Impervious Surface Analysis of Terrestrial Watersheds of the US Virgin Islands

Dr. Colin Finney
Dr. Denise Rennis
Dr. Henry Smith

November 2008

Water Resources Research Institute
University of the Virgin Islands
St. Thomas, USVI 00802

DISCLAIMER

The research on which this report is based was financed in part by the U. S. Department of the Interior, United States Geological Survey, through the Virgin Islands Water Resources Research Institute. The contents of this publication do not necessarily reflect the views and policies of the U. S. Department of the Interior, nor does mention of trade names or commercial products constitute their endorsement by the United States Government.

ACKNOWLEDGMENTS

We would like to thank Dr. Phil Dustan and Dr. Norman Levine from the College of Charleston (South Carolina) for their help with ERDAS IMAGINE and data analysis and Dr. Gary Ray of Virgin Forest Restorations (St. John, VI) for the field data validation. We thank both Drs. Dustan and Ray for their comments and inputs on the drafts and final document.

ABSTRACT

This study developed a remote sensing/GIS-based methodology, using IKONOS satellite imagery and spectral signatures, to accurately map, classify, and quantify impervious surface cover to a much finer level than currently exists from using aerial photographs or ground mapping. ERDAS IMAGINE 8.7 was used for image processing and analysis. The Coral Bay watershed on St. John, where nonpoint source pollution from incompatible upland development has been identified as a major problem, was used as a case study. The methodology for land-use determination and image processing and analysis is detailed. The change occurring in the watershed over the past 11 years is assessed. Applying infiltration coefficients and thresholds, we found that impervious surfaces within the Coral Bay watershed, as a whole, cover an area of less than 10%. The extent of impervious surface cover in specific areas of the watershed, however, warrants concern, and growth in these areas should be monitored more closely as early detection of environmental problems helps to limit or prevent environmental degradation and helps to protect biological diversity. Impervious surface class analysis using the described method allows land managers to easily monitor and quantify growth across a watershed or at a subwatershed level on a frequent basis if necessary. The developed methodology can be applied to other watersheds, such as the St Croix East End Marine Park, where management of the terrestrial watershed is of particular concern because of the watershed's effects on the biodiversity of the designated natural area.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDICES

ABBREVIATIONS AND ACRONYMS

C-CAP	Coastal Change Analysis Program
EDA	estuarine drainage area
ETM	(Landsat) enhanced thematic mapper
ETM+	(Landsat) enhanced thematic mapper +
GIS	geographical information systems
IR	infrared
IRF	Island Resources Foundation
ISODATA	iterative self-organizing data analysis techniques
NAD	North American Datum
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NRCS	Natural Resources Conservation Service
SXEEMP	St. Croix East End Marine Park
USACE	US Army Corps of Engineers
USGS	US Geological Survey
USVI	US Virgin Islands
UTM	Universal Transverse Mercator
WGS	World Geodetic System
WRI	World Resources Institute

INTRODUCTION

The natural landscape consists of both pervious (i.e., porous) surfaces (areas vegetated with trees, shrubs, and grasses) and impervious surfaces (rock substrates) with a gradient of porosity between the two depending on a number of variables, including soil type, soil compaction, slope, and ground cover. Under normal conditions, pervious surfaces allow precipitation to infiltrate the soil, while sheet flow runoff occurs over impervious surfaces.

One of the principal effects of development and urbanization is the conversion of pervious surfaces into impervious surfaces—anthropogenic surfaces that inhibit the infiltration of water into the soil. In the US Virgin Islands (USVI), housing, roads, and commercial and industrial development are increasingly replacing natural terrestrial environments, such as grasslands and forests. The increase in impervious surfaces that occur from ground clearing, ground compaction, and paving increases runoff during rain events, and this runoff carries pollutants from roads (e.g., hydrocarbons, heavy metals), pollutants from disturbed land (e.g., animal wastes, fertilizers, pesticides), and increased sediment loads from unpaved areas. In addition, during summer months, the temperature of impervious surfaces increases and this heat is transferred to the surrounding air and, during rainfall events, to the surface runoff (Barnes et al., 2000–2001). This nonpoint source pollution is a major cause of water quality degradation (EPA, 1994).

Increased impervious surfaces result in a greater amount of runoff during even small rain events because these surfaces are more impermeable and provide less frictional resistance to runoff flow than natural vegetated surfaces. This can cause a greater frequency of flooding because there is a reduced ability for water retention in the watershed. Where impervious surfaces are directly connected to the downstream drainage system (in the USVI this is primarily via guts, which are ephemeral streams), increased pollutant loadings in the watershed often result in degradation of inshore marine communities, particularly coral reefs and seagrass beds, which require clear water and high light levels to persist. Rogers (1990) has suggested that the primary cause of coral reef degradation in coastal areas of the USVI is development activities, especially land disturbances and dredging. On St. John, unpaved roads have been identified as being a major source of sediment production (MacDonald *et al*., 1997) with graded roads contributing more sediment than ungraded roads (Ramos-Scharrón and MacDonald, 2005).

Most impervious surfaces are not 100% impervious. Surface materials and cracks and gaps allow some amount of water infiltration. For example, Dougherty et al. (2004) estimated that the imperviousness of construction sites may be more in the order of 50–70% even though these sites are often reported as being 100% impervious. Some impervious surfaces contribute little to surface runoff; in residential areas outside the USVI, house rooftops, which are impervious, direct runoff to lawns, which are pervious, and in the USVI, rainwater from impervious roofs are diverted into private cisterns that collect the water and limit runoff.

Research over the past two decades has indicated that increased quantities of impervious surfaces are closely associated with environmental degradation (Schueler, 1994; Arnold and Gibbons, 1996), specifically that the quantity of impervious surfaces in a watershed is inversely correlated with the health of that watershed and the health of waterbodies, such as coastal environments, that receive discharges from that watershed (Center for Watershed Protection, 2003). Stream degradation is reported to occur at even small (10-20%) increases in imperviousness (Schueler, 1994).

Land-use regulations have placed some controls over development activities and these help to limit the impacts from impervious surfaces; however, the effectiveness of these controls can only be evaluated by long-term monitoring of the environmental impacts, both site-specific and cumulative, of land-use decisions, and this rarely occurs. Field monitoring sites are often difficult to reach, the weather may be too inclement, and field sampling is expensive both in terms of budget and staff resources. Using imperviousness as an environmental indicator for watershed health has been gaining popularity over the last decade. Imperviousness is measurable and the data can easily be presented in geographical information systems (GIS).

The goal of the proposed study is to develop a remote sensing/GIS-based methodology that classifies impervious cover to a much finer level than currently exists so that it can be monitored as an index of watershed health. The Coral Bay watershed on St. John, where nonpoint source pollution from incompatible upland development has been identified as a major threat, will be used as a case study. The developed methodology could then be applied to other watersheds, such as the St Croix East End Marine Park, where management of the terrestrial watershed is of particular concern because of the watershed's effects on the biodiversity of the designated natural area. The major thrust of this study is focused on the GIS-based methodology for discriminating, mapping, and quantifying terrestrial impervious surfaces at a watershed and subwatershed scale, using remote sensing imagery.

Remote Sensing

Remote sensing imagery from aerial photography has been used extensively in the past to examine trends occurring in the USVI coastal zone (for example IRF, 1977). The advantages of aerial photography include i) high spatial resolution images that typically are able to detect features on the order of 1 m, ii) often easier to interpret than digital satellite imagery, and iii) some systems produce multispectral imaging. The disadvantages of aerial photography include:

1) 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 georeferencing;

2) 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 (IR) wavelengths (400-900nm);

3) Expensive for widespread coverage. To achieve synoptic coverage multiple images must be mosaiced together;

4) Not routinely produced because of the cost and extensive preparations necessary 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), and 2004 (color). Five-year intervals between imagery collections reduce the usefulness of this type of imagery to analysis of long-term trends.

Remote sensing satellite imagery, particularly that produced by the Landsat thematic mapper, has often been suggested as providing low-cost synoptic data necessary for coastal managers to monitor and conserve coastal habitats (Costick, 1996; Stumpf *et al*., 1997; Wertz, 1999), and this technique has been used to monitor and map vegetation and/or land-use changes in the Caribbean (e.g., Green et al., 1998; Ramos and Olga, 2001), to assess sedimentation in nearshore waters of the USVI (e.g., Rennis *et al*., 2006), and to assess changes in coral reef communities (e.g., Dustan *et al.*, 2001; Palandro *et al.*, 2003). 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 been much slower in making the transition to being an effective management tool used by land managers.

To some extent this is because of the computer hardware requirements necessary to manipulate files that often reach 360 megabytes in size and software that is expensive and difficult to use. However, in recent years personal computers have become powerful enough to handle the file sizes, although software remains an issue.

Satellite remote sensing offers the following potential advantages:

1) Repeat imaging is offered on a relatively short time period. Current Landsat satellite imagery has a repeat time of 16 days and IKONOS imagery has a repeat time of 3 days at 40^{o}N. This repeat cycle potentially produces 22 and 121 images, respectively, each year.

2) Large areal coverage. Landsat satellite imagery has a footprint of approximately 185 km by 170 km and IKONOS imagery has an image swath of 11.3–13.8 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) are included in Worldwide Reference System Path 004, Row 047. St. Croix is included in Path 004, Row 048.

3) Much of the satellite imagery is multispectral. Table 1 shows the bands available from the current Landsat sensor enhanced thematic mapper plus (ETM+) and the IKONOS satellite:

Table 1. Comparison of the Landsat thematic mapper plus and IKONOS band layers.

Enhanced Thematic Mapper Plus (ETM+)		IKONOS	
Band	Wavelength	Band	Wavelength
1	0.45-0.52 µm (blue)	1	0.445-0.516 µm (blue)
2	0.52-0.60 µm (green)	2	0.506-0.595 µm (green)
3	0.63-0.69 µm (red)	3	0.632-0.698 µm (red)
4	0.76-0.90 µm (near IR)	4	0.757-0.853 µm (near IR)
5	1.55-1.75 µm (mid IR)	5	Panchromatic 0.526-0.929 µm
6	10.4-12.5 µm (thermal IR)		
7	2.08-2.35 µm (mid IR)		
8	Panchromatic		

4) Multispectral imaging increases the potential for the use of digital image processing to extract additional information from each image.

5) Satellite imagery, particularly Landsat imagery, has a well-established infrastructure for the dissemination over the Internet. The availability of 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.

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

There are a number of disadvantages in the use of satellite imagery:

1) The spatial resolution of satellite imagery is often relatively coarse (Landsat 7 ETM+: 30 x 30 m multispectral data, 15 x 15 m panchromatic data; the National Oceanic and Atmospheric Administration’s (NOAA) Advanced Very High Resolution Radiometer: 1.1 km pixel size, 2399-km swath width). More recently launched satellites (IKONOS, Quickbird) offer resolution down to 1 m 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). Additionally, Landsat 7 ETM+ does not acquire data continually. In any given 24-h 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 one or two dates per year.

Coral Bay Watershed, St. John, USVI

Coral Bay is a large, picturesque bay on the eastern side of St. John, USVI (18.35^{o}N, 64.71^{o}W) (Figure 1). Its watershed encompasses an area of 18,851 ha and ranges in elevation from sea level to approximately 375 m. The Coral Bay watershed has one of the highest growth rates in the Virgin Islands, and, as a consequence, nonpoint source pollution and the pressure for new coastal development have been increasing.

Figure 1. The study site of the Coral Bay watershed on St. John, USVI. (Image from NOAA/NOS, 2001)

METHODOLOGY

Defining the Watershed

Limits of the Coral Bay watershed were defined according to NOAA's Coastal Change Analysis Program (C-CAP) definition for the estuarine drainage area (EDA): "An Estuarine Drainage Area is that component of an estuary's entire watershed that empties directly into the estuary and is affected by tides. EDAs may be composed of a portion of a single hydrologic unit, an entire hydrologic unit, more than one hydrologic unit, or several complete hydrologic units and portions or several adjacent hydrologic units" (http://www.csc.noaa.gov/crs/lca/gloss.html).

Digital data for the Coral Bay watershed boundary and shoreline were obtained as published spatial base data sets for the USVI (WRI and NOAA, 2005).[1]

Identification of the Land-cover Classes

Land-use categories in the USVI and specifically the Coral Bay watershed were evaluated from high resolution aerial photographs (NRCS/USACE, 2004) and IKONOS satellite imagery from late 2005 and linked to currently used land-use categories that are consistent with C-CAP.

Identification of Remote Sensing Data Components

Two specific satellite imagery data sets were evaluated in developing the impervious surface methodology for this study: aerial photography taken in September 2004 and IKONOS satellite imagery from late 2005 and early 2006. The aerial photography image set is courtesy of the Natural Resources Conservation Service (NRCS) and the US Army Corps of Engineers (USACE). The IKONOS satellite imagery is courtesy of NOAA.

Image Analysis and Processing

All image analysis was performed with ERDAS, Inc. (Norcross, GA) IMAGINE® 8.7 Professional software. IMAGINE is geographic imaging software that incorporates a number of functions, such as GIS analysis, image processing, map projections, and statistics.

Impervious Surface Class Validation

Impervious surface classes identified from image processing were validated by a combination of field data ground-truthing and examination of remote sensing images in order to refine the data set and to assess the accuracy and precision of the spectral

---

[1] Base files originate from geospatial data sets produced by the Islands Resources Foundation, University of the Virgin Islands –Conservation Data Center, and the US Geological Survey (USGS) in 2001. The base files stem from a larger work "Hydrologic Unit Boundaries for the US Virgin Islands" published by the USGS and Natural Resources Conservation Service in 1999.

resolution. Validation was carried out by Dr. Gary Ray of Virgin Forest Restorations (St. John, VI) in September 2008. Field data ground-truthing consisted of field surveys of five preselected subsets, representing different areas of the watershed, from the false-color image.

