effective approach to guide Koh Tao in developing strategies to reduce land-based threats to coral reefs. Rather than using only marine approaches to protect their valuable reef ecosystem, the paper offers information to reduce one of the many land-based reef threats of Koh Tao before reaching the ocean.

## Analysis

### **Analysis: Geographic characteristics of land and coral reefs**

Although St. John and Koh Tao are located on opposite sides of the world, they share similar geographic characteristics. Maps of both islands are shown in Figures 3 and 4 below.



Figure 3: Map of Koh Tao, Thailand.  
<http://dansmuaythaimma.com/?p=2445>



Figure 4: Map of St. John, USVI.  
<http://www.estaterose.com/>

From a geographic standpoint, both islands demonstrate a relatively consistent comparison for several categories. Using sources from tourist websites, scholarly articles, and governmental agencies, Table 1 displays a geographic comparison between St. John and Koh Tao. Figures 5, 6, and 7 give visual pictures of the island's geography.

Table1. A geographic comparison between St. John, USVI and Koh Tao, Thailand.

<b>Geographic Characteristics</b>	<b>St. John, USVI</b>	<b>Koh Tao, Thailand</b>
Location	18.2N 64.5 W See map	10.1 N, 99.8 E See map
Size	51.8 square kilometers	20.97 square kilometers
climate	Subtropical dry	tropical
Average temperature	77-81 F	86 F
Annual precipitation	115 cm/year	163 cm/year
Seasons	Wet season: February-July Dry season: August-January	Dry Season: December-February Hot Season: March-August Wet Season: September-November
Lithology	Basalts and volcanic wackes	Volcanic granite

Soil	-Clay, silt, sand - shallow, moderately permeable, well drained, and underlain by nearly impervious bedrock	- Clay, silt, sand
Topography	Mountainous terrain (Figure 3) Rugged, 80% of slopes > 30%	Mountainous terrain (Figures 4 and 5) Rugged
Island cover	63%- Dry evergreen forests + shrubs 30%-moist forest and secondary vegetation 2%- urban, wetland, and pasture	>90%: Dominated by secondary tropical forests in highlands, coconut plantations at lower elevations <10% developed land
Highest elevation	Bordeaux Mountain, 387 meters	379 meters

Table1: A geographic comparison between St. John, USVI and Koh Tao, Thailand.



Figure 5: Geography of St. John, USVI.  
<http://www.stjohn-virginislands.com/st%20john%20usvi.htm>



Figure 6 and 7: Geography of Koh Tao, Thailand.  
Photos from Dillon Vassallo

The similarities between the two islands, seen in the above table and figures 3-7, provide vital information for evaluating the effects of sedimentation on the surrounding coral reefs. Macdonald and Anderson (2001) explained sedimentation rates from unpaved

roads on St. John depend greatly on the slope of the terrain, precipitation, and storm intensity. Parallels exist between the volcanic mountainous terrains on both islands. Both islands feature a maximum elevation point just below 400 meters, and similarities in their topography can be seen in images of the islands. (Haad Tien, 2012). Koh Tao gets about 50 more centimeters of rain on average per year, and both islands have a dry and wet season and are characterized as a tropical climate (Thai Meteorological Department, 2006). On Koh Tao, the wet season consists of torrential downpours and tropical storms from the northeast monsoon winds. The precipitation usually comes in fast, heavy showers with large amounts of rainfall. The precipitation in November averages more than twice any other month, with October being the second highest precipitation month (Holiday Weather, 2012). Many roads on Koh Tao wash out completely, and parts of the island can only be accessed by boat during the wet season (Visit Thailand, 2007). As noted, storm intensity plays a vital role in the sedimentation rate from unpaved roads (Ramos-Scharron and MacDonald, 2005). The geographic parallels on both islands offers evidence to the possibility of Koh Tao having major sedimentation flows from unpaved road segments.

