EVALUATING THE SEDIMENT RETENTION FUNCTION OF SALT POND SYSTEMS IN THE U.S. VIRGIN ISLANDS

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ABSTRACT

Salt ponds and the specialized salt-tolerant vegetation communities that they support perform a variety of biological, hydrologic and water quality functions with benefits to both wildlife and humans. This study identified and evaluated the features of salt ponds and their watersheds (salt pond system) that are important in contributing to the effectiveness of the sediment retention function. The study focused on providing information upon which sound management policies could be formulated to protect valuable coastal resources. As part of this study, the use of remote sensing to aid monitoring of sedimentation in coastal waters was evaluated for its potential use as an additional management tool.

Thirteen key parameters were identified as being important in the function of sediment retention in salt pond systems of the US Virgin Islands. Data were collected in the field or through GIS analysis of orthophotography for 17 salt pond systems on St. Thomas (8), St. John (7), St. Croix (1) and Water Island (1). Key parameters of wetland features comprised berm elevation, presence or absence of an outlet, pond depth, submerged aquatic vegetation, water/woody vegetation interspersion, wetland fringe vegetation density and wetland fringe width while watershed parameters comprised flood plain, presence or absence of guts, land use, slope, soil erosion potential and wetland to watershed area.

Salt pond systems were found to be highly variable in their potential to retain sediment. Those with the least human-induced disturbance reflected the most natural environmental conditions but not necessarily the most effective functional performance for sediment retention. Using the data collected for each pond system as a guide to the variability of each parameter provides a valuable reference for assessing conditions of other pond systems or for monitoring changes to the pond systems studied in this investigation.

Data analyses led to a number of conclusions of salt pond system functional effectiveness for sediment retention. Perseverance, Salt and Southgate pond systems were identified as functioning most effectively. Compass Point, Flamingo, Fortuna and Mandahl pond systems were noted as being ineffective for the most parameters. This can primarily be attributed to human-induced changes in these systems. A number of conclusions were also drawn with regard to potential risks to salt pond systems to effectively retain sediment, and recommendations were made to help guide sustainable management policies.

In addition to the analysis of salt pond system features, the use of remote sensing was examined as a means of monitoring sediment plumes in the vicinity of the salt ponds as well as other locations around the US Virgin Islands. Thirteen sets of Landsat satellite imagery were obtained of St Thomas and St John and two of St Croix, and acquisition dates were matched to significant precipitation events. Different image processing techniques were applied to the satellite images to evaluate indications of sediment suspension in inshore waters, but no evidence of sediment suspension in the coastal waters of the USVI was found. Aerial photographs taken in 2004 of the USVI coastline shortly after Tropical Storm Jeanne were also examined for evidence of suspended sediment, but only two locations on St Thomas showed evidence of suspended sediment in nearshore waters. Using remote sensing through Landsat imagery to detect and monitor suspended sediment in the coastal waters of the USVI was found to be unfeasible. Recommendations were provided for courses of action that could be pursued in the future if remote sensing is to be considered as a management tool.

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INTRODUCTION

Background

Salt ponds and the specialized salt-tolerant vegetation communities that they support perform a variety of biological, hydrologic and water quality functions with benefits to both wildlife and humans. Capturing and retaining sediments is an important water quality function of wetlands (Ramsar, 2004; Brody *et al*., 1970; Adamus and Field, 2001), and in the case of surface water runoff, salt ponds act as a retention basin (Brody *et al.*, 1970; Hodge, undated; Brin *et al*., 2003) and facilitate deposition of particles within the pond or among the dense root systems of the plants fringing the pond. This gives many salt ponds their characteristic turbid appearance (Brody *et al.*, 1977; Stengel, 1998) but in turn helps to protect sensitive coastal resources, such as coral reefs and seagrasses, that can be adversely impacted from siltation. The variety of functions within a watershed's wetlands can be used as an indicator of watershed health (Adamus and Field, 2001), but because biological and structural functions are easier to assess, less information is available on hydrologic and water quality functions (PERL, 1990).

The role of sediment retention in the USVI salt ponds has gained little attention other than noted as being beneficial. Both federal and state regulatory agencies are placing greater importance on the functional roles of wetlands (USACE/EPA, 2002), and sediment retention is noted as being an important function (Adamus and Field, 2001). Functional assessment methodologies have been used to compare functional and nonfunctional wetlands based on particular geomorphic characteristics. These methodologies are based on some understanding of conditions within a wetland and/or its watershed and change as a result of anthropogenic or natural disturbances.

Because of their position along the coast and close proximity to potentially valuable waterfront real estate, all the salt ponds on the U.S. Virgin Islands (USVI) are threatened by intense development pressure. Hotels, condominiums, marinas and ferry facilities have been built, or could in the future build, in or adjacent to these unique ecosystems. Development has already resulted in the complete loss of some salt ponds: on St. Thomas several salt ponds were used as a dump site before becoming the Wyndham Sugar Bay Resort; the Cabrita Point condominium complex replaced a large salt pond and a salt pond at Vessup Bay was filled to create a road (Stengel, 1998).

Development, land clearing and roads on the hillsides above the salt ponds may result in excessive runoff that can and often does drain into the wetlands (Island Resources Foundation, 1977; Stengel, 1998; Brin *et al*., 2003) or nearshore coastal waters (Hodge, undated; Nemeth and Nowlis, 2001). The full impact of this development on wetlands is unknown, however limitations in the ability of mangroves to filter out sediment have been noted (Bossi and Cintron, 1990). Similarly, sedimentation into a salt pond that is in excess of what can be naturally assimilated must lead to physical changes within the salt pond and/or its connection to the sea and impairment of its functional ability to limit the transfer of suspended particles to the nearshore coastal zone. What these functional limitations are and whether there have been changes to the capacity of the USVI salt ponds and their watersheds (the ‘salt pond system’) to perform the sediment retention function as a result of development is unclear.

Island Setting

The U.S. Virgin Islands are part of the Lesser Antilles and are mostly volcanic in origin. Two of the main islands, St. Thomas and St. John, and most of the surrounding smaller islands and cays have steep slopes and irregular shorelines, while St. Croix has a flatter terrain with mountainous areas in the northern part and a broad, coastal plain in the south. The highest elevation on the three largest islands is on St. Thomas (474 m above sea level), while the highest elevations on St. John and St. Croix are 395 m and 355 m above sea level, respectively. All the islands and cays are surrounded by coral reefs and seagrass beds. St. Thomas has an area of approximately 7861 ha and is the most densely populated of the islands, while over one-half of the approximately 4965 ha of St. John is covered by the Virgin Islands National Park (VINP). St. Croix is the largest island at over 22,127 ha (USDA-NRCS, 1998). Water Island, often called the fourth island, is the smallest with an area of 191 ha; its highest point is 91 m.

The climate of the islands is dominated by the easterly tradewinds. Rainfall varies across the islands but increases with increasing elevation (USDA, 1998). Annual precipitation from 30-60 inches (76 - 52 cm) falls across most areas of St. Thomas and St. John while rainfall across St. Croix differs significantly with the eastern end of the island receiving substantially less (20-30 inches [51-76 cm] annually) than the northwestern areas (>50 inches [127 cm] annually) (USDA, 1998). The islands have no distinct wet and dry periods or seasons; in general the wettest period is from September to November and the driest from January to June, however large rainfall events can, and often do, occur during the first half of the year. In the Southgate Pond watershed on St. Croix, the water year (September thru August) has been shown to have three patterns (Knowles, 1996 in Gaines, 2004): wet autumn/winter and dry summer; dry autumn/winter and wet summer and dry all year.

Salt Ponds in the US Virgin Islands

Salt ponds are unique coastal ecosystems that are intermittently connected to coastal waters. Once open bays or inlets, these water bodies became more isolated over time as accretion from soils and sediment formed an effective barrier from the sea. There are over 60 salt ponds located on the US Virgin Islands, and these form the dominant type of wetland (Montella *et al*., 1994 in Stengel, 1998).

The evolution of some salt ponds has been hypothesized from sediment core analyses (Brooks *et al*., 2004). The depositional history of the ponds suggests a terrestrial phase prior to sea level rise during the Holocene period about 4000 years ago, and then a marine depositional phase as sea levels rose. Gradually the establishment of mangrove vegetation and/or the accretion of reefs closed off coastal embayments, separating the ponds from the sea. Terrestrial sources of sediment in the upper layers of the pond document the final phase of pond development as the pond evolved from wetland to more upland conditions. The final stage has been noted as leading to island accretion and coastal straightening (Brooks *et al*., 2004) and in some cases as being accelerated by anthropogenic activities (Brooks *et al*., 2004; Nichols and Brush, 1988).

The physical, chemical and biological features of salt ponds are subject to seasonal change depending on a number of natural environmental conditions including the frequency of inundation by the sea, rainfall and evaporation (Barnes, 1980). These factors affect the salinity, water depth and pond boundaries (Brody *et al.*, 1970; Stengel, 1998) resulting in potentially significant temporal changes to the functions that the ponds provide. Salt ponds also vary to the degree they receive intertidal exchange (Brin *et al*., 2003). Many are separated for long periods of time except during extreme events, such as hurricanes, storm surges or extreme high tides. Others receive regular tidal flushing through channels or seepage of seawater through or over the permeable barrier berm (Brody *et al*., 1970). Still others have been completely opened to the sea as a result of development activities; in the USVI these include Flamingo Bay on Water Island, Mandahl Pond and what is now Sapphire Bay Resort Marina on St. Thomas and Chocolate Hole North and Enighed Pond on St. John (Stengel, 1998).

Rainfall, Runoff and Sedimentation

The amount of rainfall a region receives can be an indicator of the amount of sediment runoff, and studies of 800 watersheds across the U.S. have indicated that areas with about 2 inches (5 cm) of annual runoff have the greatest sediment yields per unit area (Dendy and Bolton, 1976, in Adamus *et al*., 1991 p. 109). In the U.S. Virgin Islands, most rainfall events produce very little runoff, and the amount generated is dependent on a number of factors including antecedent conditions. Storm runoff following 2.17 inches (5.5 cm) of rainfall at Guinea Gut at Bethany Church, St. John, in April 1965 was about 0.1 percent of this amount, but this storm was preceded by dry weather. Another storm of 2.93 inches (7.4 cm) in November of that year generated approximately 15.1 percent of this as runoff, but this was preceded by another recent storm (Cosner, 1972).

The drainage basin of Mangrove Lagoon, St. Thomas, receives approximately 40 inches (102 cm) of rainfall annually, however runoff has been reported as only 2-8 percent of this with only major storm events of more than 4 inches (10 cm) generating enough runoff to reach the lagoon (Nichols and Towle, 1977). On St. Croix, Gaines (2004) reported that, on average, only 13% of rain falling within the Southgate watershed reached the salt pond with approximately 6% of this entering the pond as direct rainfall. The two principal streams in the Southgate watershed flowed for only a few days each year during heavy rains.

Island streams, known as guts, are not perennial, but because of the generally steep slopes on the islands, guts are subjected to large volumes of water over a short time duration during major storm events. This can lead to a rapid surface flow of water into and beyond the lower watershed. Rainwater is removed by evapotranspiration, infiltration through the ground or, if the soil becomes saturated, surface flow to channels, ponds or the sea.

Sedimentation in the salt ponds originates from upland runoff, tidal washover or autochthonous sources and consists of both mineral and organic fractions. The threat of soil deposition to a salt pond decreases with increasing distance from the soil source (Shafer and Yozzo, 1998). MacDonald *et al.* (1997) reported that even during large storm events on St. John, undisturbed areas generally were not affected by sheetwash, rilling and gullying because of the dense vegetative cover and rocky soil, however unpaved roads on St. John were found to have the potential to contribute four orders of magnitude more sediment than natural conditions (Ramos-Scharron and MacDonald, 2005). Although MacDonald *et al*. (1997) observed little evidence of erosion from construction sites on St. John as most sediment was trapped by adjacent vegetation, Nemeth and Nowlis (2001) found that sediment runoff from a construction site on St. Thomas correlated with both rainfall and construction activity.

Overview of Functional Assessment Methodologies

In recent years, regulatory agencies have been applying different habitat assessment methodologies to examine the health of wetlands in order to evaluate loss of function from proposed or completed development. Methodologies that use a functional approach to assessment are considered to give a balanced perspective of the attributes wetlands provide not only to wildlife but also to society on a sustainable basis (Adamus and Field, 2001).

Unfortunately these methodologies are limited, in part, to a lack of understanding of wetland formation and maintenance processes, particularly in highly altered landscapes (Adamus and Field, 2001). Understanding how disturbance has affected the wetland system over time and the trends that have occurred is important in understanding the function (PERL, 1990). A full review of the various procedures, rationale and objectives of the different functional assessment methodologies is not provided in this report. For detailed reviews of single or multiple methods see Bartoldus (1999), Smith *et al*. (1995), Adamus (2001) or Hruby *et al*. (1999).

There are a number of approaches to carrying out a functional assessment including subjective approaches based on best professional judgment and numerical approaches based on scoring. It is recognized that methods generally need to be modified to reflect local conditions (Hruby and Miller, 1995) which in turn need to be viewed within the landscape context (Sutter, 2001). For a functional wetland assessment to be practicable, it must use information that can be collected easily and quickly at any time of the year (i.e. rapid assessment).

Only one function – sediment retention **-** is being assessed in this study, however the approach is similar to that described by Smith *et al*. (1995) which uses hydrogeomorphic (HGM) classification (Brinson, 1993) to classify wetlands into groups that function in similar ways. The function(s) are characterized taking into consideration the attributes of the ecosystem and landscape that influence the function (Smith *et al*., 1995). The process for characterizing sediment retention in this study can be summarized as follows:

1. A study set of salt ponds was identified that represented the topographic variability of the USVI.
2. Key parameters, which are easily observed or measured characteristics, were identified and defined for the range of salt ponds being examined. These parameters have a documented or hypothesized association with the function that provides some information on functional performance (Kentula *et al*., 1992; Hruby *et al*., 1995).
3. Further analysis of the parameters was then undertaken to determine whether indicators - which can be used to distinguish a particular condition of the salt pond, for example a low-impacted pond from a high-impacted one - were identifiable.

Reference standards can then be developed which represent the undisturbed or ‘least altered’ conditions (Smith *et al*., 1995). This does not necessarily mean that the undisturbed condition will function at the highest level; for instance, Hruby *et al.* (1999) reported that the highest functional value was not always correlated with lack of alteration but depended on conditions within the wetland.

Sediment Retention: Function Definition and Evaluation

For this study, the function of sediment retention in salt ponds is defined as the ability of the salt pond system (i.e. salt pond and its watershed) to remove sediment from flowing water, thus preventing it from reaching adjacent coastal waters. Physical conditions of the pond as well as the watershed contribute to the short and long-term effectiveness of this function, and both pond and watershed characteristics are analyzed in this study.

The source, movement and quantity of sediment within the watershed are not examined in this study; nor is the opportunity to remove sediments, which depends on the availability of sediment to provide the salt pond with the chance of trapping and retention. Instead, the approach in this study addresses the contributing physical features of the salt pond system that enhance trapping and retention of sediment.

Sediment retention within the salt pond is considered to be the last step in protecting sensitive resources beyond the pond. The effectiveness of this function is influenced by what is happening in the contributing watershed, and the watershed plays a major role in determining the long-term functionality of the pond. Historic conditions in the USVI may have been such that little sediment found its way into the lower reaches of a watershed even during extreme events; shallow soils and dense vegetation would have limited such flows of sediment and studies of sediment accumulation in the ponds appear to support this (Brooks *et al.*, 2004). However, with impervious surface development replacing natural vegetation communities, an expansion in the number of unpaved roads particularly in upland reaches of a watershed and encroachment into the immediate areas surrounding a pond, the role the landscape plays in limiting soil export to salt ponds becomes extremely important not only to protect downstream coastal resources but also to ensure the longevity of the pond and its continued effectiveness to trap sediment and perform other functions.

Goal and Objectives of the Study

The goal of this study was to evaluate the effectiveness of the sediment retention function of salt pond systems in the USVI. To attain this goal, the following objectives were carried out:

1. Identify and evaluate the features of salt ponds and pond watersheds (salt pond system) that are important in contributing to the effectiveness of sediment retention;
2. Evaluate historical changes and trends to the functional capacity of USVI salt pond systems to retain sediment in order to enable sound regulatory and land-use management decisions that will help to ensure a high functional performance;
3. Evaluate remote sensing as a management tool to predict and monitor the performance of sediment retention in salt pond systems.

METHDOLOGY

Rainfall

Rainfall data between the years 2000 and 2005 were reviewed for a number of stations located on St. Thomas, St. John and St. Croix (Table 1). Rain events exceeding 1.0 inch (2.5 cm) of precipitation in one day and major storm events in which daily rainfall exceeded 4 inches (10 cm) were identified in order to help focus the search for appropriate remote sensing imagery that would document nearshore coastal sedimentation from terrestrial sources.

Average annual rainfall patterns across the islands (DCCA, 1970) were also examined to aid in the evaluation of site-specific conditions.

Table 1. Sources of rainfall data for the US Virgin Islands

Source	Location	Dates	Reference
USGS	Bonne Resolution Gut, ST 18°21'57"N, 64°57'34"W	3/03 to present	http://vi.water.usgs.gov/public/rt/vi/index.html
	Turpentine Run, Mt Zion, ST 18°19'55"N, 64°53'20"W	3/03 to present	
	Guinea Gut, Bethany, SJ 18°19'55"N, 64°46'50"W	3/03 to present	
	Jolly Hill Gut, Jolly Hill, SC 17°44'00", 64°51'47"	3/03 to present	
WRRI, VI	University of the Virgin Islands, ST 18.34° N, 64.97° W	2000 to May 05	http://rps.uvi.edu/WRRI/weathercenter.html

Parameter Identification

A number of published functional assessment methodologies were reviewed to identify pond and watershed parameters considered to be important in contributing to the ability or the effectiveness of a salt pond to trap and retain sediments.

An initial set of parameters was identified from functional assessments described by Adamus *et al.*, 1987, 1990, 1991; Adamus, 2001; Adamus and Field, 2001; Amman *et al.*, 1986; Bradshaw, 1991; Brinson *et al.*, 1995; Hauer *et al.*, 2002; Hruby *et al.*, 1999, 2000; James and Hewitt, 1995; Marble, 1992; Null *et al.*, 2000; Shafer and Yozzo, 1998; Smith *et al.*, 1995; Sutter, 2001 and USACE, 1995. A sub-set of these parameters was then selected based on i) identification by the local survey team as being applicable to salt ponds in the US Virgin Islands and ii) ability to easily and rapidly collect the information. The selected parameters were then divided into either salt pond or watershed features for data collection.

Pond Selection

Following a review of the wetland assessment methodologies and existing data of salt ponds on St. Thomas, St. John, St. Croix and Water Island, site visits to 25 salt ponds were made in order to identify a set of salt pond systems that represented a range of conditions of both natural and human-induced origins. Of the 25 sites initially visited, 17 salt pond systems, representing a range of disturbance conditions, were selected for further data collection.

Historical Reviews

Department of Planning and Natural Resources (DPNR) Coastal Zone Management (CZM) permits were examined for any development applications affecting the selected 17 ponds. In addition, DPNR Fish and Wildlife case files, including Environmental Assessment Reviews, were also examined for the same ponds. The purpose of this task was to identify documented information on changes that have occurred to the ponds or the immediate areas surrounding the ponds.

Eleven pre-1999 aerial photographs were identified for the17 selected salt ponds and scanned into digital format. These included eight photographs from St. Thomas, two from Water Island and one from St. Croix. The photographs, provided by the University of the Virgin Islands (UVI) Conservation Data Center (CDC), were examined to identify changes that have occurred over time to the salt pond features. Dates of the aerial photographs are listed in Table 2.

Table 2. Dates of aerial photographs examined from the UVI-CDC collection

3/78	Bolongo, Frenchman, Compass Point, Redhook, Coculus (STT)
2/7/71	Bolongo to Frenchman (STT)
1947	Flamingo Bay (WI)
2/7/71	Flamingo Bay (WI)
3/22/88	Mandahl (STT)
1/29/54	Mandahl (STT)
1947	Mandahl (STT)
2/18/64	Perseverance and Fortuna (STT)
1/29/54	Perseverance (STT)
1947	Perseverance (STT)
1946	Southgate (STC)

In addition a number of digital maps were downloaded from the internet at the following locations:

NOAA historical aerials 1971-1984 http://www8.nos.noaa.gov/biogeo_public/aerial/search.aspx
NOAA aerials 1999 http://nos.noaa.gov/dataexplorer/welcome.html
NOAA historical nautical charts http://historicals.ncd.noaa.gov/historicals/histmap.asp

Data Collection

Field collection of data took place between March and December, 2005 for parameters that could not be obtained from available maps. Data were collected by Denise Rennis, James Rennis or Colin Finney. The remaining parameters were calculated by UVI-CDC, Colin Finney or Denise Rennis using ArcView 3.3 or ArcGIS from GIS-based digital orthophotography produced by the US Army Corps of Engineers (USACE) from aerial photographs flown in February 1994 (USACE, 1994). Developed areas and roads were updated using orthophotography produced by the US Department of Agriculture (USDA)-Natural Resources Conservation Service (NRCS) and USACE from aerial photography collected by 3001, Inc. on 21 September 2004 using a ADS40 digital camera.

Berm Elevation
Elevations of the top of the berm were taken from the estimated high water line, as evidenced from the drift line or water mark, using a Keson LLA38 adjustable laser torpedo level and a staff gauge with 0.1 inch gradations. Locations of measurements were recorded using a Magellan ProMark X differential global positioning system (dGPS) unit. Elevations were obtained along the length of the berm until the lowest point of the berm was identified. Elevations were referenced to Mean Low Low Water (MLLW) for Charlotte Amalie (Station No. 9751639, 18^{o}20.1'N, 64^{o}55.2'W) provided by NOAA/NOS Center for Operational Oceanographic Products and Services (CO-OPS) [http://tidesonline.nos.noaa.gov/]. The exception to this was at Southgate Pond where the lowest point for the pond was an adjacent causeway. The elevation for the causeway was obtained from ancillary data collected for the USACE 1994 orthophotography.

Flood plain area
Area of the salt pond and within 0-3% slopes or 'flat land' surrounding the pond was calculated using ArcGIS with appropriate extensions. Polygons within this slope range were included in the flood plain calculation only if there was a direct connection with the pond or with other polygons connected to the pond. The pond area was included in this calculation to avoid discrepancies between wet and dry season pond boundaries. Developed areas, if any, were included in the overall calculation.

Gut presence/absence
Gut locations were based on information in the U.S. Virgin Islands Watersheds (Island Resources Foundation *et al*., 2002). Information for Flamingo Pond was obtained from Stengel (1988).

Land-use area
Land cover within the pond watershed and according to different slope categories (0-3%, 3.1-8% and >8.1%) was calculated using ArcView 3.3 or ArcGIS with appropriate extensions. Land-use categories included vegetation, developed (impervious surfaces excluding roads), crop land, pasture and roads. (Also see introductory paragraph to this section.)

Outlet
The presence or absence of an outlet was determined during the site visits. The width of the outlet was calculated from orthophotographs in ArcGIS.

Pond area
The water surface area of the salt pond in February 1994 was calculated using ArcView 3.3 with appropriate extensions.

Pond depth and bottom profile
Pond depths were recorded along the midline from one side of the pond to the opposite side. The edge of the pond was identified at the mangrove canopy line or, in the absence of vegetation, at the water line. Because the canopy edge was not necessarily the water/land interface, it was possible for pond depth measurements to begin at a depth greater than 0. Measurements across the pond were taken every 10 steps which equated to approximately 6.1 m (20 feet). Where the pond bottom was too soft to walk or clogged with dead wood, readings were taken as far into the pond as possible, and the remaining section of the pond estimated by visual observation. In four cases (Compass Point, Salt, Southside, Reef), shallow water and a soft pond bottom precluded collection of a complete set of data.

In water less than 0.76 m (2.5 feet), measurements were taken with a yard stick graduated in inches and recorded to the closest 0.5 inch. In water deeper than 0.76 m, measurements were taken with a NorCross DF2200PX digital hand-held sonar system from a kayak. Locations of all measurements were recorded with a hand-held Magellan ProMark X dGPS.

Staff gauges were placed in four ponds (Perseverance, Fortuna, Great Lameshur East and Bolongo) to help track changes in water depth. Readings were taken in March, May, June and December, 2005.

Pond watershed area
Area of the watershed that drained to the pond was delineated based on a flow accumulation model and digital terrain model using Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) 1.1 for ArcView 3.3. The flow accumulation model computes the flow across the landscape on a cell by cell basis based on the direction of the greatest elevation gradient. High flow accumulation is identified as a stream network, and the pond watershed is delineated for each stream segment using the watershed polygon processing and watershed aggregation operations. All polygons that overlapped the pond edge were selected as part of the pond watershed. The pond area was not included in the watershed calculation. The default setting of the program was selected in all cases. The final delineated boundary was checked against the elevation contour lines from the 1994 orthophotographs and adjusted, where necessary, based on best professional judgment.

Salinity
Salinity of water samples taken in March and April was determined by a Vernier Lab Pro used with a salinity sensor. Samples with salinities greater than 50^{o}/oo were sequentially diluted to obtain salinity values. Salinity from ponds surveyed in May and December was recorded with a Vee Gee A366ATC portable refractometer. Samples of pond water having salinities greater than 100^{o}/oo were sequentially diluted to obtain salinity values.

Slope
Areas within 0-3% slopes, 3.1-8% slopes and >8% slopes within the pond watershed, but excluding the pond, were calculated using ArcView 3.3 of ArcGIS with appropriate extensions.

Soil erosion potential

The Kf-factor for each of the upper watersheds was obtained from the Coastal Data CD for the US Caribbean (WRI and NOAA, 2005). This index is used to help predict the long-term average soil loss, which results from sheet and rill erosion under various alternative combinations of crop systems and conservation techniques (USDA-NRCS, 2005). The Kf-factor considers only the fine-earth fraction, which is the material < 2.0 mm in diameter. For this study, the percent of the watershed having a Kf-factor noted as ‘high erodibility potential’ was estimated from the data provided by WRI and NOAA (2005). Where more than one Kf-factor was presented as high erodibility, the Kf-factor values were averaged.

Submerged aquatic vegetation (SAV)

Visual observations were made of pond bottom cover by SAV which included all types of visible bottom cover including mat and filamentous algae. Cover categories were determined according to the following guide:

Category	Percent Cover
1	0-5%
2	6-25%
3	26-50%
4	51-75%
5	76-95%
6	96-100%

Water/woody vegetation interspersion

Percent cover of woody vegetation within the pond was determined by visual observation according to the following guide:

Category	Percent Cover
1	0-5%
2	6-25%
3	26-50%
4	51-75%
5	76-95%
6	96-100%

Wetland fringe vegetation density

Transects were used to determine vegetation density in the wetland surrounding the pond. The size of the pond determined the number of vegetation transects: one transect was laid perpendicular to the pond edge for every 120 m estimated distance across the longest length of the pond. Each transect extended up to 50 m, depending on the width of the wetland. At the beginning of each transect, a bearing was taken with a Suunto Tandem compass and latitude/longitude was taken with a Magellan ProMark X dGPS unit.