Change in Impervious Surface Cover since 1994

A GIS-based digital orthophotography set produced by the USACE from panchromatic aerial photographs flown in February 1994 (USACE, 1994; resolution 1 foot) was used for assessing the change in impervious surface cover since 1994. The 1994 images (initially in the State Plane Coordinate System, North American Datum [NAD] 1983) were converted to a geotiff format registered to the IKONOS image and then geolinked in ERDAS IMAGINE 8.7 to the five preselected subsets of the watershed to identify identical boundary lines for the 1994 calculations. All houses, roads, and driveways were identified, reproduced as graphics, and surface area calculated in ESRI (Redlands, CA) ArcView GIS 3.3. An infiltration coefficient from the literature that best corresponded to the surface type was applied.

RESULTS AND DISCUSSION

Selection of the Remote Sensing Component

There are a number of considerations to evaluate when selecting a remote sensing system for monitoring impervious surfaces or for other land-use changes (from NOAA, 1995):

1) Temporal resolution. Remote sensing data should be acquired at approximately the same time during the day and, if only acquired annually or longer, at approximately the same time of the year. These acquisition times help to eliminate differences in reflectivity caused by the angle of the sun.

2) Spatial resolution. The remote sensing system should acquire data with the same field of view (i.e., ground footprint) so that subsequent images can be registered to each other.

3) Spectral resolution. The electromagnetic spectrum wavelength ranges used should be sufficient to resolve features.

4) Radiometric resolution. The remote sensing system should sufficiently distinguish different levels of intensity (i.e., reflectivity).

5) Atmospheric considerations. As mentioned previously, cloud cover, haze, or humidity can affect the spectral signatures acquired by satellites.

The aerial photography imagery from September 2004 (Fig. 2) was our initial target imagery as it was both high quality and high resolution. In aerial photography the color is a film-recorded product as opposed to a radiometric measurement as in a satellite multispectral scan. This can introduce errors into multispectral classification schemes because the color values are not radiometrically calibrated. Because it is generally limited to three color bands or may only have one band, i.e., panchromatic (black and white), aerial photography imagery is very restricted in the digital image processing that can be used. For instance, unless the color bands include a near IR band, the generation of standardized vegetation indices, such as discussed below, is not possible. The color bands available from the NRCS/USACE 2004 aerial photography were the traditional red, green, and blue bands.

Figure 2. Aerial imagery of the Coral Bay watershed, September 2004 (NRCS/USACE, 2004).

The other major disadvantage of aerial photographic imagery is that it is expensive and produced at infrequent intervals. Aerial photography in the USVI generally is commissioned by federal agencies, such as the USACE, and is dependent on departmental budgets of the USACE as well as collaborating agencies, such as the NRCS. This makes it difficult to predict future availability of imagery sets for comparative purposes.

Eight IKONOS satellite imagery sets from late 2005 and early 2006 became available during the project (courtesy of NOAA). As mentioned previously, satellite imagery has a number of advantages. The IKONOS satellite has a temporal resolution of 3 days, at approximately the same time each revisit, and captures an image swath of 13.8 km at 26^o off nadir (see Appendix I for sensor characteristics) so that equivalent imagery should be available in the future, allowing comparisons to be made between data sets. The future cost of these data sets is unknown, but they will be substantially less than commissioned aerial photography, and it is quite possible, as with the IKONOS imagery available for this study, that they may be available at no cost.

IKONOS satellite imagery produces four bands (red, green, blue, near-IR) with a 4-m spatial resolution (26^o off nadir) as well as a panchromatic band (1-m resolution). As noted above, sufficient bands allow digital imaging techniques to be used. The use of the near-IR band in the IKONOS data allows Normalized Difference Vegetation Index (NDVI) to be readily calculated.

Both the 2004 aerial photographs and IKONOS imagery sets available for this study have significant amounts of cloud cover, a perennial problem in the tropics, obscuring areas of interest. Following an examination of the eight IKONOS sets, we chose the imagery of September 19, 2005 (PO-177850) for this project because it had much less cloud cover over the Coral Bay watershed. After digital image processing, a mosaic of the IKONOS imagery was made to produce a single image of St. John (Fig. 3; for metadata, see Appendix I).

Other remote sensing components used in this study include the 1994 USACE aerial photography described in the methodology section and individual .shp files (WRI and NOAA, 2005) that are used as overlays to the IKONOS image.

Projections

The IKONOS imagery was provided as geometrically corrected in the Universal Transverse Mercator (UTM) coordinate system, zone 20, NAD83, US Survey meters.

The map projection for the watershed and shoreline files (WRI and NOAA, 2005) is UTM Zone 20, World Geodetic System (WGS) 1984, US Survey meters. These files were rectified to the IKONOS image.

The 1994 aerial photography (USACE, 1994) was provided in State Plane Coordinate System 1983, NAD83, Puerto Rico and Virgin Islands, US Survey feet. We mosaiced the following St. John .tif images and converted the mosaiced image to a geotiff file registered to the IKONOS image: Jon2 –Jon5, Jon9 –Jon13, Jon17 –Jon22, Jon26 – Jon30, Jon35 –Jon37.

Figure 3. IKONOS imagery (September 2005) of eastern St. John, USVI. (Image © Space Imaging LLC, all rights reserved).

Establishing the Classification Categories

The main categories of impervious surfaces in the Coral Bay watershed were identified from remote sensing images to be the following:

- roads, which may be separated into primary and secondary, asphalt, concrete, or dirt
- house roofs (which catch water)
- bare rock
- cleared land. In the Coral Bay watershed the thin bare soil is volcanic in origin and has a fast runoff potential due to steep slopes; agriculture is insignificant, and grass lawns are infrequent due to water scarcity.

The identified impervious surface categories were linked to currently used land-use categories that are consistent with NOAA's C-CAP classification (Table 2). C-CAP is NOAA's nationally standardized baseline of land cover that was developed to help monitor land-cover changes in coastal wetlands and adjacent upland habitat (NOAA, 1995; http://www.csc.noaa.gov/crs/lca/ccap.html). The C-CAP program uses satellite imagery for mapping habitat and GIS technology for monitoring changes. Being able to link land-use categories between our data sets and the C-CAP data sets allows comparisons to be made between land-use changes in the USVI and other nationwide sites.

Table 2. NOAA's C-CAP land-use categories and corresponding land use in the USVI and the Coral Bay watershed, St. John.

NOAA C-CAP Classification Number	**NOAA C-CAP Classification Category**	**Land Use USVI**[1]	**Land Use Coral Bay Watershed, St. John**[1]
1.1	Developed Land		
1.11	Developed Land – High intensity	Commercial, paved roads, paved parking	Paved roads
1.12	Developed Land – Low intensity	Residential, paved driveways	Residential (including house roofs which catch water), paved driveways
1.2	Cultivated Land		
1.23	Cropland	Cropland	N.A.[2]
1.3	Grassland		
1.31	Unmanaged Grassland	Low-growing grasses and forbs	Low-growing grasses and forbs with or without rocky outcrops
1.32	Managed Grassland	Parks, golf courses, yards	Yards, playgrounds, pastureland
1.4	Woody Land		
1.412	Deciduous Scrub/Shrub	Edges of disturbed areas	Edges of disturbed areas
1.5	Bare Land	Bare rock, unpaved roads and driveways, cleared land	Bare rock, unpaved roads and driveways, cleared land, gravel roads

[1] Identified from remote sensing images. [2] Not applicable

Image Analysis and Processing

The steps that we completed to process the IKONOS image so that we could classify impervious surface cover are discussed below and summarized in Figure 4. We do not include in this discussion a detailed explanation of digital image processing or terminology for which there are a number of references available (e.g., Sabins, 1987; Jensen, 1996; ERDAS, 1997).

Shoreline masking

Shoreline masking was carried out to remove the high reflectivity generated from the sea, salt ponds, and sandy beaches, which would overlap with the high reflectivity of impervious surfaces. This masking process also removes breaking waves, reefs, and grass beds from the analysis of terrestrial features. Water was masked using the near IR band of IKONOS (Fig. 5). We then converted the .shp file <stsj_shoreline> (WRI and NOAA, 2005) to a raster .img file and combined this with the IKONOS image (Fig. 6). We generated an inland boundary zone from the sea edge, using a 10-pixel-wide mask, which is the equivalent of 20 m of shoreline (five IKONOS pixels), and recoded this to remove the shoreline area (Fig. 7). This removed much of the high reflective sand/coral beach.

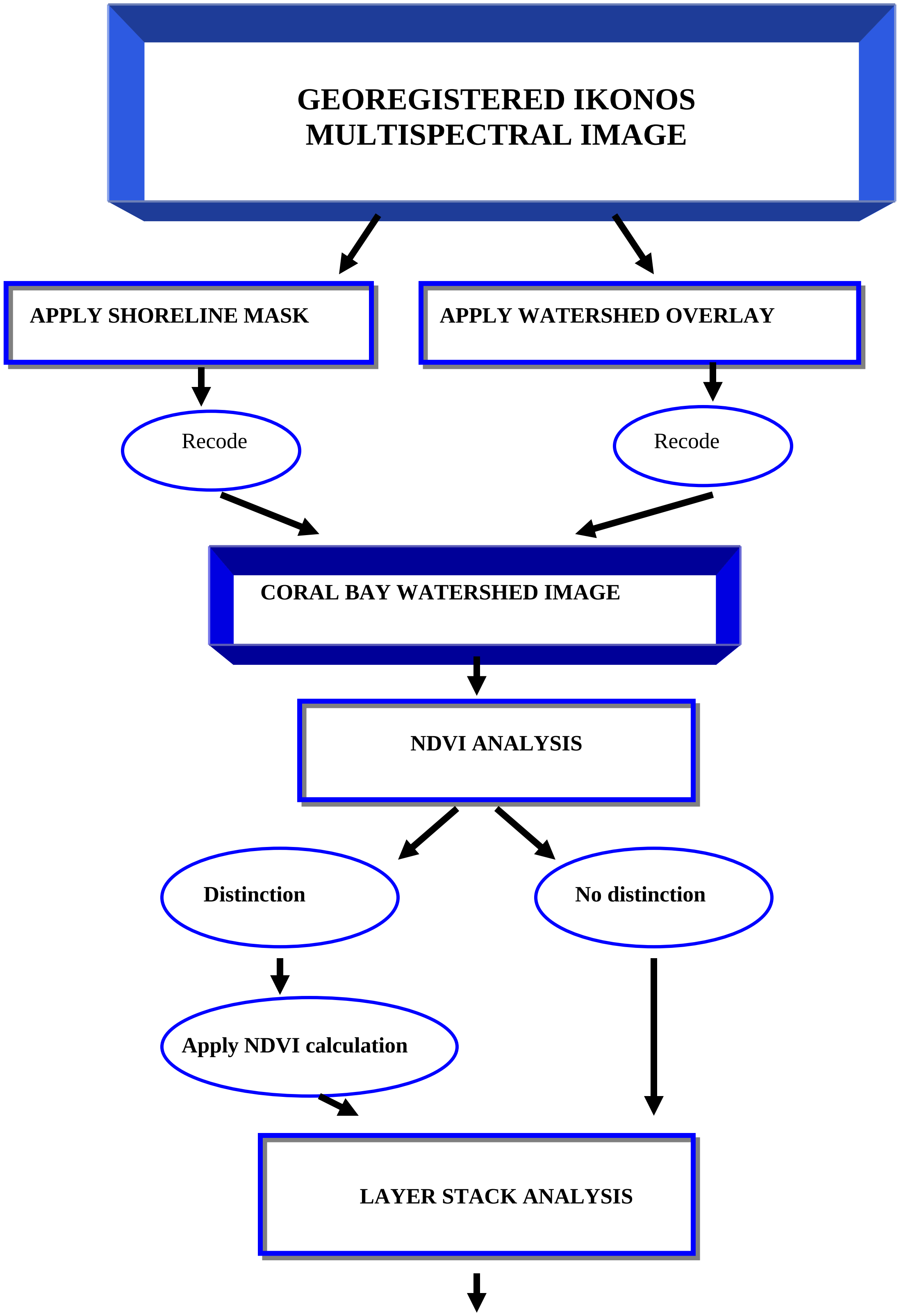
Delimiting the watershed

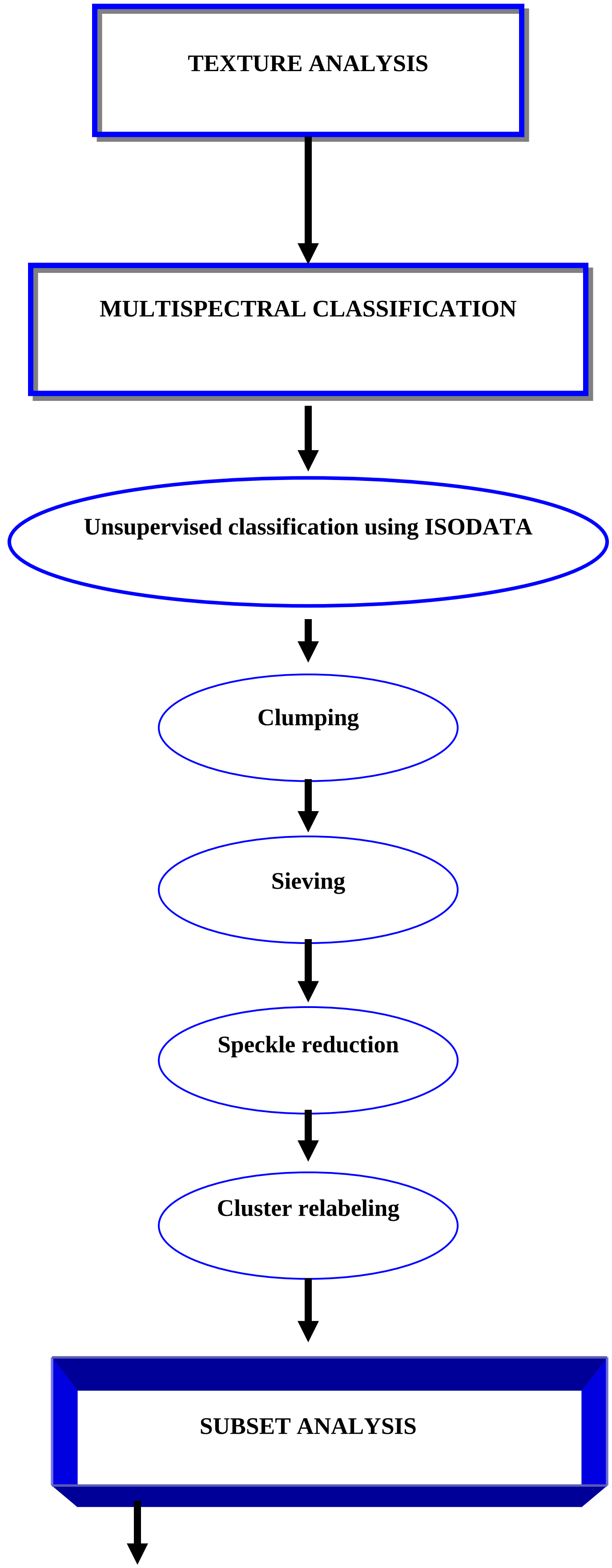
We converted the .shp file <sttj_ws_uwi> (WRI and NOAA, 2005) to a raster .img file to show the boundaries of the St. John watersheds and combined this with the IKONOS image to generate a watershed overlay for Coral Bay (Fig. 8). This image was recoded to remove all features outside the watershed (Fig. 9).