Similarly, the coral reefs on Koh Tao hold many similar characteristics of the reefs around St. John. As seen in Figure 3, a high number of bays surround the coastline of Koh Tao. All bays contain coral reef ecosystems, and over 25 dive sites exist around the island. Most coral reef dive sites are located within 50 meters from shore, demonstrating the reef locations exist right off of the coastal land (See Figure 12). Average depth of dive site reefs equal 14 meters, yet many coral ecosystems around Koh Tao begin right along the coastline at much shallower depths (Koh Tao Info, 2002). Similar to Koh Tao, St. John also has several shallow bay areas, with large reef patches surrounding the island. Rogers (1990) explains an individual reef threat from sedimentation can be based on “the amount of sediment which will be introduced into the reef environment, the coral community composition, the depth of the reef, the percent coral cover, and the current patterns”. Additionally, “reefs in poorly flushed semi-enclosed bays or lagoons, and reefs surrounded by a shallow sea floor, are at greatest risk of degradation, probably because materials are retained for prolonged periods of time, extending the period of exposure to more ‘chronic’ conditions” (ISRS, 2004). Both St.

John and Koh Tao's reef ecosystems possess the characteristics to make them highly threatened from sedimentation (Save Koh Tao, 2012, Ramos-Scharron and MacDonald, 2005). Koh Tao and other southern islands in Thailand recently lost over a third of their coral reefs from sediment (Sarnsamak, 2012). Similarly, the largest threat to coral reefs on St. John is sedimentation (Ramos-Scharron and Macdonald, 2007). Sedimentation poses as a major threat to the coral reefs of both islands because of their mountainous terrain, heavy rainfall, and volcanic properties. However, where does the sediment come from? In Thailand, studies found land development and coastal expansion to be the main cause of sedimentation onto the reefs, but no research looked further into the analysis to determine what parts of the expansion contributed the most (Sarnsamak, 2012). However, on St. John, studies show the unpaved road network to be the main source of sedimentation onto the reefs (Ramos-Scharron and Macdonald, 2005). While the geography of both islands prove very similar, their road networks must be compared to determine whether or not unpaved roads play a vital role in the destruction of coral reefs from sedimentation on Koh Tao.

### **Analysis: Historical development and unpaved roads**

Roads alter the natural processes of water storage and distribution on a landscape. Roads increase the frequency and magnitude of surface runoff because they create a compacted, low-permeability surface (Bren and Leitch, 1985), and also affect runoff because they intercept subsurface flows and disrupt natural drainage patterns (Dutton et al., 2005). Unpaved roads greatly increase the rate of sedimentation, where materials transport down the dirt road network during precipitation. Surface erosion rates are generally many times higher than erosion rates from undisturbed hillslopes, especially on steep mountainous terrains, like St. John and Koh Tao (Ramos-Scharron and Macdonald, 2005).

Due to a tourism boom and rapid expansion on St. John, the density of roads greatly increased over the past 30 years. For example, from 1971 to 2000, the road network expanded around Fish Bay basin from 6.0 square kilometers to 23.2 square kilometers (Ramos-Scharron and Macdonald, 2007). In 1980, the annual visitor rate to the USVI was only 530,000, yet by 2009 the number of annual visitors reached almost



2.25 million (USVI Annual Tourism Indicators, 2010). In 2010, an estimated 110,000 people lived on the US Virgin Islands of St. Thomas, St. Croix, and St. John, and the island welcomed an additional 2.6 million annual visitors. On St. John, the population expanded by 171% from 2000 to 2008. Many private owners built homes high up in the mountainous terrain, requiring long dirt road segments to be built for access (Crosset et al., 2008). The rapid pace of expansion called for quick development schemes, and minimal planning went into road and building construction on the steep slopes and highly erosive soils of St. John. Further, a majority of developments on St. John “lack properly designed and implemented storm water drainage plans, and most access is still provided by a network of unpaved roads. These unpaved road systems have become both primary sources of sediment and primary drainage conveyances, effectively transporting sediment-laden runoff into sensitive coastal habitats” (VI RC&D, 2010). Many of the steep unpaved road segments develop deep rills because of their poor drainage structures (Ramos-Scharron and MacDonald, 2007). Figure 8 displays the road segments of St. John and their vulnerability to erosion based on slope, precipitation, and soil erodibility. Figures 9-11 show satellite images of the road network and a visual photograph of a deep rill and the poor unpaved road conditions on St. John.