Three 2x0.5 or 1x1 m^2 quadrats were laid along each transect, one at the pond edge – determined by edge of water, mangrove canopy or pneumatophores - one at the edge of the wetland/upland boundary and one halfway between. Quadrats were placed to the left of the center line at the pond edge location, right of the center line at the midway point and left of the center line at the furthest plot. Prior to laying the center line, the area was evaluated for representativeness and the center line adjusted if necessary. Total vegetation cover of herbaceous and woody species was visually estimated within the quadrat. The percentage of bare ground was also visually estimated.

Wetland fringe width
The width of the wetland surrounding the pond was measured with a 50m tape or estimated where dense canopy precluded the use of a tape measure. The fringe width in this study is considered synonymous with 'wetland buffer'.

Wetland:watershed area
Wetland area included all salt pond, salt flat or mangrove communities within 0-3% slope, flat land or polygons with 'no data'. Watershed area included both the 'pond watershed area' and the 'pond area' described above. Calculations were carried out in ArcGIS.

Remote Sensing of Sediment in Coastal Waters

An evaluation was carried out on the use of remote sensing imagery as a tool for monitoring sediment in the nearshore water column. This included an assessment of both Landsat satellite imagery and aerial photography.

RESULTS

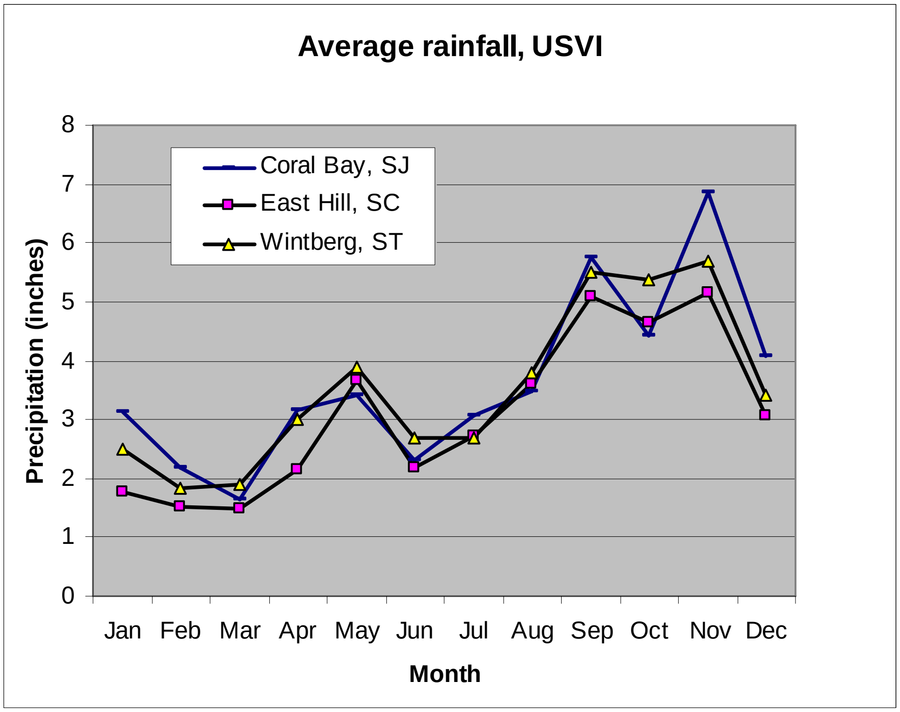
Rainfall

Rainfall in the USVI occurs throughout the year with the heaviest concentrations usually between August and December (Figure 1). In general highest rainfalls occur along the northern and central portions of the islands with lowest rainfalls on the eastern end (Figure 2).

Cosner (1972) reported that rainfall events on St. John exceeding 2.5 cm/day (1 inch) occurred less than 10 times annually. Rainfall events recorded from three stations on St. Thomas in 2005 exceeded 2.5 cm of rainfall/day on 26 occasions; events recorded at Guinea Gut, Bethany St. John and at Jolly Hill, St. Croix, exceeded 2.5 cm/day on only four occasions. During 2005, large storm events measuring more than 10 cm/day (4 inches) occurred only during the month of October on St. Thomas. Because rainfall amounts vary across the individual islands and there are more regular monitoring stations on St. Thomas (3) than on the other two islands, the data more accurately reflects rainfall across St. Thomas than St. John (1) and St. Croix (1).

Rain events on the three islands that exceeded 2.5 cm of rain in one day and major storm events in which daily rainfall exceeded 10 cm are shown in Table 3. Precipitation data for these events are listed in Appendix A.

Figure 1. Average monthly rainfall (1972 – 2000)



Data from ftp://ftp.wcc.nrcs.usda.gov/support/climate/wetlands/vi/

Table 3. Number of precipitation events 1-3.9 inches (2.5-10 cm) per day and >4 inches (10 cm) per day (in bold) on St. Thomas, St. John and St. Croix during the years 2000-2005 (source: maximum amount recorded from St. Thomas stations: WRRI, VI at University of the Virgin Islands, USGS at Turpentine Run or USGS at Bonne Resolution Gut; Guinea Gut at Bethany, St John; Jolly Hill Gut at Jolly Hill, St. Croix). See Appendix A for complete listing of dates and rainfall amount.

Month	**2000**	**2001**	**2002**	**2003**		**2004**			**2005**		
	ST	**ST**	**ST**	**ST**	**SJ**	**ST**	**SJ**	**SC**	**ST**	**SJ**	**SC**
January	0	1	0	0	N/A	0	1	N/A	3	2	0
February	0	0	0	0	N/A	0	N/A	0	0	0	1
March	0	0	0	0	N/A	2	N/A	N/A	0	0	0
April	0	0	0	7, **1**	3	0	0	0	1	1	1
May	2	2	0	0	0	0	N/A	N/A	3	0	1
June	0	0	0	0	0	0	N/A	0	2	1	0
July	1	1	0	1	0	0	1	0	4	0	0
August	0	0	0	1	1	2	0	0	3	0	0
September	0	0	4	2	1	1, **2**	1, **1**	1	5	0	0
October	0	0	1	2	1	1	N/A	N/A	3, **2**	0	0
November	0	0	1	6, **1**	4, **1**	4	N/A	N/A	0	0	1
December	0	1	1	2	1	0	N/A	N/A	0	0	0

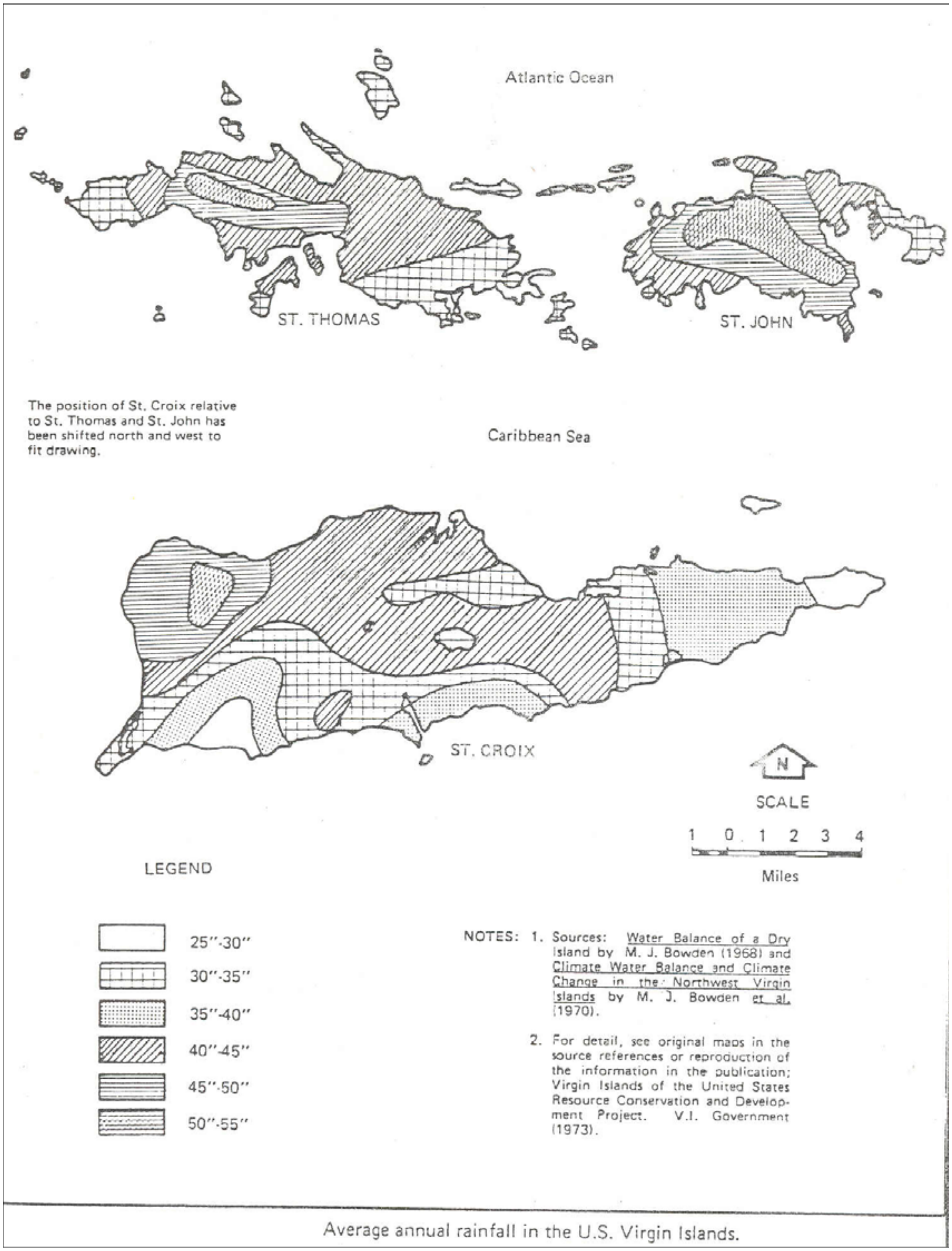


Figure 2. Average annual rainfall in the US Virgin Islands
(reproduced from DCCA, 1970s)

Salt Pond System Selection and Categories

Seventeen salt pond systems were selected as representative of the topographic variability of the USVI and for exhibiting a range of conditions of both natural and human-induced origin. These are listed in Table 4 with their geographical coordinates. Their locations are shown in Figure 3, and Appendix B contains representative photographs.

Salt ponds in the US Virgin Islands are characterized by their close location to the shoreline, historical separation from the sea by a sand or coral rubble berm, topographic depression in the landscape, similar source of hydrology including rainfall, surface runoff, groundwater discharge and storm surge, similar hydrologic outflow during normal conditions including evaporation, transpiration and groundwater seepage and a wide range of salinity conditions over the year. Natural channels linking the salt pond to the sea may or may not be present. Salt ponds with man-made channels to the sea are included in this classification because the channel represents a modification from the historic condition which may affect the salt pond's ability to perform the function of sediment retention.

Because salt ponds are limited in number and all appear to have evolved as inlets separated from the sea, this study does not place them into subclasses as described by Smith *et al*. (1995). Characteristics, such as duration of inundation and the presence of an outlet, which are used as subclass identifiers in other methods (Hruby *et al*., 1999) are considered to be features of all tropical island salt ponds which contribute to their ability to perform the sediment retention function.

For facilitating discussion about functional performance, the 17 selected salt pond systems were categorized by the degree of human-induced, land-use change in the pond watershed (Table 5). Because historical land use affected most watersheds on the USVI, ponds in watersheds with minimal impervious surfaces were chosen to reflect the least disturbed conditions even though they may not be representative of historical conditions. Conditions for division into categories were as follows:

Low disturbance (Natural condition) :	Presence of roads (excluding foot paths), buildings - none within 100 m of pond edge AND < 10% of watershed
Moderate disturbance:	Presence of roads (excluding foot paths), buildings – none within 25 m of pond edge AND <20% of watershed
High disturbance:	Presence of roads (excluding foot paths), buildings – <25 m from pond edge OR >20% of watershed

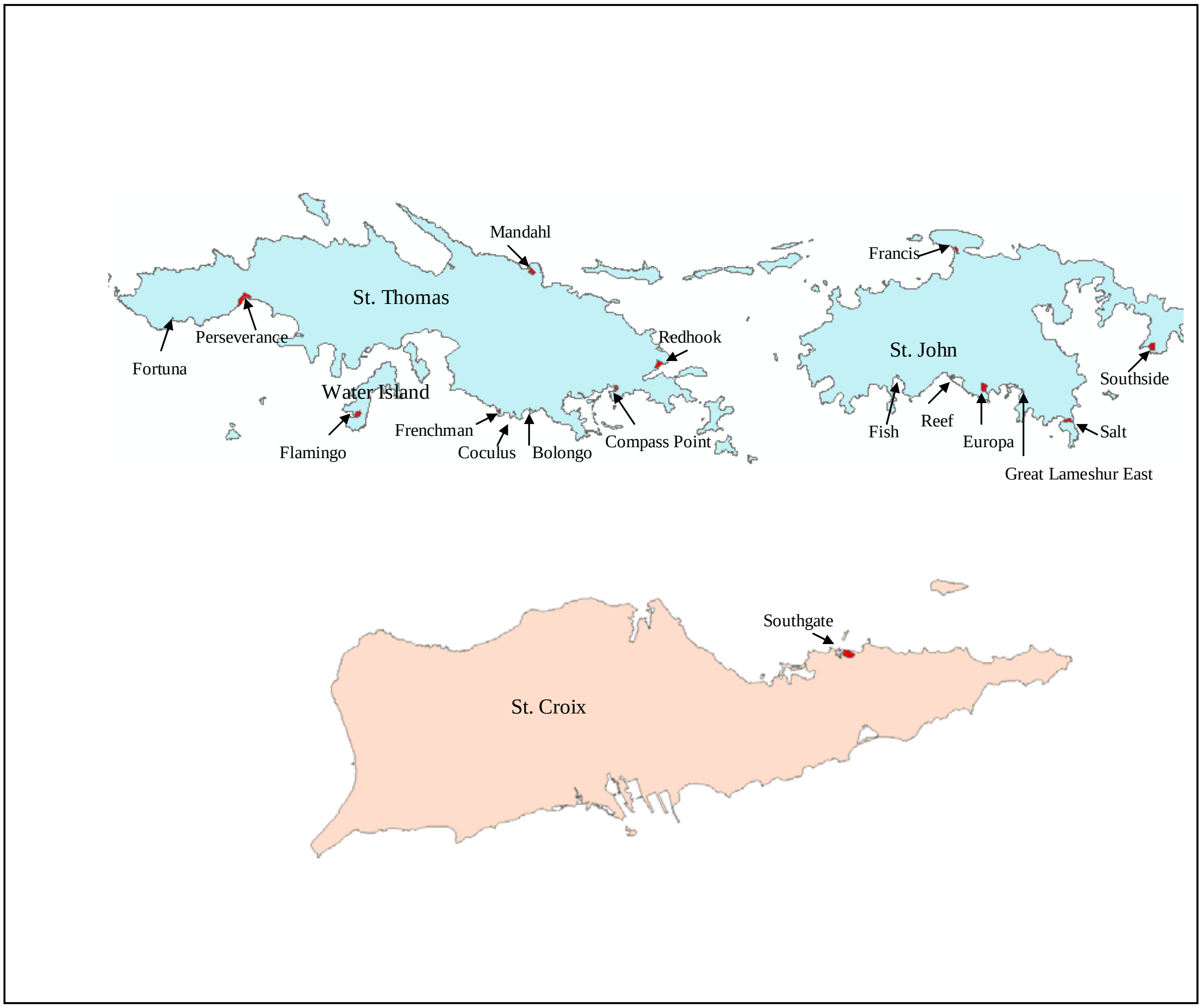
Table 4. Selected salt ponds and geographical coordinates

Salt Pond	Island	Location (Lat/Long)
Bolongo	ST	18.3128N 64.8944W
Coculus	ST	18.3117N 64.9003W
Compass Point	ST	18.3197N 64.8642W
Europa	SJ	18.3186N 64.7333W
Fish	SJ	18.3194N 64.7608W
Flamingo	WI	18.3117N 64.9561W
Fortuna	ST	18.3447N 65.0211W
Francis	SJ	18.3656N 64.7431W
Frenchman	ST	18.3122N 64.9056W
Great Lameshur East	SJ	18.3178N 64.7197W
Mandahl	ST	18.3603N 64.8942W
Perseverance	ST	18.3514N 64.9964W
Redhook	ST	18.3281N 64.8486W
Reef	SJ	18.3186N 64.7419W
Salt(L)	SJ	18.3075N 64.7036W
Southgate	SC	17.7586N 64.6644W
Southside	SJ	18.3324N 64.6737W

Table 5. Selected salt ponds categorized by level of disturbance in the pond watershed

Low Disturbance	Moderate Disturbance	High Disturbance
Europa (SJ)	Bolongo (ST)	Compass Point (ST)
Perseverance (ST)	Coculus (ST)	Fish (SJ)
Reef Bay (SJ)	Fortuna (ST)	Flamingo (WI)
Salt (SJ)	Francis (SJ)	Redhook (ST)
Southside (SJ)	Frenchman (ST)	Southgate (SC)
	Great Lameshur East (SJ)	
	Mandahl (ST)	

Figure 3. Locations of study sites



(not to scale)

Pond Histories

Permit reviews, case studies, published reports and aerial photographs were examined to identify changes that have occurred to the salt pond features and pond watersheds over time. Appendix C contains selected historical aerials. The following information summarizes the reviews.

Bolongo Pond, St. Thomas. Historical aerial photography indicates development on the eastern boundary of the pond watershed was present by 1971. Some additional development has occurred since then. The road adjacent to the pond was present in a 1946 topographic map, however no changes to the pond features appear to have occurred since at least 1946.

Coculus Pond, St. Thomas. No obvious changes to the pond features occurred between 1971 and 1999, and most of the development and roads apparent on the 1999 aerial produced by NOAA were also present in the 1971 photograph. These were not depicted on a 1946 topographic map.

Compass Point Pond, St. Thomas. Compass Point Pond has undergone a number of changes since the second half of the twentieth century, but based on a comparison of 1946 and 1968 nautical charts and a 2004 aerial photograph, the extent of the coastal land separating the pond from Benner Bay has not changed appreciably. The 1946 nautical chart does not show a pond, however this is probably an omission from the chart since other ponds were also noted as being absent on certain charts but present on others. Written evidence in DPNR permit files indicates that the pond historically dried out on a regular basis and suggests that although the pond was bordered on its bay side by red mangroves, there was a continuous flat or 'berm' which completely separated the pond from the bay. This appears to be supported by core samples which showed terrestrially-derived sediments on the pond side (Anonymous, DPNR permit files). In 1968 a temporary haul road was placed along the western side of the pond during fill activities for Compass Point (Anonymous, DPNR permit files). The fill was judged to be illegal and was removed post-1979 to a depth below the original surface elevation (Anonymous, DPNR permit files), although Stengel (1998) and aerial photos indicate that the fill was only partially removed. The pond is now open to the adjacent marina in Benner Bay by a narrow channel (Stengel, 1998) which is presumably a result of the fill and original surface removal. An ineffective sheet metal barricade has been placed across the opening (personal observations, 2005). Brooks *et al*. (2004) noted an increase in island-derived sediment in the surface layer of the pond and linked this to deposition due to development within the watershed.

Europa Pond, St. John. This pond is located within the VINP. No evident changes to the pond configuration or pond watershed occurred between 1971 and 1999.

Fish Pond, St. John. Land clearance and agriculture dominated the upper part of the watershed in the 18^{th} century, however by the mid 18^{th} century, cultivation around Fish Bay was apparently discontinued in favor of grazing and lumber (Tyson, 1987). By the end of the 18^{th} century agriculture was in decline, and by 1915 much of the watershed had reverted to woodland (Tyson, 1987) although the area immediately around Fish Pond was being cultivated as late as 1919 (Fig. 11 in Tyson, 1987). In 1971 Fish Pond appeared as a relatively small area in an undeveloped watershed. By 1999, the unvegetated areas surrounding the original pond had expanded and development with an extensive road network had appeared in the watershed. MacDonald *et al*. (1997) noted that the road network in the Fish Bay catchment area had tripled since 1982 and that many of these roads were steep, unpaved access roads to new home sites. Further study suggested that only 46% of the roads in the catchment area were paved (Anderson and MacDonald, 1998). Brooks *et al*. (2004) found a significant increase in sediment accumulation rates in the pond within the past 100 years, which is consistent with the increase in development within the watershed.

Flamingo Pond, Water Island. This pond was opened to the sea sometime between 1947 and 1958 and currently receives constant tidal flushing. A road network around the pond was present in 1947, however additional development around the pond occurred prior to 1971. The pond was dredged and is now used as a mooring area for boats and supports two docks (Stengel, 1998). According to the Water Island Administrator, James O'Bryan (pers. comm. 2005), the pond is not dredged regularly and has probably not been dredged for at least 10 years.

Fortuna Pond, St. Thomas. No obvious changes to the pond features occurred between 1964 and 1999. Although roads were present in the watershed by 1964, residential development increased between 1964 and 1999.

Francis Pond, St. John. This pond is located within the VINP. No change is evident in the configuration of the pond between 1971 and 1999, however the construction of some roads and other development in the southern part of the pond watershed occurred during this time.

Frenchman Pond, St. Thomas. No obvious changes to the pond features occurred between 1971 and 1999. The pond is not present on a 1946 topographic chart, however this is likely to be a reflection of its shallow depth. A road leading to the pond was evident as early as 1946, however the road network increased significantly by 1999. Brooks *et al*. (2004) found no evidence of sedimentation linked to anthropogenic activities and hypothesized that the denseness of the surrounding vegetation filtered out sediment before it reached the pond.

Great Lameshur East, St. John. This pond is located within the VINP. No evident changes to the pond configuration or pond watershed occurred between 1971 and 1999. An unpaved road adjacent to the salt pond was present by 1971.

Mandahl Pond, St. Thomas. Aerial photography indicates that the pond was reduced in size by at least a third between 1965 and 1971. A 1964 agreement with the USVI government gave permission to the Hans Lollick Corporation for the construction of a marina and related facilities at Mandahl Bay and included a provision requiring the government to repair and hard surface the public access road leading from the main Mandahl highway to the marina. In 1969 stone jetties were constructed and a channel to the salt pond formed to provide access from Mandahl Pond, which was also dredged, to Hans Lollick Island (Buttler, 1990). Several roads were present leading to or around the pond as early as 1947, however the road network and some development in the watershed had increased by 1971 and even further by 1999. The pond is presently used as a mooring location by boats, but the marina and facilities have not been constructed although the main road leading to the pond has been paved.

Perseverance Pond, St. Thomas. There has been no obvious change in pond configuration between aerial photography taken in 1947 and 1999. Ruins of a former plantation exist just to the northwest of the ponds and residential development has increased in the upper part of the watershed since 1947. The 1947 photo indicates a causeway between the two ponds which, because of its relatively straight alignment, was probably man-made. Aerial photography from 1954 also indicates a relatively straight channel across the southern portion of the eastern pond, and Nichols and Towle (1977) commented that this was a former drainage channel. Brooks *et al*. (2004) found no evidence of sedimentation linked to anthropogenic activities and hypothesized that the denseness of the surrounding vegetation filtered out sediment before it reached the pond. Nichols and Towle (1977), however, noted that over the last 200 years, terrestrial sedimentation has slightly exceeded the long-term rate of submergence, and if this rate were to continue, the pond area would be progressively reduced.

Redhook Pond, St. Thomas. No obvious changes to the pond features occurred between 1946 and 1999. The main road on the western side of the pond was present in 1946, and a dirt road along the north side of the pond was present by 1972. Development now found to the west of the pond had begun by 1972. Brooks *et al*. (2004) noted an increase in coarse-grained sediment in the surface layer of the pond and found it to be consistent with increased deposition due to development within the watershed.

Reef Pond, St. John. This pond is located within the VINP. The watershed was extensively cleared for plantation use in the 18th century, but agriculture declined after 1800 and much of the land reverted to woodland (Tyson, 1987). A U.S. Coast and Geodetic Survey map of 1919 shows a cleared valley floor leading to the pond and banana and coconut groves surrounding the pond (Fig. 7 in Tyson, 1987). This map also appears to depict a channel leading from the pond to the bay. According to Nichols and Brush (1988), the pond and swamp surrounding the pond were used as a dump for sugar factory wastes. By the mid-1950s, much of the cleared land had reverted to scrub or forest (Tyson, 1987). No significant changes to the configuration of the pond or pond watershed are obvious in aerial photographs between 1971 and 1999. A relatively straight channel leading from the western boundary of the pond to the sea is obvious in the 1971 aerial. Because of the channel's straight and deep (up to 2 m) configuration, Nichols and Brush (1988) assumed that it was man-made. Nichols and Brush (1988) found that Reef Pond had little capacity to absorb and store sediment and that infilling rates exceeded submergence with sedimentation rates having increased fivefold over the last 1800 years. They concluded that man's effects were small on the long-term evolutionary scale, however the pond would be doomed if recent sedimentation rates continued or increased.

Salt Pond, St. John. This pond is located within the VINP. No evident changes to the pond configuration or pond watershed occurred between 1971 and 1999.

Southgate Pond, St. Croix. In the early 20th century the area of the main pond was larger than its present configuration and extended east into the present East Gut basin, west into what is now a marina and southward towards the road (Gladfelter and Gaines, 2004). The main road to the south of the pond was constructed prior to 1942. The pond was divided by the construction of a causeway during the late 1950s and early 1960s, and the western portion of the original pond is now Green Cay Marina and is permanently connected to the sea. By 1982, dimensions of the pond were approximately the same as the present time (USGS quad, East Point, VI). Road and other development within the pond watershed have increased significantly since.

Southside, St. John. This pond is located on the eastern end of St. John outside the boundary of the VINP. No changes to the pond configuration have occurred since 1971. Roads were present in the upper watershed by 1971, and other development has increased slightly since that time.

Key Parameters

More than 40 different wetland or landscape features and processes were identified from the functional assessment reviews as having a role in the wetland function of sediment retention. Of these, seven wetland and six watershed parameters were selected as being applicable to USVI salt pond systems and as being suitable for rapid assessment of site conditions, an important consideration for a functional assessment study. Parameters that were excluded from further consideration, along with an explanation for exclusion, are listed in Appendix D.

Data for each of these selected parameters were collected either in the field or from GIS-based orthophotography as described in the Methodology section. Summary tables of the data collection results are presented in Appendices E and F. Maps of the salt ponds and their watersheds are contained in Appendix G.