Calculation of NDVI

Initial analysis of the IKONOS image indicated that forested / vegetated areas on St. John are readily discriminated from other areas through the use of the Normalized Difference Vegetation Index (NDVI; Rouse *et al.*, 1973) (NDVI = near IR band - red band) / (near IR band + red band). By distinguishing vegetation from other features, we hypothesized that impervious surfaces would be more distinct. However, upon further examination we found that the NDVI did not provide as sharp a distinction, possibly because the vegetation seems to reflect a high amount of light in the intense tropical sunlight (Fig 10). We therefore did not include an NDVI calculation.

Figure 4. Image analysis and processing protocol for classifying impervious surface cover.




TEXTURE ANALYSIS
MULTISPECTRAL CLASSIFICATION
Unsupervised classification using ISODATA
Clumping
Sieving
Speckle reduction
Cluster relabeling
SUBSET ANALYSIS

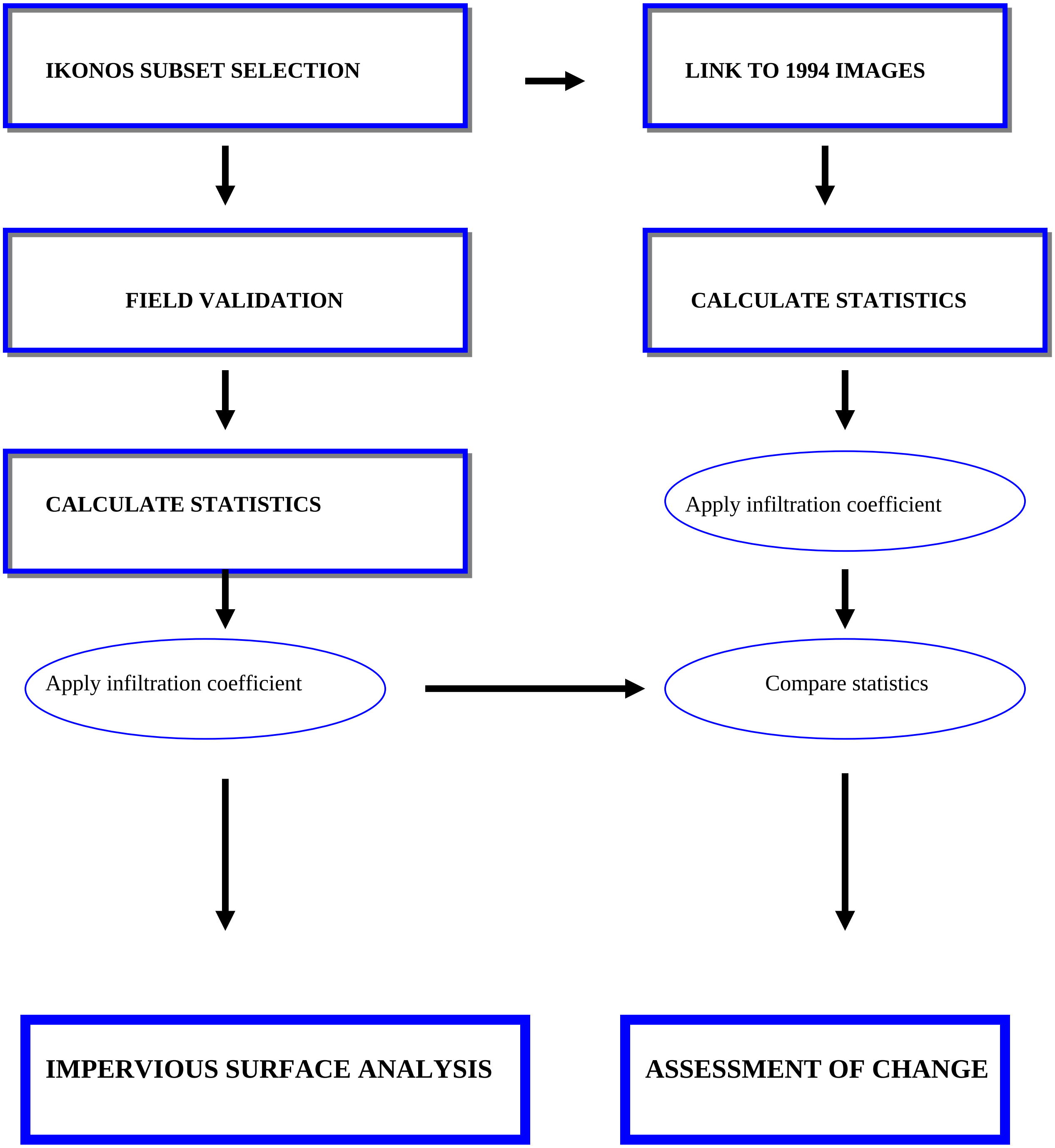

IKONOS SUBSET SELECTION
LINK TO 1994 IMAGES
FIELD VALIDATION
CALCULATE STATISTICS
CALCULATE STATISTICS
Apply infiltration coefficient
Apply infiltration coefficient
Compare statistics
IMPERVIOUS SURFACE ANALYSIS
ASSESSMENT OF CHANGE

Figure 5. IKONOS image with water masked using the near IR band (includes material © Space Imaging LLC, all rights reserved).

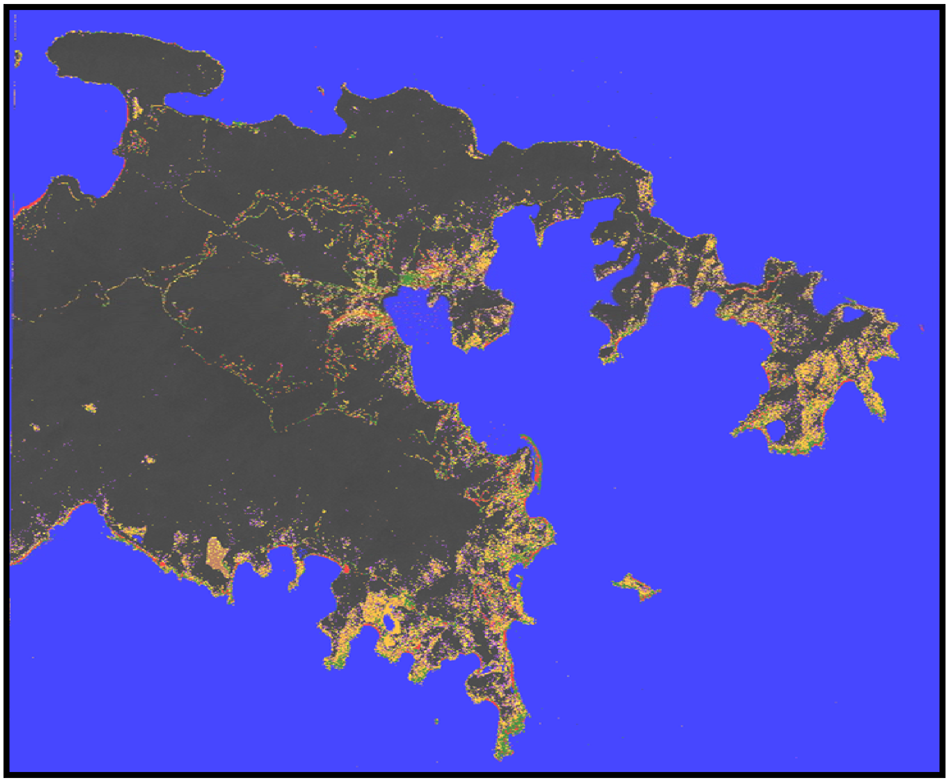


Figure 6. St. John shoreline using a 10-pixel wide boundary overlaying the IKONOS image (includes material © Space Imaging LLC, all rights reserved).

Figure 7. Recoded image to remove 20 m of shoreline (includes material © Space Imaging LLC, all rights reserved).

Figure 8. Watershed boundaries of St. John overlaying the IKONOS image (includes material © Space Imaging LLC, all rights reserved).

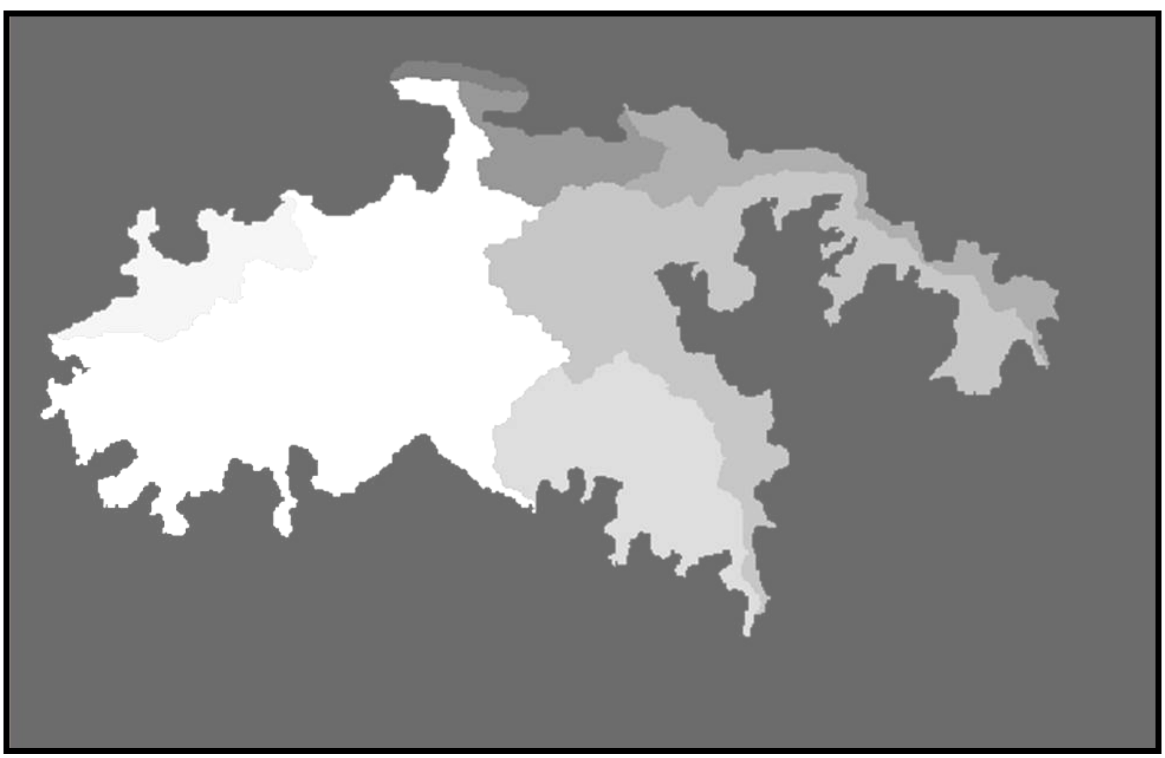
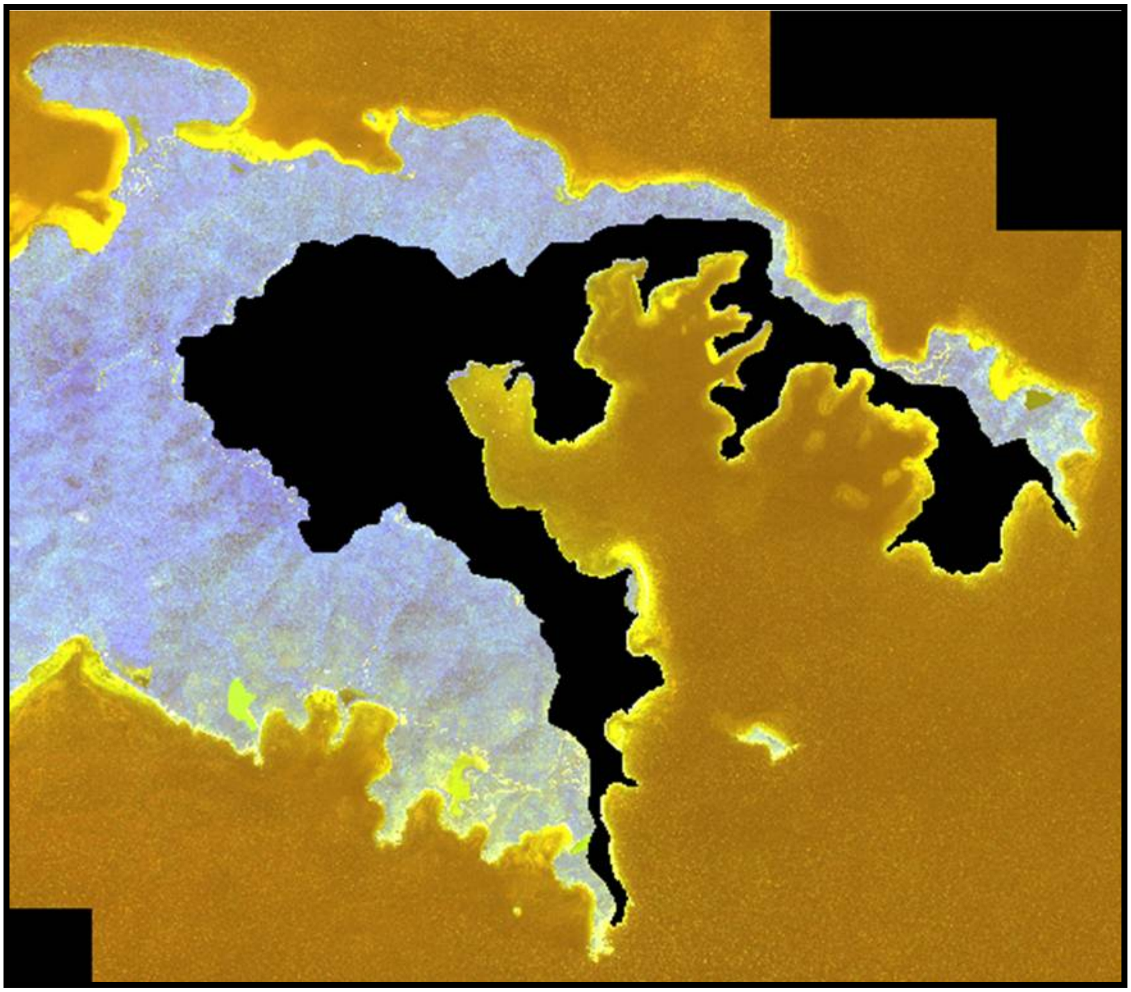


Figure 9. Recoded IKONOS image showing the Coral Bay watershed. Removed shoreline area is also shown (includes material © Space Imaging LLC, all rights reserved).