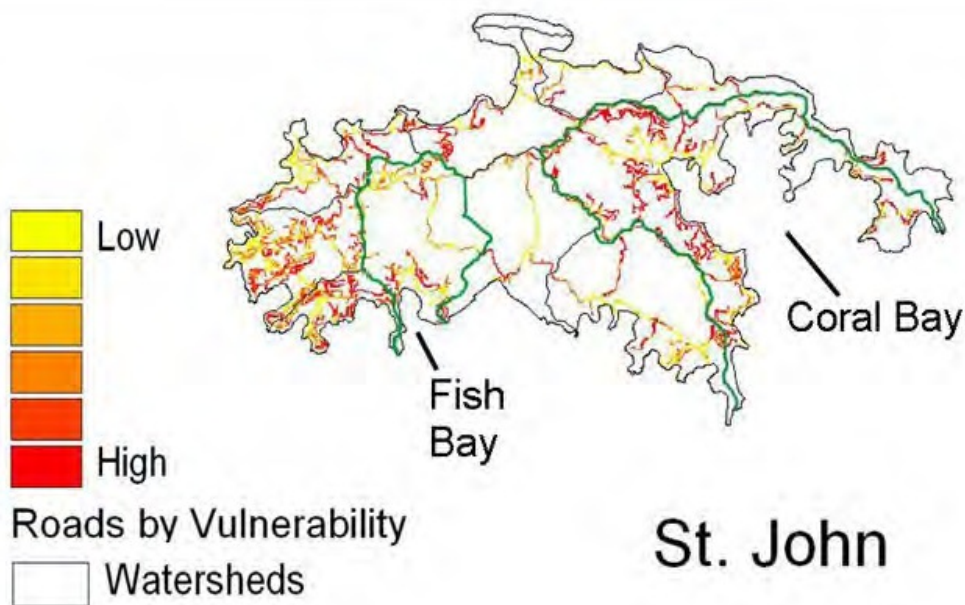


Figure 8: Road vulnerability on St. John. (VI RC&D, 2010)