In the following sections the rationale for including each parameter was described and any documented performance criteria listed; data collected for the parameter were analyzed with respect to documented performance criteria, site variability and disturbance levels; considerations that addressed potential correlations based on site-specific features were evaluated, however not exhaustively; and a conclusion was formulated as to whether the parameter provided evidence of the functioning condition of the salt pond systems.

Values of the measured parameters are shown in bar-graph form with each of the disturbance categories (H, M, L) grouped together to facilitate analysis and discussion. It is important to note that an individual parameter may not be important for all salt ponds as local conditions may play a factor.

The assumption inherent in the analysis was that the selected parameter played an important role in sediment retention.

Salt Pond Features

1. Berm elevation

<u>Rationale</u>
The impounding effect from a dam or dike allows sediments to settle out within the pond behind the impoundment (in Adamus *et al*., 1991). The maximum elevation of water storage in the impoundment is determined by the lowest point of the berm.

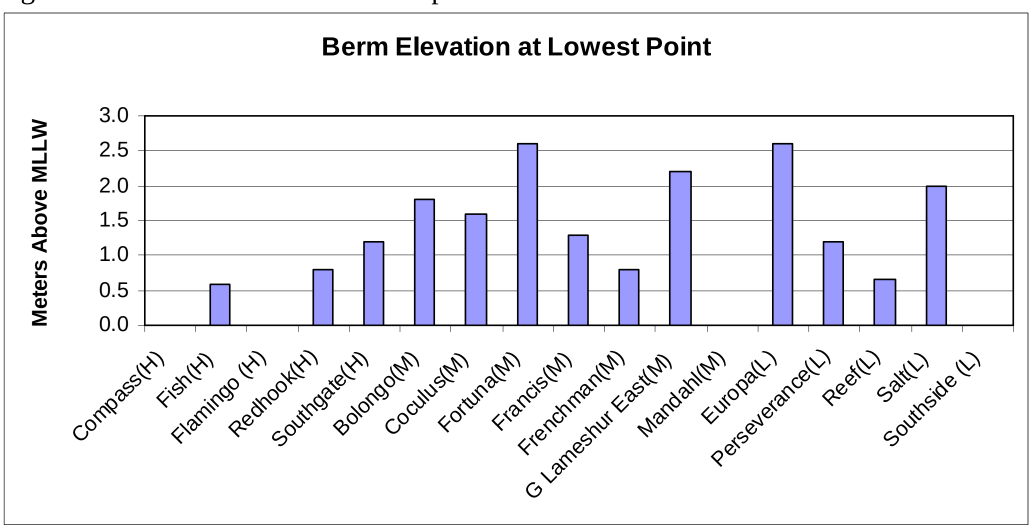
<u>Data analysis</u>
This analysis excluded four ponds: three ponds have been opened to the sea (Mandahl, Flamingo, Compass Point) and no data was collected for Southside. With the exception of Southgate Pond, the berm is a natural sand, coral rubble and/or cobble feature separating the pond from the sea. At Southgate, a man-made causeway dividing the original pond into a smaller pond and a marina was the lowest elevation surrounding the pond, and this was considered the 'berm' since during high pond water levels, this is the first area of overflow.

Elevations of the lowest point of the berm (measured in reference to MLLW) ranged from 0.59 m (Fish) to 2.6 m (Fortuna, Europa) (Figure 4). With the exception of Southgate Pond, the elevation of any point along the berm may be modified by extreme events, both from land-derived floods that blow out the berm from the landward side and from high wave energy that breaches the berm from the sea. The berm elevation may also be modified from more frequent tidal events that rebuild and reshape it.

Higher berm elevations may reflect a lack of recent natural disturbance, greater wave energy exposure which is building up the berm, the berm's directional aspect in relation to prevailing seas or other unrecognized factors. With increasing berm height, a greater volume of water can be contained landward of the berm which is an important sediment retention feature. Salt ponds with the highest berm elevations were Fortuna, Great Lameshur East, Europa and Salt.

Low berm elevations may reflect low energy conditions that do not contribute to berm build-up or more frequent blow-outs or overtopping. Redhook and Frenchman ponds had no distinct channel leading from the pond to the berm so may fall into the former category. The lowest area of the berm fronting Reef Pond was at the mouth of a deep, man-made channel that led from the pond to the berm; channelized, land-derived flows with potentially higher velocities than would otherwise occur under natural conditions may contribute to hampering berm build-up at the channel mouth. This seems to be the case in the Southgate watershed where land-use activities and changes to the historical configuration of Southgate Pond appear to contribute to blow-outs of the beach berm (elevation not shown) from the East Gut (which lies to the east of the pond but is no longer part of the pond watershed) during storm events as reported by Gaines (2004). Similarly in the Fish Pond watershed, flows during rain events may occur more often or with greater velocity due to vegetation removal and road construction activity that has taken place in the watershed. This may be contributing to the relatively low berm elevation (i.e. more frequent blow-outs or overtopping) found at the mouth of the shallow channel that led from the pond to the berm.

Figure 4. Berm elevation at lowest point



<u>Considerations</u>

Berm substrate. Berm substrates consist of cobble, coral, sand or a combination of these. No relationship to berm elevation is evident.

Distance of pond from berm. The salt ponds selected for this study are located at an average distance of 34.5 m (+/- 16 m) from the berm at their closest point and with few exceptions have some type of shallow channel leading to the low point of the berm. Redhook Pond is an exception in that its adjacency to the berm (5 m) allows for water exchange between the pond and the sea through the permeable coral and cobble substrate making up the berm, and its surface water level fluctuates with sea level accordingly. No correlation of distance to berm elevation is evident.

Pond channels. Pond channels may be indistinct, as found at Perseverance, Salt, Francis, Frenchman, Coculus, Southgate, Redhook and Europa ponds; distinct but shallow, as found at Fortuna, Lameshur East, Fish and Bolongo ponds, or distinct and deep, as found at Reef Pond. Mandahl, Flamingo and Compass Point ponds are connected to the sea by man-made channels. There is possibly a correlation as discussed in the analysis section above.

Other considerations: Flood plain area.

<u>Conclusions</u>

- Higher berms contribute to a more effective sediment retention function.
- Deep, straight channels behind the beach berm, such as found at Reef pond, may cause earlier or more frequent breaching of the berm than would occur naturally. This would reduce sediment retention effectiveness and warrants further investigation.
- The data and pond histories suggest that Reef and Fish ponds may not be functioning effectively due to man-made changes within the pond and/or watershed.
- The causeway separating Southgate Pond from the marina appears to be at an adequate height to preserve sediment retention functional performance in the reduced pond, however changes to the historical pond configuration and land-use activities in the upper watershed may be causing reduced sediment retention performance within the adjacent East Gut and potential damage to nearshore coastal waters.

2. Outlet

<u>Rationale</u>

An outlet from a pond reduces retention time and allows sediment to leave a pond, particularly during storm events when high flows and bottom disturbance can mobilize sediment in the pond basin. A constricted outlet or no outlet results in a longer retention time allowing material to settle and be retained within the pond (Adamus *et al*., 1991). The absence of an outlet is considered to be highly important for sediment removal and retention effectiveness (Adamus *et al*., 1987; Adamus *et al*., 1991; Hruby *et al*., 2000).

<u>Data analysis</u>

Only three ponds, Mandahl, Flamingo and Compass Point, are opened to the sea by man-made channels. The other ponds are impounded by a coastal berm. Water levels within Flamingo and Mandahl ponds, which had minimum channel widths of 28 m and 24 m, respectively, and channel depths of up to 2.8 m and 3.4 m, respectively, fluctuate with tidal levels, although both ponds had very shallow sections where dredging had not occurred.

The outlet for Compass Point Pond was constricted and approximately 10 m wide. Visual observations of water movement in the pond indicated the presence of a narrow channel extending from the outlet to the southern portion of the pond that appeared to ebb and flow with the tide.

Despite the presence of an outlet, sediment core analysis of Compass Point Pond suggests that sediment accumulation (and therefore retention) is occurring (Brooks *et al*., 2004). In the case of Flamingo Pond, little sediment accumulation seems to be occurring as the pond has not been dredged within the last ten years (Water Island Administrator, pers. comm, 2005). There is no information about historic sediment accumulation in Mandahl Pond.

<u>Considerations</u>

Width of channel to area of pond. This calculation for both Flamingo and Mandahl ponds was 0.1%. Surface water levels of both ponds are at sea level and ebb and flow accordingly. The calculation for Compass Point Pond was 0.04%. Despite the connection to Benner Bay, surface water in the main pond is not specifically controlled by the tide, indicating more restriction to water exchange than occurs at Mandahl or Flamingo ponds. Greater restriction to flow suggests a longer retention time for sediments.

Pond depth. All three modified ponds had some shallow areas around their perimeters which may contribute to slowing water flow and enhancing particle settlement. During storm events, however, greater flow velocities and wave and wind energy within the pond could resuspend shallow sediments and export these to coastal areas.

<u>Conclusions</u>

- Based on the literature, the absence of an outlet represents the most effective functioning condition.
- Ponds with restricted outlets, such as Compass Point, will still retain sediment but will not function as effectively during the ebbing tide or storm events as ponds with no outlet.
- More sediment will escape from ponds with wider channel links to the sea. Flamingo and Mandahl ponds may not be functioning effectively due to man-made changes to the pond.

3. Pond depth

<u>Rationale</u>

Shallow ponds offer greater frictional resistance to incoming sediment, increasing the ability to retain sediment within the pond (Adamus *et al*., 1991; Marble, 1992). Marble (1992) suggested a guideline for pond design for retaining sediment should be a depth of less than approximately 1 m (40 inches) except where resuspension by wind was likely. Adamus *et al*. (1991, p. 121) noted a number of studies indicating that sediments can be mobilized by wind in shallow wetlands and sediment retention may be greater in deeper wetlands due to longer retention times and greater storage capacity. The benefit of increased pond depth where resuspension by wind is likely was supported by Adamus (2001).

<u>Data analysis</u>

Pond depths were collected between March and December. Pond depths varied over the course of the year with some ponds drying completely, reflecting local rainfall and temperature conditions. Staff gauges placed at three ponds on St. Thomas indicated higher water levels in May compared to March, whereas gauge readings at Great Lameshur East, St. John, indicated a lower water depth in May compared to March. Highest readings for all ponds occurred in December (Table 6).

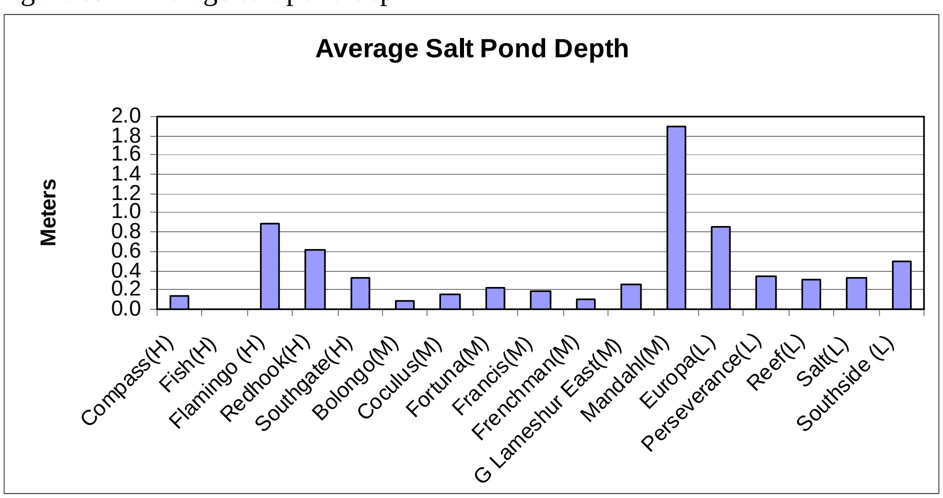
Pond depths are generally greater from August through December when higher rainfalls occur (see Figures 1, 2). Pond profiles (Appendix H) show the ponds as generally steep-sided basins, with the exception of Flamingo and Mandahl, which have been dredged, and Compass Point which is open to the sea through a constricted inlet and has been dredged along its western boundary. Excluding the dredged ponds, average pond depth ranged from dry (Fish) to 0.85 m (Europa) (Figure 5). The depth of Redhook Pond, which is deeper than most of the ponds, appears to be controlled by seawater penetrating the porous berm, and its depth rises and falls on a daily basis. Ponds subjected to the least disturbance (noted as 'L') appear to be slightly deeper than other unmodified ponds, however this may be a direct consequence of size rather than an effect due to disturbance as these ponds are also larger (see Figure 6).

Table 6. Water depth readings at staff gauges, 2005 (in cm)

Pond	March	May	December
Bolongo, ST	10.2	43.2	61.0
Fortuna, ST	14.0	24.1	36.6
Perseverance, ST	30.5	38.1	48.3
Great Lameshur East, SJ	22.9	3.8	76.2

In the USVI, storm events are often accompanied by strong winds, and sediment is less likely to become suspended in deeper ponds. In impounded ponds when the berm is not breached, resuspension of sediment within the pond is not considered problematic. In open ponds, such as Flamingo, Compass Point and to a lesser extent Mandahl which has been dredged more extensively, resuspended material from the shallow sections of the ponds has a greater chance of being exported to the sea.

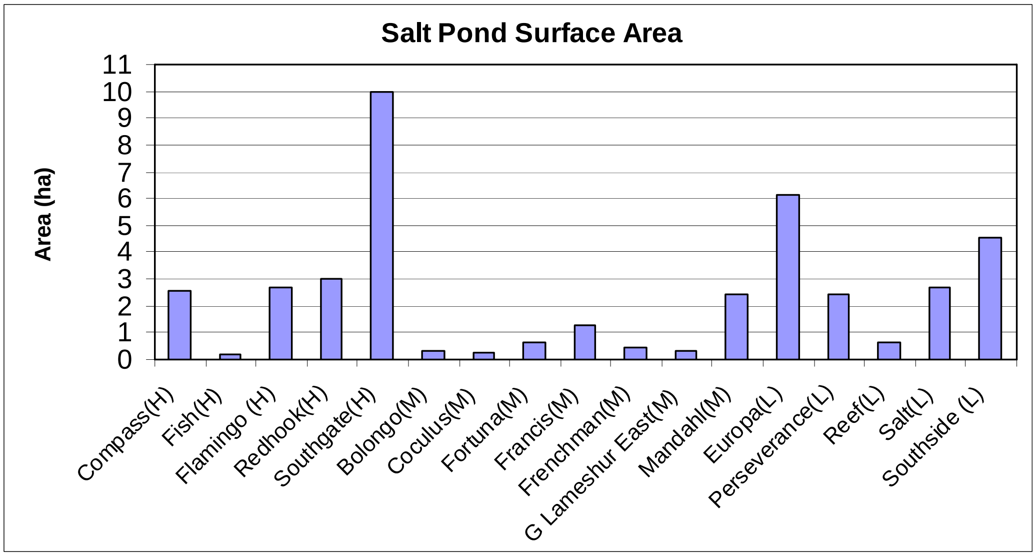
Figure 5. Average salt pond depth



Considerations

Pond surface area. Depth of the pond may be a factor of its surface area. In 1994 surface areas ranged from 0.17 ha (Fish) to 10.0 ha (Southgate). Nine of the 17 salt ponds had a surface area greater than 2 ha (5 acres), and only Fish Pond was under 0.2 ha (0.5 acre). In general, the larger ponds are also the deeper ponds. Notable exceptions are Compass Point and Southgate, both of which appear to be much larger in relation to their depths.

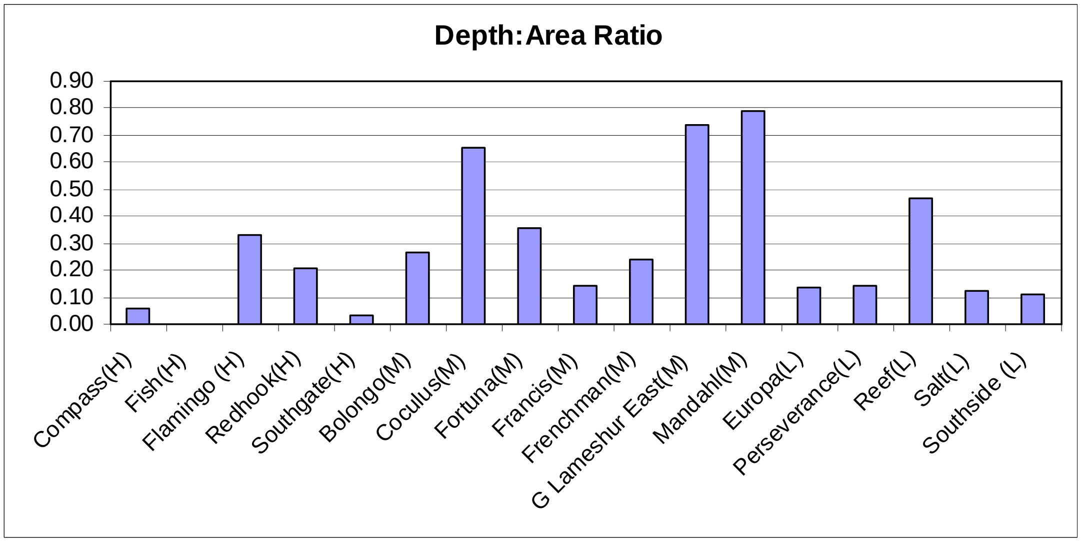
Figure 6. Pond surface area



Pond depth to surface area ratio. Ponds in general have a depth (m) to area (ha) ratio greater than 0.1:1 (Figure 7). The three exceptions are Compass Point Pond (0.06:1), Southgate Pond (0.03:1) and Fish Pond (dry), and these lower ratios may reflect elevated sediment inputs from their watersheds and a trend towards infilling. This is consistent with the findings of Brooks *et al*. (2004) who noted an increase in sediment accumulation in Compass Point and Fish ponds and with the observations of Gaines and Crawford (2004) and Gladfelter and Gaines (2004) on the reduction in size of Southgate Pond due to possible infilling and other modifications in the watershed. Since pond surface area is a fixed calculation based on full pond level, the ratio will vary based on when depth sampling occurs.

Age of the pond. Age of the pond and its state of evolution is another consideration that could affect depth, however pond age cannot be quickly or easily determined.

Figure 7. Pond depth: pond area ratio



<u>Conclusion</u>

- Pond depth appears to be related to pond surface area with the larger ponds also being the deepest.
- The ratio of pond depth to surface area appears to be a good indicator for identifying a potentially impacted condition.
- Compass Point, Southgate and Fish ponds have low depth:area ratios suggesting that these ponds are receiving or have received abnormally high sediment loads in the past. This has implications for the longevity of the ponds as depressional basins and could compromise their ability to retain sediments in the long-term.
- Depth of a pond in its natural state is not considered to be of particular importance in sediment retention functionality in impounded ponds.
- Flamingo and Compass Point ponds with their connections to the sea are unlikely to be functioning effectively in retaining sediment during high wind events that resuspend material from the shallow perimeter of the ponds. Mandahl Pond has been dredged more extensively causing it to be deeper with reduced shallow areas; as a consequence it may not be as affected by strong wind events.

4. Submerged aquatic vegetation

<u>Rationale</u>

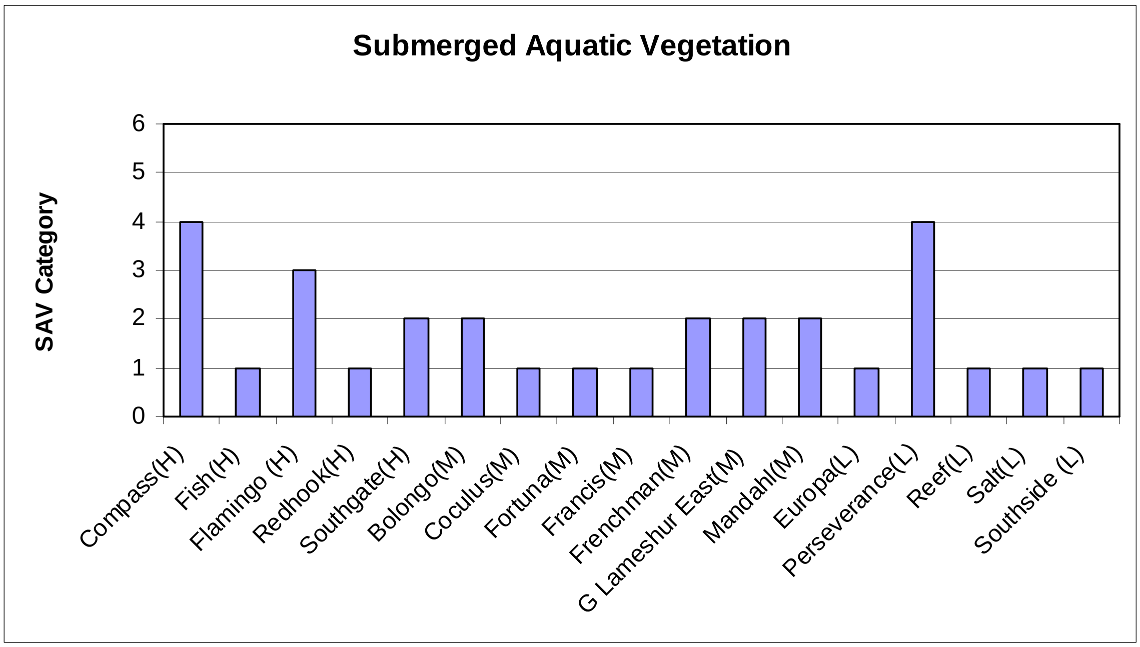
Roots and rhizomes of emergent macrophytes help to entrap and stabilize soil (Shafer and Yozzo, 1998). Algal mats are considered helpful in binding particles (Shafer and Yozzo, 1998), however moss and lichen cover generally do not contribute much to the attenuation of flow and so are less effective in enhancing sedimentation (Adamus *et al*., 1991). Aquatic bed vegetation generally does not offer much resistance to flow but may provide enough resistance to induce particles to settle out of the water column (in Adamus *et al*., 1991). In some depressional wetlands in the state of

Washington, however, aquatic bed vegetation has been considered to be as effective as erect vegetation because of the slower flow velocities that occur in these wetlands (Hruby *et al*., 2000). (See also 5. Water/woody vegetation interspersion below)

Data analysis

Filamentous algae, macroalgae and aquatic vascular plants were found covering portions of most salt pond beds included in this study although the extent of cover varied dramatically (Figure 8).

Figure 8. Submerged aquatic vegetation cover



Considerations

Depth. Deeper ponds, such as Europa and Redhook are less likely to support SAV due to limitations on photosynthesis. Sediments in deeper ponds are also less likely to be disturbed by wind events.

Water clarity. Turbid ponds, such as Redhook and Southgate, are unlikely to support substantial areas of SAV due to reduced light penetration for photosynthesis. Of particular note was the very clear water in the shallow areas of Flamingo Pond which supported extensive beds of the macroalgae *Caulerpa*.

Temperature, salinity. Elevated temperatures and high levels of salinity during the dry months, such as found in Salt, Southside and Europa ponds (Table 7), are factors that likely affect the establishment and survival of SAV.

Table 7. Salt pond salinity (in ^{o}/oo) during 2005

Location	**March**	**April**	**May**	**Dec**
Bolongo	33.1		10	7
Coculus	ND	ND	ND	ND
Compass Point	39		26	
Europa			156	
Fish			24	10
Flamingo	34			
Fortuna	24		17	
Francis	14.6		12	
Frenchman			25	
Great Lameshur East	15.1			10
Mandahl	38			
Perseverance East	18.8	22.6	11	5
Redhook	31.8			
Reef			19.5	
Salt		178.5	230	140
Southgate	ND	ND	ND	ND
Southside				85

ND – not determined

Conclusion

- A number of environmental variables contribute to the establishment of SAV cover.
- The more extensive areas of SAV in Perseverance Pond and in the shallow areas of Compass Point and Flamingo ponds contribute to increased functional performance.
- SAV is of particular importance in ponds that have a direct connection to the sea, and the extensive cover in Flamingo and Compass Point ponds aids functional performance in these modified ponds.
- The benefits of SAV in trapping and stabilizing soil in shallow waters may not be as important in deeper ponds, such as Mandahl, where bottom sediments are less likely to be disturbed by wind events.

5. Water/woody vegetation interspersion

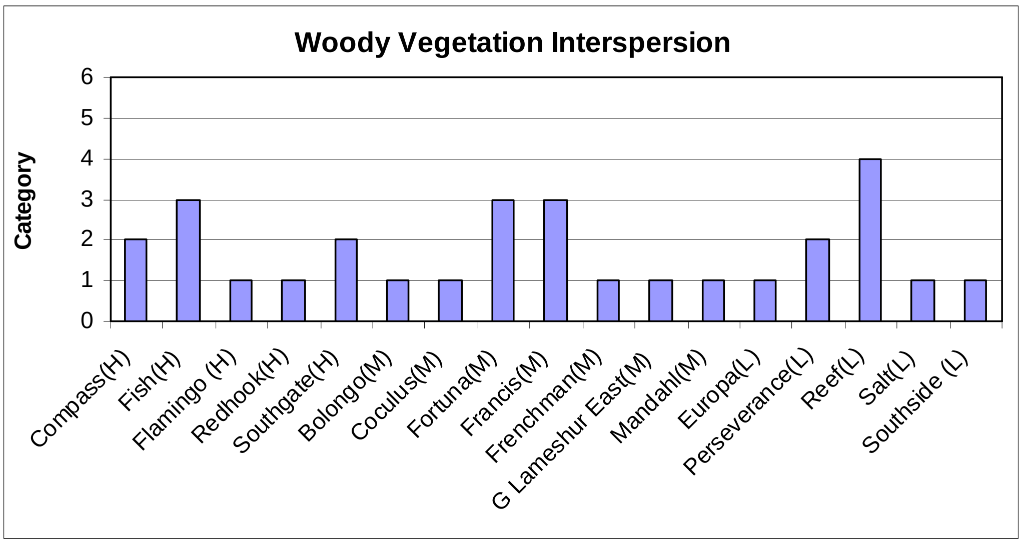
Rationale

Vegetation within a wetland increases the frictional resistance to sediment-laden water, which in turn enhances particle settlement (Adamus *et al*., 1991; Stumpf, 1983 in Shafer and Yozzo, 1998). Where there is vegetation and water flow, the shallower the water level, the more frictional resistance produced by the vegetation (Adamus *et al*., 1991), however, Adamus and colleagues also noted that some studies have found greater sediment retention in adjacent deep water than in wetlands. Single-stemmed, widely spaced vegetation is less effective in sediment removal than multi-stemmed species (in Adamus *et al*., 1991) (see also 4. Submerged aquatic vegetation above).