Layer stack analysis

Changing the band ratios of the layer stack of the IKONOS image effectively distinguished bright impervious surfaces from darker vegetation. We found that the blue band of IKONOS provides the cleanest distinction between vegetation and impervious surfaces (Fig. 11), and the panchromatic band reinforces the blue band but has much more variation due to its panchromatic spectral responsivity. We were, however, not able to identify a band pattern that created a clear distinction between the spectral signatures of the different types of impervious surfaces.

Figure 10. IKONOS image showing high vegetation reflectivity using NDVI mask (includes material © Space Imaging LLC, all rights reserved).

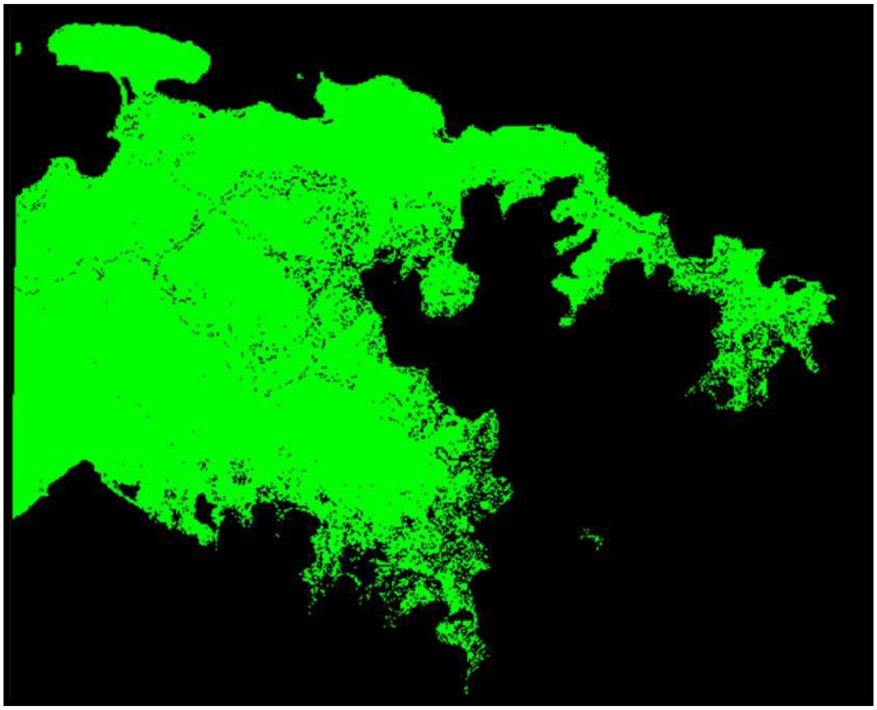
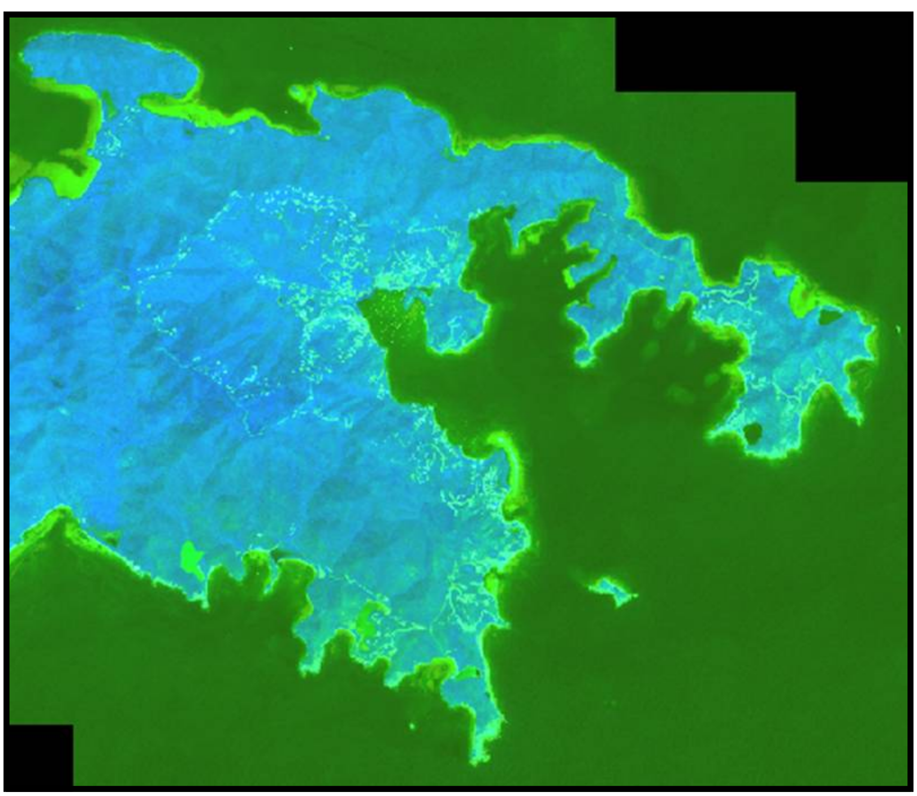


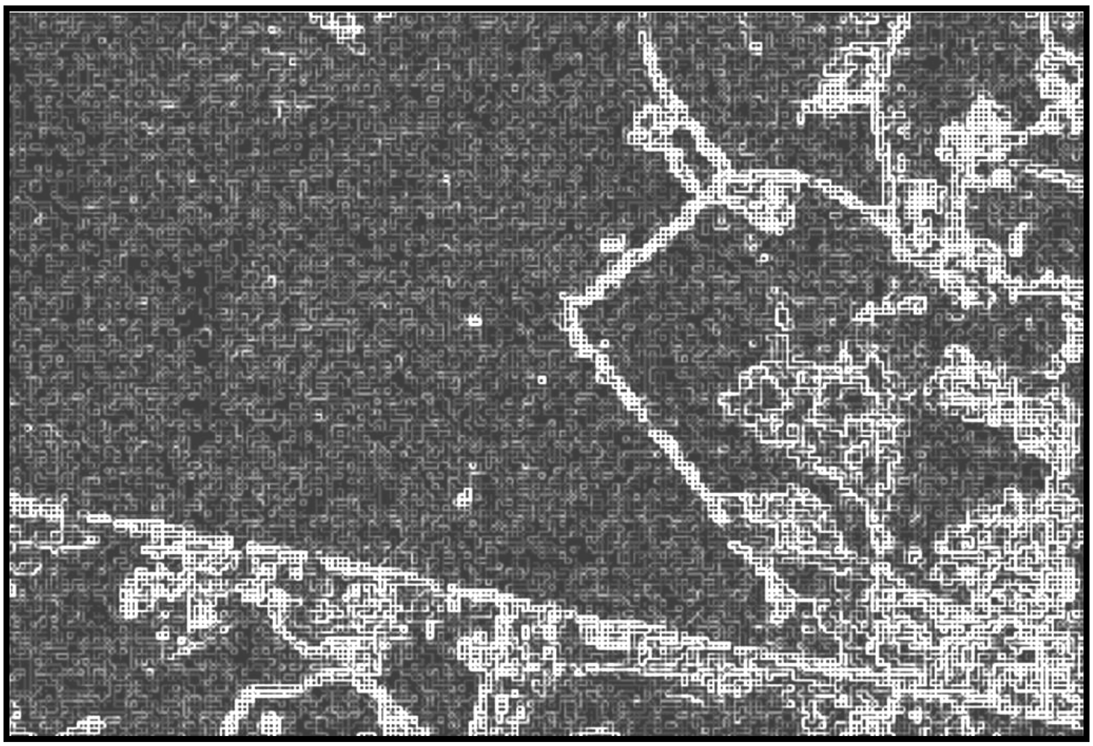
Figure 11. An example of layer stack manipulation of the IKONOS image using the blue band to distinguish vegetation from impervious surfaces (includes material © Space Imaging LLC, all rights reserved).



Texture analysis

We initially used <roads_st_sj.shp> (WRI and NOAA, 2005) to identify the road network in the watershed. However, we found that road locations from this file had little resemblance to the road network seen in more recent aerial photographs. We then used texture spectral analysis in ERDAS IMAGINE to define the edges of linear features. The process yields a complex pattern of double-edged features (Fig. 12) in which the outline of roads was prominent.

Figure 12. Enlarged view of the roads into the town of Coral Bay, using texture analysis of the IKONOS image to identify edges (includes material © Space Imaging LLC, all rights reserved).



Multispectral classification

We performed unsupervised classification of the multispectral image data, using the iterative self-organizing data analysis technique (ISODATA) (Tou and Gonzalez, 1977 in Jensen, 1996), which groups pixels into spectral clusters. We experimented with cluster number for discriminating the spectral values of impervious surfaces and specified criteria for the algorithm that generated 5, 10, and 20 clusters. We compared these cluster combinations and found that extraneous speckling was greatest and resolution of different types of impervious surfaces was least when clusters were limited to five (Fig. 13) and speckling was least and impervious surface resolution greatest at 20 (Fig. 14).

Figure 13. Classification of the Coral Bay watershed with five clusters (includes material © Space Imaging LLC, all rights reserved).

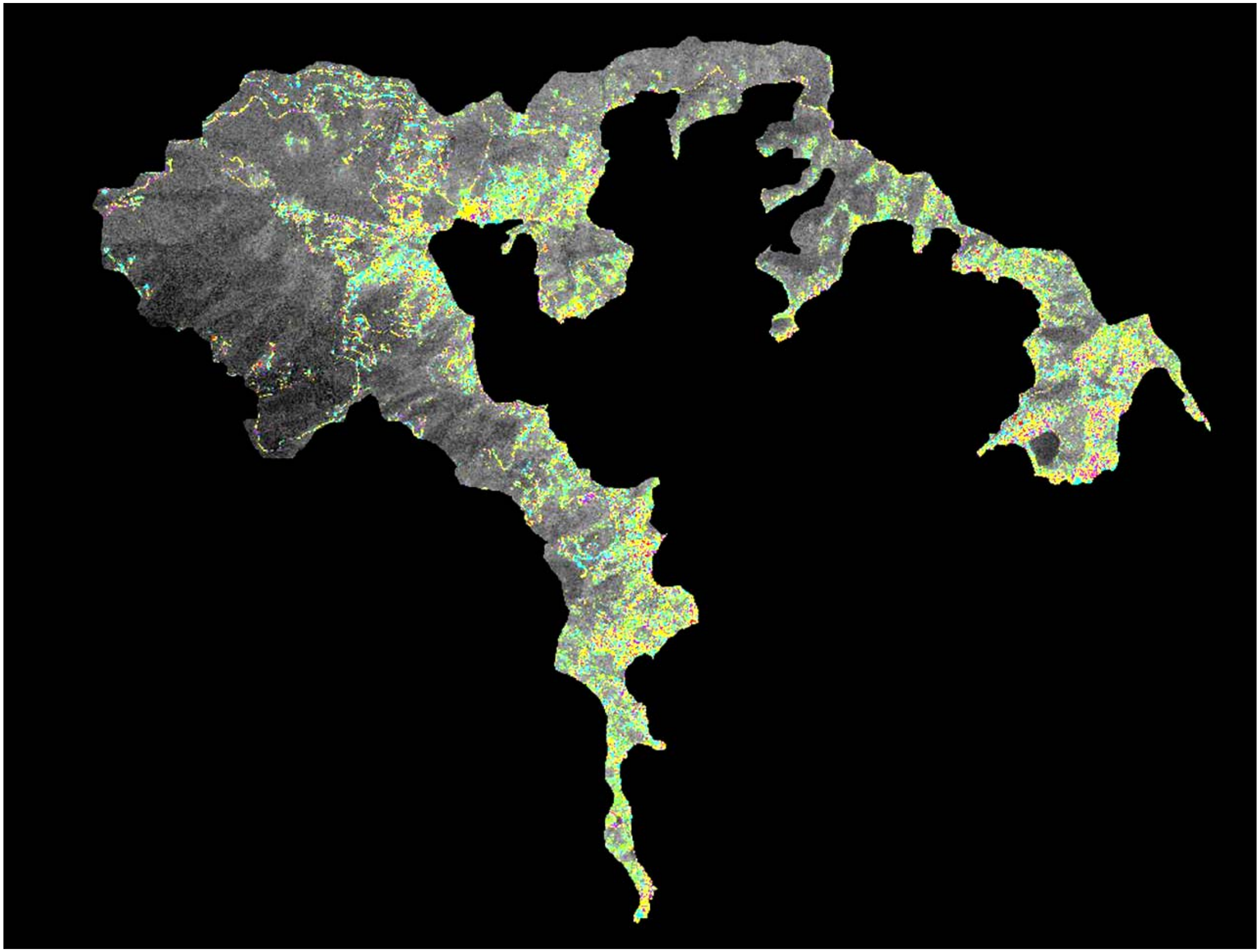


Figure 14. Classification of the Coral Bay watershed with 20 clusters (includes material © Space Imaging LLC, all rights reserved).