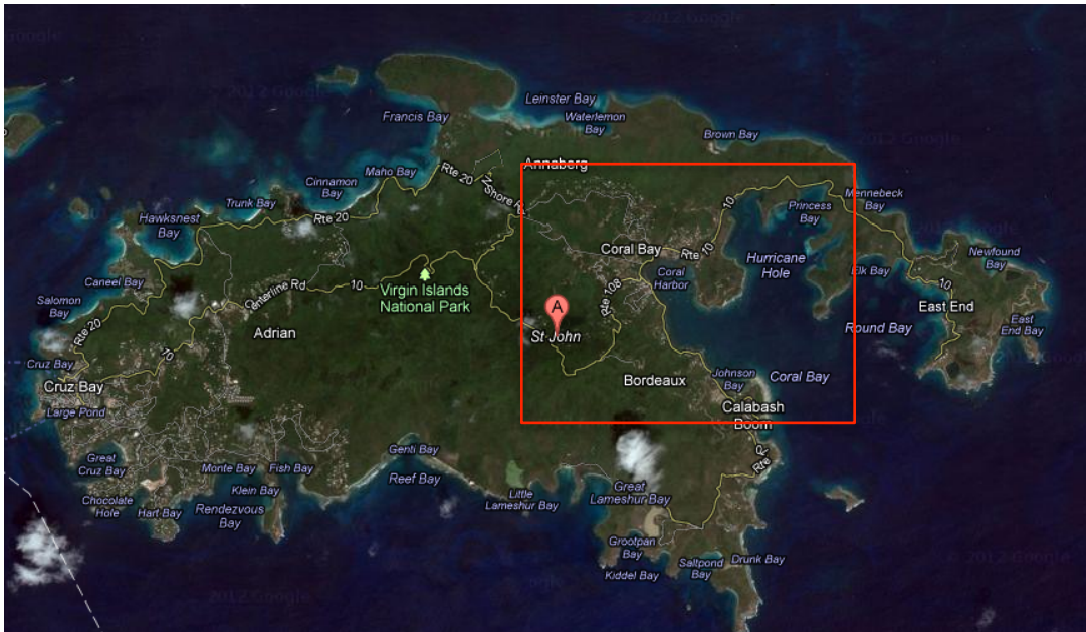


Figure 9: St. John Road Network.  
Google Maps

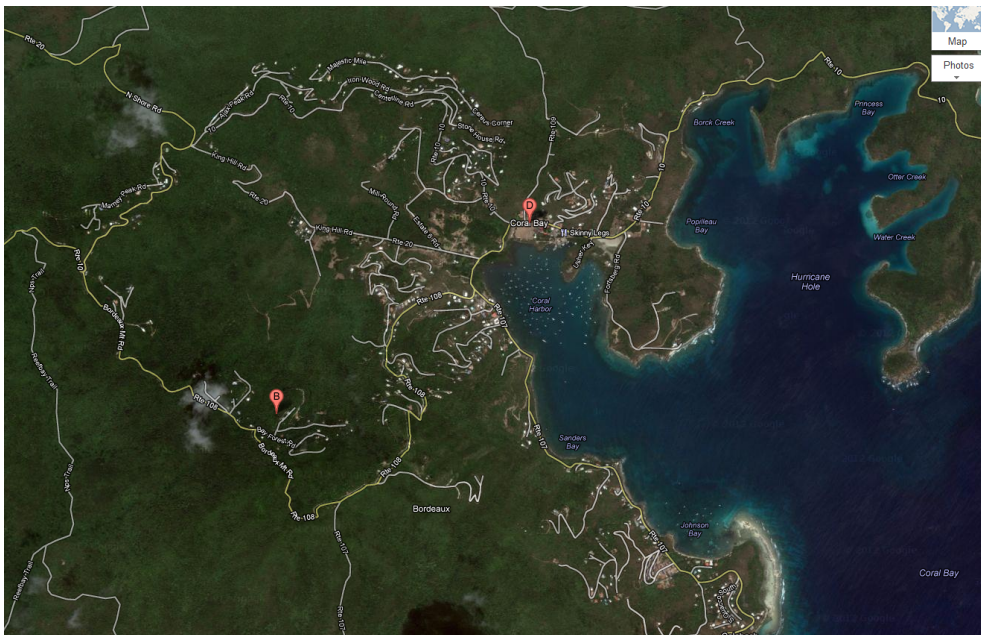


Figure 10: Coral Bay, St. John. (Red Area Above)  
Google Maps



Figure 11: Deep Rill on the side of a dirt road, St. John. (VI RC & D, 2010)

The extensive research conducted on St. John over the last decade provides locals with vital information on how to minimize sedimentation rates. Different local and international organizations now use the research to implement the best sediment and erosion mitigation techniques.

Although no studies exist on unpaved road sedimentation rates for Koh Tao, the geographic data on the island combined with a better understanding of the road networks will help determine if unpaved roads pose a threat to coral reefs. The first tourists discovered Koh Tao in the 1980's and quickly turned it into a popular travelling destination for international backpackers. Today, Koh Tao is recognized as one of the busiest scuba diving centers in Southeast Asia, with nearly 1 million foreign and Thai tourists visiting each year. As a consequence of the rapid development, over 2,500 hotel rooms and bungalows exist on the island to accommodate guests for their diving adventures. Most construction and development lies along the coastline rather than the steep hill slopes on the island (Szuster et al., 2011). Figures 12 and 13 show satellite images of Koh Tao's development and Figure 14 depicts the island's road network.