Data analysis

This analysis concentrates on woody vegetation within the pond interior (distant from the fringe), rather than within the surrounding wetland. Isolated groups of mangroves within the pond are a feature of some salt ponds on the USVI. Live mangrove clumps and dead mangrove wood were found scattered in some ponds surveyed for this study, but the majority of ponds were devoid of woody pond vegetation or woody debris (Figure 9). Reef Pond had the highest density of cover, and this was primarily dead mangrove wood which formed an extensive interlocking mass.

Figure 9. Woody vegetation within the salt ponds



Considerations

Pond depth. Shallow ponds are more likely to have conditions favorable for mangrove establishment. Compass Point, Fish and Southgate ponds supported greater than 5% woody vegetation cover within the pond and have been noted as receiving an increased amount of terrestrially-derived sediments in recent times (Brooks *et al.*, 2004; Gaines and Crawford, 2004; Gladfelter and Gaines, 2004). As cover in these ponds was primarily live mangrove, it is plausible that the infilling from sedimentation has created suitable conditions for mangrove growth and spread across the pond.

Wetland fringe. Ponds, such as Salt and Southside, have little to no wetland fringe to provide a source of mangrove propagules. This is a reflection of a number of conditions including surrounding topography.

Conclusion

- Mangroves, with their multi-stemmed growth habit and complex root system, function particularly well as sediment traps.
- Mangrove growth within Compass Point, Fish, Southgate, Fortuna, Francis, Perseverance and Reef ponds contribute to improved functional performance in these ponds.

- The benefits of woody material in trapping and stabilizing soil in shallow waters may not be as important in deeper ponds, such as Europa, Redhook and Mandahl, where bottom sediments are less likely to be disturbed by wind events.

6. Wetland fringe vegetation density

Rationale

Flow velocity is considered by some to be the most important factor affecting sediment trapping efficiency (Dendy, 1974, Karr and Schlosser, 1977 in Adamus *et al*., 1991), and the increase in frictional resistance to flow is proportional to stem density (Marble, 1992). Multi-stemmed woody vegetation or persistent emergent vegetation helps to increase frictional resistance to water flow, enhancing particle settlement (Adamus *et al*., 1991). This is considered to be particularly important in the fringe vegetation surrounding the pond (Cooper *et al*., 1986). Dense herbaceous grasses and brush have been observed as providing a better impediment to sediment movement than trees (Cooper *et al*., 1986), however trap efficiency of forested or scrub-shrub wetlands have been rated high by Ammann *et al*. (1986). Hruby *et al*. (1999) noted that forest vegetation with low stem density near the surface has less potential for slowing velocities. Vegetation does not need to be erect and persistent in order to trap sediment (Hruby *et al*., 2000).

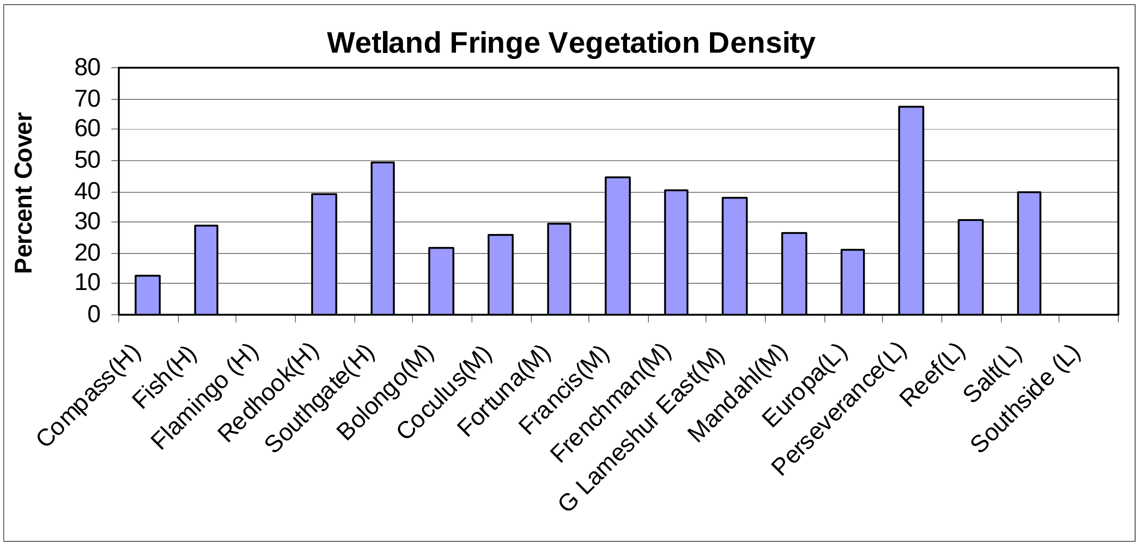
Herbaceous plants, shrubs, tree basal area, tree density, coarse woody debris and microtopographic complexity all contribute to attenuating flood flow, increasing resistance and enhancing sediment deposition (Arcement and Schneider, 1989; Brinson *et al*., 1995; Burkham, 1976, Taylor and Barclay, 1985, in Sutter, 2001). The combined effect of these features has been described by the Manning's roughness variable for non-tidal wetlands (Arcement and Schneider, 1989). One method for determining the roughness variable involves evaluating the vegetation density of the flood plain (Arcement and Schneider, 1989). Because the make-up of the mangrove community in the flood plain with its dense network of prop roots and/or pneumatophores make determining the Manning's roughness variable problematic for rapid assessment, in the present study ground cover density was determined instead.

Data analysis

Percent cover within the wetland fringe ranged from 0 (no wetland fringe at Southside) to 68% (Perseverance) (Figure 10). Wetland cover at Flamingo Pond could not be determined because the bases of the mangroves fringing the pond were submerged. The majority of ground cover at the study sites was attributable to the root systems of mangroves, with the numerous pneumatophores of black mangrove (*Avicennia germinans*) contributing the most to ground cover at ponds where this species was found. The higher density of cover at Redhook Pond was due largely to the pneumatophores of this species. Massive roots of white mangrove (*Laguncularia racemosa*) and red mangrove (*Rhizophora mangle*) also contributed to extensive ground cover, and at some ponds, such as Southgate and Perseverance, the fringe was impenetrable because of the density of the root systems. Due to the relatively thick canopy cover and little sunlight penetration, ground between mangrove roots was essentially bare or leaf-covered. Bare ground in the fringe surrounding Compass Point Pond was occasionally mixed with rock or trash debris, but mangrove cover was relatively low.

The exception to the typical mangrove cover was found at Salt Pond where ground cover consisted primarily of herbaceous wetland grass *Sporobolus virginicus* or the wetland forb *Sesuvium* *portulacastrum*. The mangrove species found at this pond was buttonwood, *Conocarpus erectus*, which does not have the extensive above ground root system typical of the other species.

Figure 10. Wetland fringe vegetation density



<u>Considerations</u>
Rainfall. Rainfall differs across the islands (see Figure 2), however ponds that are found in similar rainfall regions, such as Compass Point, Redhook, Bolongo, Coculus and Frenchman, varied significantly in percent cover.

Slope. Steep terrain surrounding a pond (Southside and Europa), does not create conditions that would support dense wetland vegetation, however gradual contours surrounding a pond (Perseverance, Southgate) would.

Wetland fringe width. This is discussed in the next section.

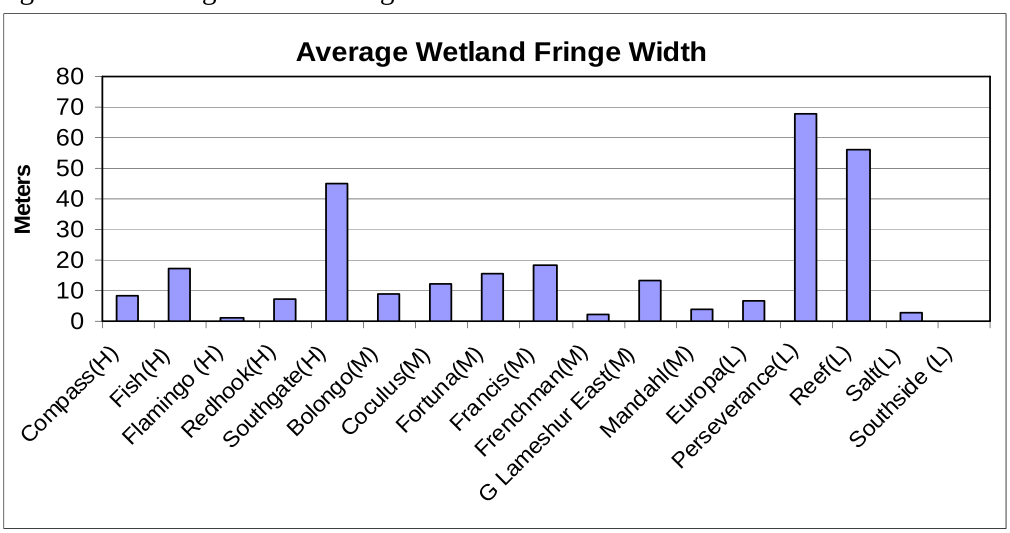
<u>Conclusion</u>
- The extensive root network of the mangrove community undoubtedly creates a high frictional resistance to water flow, aiding in the trapping and retention of sediment.
- Functional performance of Perseverance Pond for this parameter is considered to be high.
- This parameter does not play a role in the functional performance of Southside Pond.
- The low density at Compass Point Pond suggests that the pond is not functioning effectively with respect to this feature.
- Although Salt Pond has a high ground cover density, the lack of a mangrove community to help attenuate flow velocities could lower the functional performance effectiveness during extreme events.

7. Wetland fringe width

Rationale: The fringe width in this study is considered synonymous with 'wetland buffer'. Vegetation surrounding a pond creates frictional resistance to water flow carrying sediment to a pond (Sutter, 2001). The more extensive the natural stand, the more frictional resistance occurs, and this enhances particle settlement, particularly where vegetation is dense and water is shallow (Adamus *et al*., 1991; Sutter, 2001). Buffer vegetation will trap sediment filtering through it from the surrounding landscape (Hruby *et al*., 2000), and greater widths allow more factors, such as woody debris, stem density and increased vegetation cover, to come into play (Sutter, 2001). To differentiate a wide from a narrow fringe width, Sutter (2001) used widths of <50 m (narrow), 50-100 m (moderate) and >100 m (wide) but noted that these were not absolute figures.

Data analysis:
Considerable variability exists between salt ponds for this feature (Figure 11). Southside Pond had no wetland fringe, whereas Perseverance and Reef ponds had the largest average fringe widths at 68 and 56 m, respectively. Three of the five highly disturbed ponds had small fringe widths (<10 m), however despite significant disturbance, Southgate Pond had the third widest fringe. In all cases, the wetland fringe graded to slopes dominated by upland forest vegetation. The width of the upland area varied with paved and/or unpaved roads occasionally being present within a short distance of the wetland fringe (e.g. Bolongo, Compass Point, Flamingo, Redhook, Great Lameshur East, Fish, Francis, Mandahl, Southgate).

Figure 11. Average wetland fringe width



Considerations
Slope. Steepness of the watershed is a factor in the width of the wetland fringe. Ponds, such as Salt, Europa and Southside, are situated near the base of the surrounding hills which gives little opportunity for a surrounding wetland fringe zone to develop.

Rainfall. Rainfall does not appear to be a factor in wetland fringe width. Reef and Europa ponds are located close to each other and yet wetland fringe widths were significantly different. Salt Pond historically receives more rainfall than Fortuna Pond (see Figure 2), however the wetland fringe width was considerably smaller.

Land use. Land use is a factor in wetland fringe width. The wetland fringe of four of the highest impacted ponds (Compass Point, Fish, Flamingo and Redhook) has been limited in expansion or has been disturbed as a result of road construction.

<u>Conclusion</u>

- The considerable variability that exists between ponds for this feature is due to both natural and human-induced conditions.
- Perseverance, Reef and Southgate ponds are functioning the most effectively with regard to this feature.
- Salt ponds where human disturbance, rather than natural site conditions, has limited the width of the wetland fringe may not be functioning effectively. These are Compass Point, Flamingo, Redhook, Bolongo and Mandahl ponds.
- Where conditions allow the development of a wetland fringe, the greater the fringe width, the more effective the functional performance will be with respect to this feature.

Watershed Features

Except for gut information, no watershed data was available for Flamingo Pond, so this pond was excluded from most of the following analyses.

8. Flood plain

<u>Rationale</u>

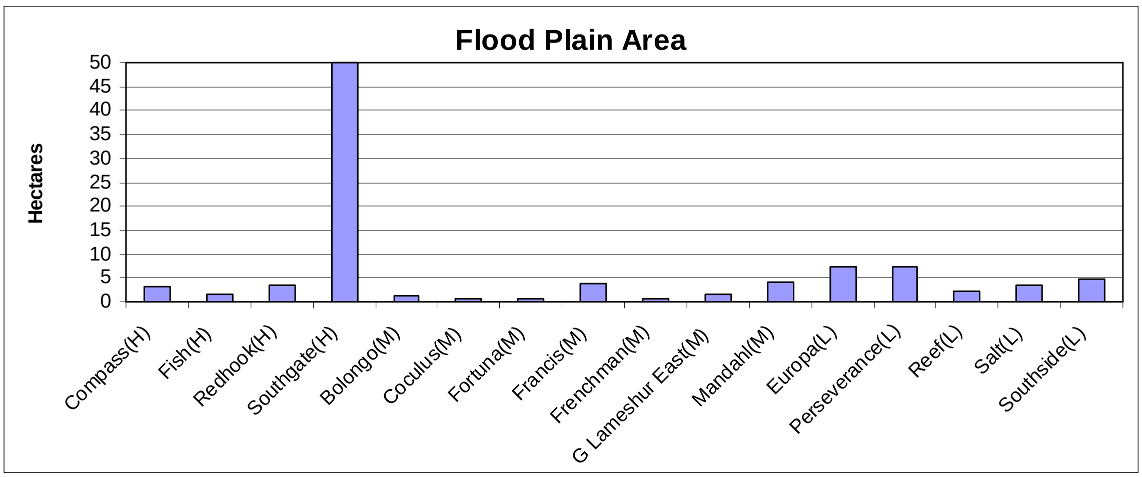
The greater the area for flooding and retention of water, the greater the area for reduction in flow velocity and potential for sediment to settle (Mitsch and Gosselink, 1993, Fennessey *et al.* 1994, in Hruby *et al*. 1999; Sutter, 2001). A larger floodplain surface area is an important factor in trapping sediment (Cooper *et al*., 1986), and as flow velocity decreases across a flood plain, sedimentation is promoted by a number of factors including surface roughness and increasing cross-sectional area of discharge (Nutter and Gaskin, 1989, in Brinson *et al*., 1995). Sediment trapping efficiency is related to the wetland's area, depth and volume (Schubel and Carter, 1984, in Adamus *et al*., 1991) which are considered to be the 'storage capacity' of a wetland (Adamus *et al*., 1991). Hruby *et al*. (1999) uses the variable 'storage volume' which is the difference between predominating high and low water levels and corresponds to the amount of water that can be retained in the wetland during the wet season. Permanently impounded pond areas have been rated as being most effective in trapping sediment during high flow when greater than 5 acres (2.02 hectares) and least effective when less than 0.5 acre (0.2 hectare) (Amman *et al*., 1986), however linking an absolute size to effectiveness must also consider the size of the conveying watershed.

<u>Data analysis</u>

Although flood plain for this study has been defined as the pond plus the adjacent area between 0-3% slopes, the overall floodplain area and storage volume will, in fact, be determined by the height of the lowest point of the berm, an elevation which varies for each pond and which can change over time depending on storm events and wave energy. A review of elevation contours around the ponds indicates that slopes on the pond side of the berm often range from 3.1-8% or higher. Despite this, flood plain is generally considered to be in the 0-2% (USDA-NRCS, 1998) or 0-3% (Ammann *et al.*, 1986; Bradshaw, 1991) slope category.

The Southgate watershed supported the largest flood plain of the ponds studied (Figure 12). On St. Thomas and St. John, the flood plain was generally small, ranging from 0.65 ha (Frenchman) to 7.41 (Europa).

Figure 12. Flood plain area



<u>Considerations</u>

Slope. Steepness of the watershed is a contributing factor determining the flood plain area, however there is no clear correlation. The steepest watersheds (those having 90% or more slopes >8%) were Fortuna, Frenchman and Great Lameshur East, along with Eastend, Europa and Perseverance (see 11. Slope, below). Southgate had the most gradual landscape.

Watershed area. This is discussed below.

<u>Conclusion</u>

- This feature plays a greater functional role at Southgate Pond than the other ponds.
- Most salt ponds on St. Thomas and St. John have little flood plain area, and this feature may not be a significant contributor to functional performance.

9. Gut presence/absence

<u>Rationale</u>
Steep channel or tributary gradients will transport sediment more rapidly to the receiving basin than no channel or a gradual channel (Hruby *et al*., 2000), however channels that deliver sediment directly to a wetland rather than filtering through a buffer area will deliver more sediment to the wetland (Hruby *et al*., 2000).

<u>Data analysis</u>
Guts drain directly to eight ponds. In one pond watershed (Fortuna), the gut bypasses the pond and draines directly to the sea, while in another pond watershed (Southgate), the gut channel disappears prior to reaching the pond. Eight pond watersheds, three on St. Thomas and five on St. John, have no guts (Table 8). Ponds which capture gut flows are important in sediment retention since otherwise gut material might flow directly to the sea with negative impacts to coral reefs and seagrass beds. These ponds, however, are also at risk from infill if too much sediment enters the pond via the guts as a result of land-use changes that increase gut flows and velocities or remove gut vegetation.

Table 8. Absence/presence of guts within the watershed

Pond	**Island**	**Guts to Pond**	**Guts not to Pond**
Bolongo	St. Thomas	1	0
Coculus	St. Thomas	0	0
Compass Point	St. Thomas	0	0
Europa	St. John	0	0
Fish	St. John	0	0
Flamingo	Water Island	3	0
Fortuna	St. Thomas	0	1
Francis	St. John	0	0
Frenchman	St. Thomas	0	0
G. Lameshur E	St. John	1	0
Mandahl	St. Thomas	1	0
Perseverance	St. Thomas	3	0
Redhook	St. Thomas	1	0
Reef	St. John	0	0
Salt	St. John	1	0
Southgate	St. Croix	1*	0
Southside	St. John	0	0

* gut channel disappears before reaching pond

<u>Considerations</u>
Landcover: Vegetated watersheds will help reduce sediment flowing into the ponds via the guts.

Conclusions

- Salt ponds with functional effectiveness for this feature are Bolongo, Flamingo, Great Lameshur East, Mandahl, Perseverance, Redhook, Salt and Southgate.
- These salt ponds are also more at risk from infill should vegetation removal in their respective watersheds result in increased sedimentation flow to the pond.

10. Land use

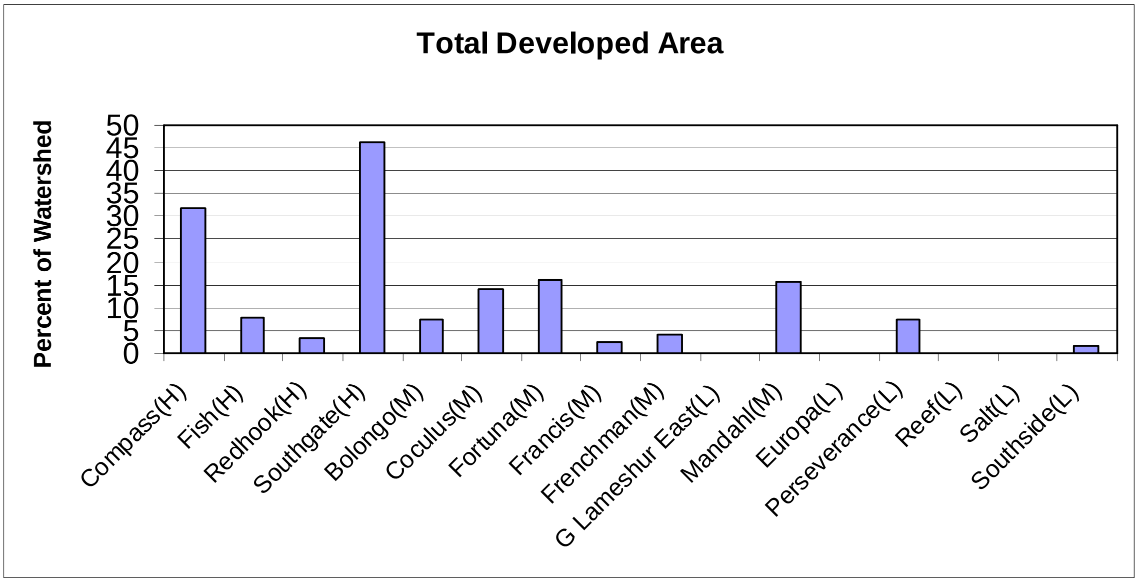
Rationale

Hard surfaces, including houses, paved roads and other built structures in a catchment replace vegetated surfaces. As a consequence, these surfaces decrease the area capable of retaining soil and potentially increase the amount of soil that could flow to a pond. Undisturbed watersheds or those dominated by forest or scrub-shrub vegetation are likely to contribute less sediment loading to 'downstream' areas than those that are anthropogenically disturbed (Hartmann *et al*., 1996, Reinelt and Horner, 1995 in Hruby *et al*., 2000; Adamus *et al*., 1991). Watersheds that are greater than 75% forested or otherwise undeveloped have been considered low contributors of sediment to downstream wetlands (Bradshaw, 1991). Watersheds having large areas of active cropland, construction sites, eroding roads and ditches have been considered as high contributors (Ammann *et al*., 1986), and those with greater than 50% developed or active cropland areas are considered to have the most potential for sediment contribution (Bradshaw, 1991). A moderate contribution of pollutants could be expected from watersheds with 25-50% of cropland and developed sites (Bradshaw, 1991). Adjacency of developed areas to wetlands is a consideration, and watersheds that have greater than 20% agriculture and developed land adjacent to the wetland are considered to have a high potential for contribution of pollutants (Sutter, 2001). Previous studies have reported that runoff is increased where vegetation is removed from hillsides (Nemeth and Nowlis, 2001), and unpaved roads on St. John were found to have the potential to contribute four orders of magnitude more sediment than natural conditions (Ramos-Scharron and MacDonald, 2005). Large upland riparian areas lead to low sediment accumulation on the flood plain, while clearing of riparian areas leads to increased inputs (Cooper *et al*., 1986). A significant increase in sediment yields due to urbanization has been demonstrated by simulation models (Arnold *et al*., 1987 in Adamus *et al*., 1991 p. 115).

Data analysis

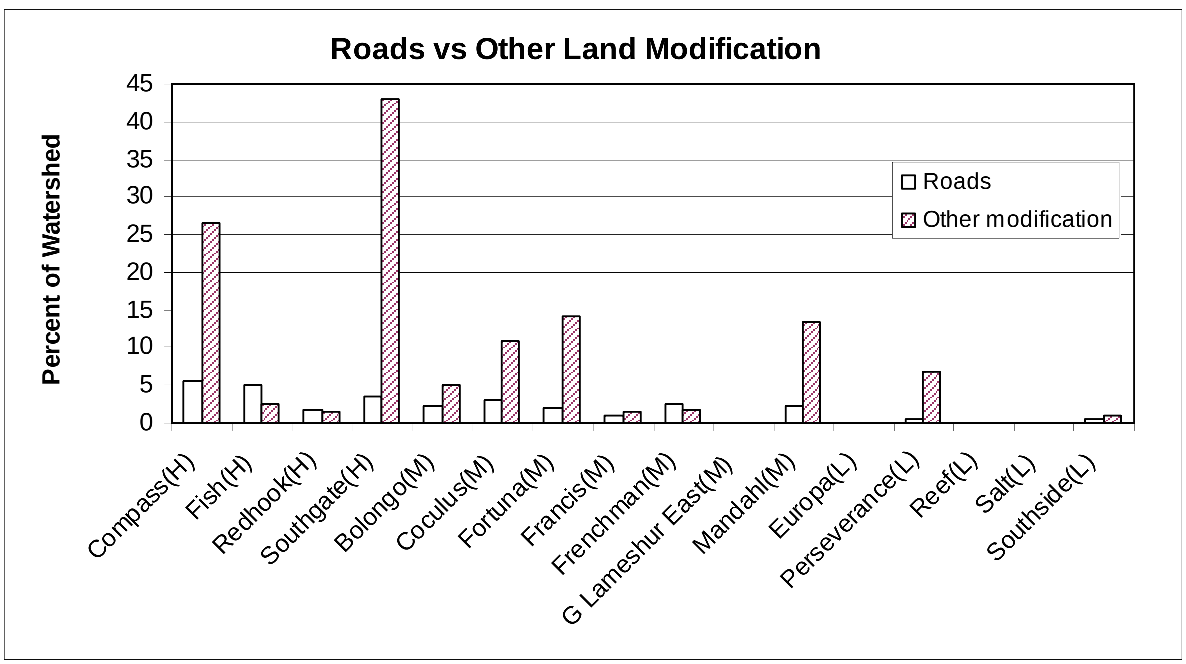
Land modification from the natural vegetation communities exceeded 30% of the Compass Point Pond watershed area and was close to 50% in the Southgate Pond watershed (Figure 13). Just under half of the modified area within the Southgate watershed was pasture. No development has occurred in the Europa, Reef and Salt Pond watersheds on St. John, while only road construction has occurred in the Great Lameshur East watershed (0.07%).

Figure 13. Developed area within the pond watersheds



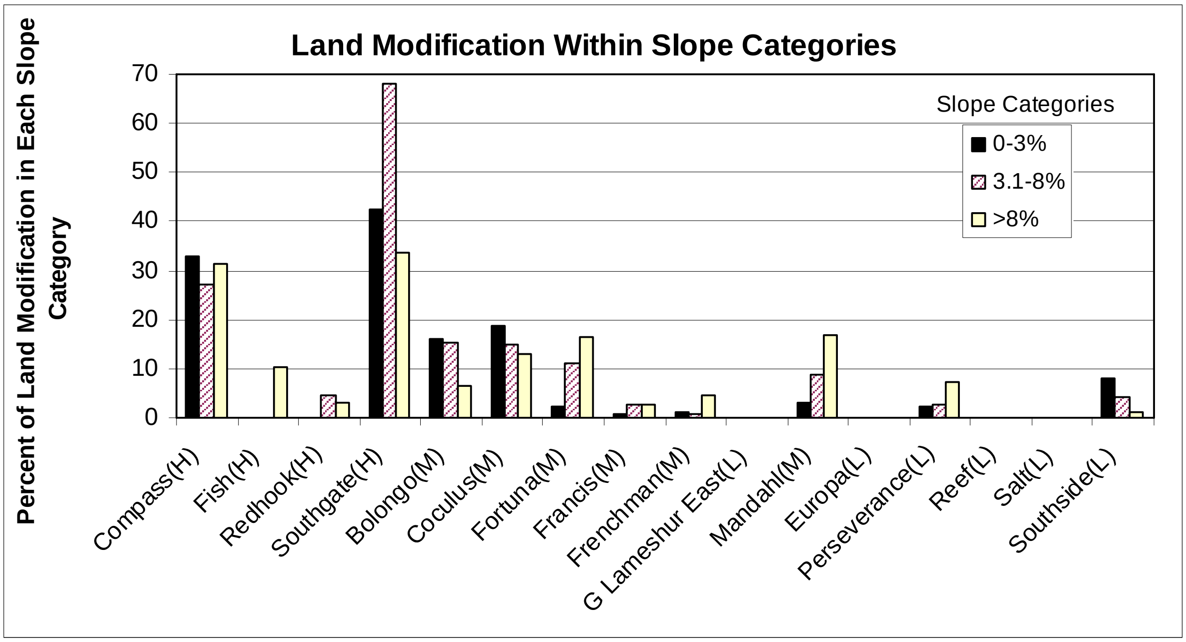
Only in the Fish, Frenchman and Redhook pond watersheds has road construction exceeded the development of other impervious surfaces or agricultural land use (Figure 14). As road construction is often the initial phase of further development, a decrease in vegetation cover in these watersheds could be expected.