Improving impervious surface discrimination

Considerable effort was spent trying to improve discrimination between different types of impervious surfaces so that we could distinguish, for example, concrete from asphalt, paved from unpaved surfaces, paved surfaces from natural rock.

We ran contiguity analysis on clumps to separate similar spectral signatures in raster regions; however, our efforts proved unsuccessful. We also attempted to eliminate single pixel "scatter", which we considered too small to be meaningful, by sieving, using 4- and 8-nearest neighbor analysis. However, we found that the minimum removal size was three pixels.

We attempted to improve discrimination between impervious surfaces by reducing speckle noise caused during remote sensing image acquisition by using the Lee-Sigma filter speckle reduction algorithm in ERDAS IMAGINE. This application proved unsuccessful in improving the distinction between different impervious surfaces.

Cluster relabeling

Using the 20 identified clusters from results of the unsupervised classification, we examined spectral features by merging and relabeling clusters to achieve a combination where linear features were evident. This resulted in five false-color categories of the original 20 clusters (Fig. 15). Some disturbed land was undoubtedly lost by this cluster elimination and some undisturbed land was included, but overall, the process resulted in excellent ground feature spectral coverage with minimal large amorphous clumps. As anthropogenic impervious surfaces generally have hard edges, we considered the removal of impervious surfaces from human sources in this process to be minimal.

Subset selection

Five subsets of the watershed were selected based on location and spectral analysis for validation (ground-truthing) of the features captured in the false-color clusters and for detailed impervious surface calculations. The five locations were from: the coast at the eastern end of the watershed, the coast in the southern part of the watershed, the upland area in the northern part of the watershed, the main part of the town of Coral Bay, and an area to the south of the town (Figs. 16, 17).

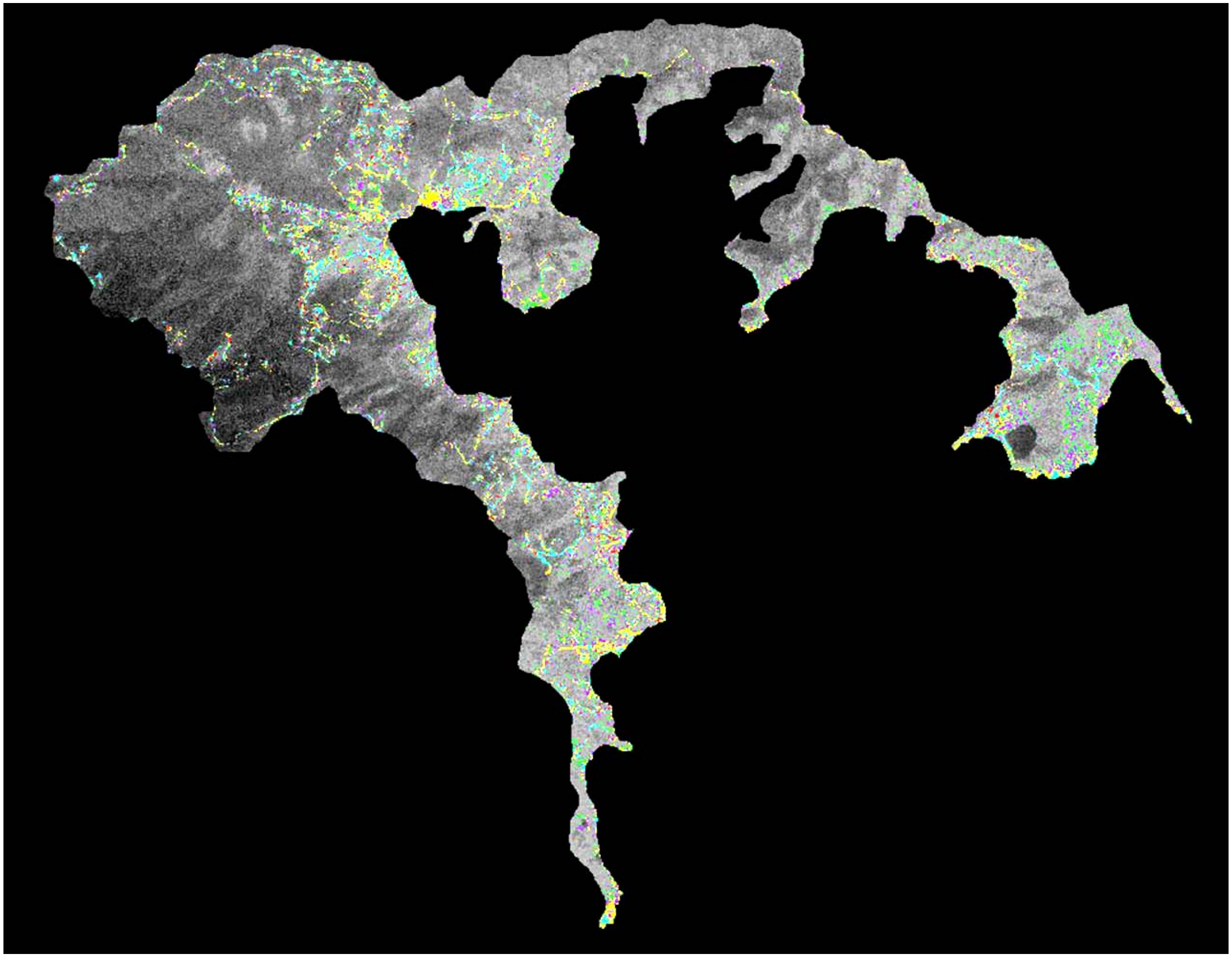


Figure 15. Final classification of the Coral Bay watershed with five of 20 false-color clusters (includes material © Space Imaging LLC, all rights reserved).

Figure 16. Locations of the selected subsets for detailed impervious surface analysis (includes material © Space Imaging LLC, all rights reserved).

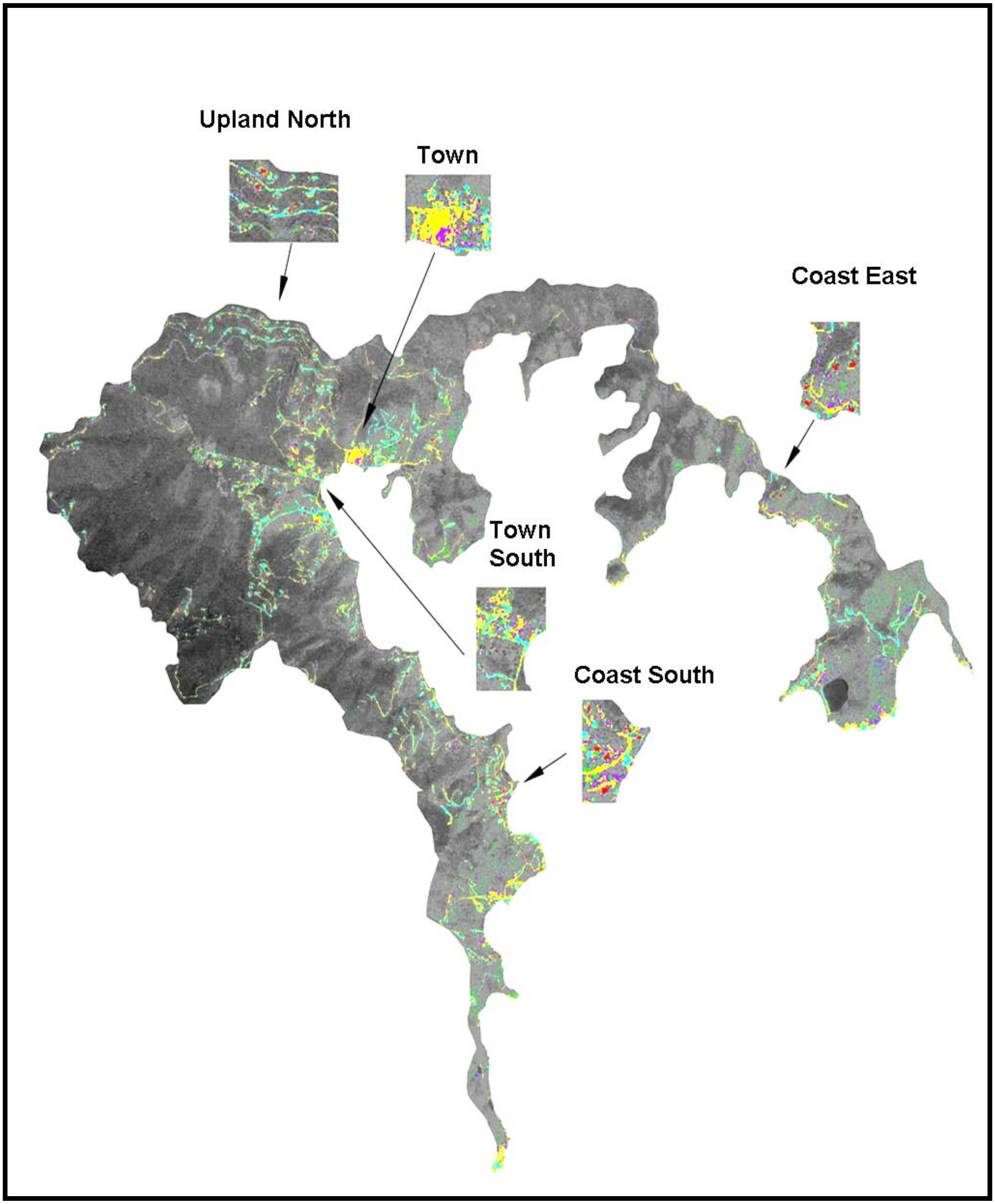
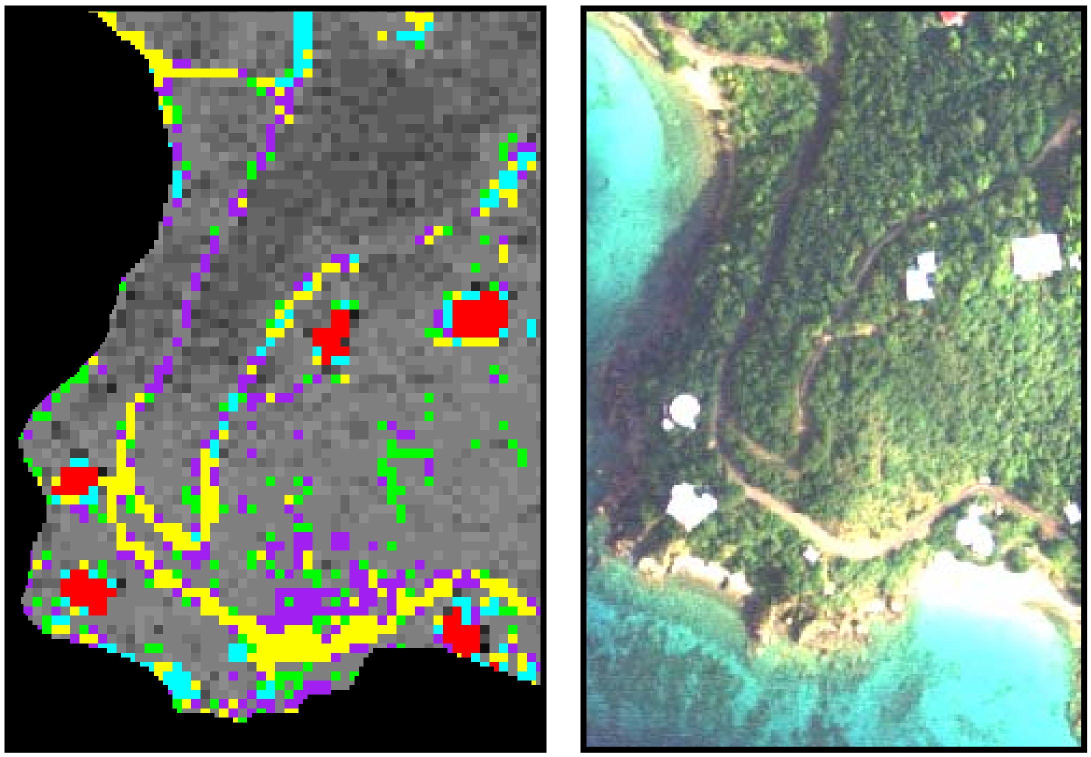
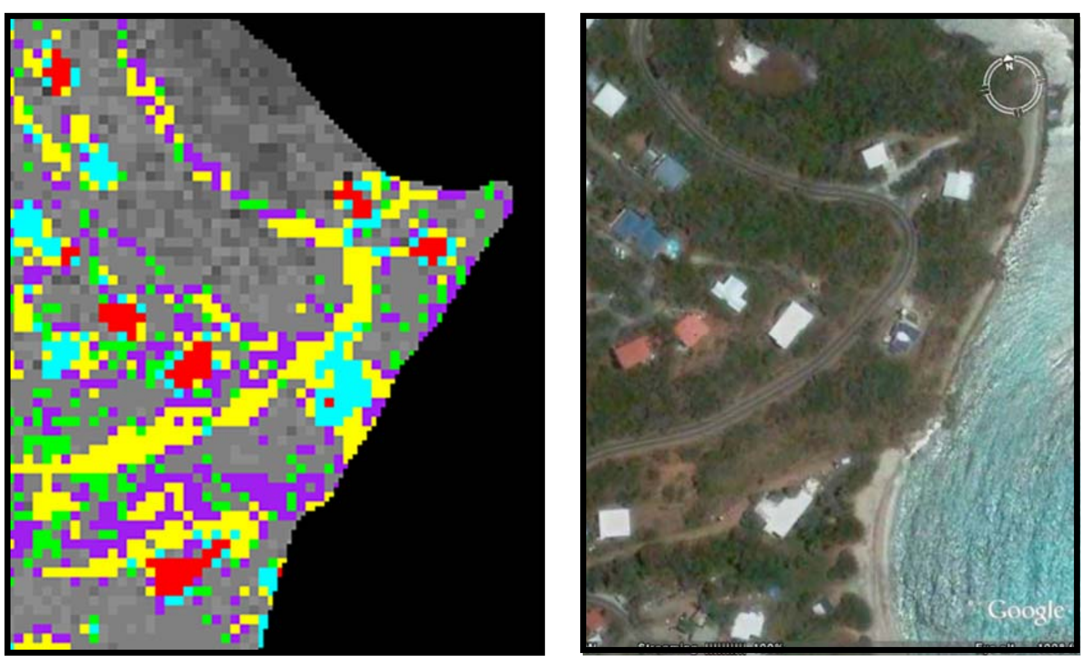


Figure 17. Details of the five selected IKONOS subsets (left) with approximate corresponding ground view (right): A) coast east, ground view from NRCS/USACE, 2004; B) coast south, ground view from Google Earth, 2008 (no 2004 cloud-free image available); C) upland north, ground view from NRCS/USACE, 2004; D) town, ground view from Google Earth, 2008 (no 2004 cloud-free image available);and E) town south, ground view from Google Earth, 2008 (no 2004 cloud-free image available) (includes material © Space Imaging LLC, all rights reserved).