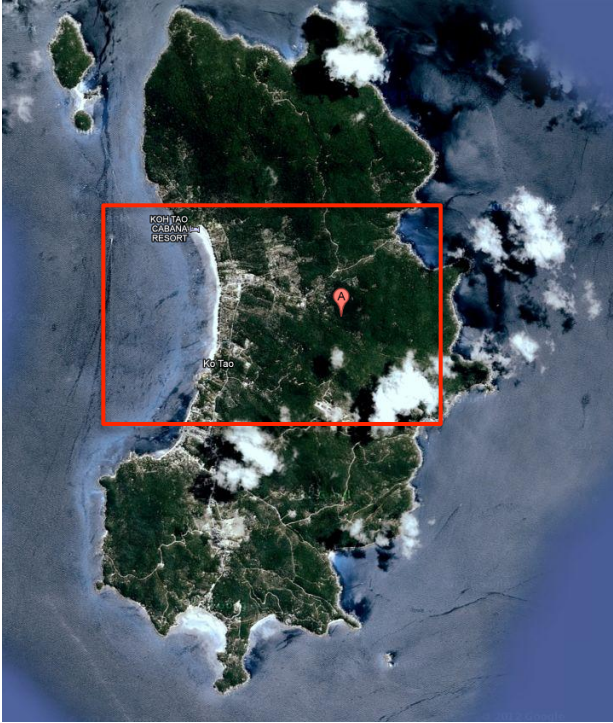


Figure 12: Koh Tao Roads and development.  
Google Maps

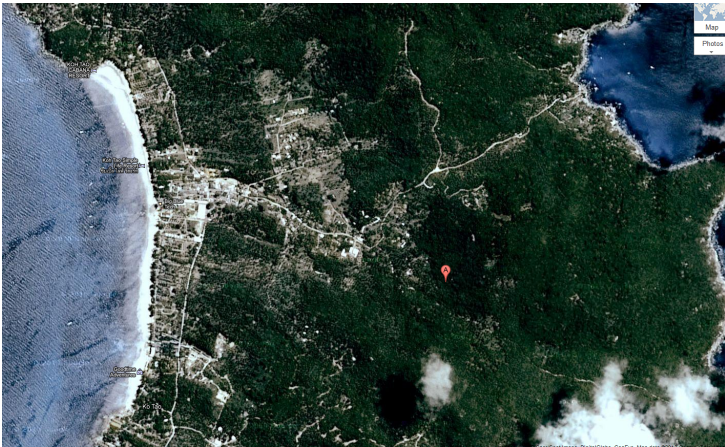


Figure 13: Sairee Beach, Koh Tao. (Red area above)  
Google Maps



Figure 14: The road network of Koh Tao.  
<http://en.kohtaозone.com/images/koh-tao-roadmap-big.png>

A main paved road extends across the west coast, linking the north end of Sairee with Chalok Baan Kao in the south. This major road passes through the main tourist village and transportation hub, Mae Haad (seen in figure 13). The main road is the spinal column for roads in Koh Tao, with all other roads extending off either down to Sairee Beach and its resorts or up and over the mountains towards other bays. Almost all roads splitting off the main road remain unpaved, except for a recent paved section towards Thian Ok Bay (Koh Toa Zone, 2012). A Koh Tao tourist information site describes the unpaved dirt roads as steep, consisting of sand and grit, and containing several fast curves, potholes, and washed out tracks (Sawadee, 2012). Figure 15 shows an image of a section of unpaved road in Koh Tao, and the effects from precipitation and runoff.



Figure 15: Dirt road in Koh Tao, Thailand.  
<http://www.travelblog.org/Photos/361481>

Several road similarities seem to exist between St. John and Koh Tao. Many of the unpaved roads on both islands wash out and require substantial efforts to replace dirt after the rainy season ends. On St. John, the high rainfall erosivity and poor drainage design results in deep rills on the road surfaces, and they must be regarded every year so passenger cars can access them (Ramos-Scharron and Macdonald, 2007). Many unpaved segments in Thailand tend to wash out completely during the rainy season, and bungalows and resorts located on the eastern bays of the island can only be accessed by boat (Visit Thailand, 2007). The steeper sloped unpaved paths in the mountainous regions of both islands produce the most erosion, and the rainy season with frequent heavy rainfall contributes the most towards sedimentation and runoff (Ramos-Scharron and Macdonald, 2007, Visit Thailand, 2007). For example, after 3 days of nonstop monsoon rains in 2011, most dirt roads across the island completely washed out. For several days after the storms, locations across the main paved Sairee Beach road had “at least 3 areas with deep, fast flowing water coming down from the causeways over the road” (KohTao.Asia, 2012). These water flows contain the sediments coming from the higher slopes of the island. [This video](#) (Thailand Floods, 2011) provides an example of floods in Koh Tao and the runoff on the poorly drained road network. Similarly, [a video](#) (St. John, USVI Flooding, 2010) of St. John during torrential downpours illustrates roads as the route for sedimentation onto the coral reefs. Despite consistent similarities between the existing roads on St. John and Koh Tao, St. John appears to be more developed with a

larger unpaved road network extending more consistently into the mountainous terrain of the island.