Figure 14. Development type in the watersheds



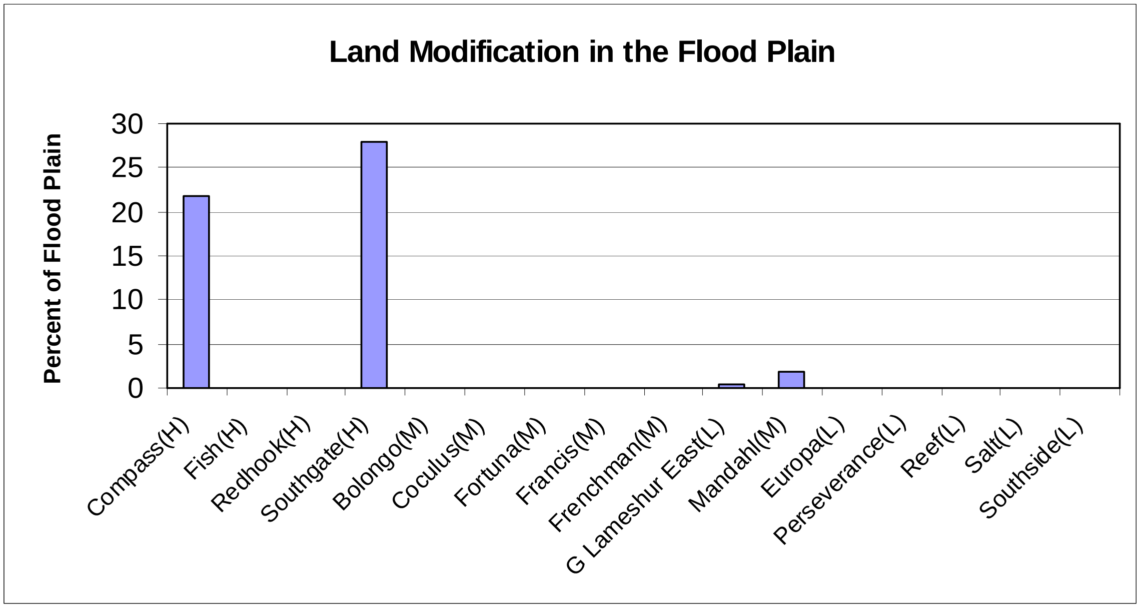
Land modification was found across all slope categories (Figure 15). Where removal of the natural vegetation communities is taking place on steep gradients, disturbed soils will be subject to higher flow velocities and a greater potential for being transported to the lower watershed. Pond watersheds where land modification exceeded 25% of the land area within gradients greater than 8% were Compass Point and Southgate. Pond watersheds where land modification exceeded 10% of these steeper slopes included Fortuna, Coculus and Mandahl on St. Thomas and Fish on St. John.

Figure 15. Land modification within slope categories.



Modification to the natural vegetation communities in the flood plain adjacent to the pond has exceeded 20% of the flood plain area in the Compass Point and Southgate pond watersheds (Figure 16). In the Compass Point Pond watershed this consisted of impervious surfaces, whereas in the Southgate Pond watershed this was almost entirely pasture. Some road construction has also occurred adjacent to Mandahl Pond and Great Lameshur East Pond.

Figure 16. Land modification in the flood plain adjacent to the pond



<u>Considerations</u>

Precipitation: Movement of material down a watershed occurs during rain events. The more significant the event, the greater potential for sediment transport, particularly where vegetation has been removed or soils have been disturbed.

Soil type: The erodibility of soils will be a factor in the quantity of sediment flowing down the watershed. Where disturbance, such as land clearing, has occurred, more soil is likely to be transported.

<u>Conclusions</u>

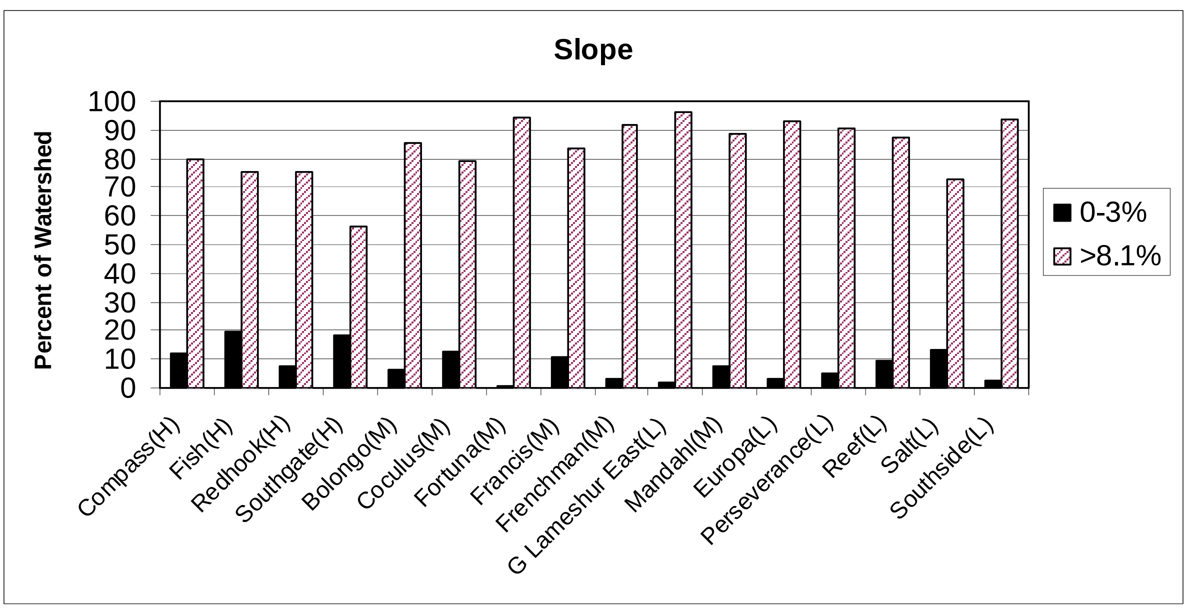
- The removal of vegetation covering approximately 25% or more of the land area coupled with the high amount of land modification in the flood plain within the Compass Point and Southgate Pond watersheds suggests that the functional ability in these watersheds may be compromised.
- Functional performance of the Compass Point Pond watershed is particularly at risk as a high proportion of development is occurring on steeper gradients.
- Although there is no information on the trigger level beyond which a negative impact might be expected on steeper gradients, watersheds where land modification has exceeded 10% of steep slopes should be monitored for sediment retention effectiveness. These include Southgate, Compass Point, Fortuna, Coculus and Mandahl on St. Thomas and Fish on St. John.
- The greater proportion of roads to other land-use categories in the Fish, Redhook and Frenchman Pond watersheds suggests that these watersheds may experience a loss of vegetated slopes to development in the near future which could further stress the effectiveness of sediment retention.

11. Slope

<u>Rationale</u>
Slope gradients affect water velocity and sediment quantity flowing into a pond. Water velocity decreases with decreasing slope gradient, and soils carried down a gradual hillside have a greater potential for being retained on the hillside compared to soil moving down a steep gradient. Steeper slopes, with their greater likelihood for higher water velocities, potentially carry more sediment (Hruby *et al*., 2000), whereas gradual slopes (0-2%) are reported as not producing measurable amounts of sediment in a North Carolina swamp watershed (Cooper *et al*., 1986). Flow velocity is reported as the most important factor affecting the deposition and retention of sediments (in Sutter, 2001 p. 12; also Dendy, 1974; Hruby *et al*., 1999; Null *et al*., 2000), and this parameter has been linked with gradient with regard to sediment retention (Adamus *et al*., 1991). Slope gradients with less than 2% slopes in North Carolina watersheds have been considered as generally flat (Gilliam *et al*., 1986), whereas other studies have categorized slopes less than 3% as low and greater than 8% as steep (Ammann *et al*., 1986; Bradshaw, 1991). The National Resources Conservation Service (USDA-NRCS, 1998) describes slopes of 0-2% as part of the floodplain, slopes of 2-5% having a moderate risk of erosion and slopes greater than 10% as having a severe risk of erosion.

<u>Data analysis</u>
Steep slopes dominated all of the pond watersheds (Figure 17). The steepest watersheds, identified as those having greater than 8.1% slopes over more than 90% of the watershed, were Fortuna, Frenchman, and Perseverance on St. Thomas and Great Lameshur East, Europa and Southside on St. John. Southgate Pond watershed on St. Croix and Fish Pond watershed on St. John had the largest extent of flat areas, however both these ponds had more than 50% of slopes exceeding 8.1% gradient.

Figure 17. Slope as a percent of the watersheds



Considerations

Landcover. Greater vegetation cover in the watershed will help filter sediments out before reaching the ponds.

Soil type. The erodibility of soils will be a factor in the quantity of sediment flowing down the watershed. Where disturbance, such as land clearing, has occurred, more soil is likely to be transported.

Conclusions

- Because flow velocities are higher where slopes are steeper, sediment retention within all of the pond watersheds, with the exception of possibly Southgate, may be limited by slope.
- Of particular concern are those watersheds where generally flat slopes comprise less than 5% of the watershed area. These are Fortuna, Frenchman and Perseverance on St. Thomas and Great Lameshur East, Europa and Southside on St. John.
- Approximately 20% of the Southgate and Fish Pond watershed areas have relatively flat gradients, and much of this lies adjacent to the salt ponds. Based on slope alone, these two watersheds are likely to be more effective in sediment retention.

12. Soil erosion potential

Rationale

Soils are more likely to be washed into wetlands if soils in the surrounding watershed are susceptible to erosion (in Adams *et al*., 2001, p. 116). Sandy soils are more porous and so enhance infiltration rate which reduces overland flow except during extreme events (Brinson *et al*., 1995). Soil characteristics within the wetland are not considered important in a wetland's capacity to remove sediment (Sutter, 2001), however wetlands with mud or organic soils are more likely to be in a depositional environment than wetlands with bedrock or more coarse sediments and so are better indicators of sediment retention (Adamus *et al*., 1991). The USDA-NRCS soil series report provides a soil erodibility coefficient (K) for different soil types which is one of six factors used in the Universal Soil Loss Equation. The WRI and NOAA (2005) data present this as two fractions, Kw and Kf . The former applies to the whole soil, whereas the latter applies to the fine-earth fraction which is less than 2.0 mm (USDA-NRCS, 2005). The index is based on soil type and does not consider land use. The higher the value, the more susceptible the soil is to erosion.

Data analysis

A number of physical factors, including slope, soil texture and the precipitation regime influence erosion in an area. Many parts of the USVI are very steep, and the nature of the soil in combination with extreme rainfall events can lead to severe erosion in these areas. Development where land is cleared and exposed also promotes erosion. The highest Kf-factor and the percent of the watershed this factor covers are listed for each pond watershed in Table 9. Watersheds having the most potential for erosion are considered to be those with a high Kf-factor covering more than 75% of the respective watershed. These were found to be Great Lameshur East, Fortuna, Bolongo, Southside, Perseverance, Fish, Reef and Europa ponds. Development in the upper watershed will increase the risk of erosion for all ponds. Those of most concern are ponds outside the Virgin Islands National Park system having the highest Kf-factor: Fortuna, Bolongo, Southside, Perseverance, Fish, Coculus, Frenchman and Compass Point.

Table 9. Soil erodibility

Kf-factor*	Pond	% Watershed
0.28	G Lameshur East	0.95
0.28	Fortuna	0.80
0.28	Bolongo	0.80
0.28	Southside	0.80
0.28	Perseverance	0.75
0.28	Fish	0.75
0.28	Reef	0.75
0.28	Europa	0.75
0.28	Coculus	0.60
0.28	Frenchman	0.60
0.28	Compass Point	0.60
0.28	Salt	0.50
0.26	Southgate	0.50
0.22	Redhook	0.75
0.15	Francis	0.80
0.15	Mandahl	0.75

* data from WRI and NOAA (2005)

Considerations

Land use. Development or the removal of vegetation which exposes the ground will increase the susceptibility of soil to erosion. Because land use is not a factor in determining the Kf-factor, ponds that have a greater percentage of development in the watershed with a high Kf-factor are also at a higher risk than those without soil disturbance. These include Fortuna, Coculus, Compass Point and Southgate ponds.

Conclusions

- Soils for most of the salt pond watersheds studied have a high potential for erosion.
- Ponds where functional performance is considered to be at risk are those with a high Kf-factor and outside the development protection of the Virgin Islands National Park system: Fortuna, Bolongo, Southside, Perseverance, Fish, Coculus, Frenchman and Compass Point ponds.
- Ponds which may not be functioning effectively due to the erodibility of the soil and amount of development in the watershed are Fortuna, Coculus, Compass Point and Southgate ponds.

13. Wetland to watershed area

Rationale

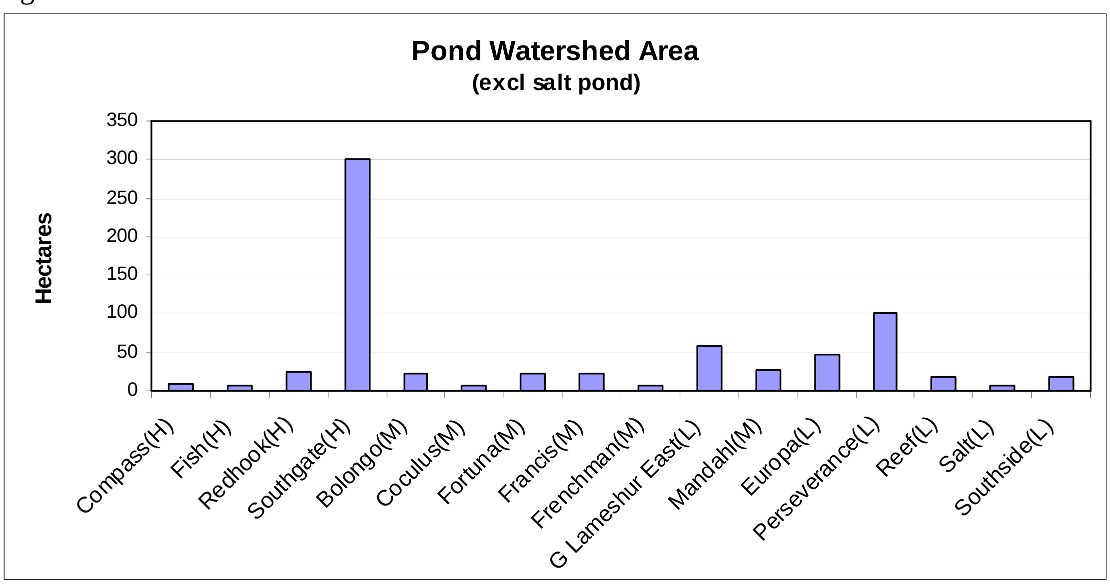
A number of studies have linked improved function with a higher wetland to watershed area ratio (Sutter, 2001; Kittelson, 1988), and the rationale has been noted as appearing to be a sound approach

(Sutter, 2001). Watersheds in Wisconsin were found to have approximately 90% lower sediment loads when wetlands and lakes made up 40% of the area compared to watersheds with no wetlands or lakes (Hindall, 1975, in Adamus *et al*., 2001), and approximately 70% of the sediment was noted as being retained by 5% of the wetlands (Adamus *et al*., 1991). Other studies have indicated that a watershed containing 10% wetlands can optimize sediment retention but beyond this, only minimal increases in sediment retention occur (Oberts, 1981, Brown, 1988, in Adamus *et al*., 1991). Wetlands occupying at least 1% of the watershed area and able to store 10% or more of their annual average inflow, have been reported as removing more than 85% of the incoming sediment (Dendy and Bolton, 1976 in Adamus *et al*., 1991). The Connecticut method of function analysis for trapping efficiency during high flow ranked watershed to wetland area as most effective when the ratio was less than 5:1, moderately effective between 5:1 and 15:1 and least effective when greater than 15:1 (Ammann *et al*., 1986). Sutter (2001) reported that a conversion of 0.54% of wetlands in a watershed to agriculture resulted in a significant increase (1%) in watershed peak discharge. A reduction in wetlands of 0.05% of the watershed was considered to have an insignificant effect on watershed peak runoff.

Data analysis

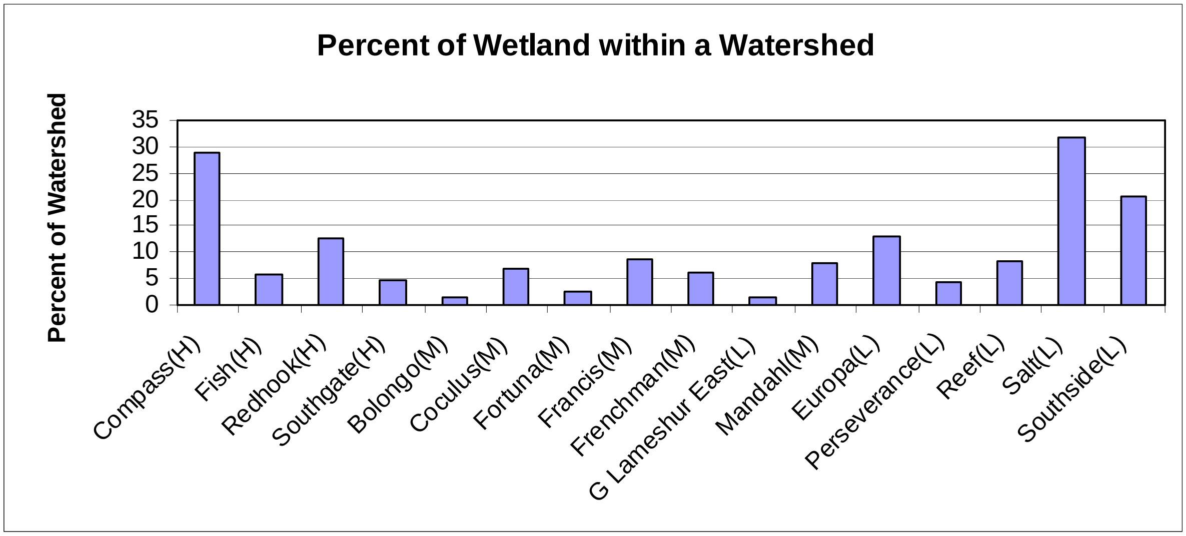
Pond watershed areas varied from 6.1 ha (Coculus, St. Thomas) to 301.6 ha (Southgate, St Croix) (Figure 18). Island landscape and island size may play a role in determining the maximum size of a pond watershed; the Southgate watershed is located on the relatively flat northeast side of St. Croix, the largest island, while the largest watershed on relatively small, but steep St. John was Great Lameshur East at 58.2 ha. Examining the remaining ponds not sampled for this study would help to confirm whether this was indeed the case.

Figure 18. Pond watershed area



Eleven salt ponds and surrounding wetland comprised less than 10% of their watershed (Figure 19). These are shown in order of increasing percentage in Table 10.

Figure 19. Wetland area as percent of watershed*



* Total watershed (watershed + salt pond)

Table 10. Ponds exhibiting sub-optimal size within their watershed for effective sediment removal/retention. Wetlands comprising less than 10% of the watershed or having a watershed:wetland ratio greater than 15 suggests sub-optimal performance (see text).

Pond	Wetland Area as Percent of Watershed	Watershed:wetland ratio
Bolongo	1.32	76:1
G. Lameshur East	1.54	65:1
Fortuna	2.50	40:1
Perseverance	4.36	23:1
Southgate	4.69	21:1
Fish	5.64	18:1
Frenchman	6.04	17:1
Coculus	6.80	15:1
Mandahl	7.92	13:1
Reef	8.47	12:1
Francis	8.52	12:1

<u>Considerations</u>

Landcover. Higher percentage of vegetation in the watershed will help filter sediments out before reaching the ponds.

Slope. Higher flow velocities with less entrapment will occur on steeper slopes resulting in greater sediment loads reaching the pond.

<u>Conclusions</u>

- Ponds that make up less than 10% of their watershed may not be performing optimally in the removal of sediment.
- Of particular concern are ponds that constitute less than 10% of the watershed with a watershed:wetland ratio greater than 15. These are Bolongo, Great Lameshur East, Fish, Fortuna, Perseverance, Southgate, Coculus and Frenchman.
- Ponds that are likely to be performing well based on the wetland size with respect to the watershed are Compass Point and Redhook on St. Thomas and Europa, Salt and Southside on St. John.

REMOTE SENSING OF SEDIMENT IN COASTAL WATERS

Sustained long-term monitoring of environmental impacts and the assessment of cumulative impact from land-use decisions rarely occurs. Field monitoring sites are often difficult to reach, the weather may be inclement and field sampling is expensive both in terms of budget and staff resources.

Remotely sensed satellite imagery, particularly that produced by the Landsat Thematic Mapper and the Enhanced Thematic Mapper Plus, has often been suggested as providing the low-cost synoptic data necessary for coastal managers to monitor and conserve coastal habitats (Green *et al.*, 2000; Mumby *et al.*, 1999; Costick, 1996). One of the goals of this project was to assess the potential of remote sensing, particularly using satellite imagery and/or aerial photographs, for cost-effective evaluation of terrigenous-sourced turbidity in nearshore waters. Furthermore, the project sought to evaluate remote sensing as a management tool to predict and monitor the performance of sediment retention in salt ponds to enhance the management and conservation of terrestrial and coastal resources.

Because of its low cost, ready availability and long history of use in monitoring the natural environment (satellite images of the Earth have been available for over 25 years), this study focused on evaluating the use of Landsat satellite imagery as a tool for monitoring sediment in the nearshore water column. Landsat images have been used previously to map sediments in nearshore waters (see, for instance Baban, 1995; Forget and Ouillon, 1998)

Advantages of Using Satellite Imagery

Satellite remote sensing of turbidity in inshore waters offers the following potential advantages:

1) Repeat imaging is offered on a relatively short time period. Landsat satellite imagery from the most recent Landsat satellite (Landsat 7) has a repeat time of 16 days. This repeat cycle potentially produces 22 images each year. An older satellite, Landsat 5, could potentially be used in conjunction with Landsat 7 to reduce the repeat cycle, but Landsat 5 has far exceeded its design lifetime and has recently suffered from intermittent breakdowns.

2) Large areal coverage. Landsat satellite imagery has a footprint of approximately 185 km by 170 km. Landsat coverage of the USVI is distributed over two images. St Thomas and St John with the outlying cays (along with the north east section of Puerto Rico, Vieques, Culebra, and the British

Virgin Islands [BVI]) are included in Worldwide Reference System Path 004, Row 047 (see Figure 20). St Croix is included in Path 004, Row 048.

3) Much of satellite imagery is multi-spectral. For instance, the current Landsat sensor, Enhanced Thematic Mapper Plus (ETM+), produces the following 7 spectral bands:

Band 1: 0.45-0.52 µm (blue)
Band 2: 0.52-0.60 µm (green)
Band 3: 0.63-0.69 µm (red)
Band 4: 0.76-0.90 µm (near infrared)
Band 5: 1.55-1.75 µm (mid infrared)
Band 6: 10.4-12.5 µm (thermal infrared)
Band 7: 2.08-2.35 µm (mid infrared)

plus one panchromatic (visible through near infrared) band (Band 8).

Multi-spectral imaging increases the potential for the use of digital image processing to extract additional information from each image.

4) Satellite imagery, particularly Landsat imagery, has a well-established infrastructure for the dissemination over the Internet. ETM+ images are available through the USGS Earth Explorer website:

http://edcsns17.cr.usgs.gov/EarthExplorer/

or the USGS Global Visualization Viewer website:

http://glovis.usgs.gov/

The availability of Landsat satellite imagery over the Internet combined with workstation-based digital image processing software has dramatically reduced the cost and complexity of obtaining and working with satellite imagery and so has made it feasible for use as a tool for managers.

5) The cost per unit area of satellite imagery is low (approximately $425/scene). While newer high resolution imagery from state-of-the-art satellites (Quickbird, Orbview) may be expensive, in most cases Landsat imagery can be obtained at low cost or *gratis*.

Disadvantages of Satellite Imagery

The disadvantages of the use of satellite imagery include:

1) The spatial resolution of satellite imagery is often relatively coarse (Landsat 7 ETM+: 30 x 30 m multi-spectral data , 15 x 15 m panchromatic data). Remote sensing satellites designed for ocean observing (SeaWIFS) have even coarser resolution, often 1 km x 1 km. Recently launched satellites (IKONOS, Quickbird, etc) offer resolution down to 1m, but have much higher image acquisition costs.

2) Satellite image acquisition is limited by fixed orbital configurations. As noted above current Landsat satellite imagery has a repeat time of 16 days (early Landsat satellites had a repeat time of 18 days). Events that an analyst may be interested in, such as sediment plumes derived from precipitation events, may not coincide with the acquisition of images because of the orbital characteristics of the satellite.

Additionally, Landsat 7 ETM+ does not acquire data continually. In any given 24-hour period, approximately 850 land scenes are passed over by the Landsat 7 ETM+, but resource limitations restrict daily acquisitions to 250 scenes. Decisions on the choice of Landsat scenes that are captured are determined by Landsat mission goals, cloud cover, seasonality, sun angle, and other factors.

3) Satellite image acquisition is limited by atmospheric conditions. Extensive cloud cover in the humid tropics often limits cloud-free Landsat satellite imagery acquisition to a few dates per year.

Evaluation of Satellite Imagery

Despite the limitations noted above it was decided to investigate the use of Landsat imagery to assess the potential for cost-effective evaluation of turbidity in coastal zone areas of the USVI. This decision was based partly on evidence of sediment plumes in archival Landsat images and partly on personal observation of extensive sediment plumes observable near Caribbean islands from commercial airline flights.

Examples of Landsat images illustrating sediment in coastal zone habitats can be found in Figures 21 and 22. Figure 22 uses digital image processing techniques to enhance visual interpretation of sediment in the water column. Initially, evaluation of Landsat imagery was to be limited to the years 2000-2004. With 22 Landsat acquisition passes per year over the USVI, potentially 110 images over the 5- year period should have been produced.