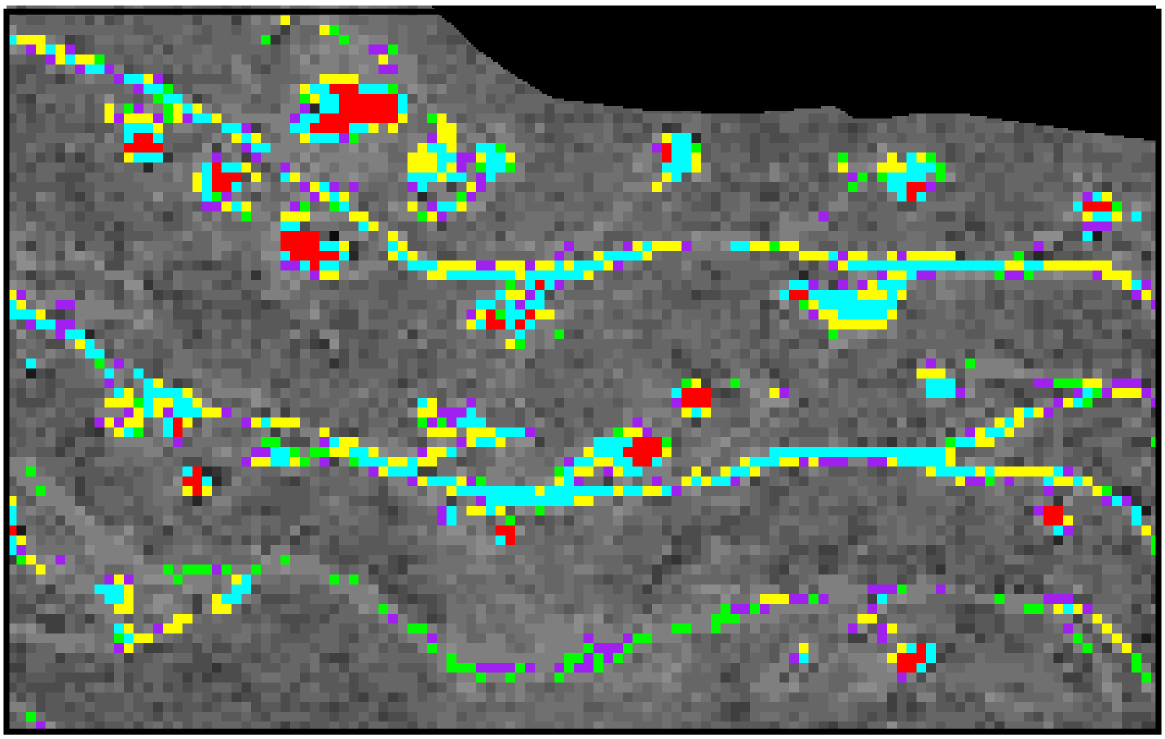
A



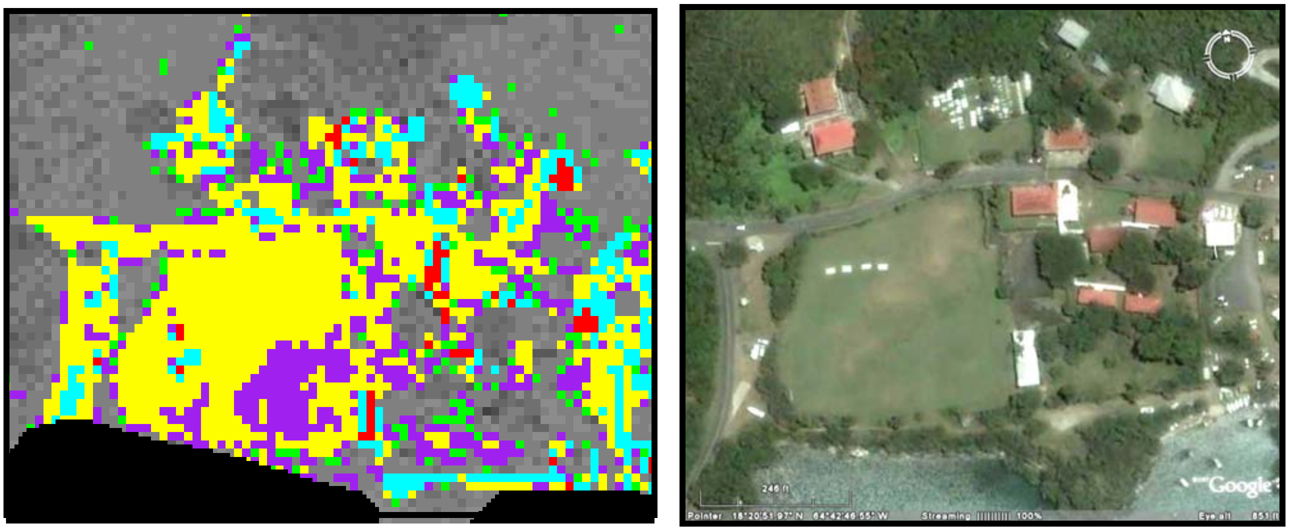
B



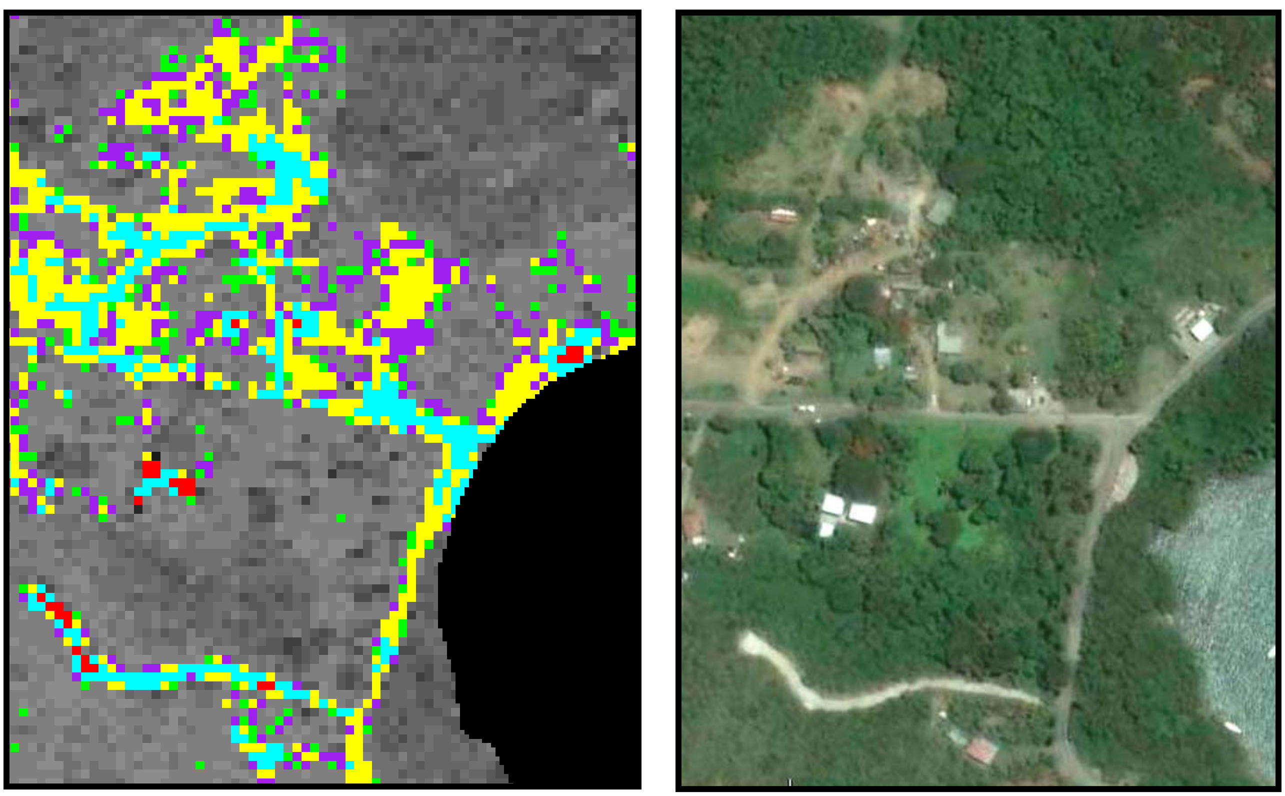
C



D



E



Impervious surface class validation

Field data validation of the IKONOS image classes (Table 3) verified that the spectral signatures were accurate indicators of a type of impervious surface, although there was notable overlap between impervious surface cover type and class. Class 1 primarily represents a white reflective surface, such as house roofs or newly concreted road surfaces. Class 2 represents concrete and asphalt roads, paved driveways and parking lots, and compacted land (both cleared and low grassland). Spectral reflectance in this class was affected by slope (moderate to steep concrete roads appeared in this class as did level to moderately sloped asphalt roads) and probably other factors, such as angle of the sun. Class 3 represents level to sloping concrete roads, asphalt roads, rooftops that have a blue- or red-reflective surface, and compacted cleared ground. Again, slope appeared to play a factor in the spectral signature in this class. Class 4 represents moderate to sloping asphalt roads and compacted ground (both trampled low grassland and cleared land). Class 5 tended to represent a vegetative cover: low shrubby ground, intensely grazed and heavily trampled grassland, and cleared land were included in this category.

Table 3. Impervious surface class validation and associated NOAA C-CAP class.

C-cap Class	**Class 1**	**C-cap Class**	**Class 2**	**C-cap Class**	**Class 3**	**C-cap Class**	**Class 4**	**C-cap Class**	**Class 5**
1.11	level, recently paved concrete road	1.1	level to mod. asphalt road	1.11	level concrete road	1.11	mod to sloping asphalt road	1.32	intensely grazed pastureland
1.12	white rooftops	1.11	steep concrete road	1.11	sloping, recently paved concrete road	1.31	sparsely vegetated, rocky soil	1.412	shrubs/ trees on edge of compacted areas
		1.11	sloping, recently paved concrete road	1.11	asphalt road	1.32	mod compacted grassland, mod density; grazed pasture	1.412	low shrubby ground
		1.12	occasional flat red rooftop	1.12	blue and red rooftops	1.5	cleared, compacted gravel ground/ shoulder	1.5	cleared compacted gravel ground/ shoulder
		1.12	concrete driveways, parking lots	1.12	parking lot, patio	1.5	heavily trampled ground	1.5	heavily trampled ground
		1.2	asphalt parking lot	1.32, 1.5	cleared areas around houses				
		1.31	sparsely vegetated, rocky soil	1.5	level, cleared compacted ground with gravel/rock				
		1.32	compacted pastureland	1.5	level, cleared, compacted unpaved parking areas				
		1.5	level, cleared compacted ground or shoulder with						

C-cap Class	Class 1	C-cap Class	Class 2	C-cap Class	Class 3	C-cap Class	Class 4	C-cap Class	Class 5
			gravel/rock						
		1.5	compacted, unpaved driveway, parking, walkways						

Calculation of percentage of impervious surface area

Impervious surface statistics were calculated using the ERDAS IMAGINE attributes layer, which lists the number of pixels per class. Class 0 (unclassified) pixels were omitted. The percentage of the watershed was calculated for each of the five classes for each subset plus the watershed as a whole (Table 4). For calculating areas, pixels were converted to meters (1 pixel has a resolution of 4 m and an area of 16 m^2).

Table 4. Percentage of impervious surface cover in each of the five classes for the Coral Bay watershed and subsets.

Impervious Surface Class	Watershed	Coast E	Coast S	Upland N	Town	Town S
Total Area (ha)	18,851.50	89.59	65.27	203.12	111.66	138.33
Class 1	0.4	2.46	3.2	1.31	1.27	0.55
Class 2	3.16	7.36	15.41	4.15	26.11	12.55
Class 3	1.88	3.04	5.62	5	6.78	5.85
Class 4	2.71	6.85	13.24	2.55	12.04	6.39
Class 5	1.95	4.16	6.53	1.61	3.84	3.41
Total (%)	10.11	23.88	43.99	14.61	50.04	28.75

Impervious Surface Class Cover in the Coral Bay Watershed

The identification of separate impervious surface classes can demonstrate the type of growth taking place within a defined area. In the case of Coral Bay, imperviousness (i.e., human disturbance) is seen disproportionately throughout the watershed (Table 4). Houses (mostly class 1) are a minor component of total imperviousness, whereas paved roads (both concrete and asphalt) and compacted ground are clearly the major impervious surfaces in the watershed. The data indicate that imperviousness, and thus disturbance, is greatest around the town of Coral Bay and along the rapidly growing south coast subset and least in the northern uplands subset.

Applying an infiltration coefficient

Surfaces determined to be impervious are often located in areas of mixed land use that support combined impervious and pervious cover, and as a consequence percent of imperviousness, also known as the infiltration coefficient, can be overestimated. Imperviousness varies depending on a number of variables, including slope, soil moisture (more impervious when the ground is saturated), soil type, and local or regional land-use practices, such as the inclusion of open space within urban residential and commercial sites and the collection of rainwater in cisterns in the USVI. On St. John, unpaved roads is an important land-use category, and Ramos-Scharron and MacDonald (2005) have reported that erosion (which for this study can be broadly equated with imperviousness) is greatest in graded roads, 42% less in ungraded roads, and 10% of ungraded roads in abandoned roads. Some ranges of imperviousness reported for major land-use categories outside the USVI are shown in Table 5.