Although Koh Tao drastically expanded from tourism over the past few decades, there remains a strong possibility of continued development on the island. Most home, hotel, and bungalow locations rest along the coast rather than along the steep slopes of the island. As the island gains more and more popularity, inland development will inevitably occur. More roads will need to be constructed to connect the developments with the rest of the island. As seen in the satellite images and road network maps above, St. John is more developed with a larger quantity of dirt roads expanding into the heart of the island and mountains. Several vacation homes and hotels on St. John are built directly into the mountainside, and these owners build private roads to connect themselves with the road network on the island (VI RC & D, 2010). Coral Bay, St. John, provides an excellent example of significant development, the use of unpaved road networks to accommodate rapid expansion, and the ensuing runoff and sedimentation onto coral reefs.

Coral Bay represents the largest sub-watershed draining into an individual bay on St. John. Figure 10 above displays a satellite image of the bay, while Figure 16 below shows the different watersheds draining into Coral Bay, and the unpaved and paved road network can be seen in Figure 17. Figure 18 provides evidence of the runoff in a section of the bay named Coral Harbor, with several homes and hotels located high up in the mountains.



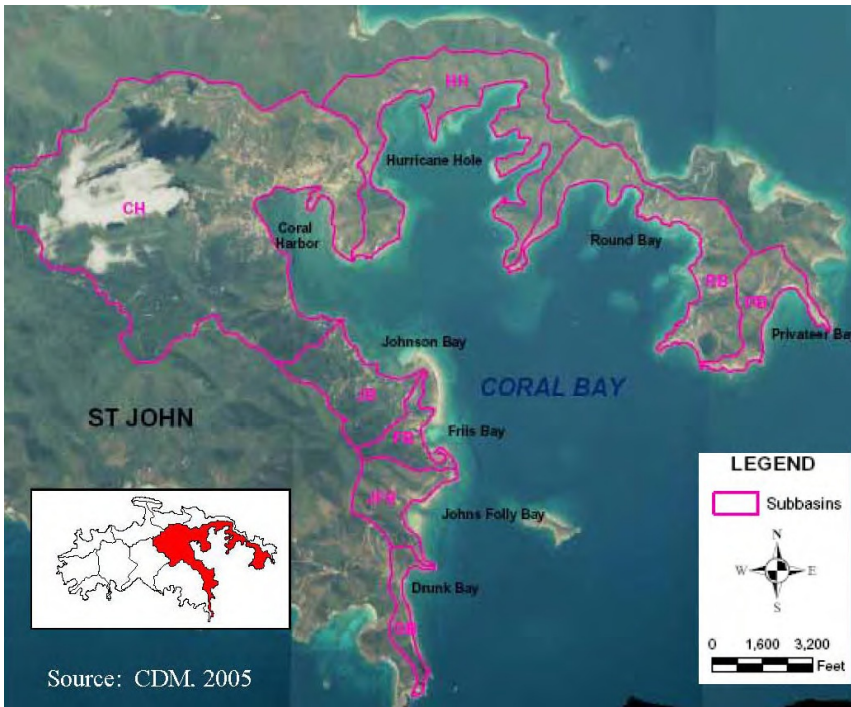


Figure 16: Coral Bay Subwatershed map. (VI RC& D, 2010)



**Coral Bay Watershed St. John. USVI**

*Land Based Sources of Pollution*

**Paved Roads and Unpaved Roads:** estimated 2009

Concrete Paved Roads -Generally no drainage structures, **Federal Highway funded paved roads**

**Dirt Roads/unpaved**

Figure 17: Coral Bay Watershed and road network, St. John USVI. (VI RC & D, 2010)