However, the USGS Global Visualization Viewer indicates that only 17 images are available from January 2000 until May 2003 for St Thomas and St John and 15 for St Croix. On May 31, 2003 a permanent failure of the Landsat 7 Scan Line Corrector, which compensates for the forward motion of the satellite, diminished usefulness of Landsat images subsequent to that date. Most of the images available on the Global Visualization Viewer for the years 2000-2003 are clustered between January and July. Restrictions on the daily number of acquisitions of Landsat scenes drastically reduced the number of scenes available for the USVI. This paucity of images may be due to the presence of extensive cloud cover during the period from September to December.

Ultimately we were able to acquire 13 sets of Landsat satellite imagery of the Virgin Islands, St Thomas and St John (Path 004, Row 047) and 2 of St Croix (Path 004, Row 048) (see Table 11). This data set extended back to1980.

Table 11. Acquired Landsat scenes of Path 004, Row 047 (Virgin Islands, St Thomas and St John) and Path 004, Row 048 (St Croix)

Path	Row	Island	Satellite, sensor	Date
4	47	STT, STJ	Landsat 3, TM	2/2/1980
4	47	STT, STJ	Landsat 5, TM	2/7/1991
4	47	STT, STJ	Landsat 4, MSS	6/25/1992
4	47	STT, STJ	Landsat 7, ETM+	3/27/2000
4	47	STT, STJ	Landsat 7, ETM+	8/2/2000
4	47	STT, STJ	Landsat 7, ETM+	1/9/2001
4	47	STT, STJ	Landsat 7, ETM+	1/25/2001
4	47	STT, STJ	Landsat 7, ETM+	2/13/2002
4	47	STT, STJ	Landsat 7, ETM+	7/23/2002
4	47	STT, STJ	Landsat 7, ETM+	8/24/2002
4	47	STT, STJ	Landsat 7, ETM+	3/4/2003
4	47	STT, STJ	Landsat 7, ETM+	3/20/2003
4	47	STT, STJ	Landsat 7, ETM+	10/16/2004
4	48	STX	Landsat 4, TM	6/25/1992
4	48	STX	Landsat 7, ETM+	10/16/2004

The acquisition dates of these Landsat scenes were then matched to significant precipitation events (Appendix A).

Although most of the acquired Landsat scenes were not correlated with significant precipitation events and therefore were unlikely to show evidence of sediment in the water column, each scene was visually inspected using UNESCO Bilko image processing software, version 3.0 beta, (http://www.noc.soton.ac.uk/bilko/) for sediment. Particular attention was paid to areas around salt ponds and guts and areas known to be undergoing significant development. No evidence of sediment plumes was found during this visual inspection, although many of the scenes had significant amounts of cloud cover over the USVI, obscuring areas of interest.

The Landsat scene image file sizes reached 360 MB of data. To reduce the files to a size more amenable for manipulation, subsets of the original 185 km x 170 km scenes were made to images that only encompassed St Thomas and St John (Path 4, Row 47) or St Croix (Path 4, Row 48) (ERDAS, 1997).

Two Landsat scenes from Table 11 were somewhat correlated with precipitation events. On July 30, 2000, 1.17 inches (3 cm) of rain was recorded on St Thomas. No substantial rainfall preceded this date. Three days later, on August 2, 2000, a Landsat scene of Path 004, Row 047 was acquired by Landsat 7, ETM+ (Landsat ID # LE700404720000802). Between April 17 and April 19, 2003, 9.37 inches (23.8 cm) of rain was recorded on St Thomas. Two days later, April 21, 2003, a Landsat scene of Path 004, Row 047 was acquired by Landsat 7, ETM+ (Landsat ID # LE700404720030421).

In preparation for analyzing these two scenes a land mask of the USVI was constructed from UVI-CDC landcover map based on a set of aerial photographs produced in 1994 by the USACE. The landmask allowed all the pixels of land to be set to a zero brightness value, enabling the water portion of the Landsat scene to be easily contrast stretched.

Bands 1-5 and 7 of both scenes were manually contrast stretched for the spectral brightness region of the water column pixels. A variety of other digital image processing techniques including histogram equalization and Guassian stretches were also applied to the images. No evidence of sediment suspension in the coastal waters of the USVI was found in these 30 m spatial resolution Landsat scenes.

At this point the UNESCO Bilko image processing software used was replaced by Leica Geosystems ERDAS Imagine Professional image processing software to achieve more detailed and sophisticated analysis. Different image processing techniques available in Imagine were applied to the satellite images to evaluate indications of sediment suspension in inshore waters. Even using this more powerful software no evidence of sediment suspension in the coastal waters of the USVI was found.

Given the coincidence of the extensive precipitation event (9.37 inches [23.8 cm] of rain over three days) between April 17-19, 2003, and a Landsat scene captured on April 21, 2003, the 15 m resolution panchromatic band of the image set was examined. Although this band (B8) has twice the spatial resolution of other Landsat bands, it is panchromatic rather than multi-spectral so is less amenable to digital image processing than the 30 m spatial resolution bands.

Figure 23 illustrates band 8 for Landsat 7 ETM+ image of Magens and Neltjeberg bays, St Thomas, April 21, 2003. Figure 24 illustrates the same image manually contrast stretched. Low level clouds obscure much of the northern part of the image. In this image brightness values (BV) of 40-46, highlighted in brown, are typically found at the edges of cloud cover and at the land-water interface. However, BVs in this range within the water column, as evidenced in Neltjeberg Bay and Lerkenlund Bay, appear to represent sediment in the water column. Other areas along the southwestern side of Magens Bay also seem to indicate sediment in the water column. Personal observations during 2004-2005 confirmed that Lerkenlund Bay can contain a visible sediment plume during and immediately after a precipitation event.

This same methodology indicated considerable sediment in the water column in the following sites on St Thomas; Long Bay (the Yacht Haven marina site), Water Bay, (the south side of Coki Beach), and the following sites on St John: the west side of Coral Harbor, Maho Bay and north coast of East End. No sediment was evident adjacent to any of the salt pond study sites or their respective bays.

Evaluation of Landsat for Coastal Monitoring

Although remote sensing by satellite has been mooted for decades as an invaluable tool for coastal zone management, for the most part satellite imaging has not lived up to its promise. Satellite remote sensing has been, and continues to be, used for research studies but has never made the transition to an effective management tool.

To some extent this has been due to the computer hardware requirements necessary to manipulate files that often reach 360 megabytes in size, and software that is expensive and difficult to use. In the past five years however, personal computers have become powerful enough to handle the file sizes. Software remains an issue and, to our knowledge, there are no licenses for Leica Geosystems ERDAS Imagine held by agencies or land mangers in the USVI.

Complicating the routine use of remote imagery are a number of other factors. Analysis and monitoring of features in inshore coastal waters is considerably more complex than analysis of terrestrial features. This complexity results from the additional medium of the water column. Light entering the water column is differentially attenuated depending on wavelength. Light in the water column also interacts with both dissolved and particulate suspended matter, and in shallow water may be reflected off the sea floor.

Additionally, Landsat satellites, as their name suggests, are primarily designed for the high reflectance values normally associated with terrestrial features rather than the much lower reflectance values associated with aquatic environments.

Although Figures 23 and 24 illustrate sediment in the inshore water column, the coarse pixel size of Landsat imagery, 30 m x 30 m for multi-spectral imagery and 15 m for panchromatic imagery, is a major problem for analysis of relatively small and transient features. Sediment plumes may be small enough that they occupy only a few pixels.

Not all available Landsat scenes sets are useful as many have significant amounts of cloud cover obscuring areas of interest, a perennial problem in the tropics. This is especially true in a study of precipitation-induced sedimentation events. Significant cloud cover was a problem for many of the Landsat scenes analyzed for this project.

Review of available remote sensing images suggests that linking a satellite image and precipitation events leading to sediment runoff to inshore habitats is problematic. Additionally, Landsat 7 ETM+ has been of reduced usefulness with the 2003 failure of the Scan Line Corrector, although after intermittent difficulties Landsat 5 TM is again producing images.

In summary, land-focused satellites may detect high concentrations of suspended sediments, record images at intermediate spatial resolutions of 15-30 m, and have acquisition cycles of 1-2 times per month. Ocean water color satellites, such as Coastal Zone Color Scanner (CZCS) (1978-1986) and SeaWIFS (1997 - on), with their sensors tuned to lower reflectance levels, can detect the lower concentrations of suspended sediment, but only at coarse spatial resolutions of 250 -1000 m. They pass over a specific region several times per week but are optimized for use over the open ocean, not the coastal zone. Neither type of satellite seems appropriate for routine monitoring of ephemeral events such as sediment intrusion into the coastal zone, although as indicated by the analysis of the band 8 panchromatic Landsat image, it is potentially possible.

Successors to the Landsat Satellite Program

NASA's current Earth Observing System (EOS), the successor to the Landsat program, includes two satellites, Aqua and Terra, which provide imagery that may be useful in monitoring the coastal environment. Launched in May 2002, Aqua carries six sensors, which include the Moderate-Resolution Imaging Spectroradiometer (MODIS) the design goals of which include mapping vegetation cover on the land, as well as phytoplankton and dissolved organic matter in the ocean. MODIS scans most of the Earth's surface daily, using a wide spectral range (36 wavelengths) and coarse spatial resolution (250m - 1km). Essentially MODIS trades off spatial resolution (less than Landsat's spatial resolution) for almost daily coverage of the Earth. Even with its coarse spatial resolution, MODIS is able to illustrate sediment in the water column if the sediment concentration is high enough (see Figure 25).

Terra, launched December 1999, carries the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) as well as a MODIS sensor. ASTER obtains moderate spatial resolution images (15 to 90 square meters per pixel, depending on wavelength) of the Earth in 14 wavelengths ranging from visible to thermal infrared light. The 15 m spatial resolution matches the panchromatic spatial resolution of Landsat 7. Each image footprint covers an area 60 kilometers wide and 75 kilometers long. With normal revisit time of 16 days, ASTER provides less repeat coverage capability than MODIS but in emergencies the pointable sensor may image a region as frequently as every 4 days. Additionally, similar to Landsat 7, ASTER does not collect data throughout its orbit, but collects an average of 8 minutes of data per roughly 100 minute orbit. Sediment in the water column in an ASTER image is shown in Figure 26.

Despite its almost daily coverage of much of the earth's surface MODIS is unlikely to provide coastal managers with an effective tool to monitor sediment in the coastal zone because of its coarse spatial resolution. ASTER, with 15 m spatial resolution seems better suited for analysis but is compromised by both its longer repeat time and selective capture of data. Nevertheless of the two sensors, ASTER appears to hold the most promise for monitoring non-predictable events such as precipitation and temporal change.

Aerial Photography

High altitude satellite remote sensing provides only one mechanism for collecting imagery. Imagery may also be obtained by aerial photography. Aerial photography has been used in the past to examine trends occurring in the USVI coastal zone (for example Island Resources Foundation, 1977). The advantages of aerial photography include:

- high spatial resolution images that typically are able to detect features on the order of 1m
- often easier to interpret than digital satellite imagery
- some systems produce multi-spectral imaging

The disadvantages of aerial photography include:

- historically produced by analog cameras in the form of 9 x 9 inch photographs. For digital processing these photographs must be scanned into digital form and require geo-referencing. Recent aerial photography is more likely to taken with digital equipment.

- may be either black and white or color. The spectral resolution of aerial films is typically limited to the visible wavelengths and the near infrared wavelengths (400-900nm)

- expensive for widespread coverage. To achieve synoptic coverage multiple images must be mosaicked together.

- because of the cost and extensive preparations necessary is not routinely produced in the Caribbean and often is taken only at 5 year intervals. For instance, in the USVI complete island coverage of high spatial resolution imagery has occurred in

  1994 Black and White
  1999 Color
  2004 Color

  Five year intervals between imagery collection reduces the usefulness of this type of imagery to analysis of long-term trends.

Fortuitously for this project, the most recent aerial photography mapping of Puerto Rico and the USVI occurred within 6-7 days of an extreme precipitation event. Given that the satellite remote sensing imagery we were able to obtain had shown limited evidence of suspended sediment in coastal waters, the 2004 aerial photography allowed a further opportunity to examine correlations between precipitation events and suspended sediment in the nearshore water column.

Tropical Storm Jeanne passed south of the USVI on September 14^{th} -15^{th} 2004, continued south of Vieques on September 15^{th} 2004 and traversed Puerto Rico from the southeast to northwest during Sept 15^{th}-16^{th}. Heavy rainfall accompanied TS Jeanne with substantial damage, particularly on Vieques (Table 12). Twenty-four hour rainfall at many recording stations in Puerto Rico and the USVI corresponded to 5 to 100 year events. Rainfall in Turpentine Run, on St Thomas, exceeded the maximum daily recorded rainfall for the past 10 years. The 14.75 inches (37.5 cm) of precipitation recorded at Vieques over 24 hours approached a 100-year event; the 9.25 inches (23.5 cm) recorded at Charlotte Amalie over 24 hours was close to a 25-year event (NOAA, 2004).

Table 12. Rainfall (inches) attributable to Tropical Storm Jeanne. Data extracted from Tropical Storm Jeanne: Hydrologic Summary for Puerto Rico and the U.S. Virgin Islands, Table 1, NOAA, 2004

Location	**Sept 15**	**Sept 16**	**Sept 17**	**3-day Total**
Camp Garcia, Vieques	2.20	14.75	6.78	**23.75**
Charlotte Amalie, St. Thomas	1.79	9.25	1.73	**12.77**

On Sept 21, 2004, complete aerial photographic coverage of Puerto Rico and the USVI was flown under the auspices of the USACE. We were able to utilize this imagery courtesy of USDA-Natural Resources Conservation Service (Tony Kimmet, George Rohaley) and the USACE (Jim Suggs).

Figures 27 and 28 illustrate sediments plumes in the nearshore waters along the northern coast of Puerto Rico on Sept 21, 2004. Figure 27 depicts the northwestern coast of Puerto Rico around Arecibo, particularly the Rio Grande de Arecibo disgorging sediment into the inshore waters. The sediment laden water can be traced upstream along the Rio Grande de Arecibo into the interior of Puerto Rico. Figure 28 depicts the north central coast of Puerto Rico just west of San Juan. To the west is the Rio de la Plata, to the east is the Rio de la Bayamon. Sediment plumes are again evident in the nearshore waters at the mouth of both rivers. Extensive suspended sediment plumes were to be found at the mouths of almost all rivers along the northern coast of Puerto Rico. Sediment plumes also occurred along the east and west coasts of Puerto Rico but were less evident along the south coast.

Although Figures 27 and 28 illustrate sediment plumes in inshore waters following an extreme precipitation event, Puerto Rico is topographically substantially different from the USVI. The island of Vieques, off the southeastern coast of Puerto Rico, is topographically more consistent with that of the USVI than Puerto Rico. The highest point on Vieques, Monte Pirata, is 987 feet above sea level, and Vieques lacks perennial surface drainage. The average annual rainfall is 36 inches (91.4 cm) (CH2MHILL, 2001).

Figure 29 shows the northern coastline of Vieques. In the lower left of the aerial photograph is the Aeropuerto de Vieques and the town of Isabel Segunda occupies the upper right of the image. The distinct sediment plumes of the perennial rivers of Puerto Rico are absent but suspended sediment in the nearshore waters is present in the image. Other sections of the north coast and south coast of Vieques in the aerial photographs did not display obvious suspended sediment in the water column. As mentioned previously, Vieques recorded 14.75 inches (37.5 cm) of precipitation over a 24-hour period, which was close to a 100-year event, and 23.75 inches (60.3 cm) of rain over a 3-day period five to six days prior to the acquisition of these images (NOAA, 2004).

The 2004 aerial photographs of the coastlines of St Thomas, St John and St Croix were carefully examined for evidence of suspended sediment in the nearshore waters. No evidence of suspended sediments was found on St John or St Croix. Only two locations on St Thomas showed evidence of suspended sediment. Figure 30 shows Neltjeberg Bay on the north coast of St Thomas. Suspended sediment is evident in the water column obscuring the sand bottom/hard pavement on the western side of the bay. An unpaved road can be seen at the bottom of the image leading down to the bay. Figure 31, depicting Lerkenlund Bay (in Magens Bay), also on the north coast of St Thomas, again shows a small plume of suspended sediment in the middle of the bay. A gut leads down to the bay. Lerkenlund Bay often exhibits sediment in the water column after substantial precipitation (personal observations, 2004-2005). Suspended sediment was evident at both these locations in the April 21, 2003, 15 m panchromatic Landsat imagery (see previous section).

Rainfall over the period 15-17 September 2004, exceeded the daily rainfall records for the previous 10 years for at least one location on St Thomas (NOAA, 2004). Although the high resolution aerial photographs were flown four to five days after this extreme precipitation event, that there were only relatively small areas that could be identified as suspended sediment plumes in only a few locations in the USVI indicates that sediment runoff into the coastal waters of the USVI is significantly less than occurs on islands such as Puerto Rico.

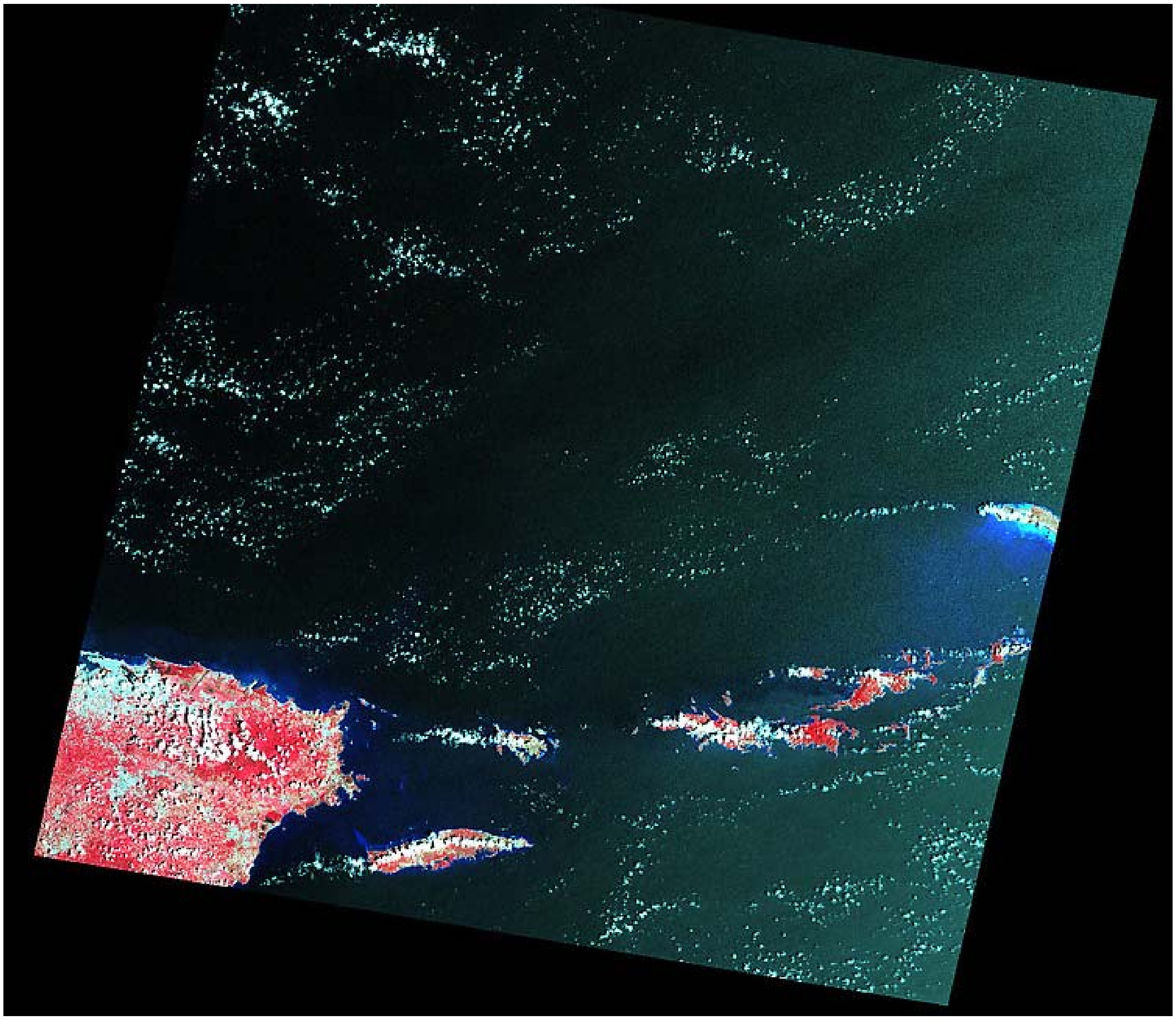


Figure 20. Landsat 7 ETM+ false color image footprint, Worldwide Reference System Path 004, Row 047. March 27, 2000 (Landsat ID# p004r047_7t20000327). Northeastern Puerto Rico occupies the lower left portion of the image, Anegada (BVI) the right central edge of the image, and St Thomas, St John and the BVIs the lower right of the image. Cloud cover obscures much of St Thomas but St John and Tortola (BVI) are evident.

Source: Image courtesy of University of Maryland, Global Land Cover Facility
http://glcf.umiacs.umd.edu

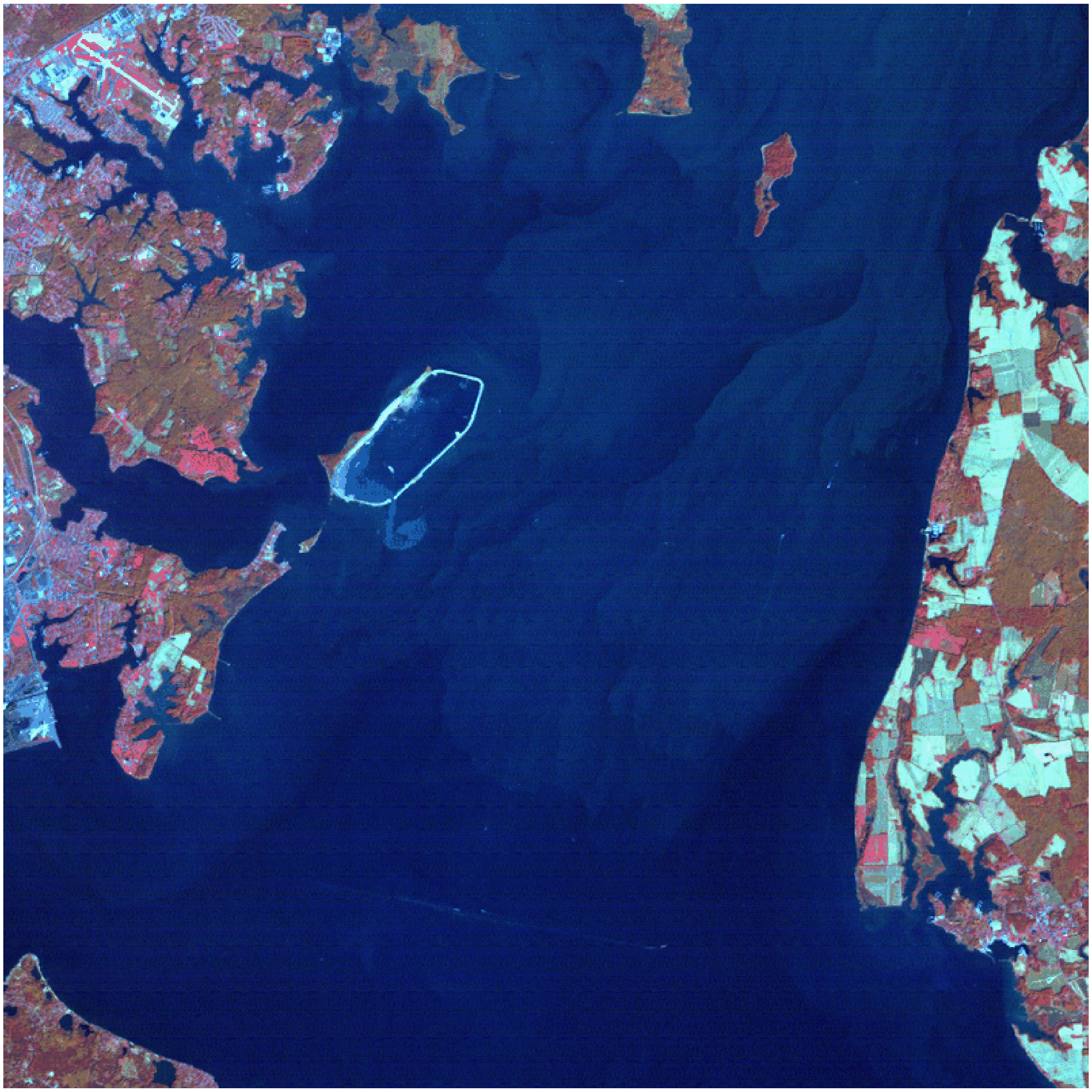


Figure 21. Landsat image of Chesapeake Bay. November 2, 1982, Color Infrared image produced from bands 4, 3, 1. A sediment plume escaping from an artificial island is visible in the bay. Diffuse sediment is also visible in the bay.