Table 5. Imperviousness of selected land-use categories using an infiltration coefficient (from Dougherty et al., 2004; Li et al., 2004; Center for Watershed Protection, 1998).

Category	**Imperviousness**
major paved roads	50-100%
paved parking	100%
unpaved parking	90%
construction sites/disturbed land	50-70%
commercial/industrial land	35-85%
high density residential	35-65%
medium density residential	20-38%
low density residential	5-20%
urban open land	3%
agricultural land/golf course	2-7%
forested land	0-7%
bare ground	14%
surface rock/fractured rock	2-7%
embedded rock	67%

We applied these percentages to the impervious surface types found in the Coral Bay watershed (Table 6), using best professional judgment in determining what value of a range should be selected, and adjusted the percent impervious surface cover for each class (Table 7) for the watershed and subsets (Table 8).

Table 6. Imperviousness of land-use categories found in the Coral Bay watershed, modified by an infiltration coefficient (see Table 5).

Surface	Imperviousness
concrete road	100%
asphalt road	100%
concrete driveways, parking lots, patios	100%
asphalt parking lot	100%
compacted, unpaved driveway, parking, walkways	90%
level, cleared, compacted unpaved parking areas	90%
level, cleared compacted ground or shoulder with gravel/rock (often used for parking)	90%
cleared areas around houses	20%
heavily trampled ground	20%
sparsely vegetated, rocky soil	14%
shrubs/ trees on edge of compacted areas	7%
compacted pastureland, grassland	7%
rooftops (which capture and hold water in cisterns)	5%
low shrubby ground	3%

Table 7. Imperviousness of each class, corrected for infiltration.

Class Number	Imperviousness
Class 1	52.5%
Class 2	70.6%
Class 3	75.6%
Class 4	46.2%
Class 5	25.4%

Table 8. Percentage of impervious surface cover in each of the five classes for the Coral Bay watershed and subsets, incorporating the infiltration coefficient shown in Table 7.

Class	Watershed	Coast E	Coast S	Upland N	Town	Town S
Total Area (ha)	18,851.50	89.59	65.27	203.12	111.66	138.33
Class 1	0.21	1.29	1.68	0.69	0.67	0.29
Class 2	2.23	5.2	10.88	2.93	18.43	8.86
Class 3	1.42	2.3	4.25	3.78	5.13	4.42
Class 4	1.25	3.16	6.12	1.18	5.56	2.95
Class 5	0.5	1.06	1.66	0.41	0.98	0.87
Total (%)	5.61	13.01	24.59	8.99	30.77	17.39

Class analysis and thresholds

Researchers have proposed thresholds for impervious surfaces beyond which significant impacts occur in the receiving waterbodies. A number of studies have recommended a threshold limit of 10% impervious surfaces to avoid water quality degradation (Schueler, 1994; Center for Watershed Protection, 2003), while a 25-30% impervious surface threshold has been suggested to avoid diminished biological diversity (Center for Watershed Protection, 2003). Watersheds having large areas of active cropland, construction sites, and eroding roads and ditches have been considered as high contributors to sediment runoff (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 to the lower watershed (Bradshaw, 1991). A moderate contribution of pollutants could be expected from watersheds with 25-50% of cropland and developed sites (Bradshaw, 1991).

If these thresholds are applied to the Coral Bay watershed, which currently shows less than a 10% impervious surface coverage, then the effects of current growth across the watershed should be low. However, on the local scale, specific areas, particularly the two town locations and the south coast subset, warrant closer examination to determine potential impacts from the higher percentages of impervious cover; this is of particular importance because downslope acceleration of sheet flow caused by the steep slopes in the watershed may amplify the impacts of decreased surface porosity.

Class analysis using the described method allows land managers to monitor and quantify growth in preselected areas of the watershed. By including subsets of a watershed in the impervious surface analysis, the identification of potential problem areas becomes possible, something that might not happen when evaluating a watershed as a whole. Obviously the size of selected subsections will influence the percentage of class imperviousness, however the size of the area of interest is a variable that can be determined in advance by land managers when setting up their monitoring protocol.

Change in Impervious Surface Cover since 1994

For determining the change in impervious surface cover since 1994, black and white aerial photographs (USACE, 1994) were geolinked (see Methodology) to the five selected subsets of the IKONOS image. From the 1994 aerial photographs, impervious surfaces were visually identified as consisting of four types: houses, primary roads, secondary roads and driveways, and indeterminate disturbance (assigned as urban/residential compacted ground). Infiltration coefficients from the literature that best corresponded to these surface types were 5%, 100%, 90% (we assumed that most secondary roads and driveways in 1994 were unpaved), and 20%, respectively. Primary and secondary roads and driveways comprised most of the impervious surface cover, although there was also a large area of disturbed ground in the town (Table 9).

Although two different methods were used for the comparison of impervious surface change between 1994 and 2005 (the date of the IKONOS image), the results (Table 10) are compatible with a visual comparison of aerial photography (1994 and 2004) (Fig. 18). Areas of growth (e.g., increased impervious surface cover) are most pronounced in the south coast subset, with growth also occurring in the two town areas. Changes in impervious surface cover in the subsets to the east of the town and in the uplands of the northern part of the watershed between 1994 and 2005 appear to be minimal.

Table 9. Percentage of impervious surface cover in 1994 for the five subsets in the Coral Bay watershed.

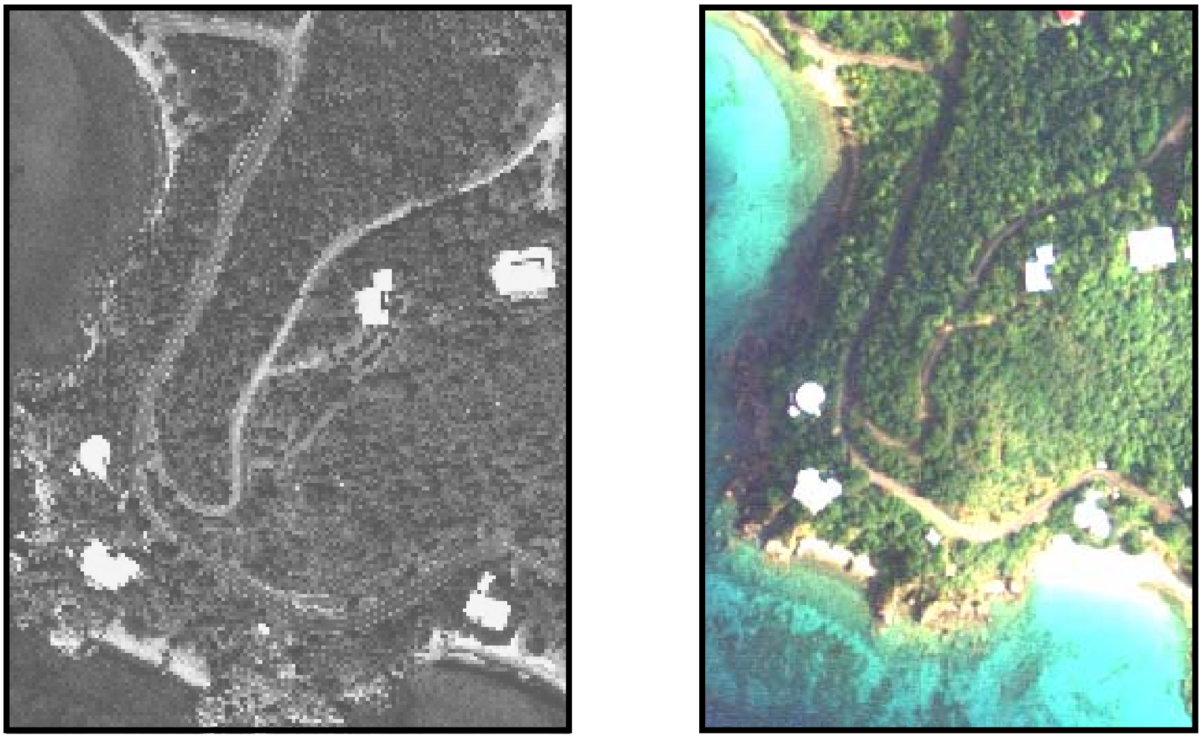
Class	**Coast E**	**Coast S**	**Upland N**	**Town**	**Town S**
houses	0.16	0.25	0.08	0.32	0.06
primary roads	6.45	4.83	6.79	5.38	1.96
secondary roads	3.75	2.09	1.55	3.73	2.18
indeterminate			0.18	6.00	
All surfaces	10.35	7.17	8.61	15.43	4.20

Table 10. Percent change in impervious surface cover over an 11-year period.

Subset	**Percent Impervious Surfaces**		
	1994	**2005**	**% Change**
Coast East	10.35	13.01	2.66
Coast South	7.17	24.59	17.41
Upland North	8.61	8.99	0.38
Town	15.43	30.77	15.33
Town South	4.20	17.39	13.20

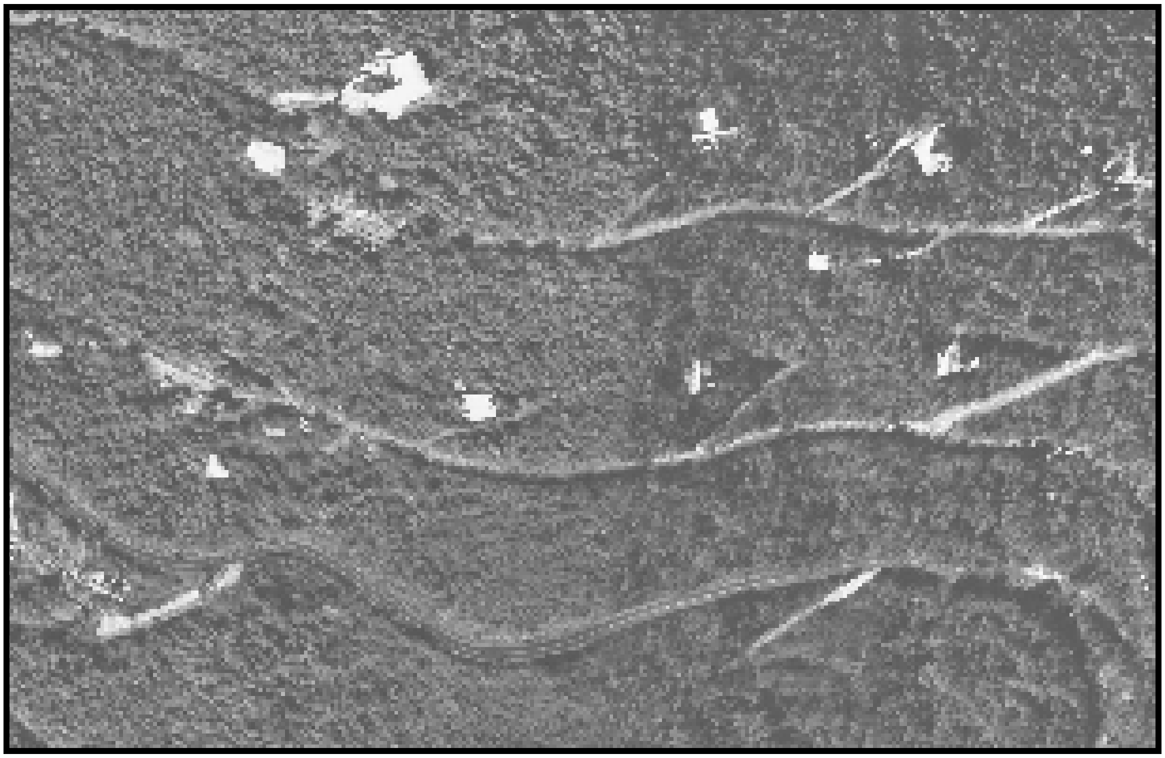
Figure 18. A comparison of the five selected subsets between 1994 (left) and 2004 or 2008 (right) (aerial photography from USACE, 1994; more recent images as in Fig. 17): A) coast east, B) coast south, C) upland north, D) town, and E) town south (includes material © Space Imaging LLC, all rights reserved)

A



B

C



D


246 ft
Google
Pointer 18°20'51.97" N 64°42'46.55" W
Streaming 100%
Eye alt 851 ft

E

CONCLUSIONS AND RECOMMENDATIONS

Regularly classifying and quantifying impervious surfaces, which are linked to nonpoint source pollution and environmental degradation, is important for monitoring the health of watersheds and ensuring that local and/or regional growth has limited negative impacts on the environment. The remote sensing/GIS-based methodology we detail in this paper provides more sensitive, detailed, and quantitative information on the imperviousness of surfaces than can be provided by the visual identification of cover classes from aerial photographs or ground monitoring.

Monitoring Impervious Surfaces

The technique we have described enables land managers and regulators in the USVI to monitor and quantify impervious surface cover on a subwatershed, watershed, or island basis. Multispectral imagery with a large footprint allows large land areas to be covered by one or two scenes; this is not possible with aerial photographs at the resolution provided by some of the satellites. Satellite imagery is becoming more frequently available and more easily obtainable, allowing assessments over a shorter time period than the 5- or 10-year periods that have been typical for monitoring changes in vegetation cover. As growth (i.e. impervious surface cover) tends to come in spurts, the ability to monitor more frequently is a necessity.

The land-cover classes identified in this study are consistent with the land-cover classes of NOAA's C-CAP initiative. Using our methodology land managers in the USVI would be able to compare changes in impervious surface cover with land-cover changes reported by NOAA for other regions over the nation where such information exists. To date, no C-CAP investigation has been undertaken for the USVI.

Our methodology was applied to the Coral Bay watershed where we showed that impervious surface cover across the watershed appears to be below a threshold that warrants concern, but specific areas of the watershed, particularly around the town of Coral Bay and in at least one area of the south coast, are experiencing growth that should be more closely examined. Early detection of environmental problems will help to limit or prevent environmental degradation and help protect biological diversity.