Figure 18. Sediment entering Coral Harbor from heavy rainstorm. (VI RC&D, 2010)

The Coral Bay watershed contains 35 miles of unpaved dirt roads, mainly connecting private homes and resorts to other areas of the mainland. The watershed encompasses steep slopes averaging over 18%, with many parts exceeding 35%. Historically, “land in the Coral Bay watershed has been subdivided and sold with poorly engineered unpaved private access roads without deed responsibilities for paving and/or maintenance (VI RC & D, 2010). Today, several techniques for reducing runoff and sedimentation onto the reefs are being used in Coral Bay and throughout St. John, which will be discussed later in the analysis. Although these techniques help mitigate runoff, better planning and proper drainage systems when building the roads would have been most effective.

The numerous studies in St. John found unpaved roads with steep slopes and large road density to be the highest contributors of sedimentation onto the reefs. Regrading the roads also produced excess sedimentation, and unpaved roads produced erosion rates of at least four magnitudes higher than undisturbed hillslopes (Ramos-Scharron and Macdonald 2005, 2007). Areas of greatest concern on St. John include Coral Bay and other bays located along the south-western part of the island (Ramos-Scharron and Macdonald, 2007). Seen in figure 9, these areas have high unpaved road densities because of heavy residential and commercial development along the coast and further inland.

An analysis from the above geographic information, satellite images, road network maps, and videos of Koh Tao, the Sairee Beach area on the west coast appears to

be the most populated area, with development and unpaved roads pushing further into the island (seen in figures 12 and 13). Drawing from the information found in St. John studies, the reefs off of Sairee Beach and its bay can be considered at great risk from sedimentation. Another area for concern appears to be the bays located on the southeast part of Koh Tao. These two areas display steep slopes, high road density, shallow reef systems, and the most developed areas on the island. Paired with heavy rainfall, an annual precipitation rate higher than St. John, and a majority of dirt roads, the analysis provides evidence of sedimentation being a major threat to the reefs in these two areas. Other areas of the island, especially inland, remain fairly untouched with minimal roads and development, and sedimentation appears to pose less of a threat to coral reefs in these areas. However, as the population and annual visitor numbers increase, these areas may be subject to future development with denser unpaved road networks.

Several organizations in St. John (including the *Virgin Islands Department of Planning & Natural Resources*, *Virgin Islands Resources Conservation and Development Council*, *Coral Reef Alliance*, and *International Society For Reef Studies*) developed Best Management Practices for controlling runoff related to roads, and these strategies now exist throughout the island. The techniques, developed on land, help prevent sedimentation from ever reaching the reefs, and should be used in Koh Tao for better reef conservation. With a collaborative effort at a local scale, sedimentation rates on individual reefs can be significantly reduced.

The most effective way to reduce runoff from roads relates to preserving existing vegetation and replanting unused roads (VI RC&D, 2010). However, roads will inevitably exist, and the best way to prevent runoff is paving roads. This action requires substantial amounts of money (over \$2 million per mile in St. John (VI RC& D, 2010)), and may not be economically feasible for all roads. The *Virgin Islands Department of Planning & Natural Resources* developed a guide on sediment and erosion control for the island with emphasis on techniques to mitigate sedimentation from unpaved roads. Some of the best practices included cross drains, broad-based dips, water turn-outs, and pipe culverts (Division of Environmental Protection, 2010). These techniques divert runoff from the surface of a dirt road to a more stable and vegetated area, preventing travel

down the mountains and onto the reefs. Figures 19- 21 display three different possibilities of dirt road drainage techniques.