Source: Johns Hopkins University, Applied Physics Lab, Ocean Remote Sensing Group
http://fermi.jhuapl.edu/s1r/landsat/chesapeake.html

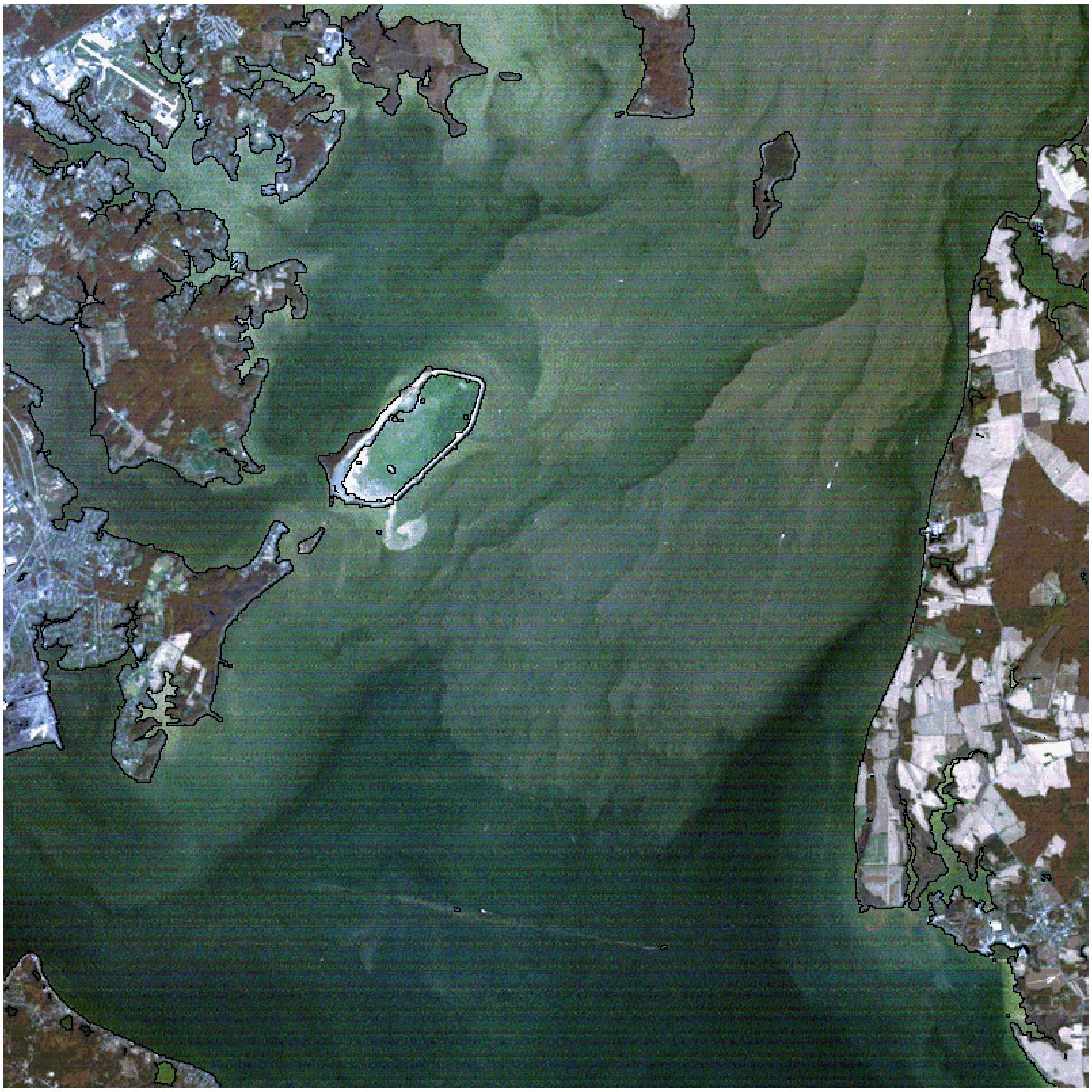


Figure 22. Landsat image of Chesapeake Bay. November 2, 1982, True color image produced from bands 3, 2, 1 with contrast stretching of the water pixels to better display sediment in the water column.

Source: Johns Hopkins University, Applied Physics Lab, Ocean Remote Sensing Group
http://fermi.jhuapl.edu/s1r/landsat/chesapeake.html

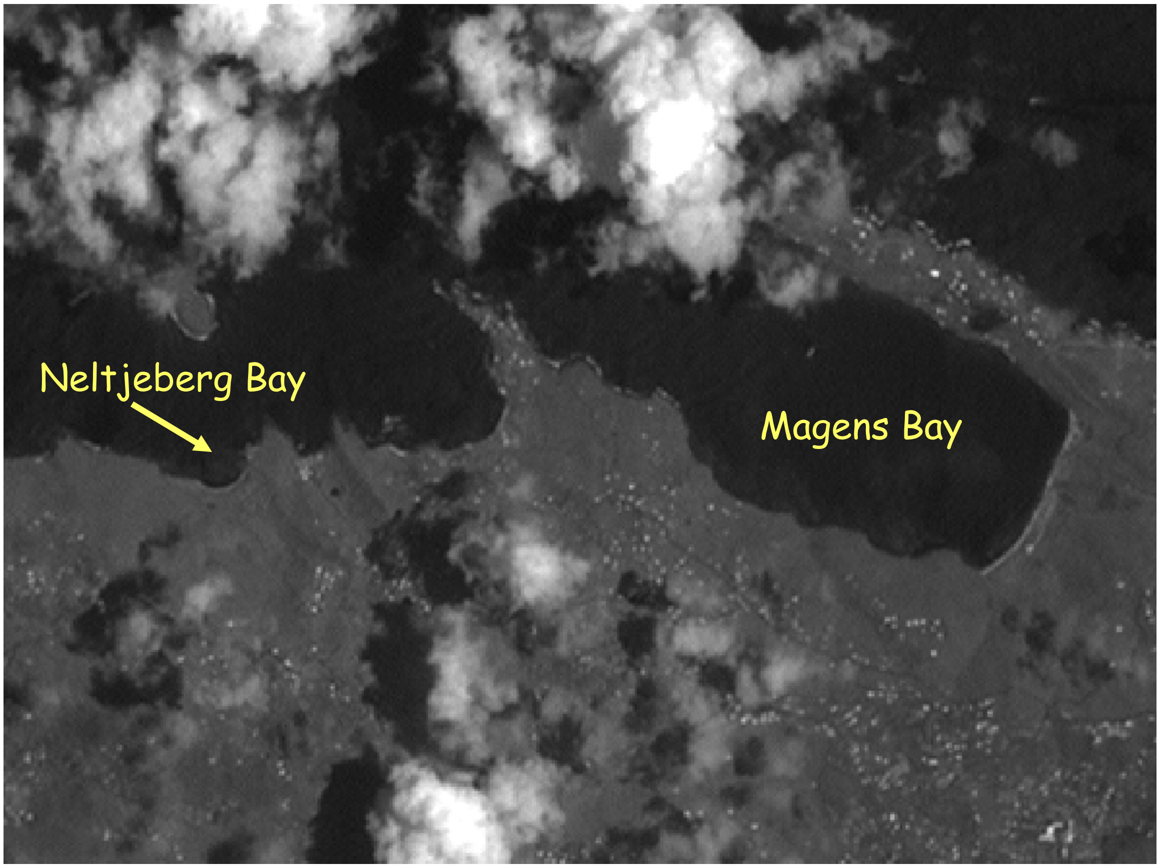


Figure 23. Landsat 7 ETM+ image of Magens and Neltjeberg bays, St Thomas, April 21, 2003. Landsat ID # LE700404720030421. 15 m resolution panchromatic band (B8)

Source: Original image courtesy of University of Maryland, Global Land Cover Facility http://glcf.umiacs.umd.edu

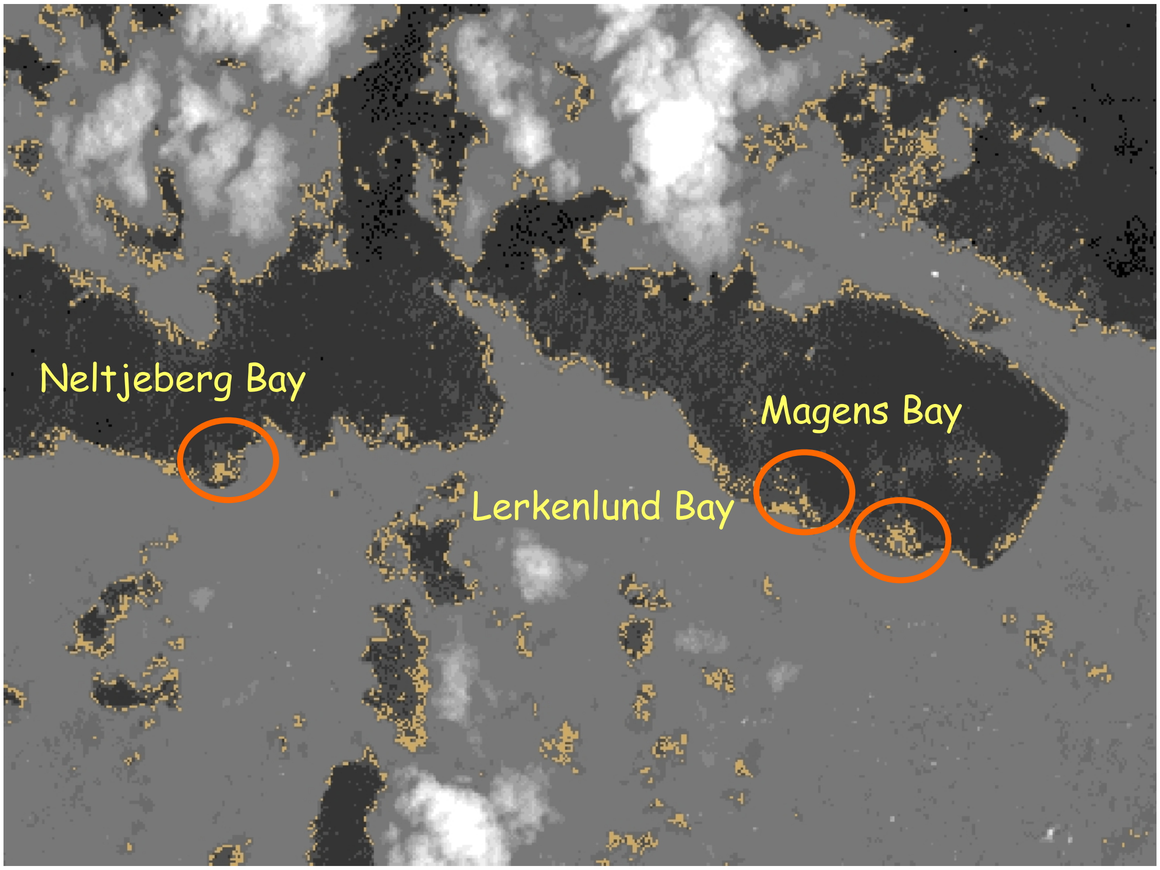


Figure 24. Landsat 7 ETM+ image of Magens and Neltjeberg bays, St Thomas, April 21, 2003. Landsat ID # LE700404720030421. 15 m resolution panchromatic band (B8)
Image manually contrast stretched. Brightness values (BV) from 40-46 highlighted in brown. In this image BVs of 40-46 are typically found at the edges of cloud cover and at the land-water interface. BVs in this range within the water column appear to represent sediment as indicated in Neltjeberg, Magens and Lerkenlund bays.

Source: Original image courtesy of University of Maryland, Global Land Cover Facility
http://glcf.umiacs.umd.edu

Figure 25. MODIS image of the Copper River (Moderate Resolution Imaging Spectroradiometer) disgorging sediment into the Gulf of Alaska. August 22, 2003

Source: Image courtesy Jeff Schmaltz, MODIS Land Rapid Response Team, NASA
http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=4196

Figure 26. ASTER image of Baltimore, Maryland (Advanced Spaceborne Thermal Emission and Reflection Radiometer), April 4, 2000. Sediment in the water column in Baltimore Harbor is evident as it disperses from the river running from the bottom left corner to the south side of the harbor.

Source: NASA Visible Earth http://visibleearth.nasa.gov/view_rec.php?id=1589

Figure 27. Northwestern coast of Puerto Rico, Arecibo, Rio Grande de Arecibo. September 21, 2004. Sediment is evident in the Rio Grande de Arecibo itself and a sediment plume is evident at the mouth of the river in the nearshore waters.

Source: Imagery courtesy of USDA-Natural Resources Conservation Service (Tony Kimmet, George Rohaley) and the US Army Corps of Engineers.

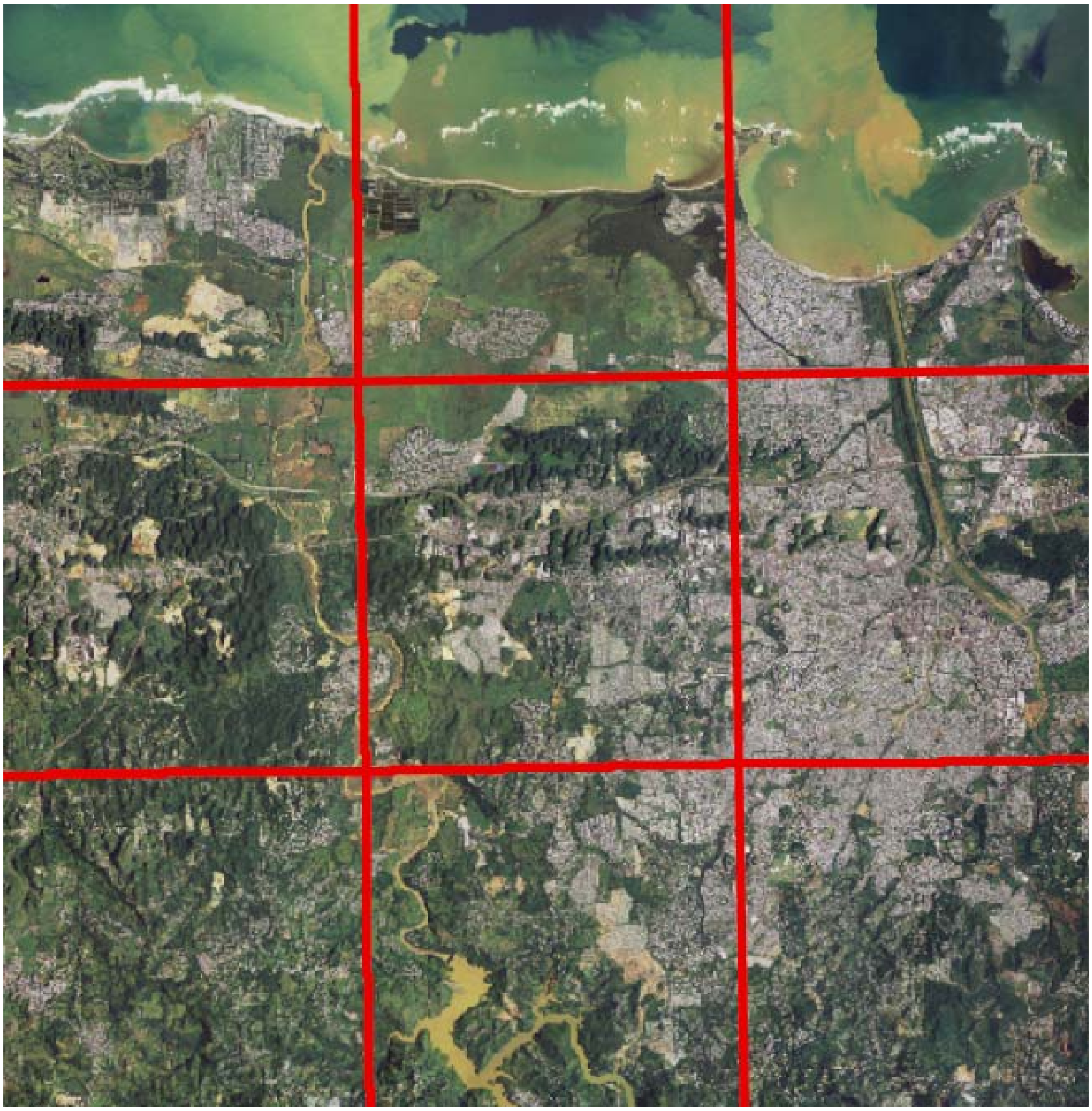


Figure 28. North central coast of Puerto Rico, San Juan area. September 21, 2004. West -- Rio de la Plata, East -- Rio de la Bayamon. Sediment plumes are evident at the mouths of both rivers.

Source: Imagery courtesy of USDA-Natural Resources Conservation Service (Tony Kimmet, George Rohaley) and the US Army Corps of Engineers.

Figure 29. Northshore of Vieques. September 21, 2004. In the lower left is the Aeropuerto de Vieques, in the upper right is the town of Isabel Segunda. Suspended sediment in the water column is evident along much of the depicted coastline.

Source: Imagery courtesy of USDA-Natural Resources Conservation Service (Tony Kimmet, George Rohaley) and the US Army Corps of Engineers.

Figure 30. Neltjeberg Bay, north coast of St Thomas, USVI. September 21, 2004. The yellowish band immediately off the beach is a sediment plume.

Source: Imagery courtesy of USDA-Natural Resources Conservation Service (Tony Kimmet, George Rohaley) and the US Army Corps of Engineers.

Figure 31. Lerkenlund Bay (in Magens Bay, north coast of St Thomas, USVI. September 21, 2004. The yellowish plume immediately off the beach is a sediment plume.

Source: Imagery courtesy of USDA-Natural Resources Conservation Service (Tony Kimmet, George Rohaley) and the US Army Corps of Engineers.

DISCUSSION

The sediment retention function of salt pond systems is only one indicator of ecosystem health but undeniably an important one in the USVI given the sensitivity of valuable nearshore coastal resources to turbidity. Functions often interact both negatively and positively with other functions such as nutrient removal and transformation, groundwater recharge, flood flow alteration, sediment stabilization, production export and aquatic diversity (Adamus *et al*., 1991). Understanding and documenting the features that play a role in a particular function, such as sediment retention, is key to using this information in scientifically sound management decisions.

Variability in Sediment Retention Characteristics

Salt pond systems are highly variable in their potential to retain sediment. For this reason, pond systems must be evaluated individually in order to determine their sediment retention effectiveness. Specific wetland or watershed features often play a role in sediment retention in conjunction with other features, and it is this combination, which can differ between ponds, that leads to effective or non-effective functional performance.

Pond systems with the least human-induced disturbance reflect the most natural environmental conditions, however as shown in this study, this does not necessarily indicate the most effective functional performance for sediment retention. Wetland fringe width, for example, is an important determinant in sediment retention effectiveness, yet a number of undisturbed ponds on St. John have a very narrow wetland fringe while the highly disturbed Southgate watershed supports a wide wetland fringe around the pond. Slope, climate and other factors, both natural and human-induced, play a role.

As a consequence, developing standards of reference based on a 'best performance' basis is not possible for most of the features analyzed in this study. However, using the data collected for each pond system (Appendices E and F) as a guide to the variability of each parameter provides a valuable reference for assessing parameters of other pond systems or for monitoring changes to the pond systems studied in this investigation. The condition of the pond as a result of human disturbance does not appear to be a reliable indication of sediment retention effectiveness.

Key Parameters as Indicators of Salt Pond System Functional Effectiveness

Data analyses of the thirteen parameters led to a number of conclusions of salt pond system functional effectiveness for sediment retention based on the evidence collected and documented literature (Table 13). No salt pond system is expected to function effectively with respect to all parameters, however the role of a pond and its watershed in carrying out the sediment retention function increases with the more parameters noted as effective in Table 13. Perseverance (6), Salt (5) and Southgate (5) were identified as being more effective for a particular parameter most often; Compass Point (6), Flamingo (4), Fortuna (4) and Mandahl (4) were found to be less effective.

The results of this study indicated that the function of sediment retention is most effective in Perseverance, Salt and Southgate pond systems. Changes to landscape features from natural or human-induced modifications that result in decreased effectiveness could compromise this functional performance. This does not mean that salt pond systems noted as being effective for fewer parameters are not playing an important role in sediment retention, however it does imply that these systems and the nearshore coastal waters they protect could be more vulnerable to increased sediment flow, should this occur. Compass Point, Flamingo, Fortuna and Mandahl pond systems were found to be ineffective for different reasons, however the underlying cause of these reasons can be attributed to human-induced changes.

Table 13. Locations where key parameters contribute to functional effectiveness (an explanation of effectiveness is given in the results section for each feature).

Feature	**More Effective**	**Less Effective**	**Not Important or Not Determined**
Berm elevation	Europa, Fortuna, Great Lameshur East, Salt	Reef, Fish	Flamingo, Mandahl, Compass Point
Outlet	Bolongo, Coculus, Europa, Fish, Fortuna, Francis, Frenchman, Great Lameshur East, Perseverance, Redhook, Reef, Salt , Southside	Mandahl, Flamingo	
Pond depth		Flamingo, Compass Point, Fish, Southgate	
Submerged aquatic vegetation	Compass Point, Flamingo, Perseverance		Europa, Redhook
Water/woody veg interspersion	Compass Point, Fish, Fortuna, Francis, Perseverance, Reef, Southgate		Europa, Redhook
Fringe vegetation density	Perseverance	Compass Point, Salt	Southside
Fringe width	Perseverance, Reef, Southgate	Bolongo, Compass Point, Flamingo, Mandahl, Redhook	Southside
Flood plain area	Southgate	Bolongo, Compass Point, Flamingo, Mandahl, Redhook	
Gut presence	Bolongo, Flamingo, G. Lameshur East, Mandahl, Perseverance, Redhook, Salt, Southgate		
Land use	Europa, Great Lameshur East, Reef, Salt	Compass Point, Fish, Fortuna, Coculus, Mandahl, Southgate	Flamingo
Slope	Fish, Southgate	Europa, Fortuna, Frenchman Great Lameshur East, Perseverance, Southside	Flamingo
Soil erosion potential	Francis, Mandahl	Coculus, Compass Point, Fortuna, Southgate	Flamingo
Wetland to watershed ratio	Compass Point, Europa, Redhook, Salt, Southside	Bolongo, Coculus, Fish, Fortuna, Frenchman, Great Lameshur East, Perseverance, Southgate	Flamingo

Salt Ponds Systems at Risk

A number of conclusions can be drawn from the findings in this study with regard to the potential risk for salt pond systems on the USVI to perform a sediment retention function effectively.

1. Sediment trapping ability will decline as wetlands fill in or if vegetation dies due to flooding or to other disturbances. Although guts that empty to ponds are noted as an effective sediment retention feature, these salt ponds are also more at risk from infill should vegetation removal in their respective watersheds result in increased sedimentation flow to the pond via the gut. Reducing the amount of sediment washing off the hills from human activity is key to ensuring a pond's natural evolution. Guts and the vegetation contained in and around them should be protected against development and modification.

2. Compass Point, Southgate and Fish ponds have low depth:area ratios suggesting that these ponds are receiving or have received abnormally high sediment loads in the past. This has implications for the longevity of the ponds as depressional basins and could compromise their ability to retain sediments in the long-term. Actions to prevent increased sediment loads to these systems should be given high priority.

3. Although there is no information on the trigger level for human disturbance beyond which a negative impact might be expected on steeper gradients, watersheds where land modification has exceeded 10% of steep slopes should be monitored for sediment flow to the lower watershed. These include Southgate, Compass Point, Fortuna, Coculus and Mandahl on St. Thomas and Fish on St. John.

4. The greater proportion of roads to other land-use categories in the Fish, Redhook and Frenchman pond watersheds suggests that these watersheds may experience a loss of vegetated slopes to development in the near future which could further stress the effectiveness of sediment retention. Actions to protect the lower watershed from increased sediment loads should be given high priority.

5. Pond systems with a high Kf-factor that are outside the development protection afforded by the Virgin Islands National Park system will be more at risk from land-use changes and consequently have more potential for erosion. These include Bolongo, Coculus, Compass Point, Fortuna, Frenchman and Perseverance ponds on St. Thomas and Fish and Southside ponds on St. John. Actions to limit removal of vegetation in these watersheds should be given high priority.

6. The causeway separating Southgate Pond from the marina appears to be at an adequate height to preserve sediment retention functional performance in the reduced pond, however changes to the historical pond configuration and land-use activities in the upper watershed may be causing reduced sediment retention within the adjacent East Gut with potential damage to nearshore coastal waters. Measures to improve flow reduction, sediment retention and sediment filtering capacity of the East Gut should be implemented.

7. Perseverance and Southgate pond systems are noted as functioning effectively for a number of key parameters, however, these ponds are also noted as being small relative to their watershed. As

a consequence, small land-use changes in the watershed could negatively impact the functional performance of these ponds and threaten the sensitive nearshore coastal resources beyond. Protection of existing vegetation cover and limiting further development or road construction in these watersheds should be given high priority.

Functional Assessment in Management

The sustainable management of coastal wetland resources is fundamental to the protection of nearshore coastal resources. Sustainable management is brought about by sound land-use and regulatory decisions, which in turn are limited by the quality of information available to the decision makers.

The data range collected for each parameter presented in Appendices E and F provide a reasonable guide for basing management decisions or evaluating potential impacts from development proposals. Such information could be applied to determining appropriate buffer zones to protect salt pond integrity, best management practices (BMPs) for adjacent development activities and key characteristics to be included in salt pond restoration design.

Land managers should ensure that effects from changes to land use do not result in changes to the key parameters that are outside the limits of its range, after evaluating site-specific considerations. This will help to ensure that salt pond systems continue to function effectively with respect to sediment retention so that sensitive downstream resources are not damaged.

A number of recommendations are likely to be of interest in management decisions. These include:

- Deep, straight channels behind the beach berm, such as found at Reef pond, may cause earlier or more frequent breaching of the berm than would occur naturally. This would reduce sediment retention effectiveness and warrants further investigation.

- The ratio of pond depth to surface area is a good indicator for identifying a potentially impacted condition.

- The extensive root network of the mangrove community in the wetland fringe creates a high frictional resistance to water flow, aiding in the trapping and retention of sediment. The presence of a dense mangrove community is a good indicator of effective sediment retention. Measures to increase mangrove density should be applied where appropriate.

- Where conditions allow the development of a wetland fringe, the greater the fringe width, the more effective the functional performance of sediment retention will be. Land-use decisions that could hinder the development of the wetland fringe or reduce the wetland fringe should be avoided.

- Human disturbance in the watershed is an important factor affecting the potential functional effectiveness of sediment retention. To help protect the function, land-use modification should not exceed 25% of the pond watershed, however conditions in the watershed may warrant less than this amount.

- The flood plain is an important contributor to sediment retention, and development within the flood plain should be avoided.

- The berm creates an extremely effective impoundment which is arguably the most important sediment retention feature; creating an opening in the berm will reduce the functional effectiveness of a pond and should be avoided.

Remote Sensing as a Management Tool

Monitoring turbidity events in the nearshore coastal zone will provide evidence to the effectiveness of sediment retention features in the adjacent watershed. Landsat images can be used to illustrate suspended sediment in inshore waters but routine use of Landsat imagery to detect and monitor suspended sediment in the coastal waters of the USVI is unfeasible. Although personal observations of the authors of this report and others indicate that suspended sediment plumes are to be found in the nearshore waters of the USVI, we were able to find no evidence of suspended sediment associated with salt ponds and only limited evidence of suspended sediment at any location in the USVI in the Landsat imagery we examined. This limited evidence of suspended sediment was only associated with extreme precipitation events, more than 9 inches (22.9 cm) of rain over two to three days.

Our inability to find evidence of sediment in coastal waters of the USVI may be due to a number of factors. First, small volcanic islands with a thin layer of topsoil and no perennial streams or rivers produce limited quantities of sediment to be carried into the nearshore waters. The sediment that is carried to coastal waters may be detrimental to susceptible marine organisms in the inshore environment, but it is much less in quantity than might be carried by perennial rivers draining larger land masses. This is evident in the comparison between sediment plumes derived from the September 15-17, 2004 precipitation event in Puerto Rico versus those that occurred in the USVI. Of obvious interest would be the condition of coral reefs of the north coast of Puerto Rico subsequent to the observed sediment plumes of September 2004.

Second, the orbital repeat time of 16 days is often too long to try to correlate with ephemeral events such as precipitation periods. In two of the three events analyzed in this report, the imaging took place from two to four days after precipitation ended. For precipitation events that are low to moderate in their severity, this may be sufficient time for much of the sediment to either disperse or to fall out of the water column. Even when an event occurs in temporal proximity to remotely sensed imaging, there is no guarantee that image will be available because of mission objectives and cloud cover.

Finally, the suspended sediment plume evident in the aerial photography of the USVI is small enough spatially that, at best, it would occupy only a few pixels in a Landsat scene, possibly too few to be picked up in analysis.

Given these pessimistic conclusions, two courses of action could be pursued in the future if remote sensing is to be considered as a management tool. One is to continue to evaluate the feasibility of recently launched remote sensing satellites for monitoring suspended sediment in nearshore waters. The ASTER sensor on NASA’s Terra satellite may prove to be useful, although its moderate spatial resolution and relatively long repeat acquisition cycle militate against it. Newer commercial satellites address some of these problems with repeat observation times as low as four to five days and spatial resolutions of 1 m or less. Commercial satellites, however, charge high prices for their imagery (although that may come down with competition), and these satellites still do not resolve the problem of cloud cover in the tropics.

Perhaps the most feasible technique might be to employ small planes or helicopters to obtain imagery through hand-held digital cameras. This approach would have the advantage of being able to document sediment plumes immediately after precipitation events, but it also suffers from a number of problems arising from the oblique rather than vertical camera angle that normally is associated with hand-held imaging. These problems include:

- Limited ability to use the imagery for digital image processing
- Limited ability to manipulate the imagery with a GIS

Nevertheless, if the objective is simply to qualitatively document nearshore sediment plumes and their relationship to land-use activities or coastal features, this approach seems to be the most feasible.

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APPENDIX A. PRECIPITATION EVENTS

Precipitation events exceeding 1 inch (2.5 cm) per day on St. Thomas, January 2000-November 2005. Major storm events greater than 4 inches (10 cm) are shown in bold.

2000	Inches	2001	Inches	2002	Inches	2003	Inches	2004	Inches	2005	Inches
23-May	1.3	30-Jan	1.11	4-Sep	1.37	5-Apr	1.48	24-Mar	1.3	9-Jan	1.79
30-May	1.5	8-May	1.53	16-Sep	2.74	17-Apr	3.85	28-Mar	1.06	10-Jan	2.09
30-Jul	1.17	9-May	1.08	17-Sep	1.48	18-Apr	**4.08**	23-Aug	1.39	13-Jan	1.09
		30-Jul	1.37	29-Sep	1.95	19-Apr	1.44	27-Aug	3.03	22-Apr	3.24
		16-Dec	1.51	12-Oct	1.12	21-Apr	1.04	15-Sep	**7.47**	15-May	2.04
				13-Nov	1.38	22-Apr	1.74	16-Sep	**6.39**	17-May	1.04
				18-Dec	1.18	23-Apr	1.53	17-Sep	3.93	23-May	1
						25-Apr	1.14	21-Oct	1.21	10-Jun	1.53
						13-Jul	1.3	8-Nov	1.53	12-Jun	2.61
						11-Aug	1.27	9-Nov	1.39	4-Jul	1
						21-Sep	1.58	14-Nov	1.37	19-Jul	3.67
						22-Sep	1.83	15-Nov	1.33	20-Jul	1.15
						22-Oct	1.07			29-Jul	1.03
						31-Oct	1.32			7-Aug	1.15
						9-Nov	1.49			16-Aug	2.18
						10-Nov	1.2			25-Aug	1.26
						11-Nov	3.15			17-Sep	1.58
						12-Nov	3.97			19-Sep	1.11
						13-Nov	3.42			20-Sep	2.19
						14-Nov	**4.08**			21-Sep	1.28
						15-Nov	2.78			27-Sep	1.37
						9-Dec	1.65			3-Oct	1.94
						28-Dec	1			4-Oct	**4.45**
										5-Oct	1.94
										10-Oct	**4.58**
										12-Oct	1.24

Source: USGS water data for Bonne Resolution Gut No. 50252000 and Turpentine Run at Mt Zion No. 50274000
http://waterdata.usgs.gov/vi/nwis/current/?type=precipvi&group_key=county_cd
and the Water Resources Research Institute Weather Center, University of the Virgin Islands
http://rps.uvi.edu/WRRI/weathercenter.html

Precipitation events exceeding one inch per day (2.5 cm) at Bethany, St. John, January 2003-December 2005. Major storm events greater than 4 inches (10 cm) are shown in bold (Source: USGS water data for Guinea Gut No. 50295000 http://waterdata.usgs.gov/vi/nwis/uv/?site_no=50295000&PARAmeter_cd=00045)

2003	Inches	2004	Inches	2005	Inches
17-Apr	3.52	6-Jan	1.25	9-Jan	2.26
18-Apr	1.39	20-Jul	1.07	13-Jan	1.50
22-Apr	1.41	**15-Sep**	**4.88**	22-Apr	1.30
11-Aug	1.27	16-Sep	3.59	10-Jun	2.55
21-Sep	1.43				
30-Oct	2.01				
8-Nov	1.02				
9-Nov	1.29				
11-Nov	1.58				
13-Nov	3.01				
14-Nov	**4.81**				
8-Dec	2.35				

Precipitation events exceeding one inch (2.5 cm) per day at Jolly Hill, St. Croix. January 2004-December 2005. (Source: USGS water data for Jolly Hill Gut No. http://waterdata.usgs.gov/vi/nwis/uv/?site_no=50345000&PARAmeter_cd=00045)

2004	Inches	2005	Inches
15-Sep	2.27	22-Feb	1.43
		23-Apr	1.5
		16-May	1.35
		24-Nov	1.77

APPENDIX B. SELECTED SITE PHOTOGRAPHS

Selected site photographs are included on the attached CD.

APPENDIX C. SELECTED HISTORICAL AERIALS

Selected historical aerials are included on the attached CD.

APPENDIX D. EXCLUDED VARIABLES

Variables from published wetland functional assessment methodologies that have been excluded in assessing the sediment retention function of salt ponds in the US Virgin Islands.

Variables excluded in this Assessment	**Reason for exclusion**
Channel gradient	Channel gradient is covered under the 'slope' parameter
Fetch/exposure Position of wetland in watershed Wetland adjacency Wetland system/type	This study is focused on depressional salt ponds. These variables are not considered to be applicable to this type of pond on the US Virgin Islands;
Presence of drainage ditches or channels	Channels are covered under the 'guts' parameter
Outlet constriction	Although salt ponds on the US Virgin Islands may have some type of channel across the berm, this parameter is captured by other variables such as berm elevation and presence or absence of an outlet.
Direct alteration	Although some salt ponds have been modified, this parameter is captured by other variables, such as presence /absence of an outlet or land use
Salinity	This parameter is common to all salt ponds.
Flood detention Flood duration Inundation Flooding extent	Difficult to easily measure or estimate. These parameters are captured by other variables, such as the presence of an outlet, flood plain area or berm elevation
Flow velocity Presence of hummocks	Difficult to easily measure or estimate. These are captured by other variables, such as slope, floodplain area, vegetation cover, vegetation class
Seasonal ponding Vegetation – bare in dry season	These vary from year to year depending on rainfall and temperatures. These are captured by other variables, such as wetland: watershed ratio, pond depth and pond/vegetation interspersion
Soil compaction Soil deposits Soil leveling/soil mixing, plowing Soil texture	Difficult to easily measure and are captured by other variables such as land use and soil erodibility
Soil depth (A and O layer) Wetland edge to wetland area	These variables are considered more important in nutrient cycling rather than sediment retention.
Vegetation fringe height	Height itself is not considered overly important for sediment retention. Other variables that are covered in the study include vegetation density and vegetation cover
Vegetation understory Vegetation roughness	This is difficult to measure, particularly when using aerials for determining watershed characteristics; it is captured by other variables, such as vegetation cover and density
Wetland age	Difficult to adequately determine
Water source Rainfall/climate Soil source Suspended solids	This study evaluates characteristics of the ponds that maintain effective functionality, and does not examine the 'opportunity' for sediment retention. Rainfall is the main source of water for all the closed depressional ponds, whether direct or as sheet flow. Variables over which there is little or no control are not covered in this study.

APPENDIX E. WETLANDS DATA SUMMARY

Pond (disturbance level)	Island	Survey Date	Berm Elevation (m)[1]	Average Channel Depth (m)	Pond Area (ha)[2]	Average Pond Depth (m)[3]	Average Pond Depth Std Dev	SAV Category[4]	Woody Veg intersper category	Average Wetland Fringe Width (m)	Average Wetland Fringe Range (m)	Wetland Fringe Ground Cover Percent	Wetland Fringe Ground Cover Range
Bolongo (M)	ST	3/18/2005	1.80		0.30	0.08	0.0222	2	1	9	4-17	22	5-65
Coculus (M)	ST	5/19/2005	1.60		0.23	0.15	0.0612	1	1	12.4	38582	26	0-50
Compass Pt (H)	ST	3/18/2005	Open	> 0.9	2.53	0.14[6]	0.0925	4	2	8.5	3-12.5	13	0-62
Europa (L)	SJ	5/22/2005	2.60		6.14	0.85	0.4642	1	1	6.5	0-16	21	0-50
Fish (H)	SJ	5/20/2005	0.59		0.17	Dry	-	1	3	17	6-36	29	14-49
Flamingo (H)	WI	5/11/2005	Open	1.95	2.70	0.89	0.5647	3	1	1	0.5-2	-	-
Fortuna (M)	ST	3/17/2005	2.60		0.65	0.23	0.0779	1	3	15.8	12-21	29	5-100
Francis (M)	SJ	3/19/2005	1.30		1.25	0.18	0.0306	1	3	18.2	3-40	45	3-90
Frenchman (M)	ST	5/19/2005	0.80		0.46	0.11	0.0369	2	1	2.1	1-3	40	10-75
G Lameshur East (M)	SJ	3/19/2005	2.20		0.34	0.25	0.0273	2	1	13.3	5-20	38	10-50
Mandahl (M)	ST	5/9/2005	Open	2.24	2.40	1.89	0.5527	2	1	3.9	1.5-7.5	27	5-90
Perseverance (L)	ST	3/17/2005	1.20		2.46	0.35	0.0422	4	2	68[8]	44-91	68	5-100
Redhook (H)	ST	3/18/2005	0.80		3.00	0.62	0.2034	1	1	7.1	1-33	39	25-50
Reef (L)	SJ	5/20/2005	0.65[5]		0.64	0.3[6]	0.0894	1	4	56	6.5-105	31	0-60
Salt (L)	SJ	3/19/2005	2.00		2.66	0.32[6]	0.0914	1	1	2.8	1-7	40	10-100
Southgate (H)	SC	7/22/2005	1.2[2]		10.00	0.33[7]	0.1329	2	2	45	12-153	50	10-85
Southside (L)	SJ	12/8/2005	N/A		4.55	0.5	-	1	1	0	0	0	0

[1] Berm elevation at lowest point above Mean Lower Low Water

[2] From 1994 USACE digital orthophotography

[3] Taken along center line of pond

[4] Submerged Aquatic Vegetation. Excludes diatoms and unicellular algae

[5] Pond has distinct channel leading from pond to berm

[6] Pond bottom too soft or clogged with dead wood; depth estimated from edge measurements and visual observation

[7] From bathymetry map provided by St. Croix Environmental Association

[8] from GIS

APPENDIX F. WATERSHED DATA SUMMARY

Pond*	Pond catchment area (exc pond)	Pond surface area	Wetland area	Wetland area	Flood plain (exc pond)	Area of Slopes 0-3%	Area of Slopes 3.1-8%	Area of Slopes >8.1%
	sq meters	sq meters	sq meters	% of watershed	sq meters	sq meters	sq meters	sq meters
Bolongo(M)	224,138.3	2,995.5	2,995.5	1.32	9,375.8	13,601.0	7,697.5	191,693.1
Coculus(M)	60,499.9	2,313.7	4,268.4	6.80	4,648.3	7,805.2	4,481.3	47,752.9
Compass(H)	78,931.9	25,344.7	30,243.5	29.00	4,931.1	9,718.7	5,736.6	62,987.7
Europa(L)	466,957.6	61,367.8	68,389.6	12.94	12,729.3	14,236.0	17,345.4	433,834.0
Fish(H)	77,776.5	1,728.6	4,486.3	5.64	15,122.6	15,122.6	3,927.7	58,726.2
Fortuna(M)	230,888.2	6,454.7	5,942.9	2.50	6,618.0	1,985.0	3,460.3	217,847.1
Francis(M)	235,505.8	12,515.8	21,141.9	8.52	24,906.8	25,277.2	11,907.9	197,297.9
Frenchman(M)	70,983.7	4,563.2	4,563.2	6.04	1,893.2	2,415.0	3,309.6	64,937.8
G Lameshur East(L)	582,039.5	3,381.3	9,010.6	1.54	12,349.3	12,795.3	8,699.9	558,721.1
Mandahl(M)	279,405.2	24,021.6	24,038.1	7.92	18,575.6	20,913.2	9,753.1	247,267.7
Perseverance(L)	1,012,806.3	24,639.0	45,205.1	4.36	48,084.2	48,093.8	40,283.8	914,913.9
Redhook(H)	251,314.4	29,785.4	35,353.3	12.58	5,567.9	18,384.0	10,033.4	189,800.1
Reef(L)	188,472.0	6,415.1	16,509.9	8.47	16,456.2	17,427.8	6,111.6	164,382.3
Salt(L)	62,161.2	26,576.0	28,241.9	31.83	8,122.9	8,287.0	8,306.6	45,210.4
Southgate(H)	3,016,001.8	99,859.2	146,287.3	4.69	401,254.8	546,817.3	775,658.6	1,693,522.1
Southside(L)	175,806.4	45,479.1	45,479.1	20.55	3,021.3	4,171.8	5,614.5	164,873.1

APPENDIX F. (continued)

Pond*	Area of development (excl roads)	Area of roads	Area of vegetation 0-3% slopes	Area of vegetation 3.1-8% slopes	Area of vegetation >8.1% slopes	Predominating soil type
	sq meters	sq meters	sq meters	sq meters	sq meters	type
Bolongo(M)	11,468.2	4,851.1	11,429.0	6,531.6	179,216.1	SrF
Coculus(M)	6,531.5	1,896.0	6,347.5	3,816.5	41,631.3	SrE
Compass(H)	20,864.8	4,314.9	6,536.9	4,172.7	43,305.6	SrE
Europa(L)	0.0	0.0	14,236.0	17,345.4	433,834.0	VsF/VsE
Fish(H)	2,049.3	3,930.0	15,121.6	3,927.7	52,747.9	VsF
Fortuna(M)	32,516.8	4,611.8	1,937.9	3,076.0	181,904.5	FsC
Francis(M)	3,412.4	2,435.4	25,051.6	11,609.7	192,014.7	AmF/AmE
Frenchman(M)	1,227.5	1,823.0	2,388.5	3,284.2	61,941.3	SrF/SrE
G Lameshur East(L)	0.0	435.4	12,795.3	8,699.9	558,285.7	VsF/VsE
Mandahl(M)	37,355.9	6,064.1	20,271.6	8,913.6	205,540.0	AmG/E/F
Perseverance(L)	69,040.2	4,589.9	47,044.1	39,174.3	849,726.9	FsF
Redhook(H)	3,829.3	4,156.1	18,384.0	9,559.7	184,297.7	SrF
Reef(L)	0.0	0.0	17,427.8	6,111.6	164,382.3	VsF
Salt(L)	0.0	0.0	8,287.0	8,306.6	45,210.4	SrE
Southgate(H)	1,295,972.3	104,419.5	314,498.0	247,297.4	1,124,775.6	GyC
Southside(L)	1,788.0	834.0	3,838.9	5,371.4	162,827.2	SrG/SrE/SrF

* H, Highly disturbed; M, Moderately disturbed, L, Low disturbance

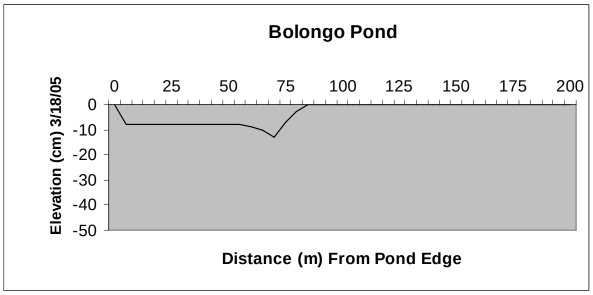
APPENDIX G. SALT PONDS AND THEIR WATERSHEDS

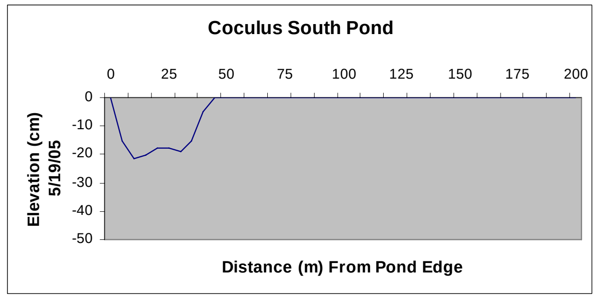
Maps of the salt pond systems are included on the attached CD.

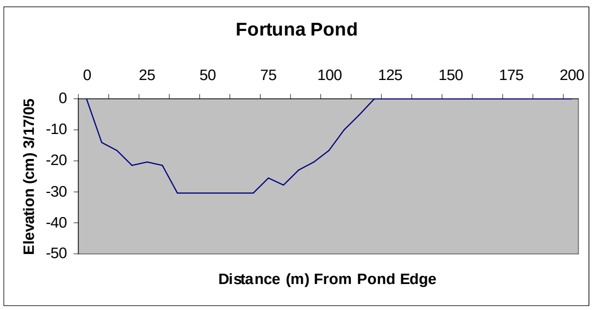
APPENDIX H. POND PROFILES

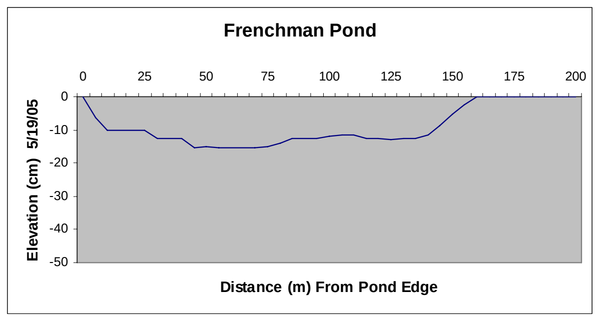
Pond profiles. Elevation was taken with reference to the water line at the pond edge. Dashed lines indicate estimated depth based on visual observation when soft sediment restricted access across the pond. Fish Pond (St. John) was dry during the survey period and no profile was obtained. Southside (St. John) was too soft and no profile was obtained.

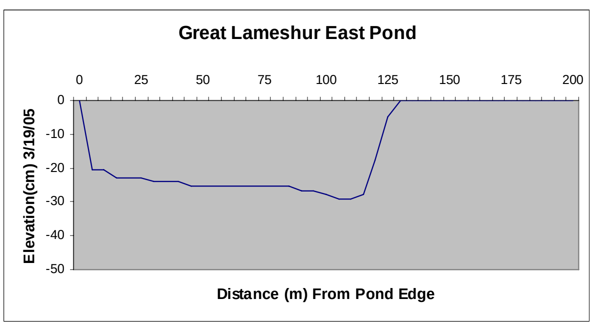
Category: Small, shallow

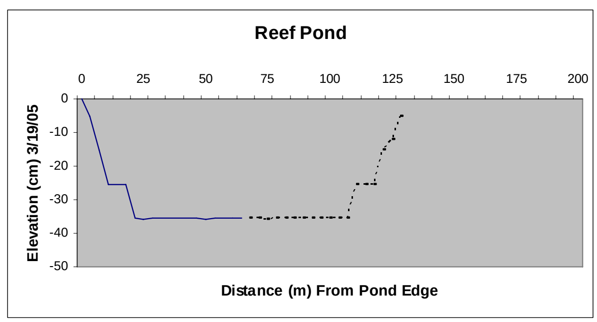












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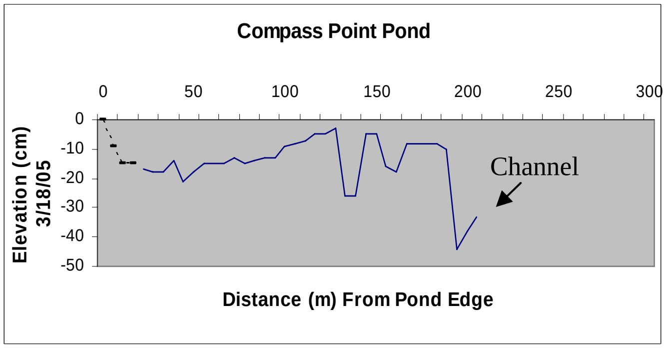
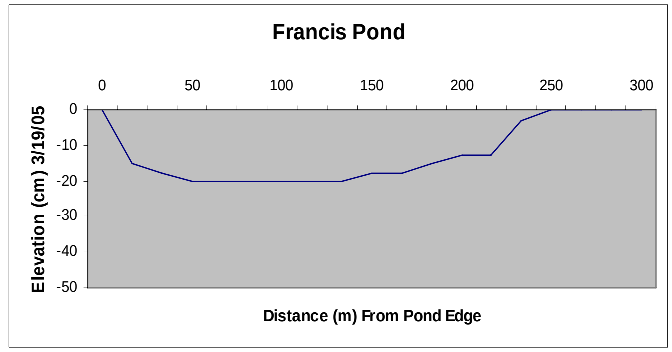
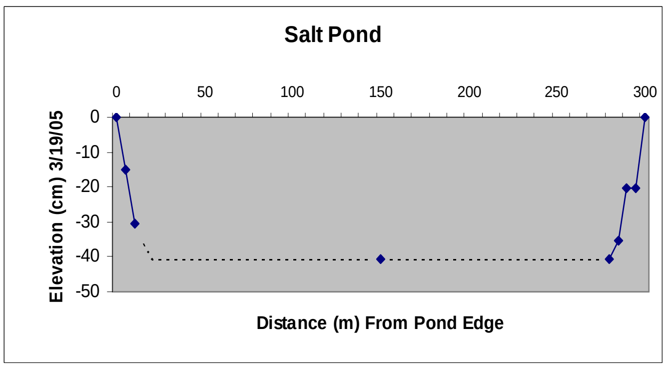
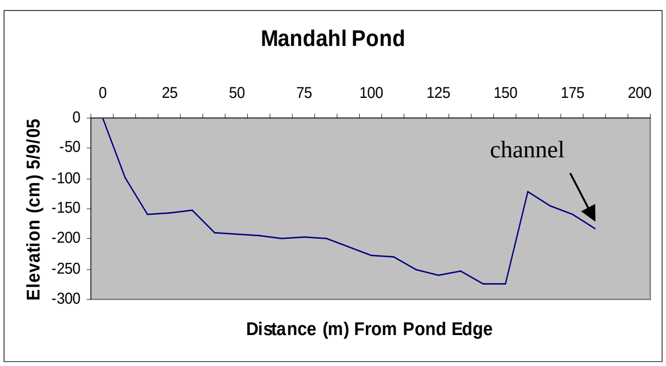
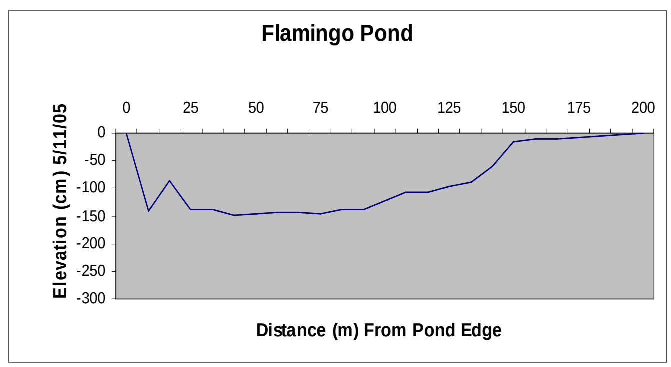


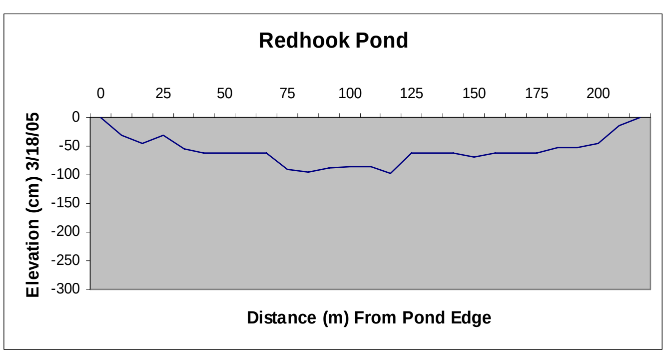




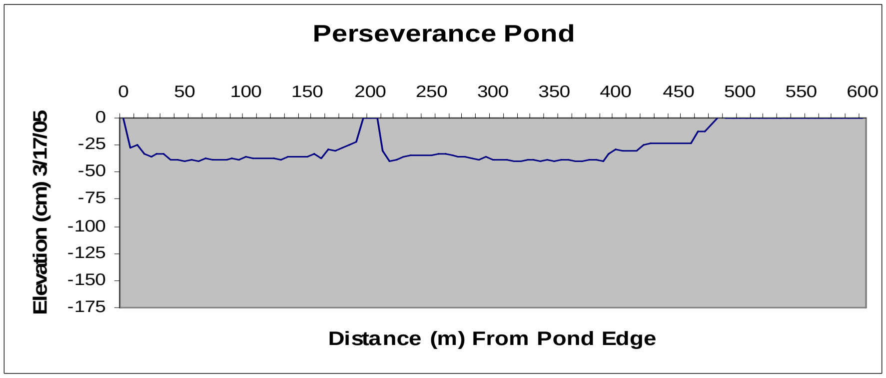
Category: Medium size, deep

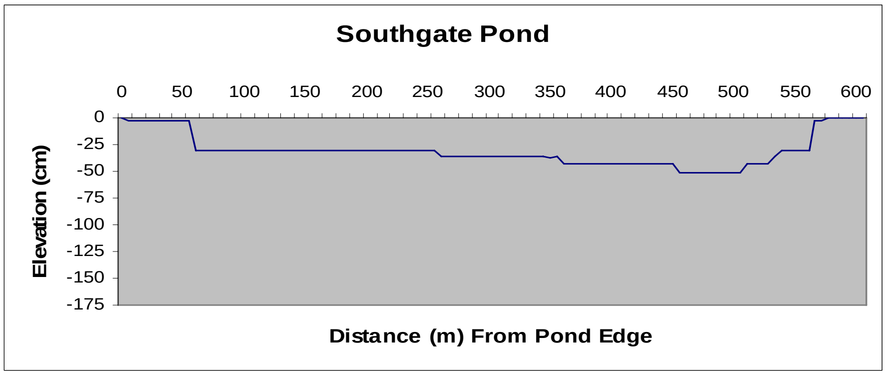






Category: Large, shallow





Category: Large, deep