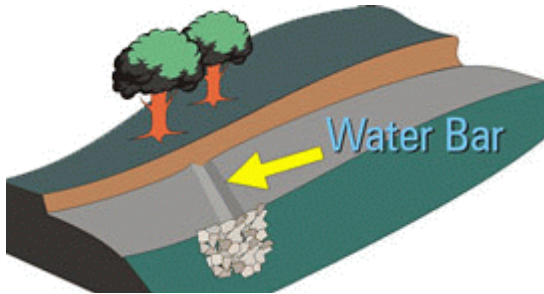


Figure 19: Cross-drain installation schematic (Division of Environmental Protection, 2010)

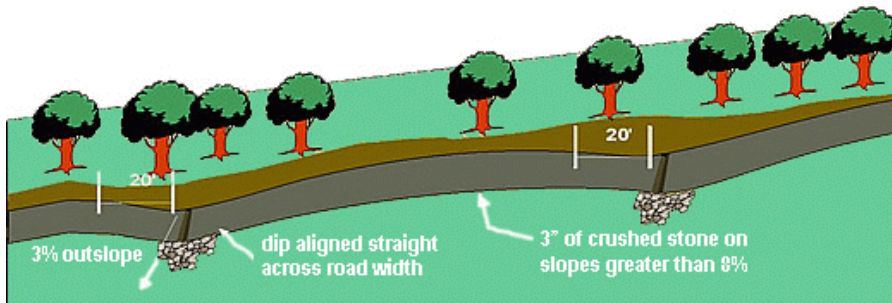


Figure 20: Broad-based dip schematic. (Division of Environmental Protection, 2010)

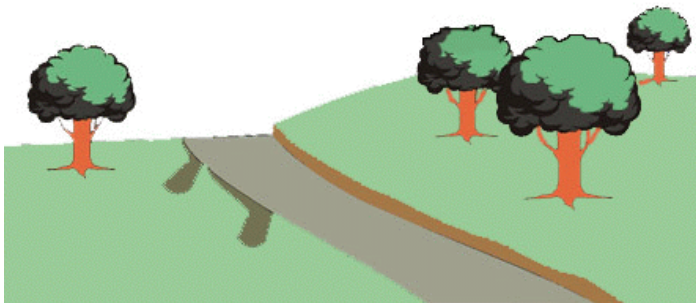


Figure 21: Schematic of water turnouts. (Division of Environmental Protection, 2010)

Cross-drains divert rainwater and sedimentation off the road network by creating an earthen filled “mound trench” placed diagonally across the surface of a dirt road. On the downslope out-fall, an energy absorber like stone or brush slows and dissipates the storm water and sediments. A broad-based dip consists of a broad, earthen dip-hump built into the surface of the road, and forms a drain to divert water across the road and into vegetated land. Broad-based dips allow traffic to maintain a uniform speed, compared to a “speed bump” for cross-drains. They can be used on dirt roads with a 12% slope or less,

while cross-drains work best for heavier sloped road segments. Water turnouts divert storm water away from a road surface with ditches, trenches, and swales. The turnouts dissipate the water and sediments into the forest or stabilized grass area.

Cross-drains, broad-based dips, and water turnouts provide basic recommendations for Koh Tao in developing a land-based approach to reduce sedimentation onto its reefs. While other techniques exist, these three approaches are cost-effective and fairly easy to maintain, and may be a good option for Koh Tao's current road system. In future years, Koh Tao should implement strategies like these when developing new road segments on the islands.

### **Conclusion**

This study provides evidence of the similarities between the islands of St. John and Koh Tao. The geographic characteristics, reef dynamics, and unpaved road networks of the two islands show consistent parallels. As mentioned, sedimentation from unpaved roads can be considered the largest threat to St. John's coral reefs. The above analysis proves sedimentation from unpaved roads a very high threat around the reefs of Koh Tao as well. Although St. John now uses existing studies to implement the best management strategies to reduce runoff before reaching the reefs, Koh Tao's approach to coral reef conservation involves only working in the water, without minimizing sedimentation rates on land. The paper suggests Koh Tao should use the information provided from St. John to develop a reef conservation effort, attacking both sea and land-based sources of pollution. As Koh Tao continues to develop in future years, the sedimentation from unpaved roads will become more and more of a threat to its reefs. By following the approaches from St. John, and understanding the mistakes the island made in development, Koh Tao can work at finding a solution to its current runoff problems, and use strategies to properly construct future roads to minimize sediment threats to its coral reefs. Rather than waiting for coral reef threats to reach the reef, Koh Tao might instead take a proactive approach on land, use the same strategies of St. John, and reduce the sedimentation from unpaved roads before the sediment damages the coral reefs.

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