By performing an analysis of change in impervious surface cover over the last 11 years, we were able to demonstrate that at least one different technique for calculating change can be compatible with our described methodology. Ideally similar techniques should be used in comparison studies to limit design differences that might affect results; however, until the use of spectral signatures from satellite imagery is more widely used, existing baseline data are likely to be in a form that is not satellite based.

Discrimination of Impervious Surfaces

Substantial effort was spent evaluating techniques to separate paved roads from unpaved roads, the latter having important implications in soil erosion and sediment runoff; these efforts were unsuccessful. Discrimination among different types of concrete roads (e.g., older versus newer roads, slope differences), other man-made surfaces, and natural rock outcrops based on their spectral signatures has also not been accomplished despite considerable effort. To some extent this was due to topographic slope and angle of the sun during image capture, both of which affect surface reflectivity. Using data from other satellite systems may improve the spectral resolution of surface features. Band ratios can be manipulated to reduce the effects of topography and increase the differences in surface reflectivity (Mather, 1987 in Green *et al*., 1998), and greater resolution should be possible with a system that uses a larger number of bands than the IKONOS system (which uses five). Impervious surfaces in the Coral Bay watershed include both anthropogenic surfaces as well as natural ones, and we consider the ability to quantify the natural imperviousness of land as essential in order to better evaluate the effects of anthropogenic changes. Further work on refining the spectral signatures will be necessary to achieve this.

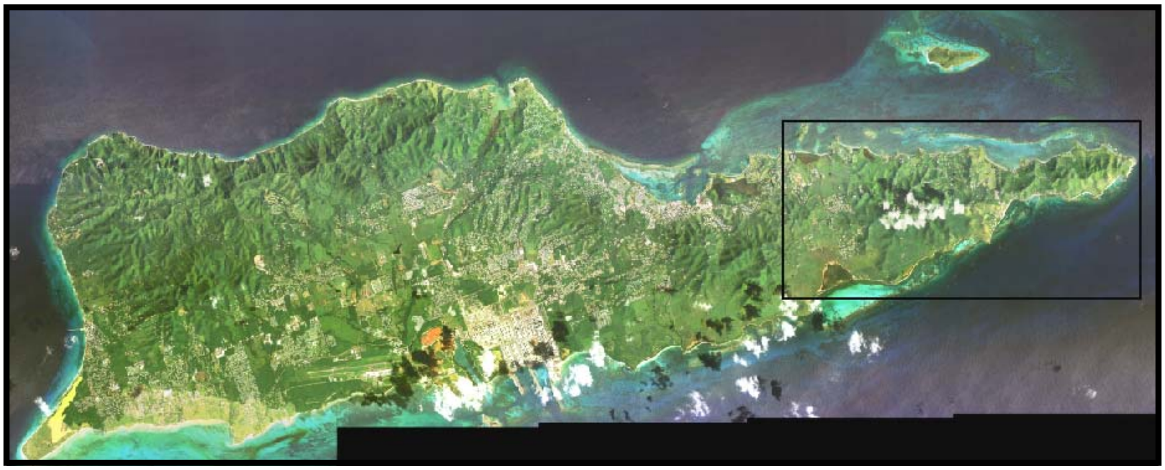
In developing our methodology, we narrowed down the number of clusters to remove scatter and large areas of vegetation, and most likely some impervious surfaces were lost and some undisturbed land was included; overall, however, the process resulted in excellent ground feature coverage with minimal scatter.

Application to Other Watersheds: the St. Croix East End Marine Park

The methodology we describe in this study can easily be applied to other watersheds and other islands. The watershed of the St. Croix East End Marine Park (SXEEMP), in particular, would benefit from extensive monitoring of impervious surfaces to ensure economic growth in the watershed does not lead to water quality degradation and loss of biodiversity in the marine park.

The marine park encompasses 155 square kilometers of territorial waters and has a shoreline of approximately 28 kilometers (17 miles) (Fig. 19). This extends around the entire east end of the island from the western border of Chenay Bay on the north shore east to Point Udall and then west to the western border of Great Pond Bay on the south shore. The land bordering the park is entirely within the First Tier of the coastal zone, and any development activity requires the approval of the Virgin Islands Coastal Zone Commission. Often the impacts of coastal development, and particularly the cumulative impacts, are not adequately addressed during project formulation or during the permitting process. Having current information on impervious surface cover in the coastal zone would aid coastal zone regulators in making decisions prior to granting permissions for development activity.

Figure 19. The watershed of the St. Croix East End Marine Park on St. Croix.
(from NRCS/USACE, 2004)



A Comprehensive Watershed and Coastal Wetlands Protection Plan is being developed for the SXEEMP, and identification and mapping of nonpoint source pollution and growth within the park watersheds has been targeted as a major component in order to prevent environmental degradation. Our methodology could easily be applied on St. Croix, and it is likely that different impervious classes than those shown for the Coral Bay watershed would be highlighted. The SXEEMP watershed has a higher density of development, particularly along the south coast, lower elevations, and more managed land (golf course, parks) than the Coral Bay watershed. In the Coral Bay watershed, we selected five subsets within the watershed and showed that some of these were experiencing growth that warranted closer monitoring. Identifying areas in the SXEEMP watershed that are or have the potential for causing environmental degradation would help park managers focus management efforts on specific locations to prevent environmental damage to the natural resources of the marine park.

Minimizing Impervious Surfaces at the Local Level

An increase in impervious surfaces is an inescapable result of development; large machinery alone can compact ground, decreasing porosity of the soil. There are numerous actions, however, that can be taken by individuals to minimize the impacts of impervious surfaces at the local level, including maintaining plant cover over bare ground, using pervious rather than impervious materials around the yard, and reducing soil compaction by parking vehicles on a porous surface or on the road. The brochure shown in Appendix III includes a simple explanation of what impervious surfaces are and the effects these have on the environment. The brochure briefly describes the project and highlights the main actions that homeowners can take to minimize the impacts from impervious surfaces. As part of this report, the leaflet is available to land-use regulators, community groups, and other interested parties to use.

Other Considerations

Cost of software and human resources to run the analyses we describe here will be an issue for land managers and regulators in the USVI. However, the ease in monitoring impervious surface cover as an index of watershed health with this remote sensing/GIS-based methodology should justify the initial outlay and setup costs.

REFERENCES

Ammann, A.P., R.W. Frazen, and J.L. Johnson, 1986, Method for the evaluation of inland wetlands in Connecticut, DEP Bulletin No. 9, Connecticut Department of Environmental Protection, Hartford, CT.

Arnold, Jr. C.L. and C.J. Gibbons, 1996, Impervious surface coverage. The emergence of a key environmental indicator, Journal of the American Planning Association, 62(2), 243-258.

Barnes, K.B., J.M. Morgan, III and M.C. Roberge, 2000-2001, Impervious surfaces and the quality of natural and built environments, http://chesapeake.towson.edu/landscape/impervious/download/Impervious.pdf

Bradshaw, J.G., 1991, A technique for the functional assessment of nontidal wetlands on the coastal plain in Virginia, Virginia Institute of Marine Science, Special Report No. 315 in Applied Marine Science and Ocean Engineering, 65 pp. http://ccrm.vims.edu/VIMSMethodReportNo315.pdf

Center for Watershed Protection, 2003, *Impacts of Impervious Cover on Aquatic Systems*, 150 pp., Ellicott City, MD.

Center for Watershed Protection, 1998, Rapid Watershed Planning Handbook, http://www.csc.noaa.gov/alternatives/indicatorMethods.html#impervious

City of Los Angeles Stormwater Program, http://www.lastormwater.org/Siteorg/businesses/susmp/singlefam.htm

Costick, L.A., 1996, Remote sensing and GIS for rapid regional watershed assessment and erosion potential monitoring,   Sierra Nevada Ecosystem Project (SNEP) Report number 3, http://www.cstars.ucdavis.edu/papers/html/costick1996a/

Dougherty, M., R. L. Dymond, S. J. Goetz, C. A. Jantz and N. Goulet, 2004, Evaluation of impervious surface estimates in a rapidly urbanizing watershed, Photogrammetric Engineering & Remote Sensing, Vol. 70, No. 11, pp. 1275–1284.

Dustan, P., E. Dobson and G. Nelson, 2001, Landsat Thematic Mapper: detection of shifts in the community composition of coral reefs using Landsat Thematic Mapper, Conservation biology, 15 (4), 892-902.

Environmental Protection Agency, 1999, Urban Stormwater Best Management Practices Study, http://www.epa.gov/waterscience/guide/stormwater/

Environmental Protection Agency, 1994, The quality of our nation's water: 1992, United States Environmental Protection Agency #EPA-841-S-94-002, Washington, DC, USEPA Office of Water.

ERDAS, Inc., 1997, *ERDAS Field Guide*, 4th ed. ERDAS, Inc., Atlanta, Georgia.

Green, E.P., C.D. Clark, P.J. Mumby, A.J. Edwards and A.C. Ellis, 1998, Remote sensing techniques for mangrove mapping, International Journal of Remote Sensing, 19(5), 935-956.

Helvarg, D., 2006, *50 Ways to Save the Ocean*, Inner Ocean Publishing, 186 pp.

Island Resources Foundation (IRF), 1977, Water sediments and ecology of the Mangrove Lagoon and Benner Bay, St. Thomas, Unpublished report, Department of Conservation and Cultural Affairs, Natural Resources Management, St. Thomas.

Jensen, J.R., 1996. *Introductory Digital Image Processing. A Remote Sensing Perspective*, Prentice –Hall, Inc., Upper Saddle River, NJ.

Li, X.Y., S. Contreras, L. Villagarcía, J. Sánchez, Y. Cantón, A. Solé-Benet, F. Domingo, R. Lázaro, B. Van Wesemael and J. Puigdefábregas, 2004, Influence of soil surface types on infiltration in a karstic area (Sierra de Gador, SE Spain). Implications for aquifer recharge, ERB2004 – Euromediterranean Conference, Turin, Italy, (http://www.eeza.csic.es/eeza/documentos/Li%20et%20al%202004-ERB(Turin).pdf#search=%22infiltration%20coefficient%22)

MacDonald, L.H., D.M. Anderson and W.E. Dietrich, 1997, Paradise threatened: Land use and erosion on St. John, US Virgin Islands, Environmental Management, 21(6), 851-863.

National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), Biogeography Program, 2001, Benthic Habitats of Puerto Rico and the U.S. Virgin Islands, NOAA Coastal Services Center, Charleston, SC, http://ccma.nos.noaa.gov/ecosystems/coralreef/usvi_pr_mapping.html

National Oceanic and Atmospheric Administration (NOAA), Coastal Services Center, Land cover analysis, http://www.csc.noaa.gov/crs/lca/ccap.html

National Oceanic and Atmospheric Administration (NOAA), 1995, NOAA Coastal Change Analysis Program (C-CAP): Guidance for Regional Implementation, NOAA Technical Report NMFS, 123, 92 pp.

Natural Resources Conservation Service (NRCS) and the US Army Corps of Engineers (USACE), 21 September 2004, Aerial imagery collected by 3001, Inc.

Natural Resources Defense Council, Stormwater Strategies, http://www.nrdc.org/water/pollution/storm/stoinx.asp

Palandro, D., S. Andréfouët, P. Dustan and F.E. Muller-Karger, 2003, Change detection in coral reef communities using KIONOS satellite sensor imagery and historic aerial photographs, International Journal of Remote Sensing, 24 (4), 873-878.

Ramos, G. and M. Olga, 2001, Assessing vegetation and land cover changes in northeastern Puerto Rico, Caribbean Journal of Science, 37(1-2), 95-106.

Ramos-Scharrón, C. E. and L. H. MacDonald, 2005, Measurement and prediction of sediment prediction from unpaved roads, St. John, U.S. Virgin Islands, Earth Surface Processes and Landforms, 30, 1283-1304.

Rennis, D.S., C. Finney and B. Devine, 2006, Evaluating the sediment retention function of salt pond systems in the U.S. Virgin Islands, University of the Virgin Islands Water Resources Research Institute, St. Thomas, USVI, 96 pp.

Rogers, C.S., 1990, Responses of Coral Reefs and Reef Organisms to Sedimentation, Marine Ecology Progress Series, 62,185-202.

Rouse, J.W., R. H. Haas, J.A. Schell, and D.W. Deering, 1973, Monitoring Vegetation Systems in the Great Plains with ERTS, Proceedings, 3rd ETS Symposium, 1, 48-62.

Sabins Jr., F.F., 1987, *Remote sensing; principles and interpretation*, Chapter 7 Digital image processing, W.H. Freeman, New York, http://www.ciesin.org/docs/005-477/005-477.html

Schueler, R.R., 1994, The importance of imperviousness, Watershed Protection Techniques, 1, 3, 100-111.

Stumpf, R., M.L. Frayer and J.C. Brock, 1997, Temporal and Spatial Change in Coastal Ecosystems Using Remote Sensing: Example with Florida Bay Emphasizing AVHRR, http://sflwww.er.usgs.gov/projects/sed_turbidity/sedturbab2.html

Tou, J.T. and R.C. Gonzalez, 1977, *Pattern Recognition Principles*. Reading, MA: Addison –Wesley, 377 pp.

US Army Corps of Engineers (USACE), 1994, U.S. Virgin Islands digital orthophotography, February 1994, Jacksonville District.

Wertz, R., 1999, Remote sensing of water turbidity and sedimentation in Florida Bay and Biscayne Bay, http://sflwww.er.usgs.gov/proposals/1999/sedturbp99.html

World Resources Institute (WRI) and the US National Oceanic and Atmospheric Administration (NOAA), 2005, Coastal data CD for the US Caribbean, Washington, DC: WRI/NOAA.

APPENDIX I.

IKONOS Satellite System: Sensor Characteristics

Launch Date	24 September 1999 at Vandenberg Air Force Base, California, USA
Operated By	GeoEye
Operational Life	Over 7 years
Orbit	98.1 degree, sun synchronous
Speed on Orbit	7.5 kilometers per second
Speed Over the Ground	6.8 kilometers per second
Revolutions Around the Earth	14.7, every 24 hours
Altitude	681 kilometers
Resolution at Nadir	0.82 meters panchromatic; 3.2 meters multispectral
Resolution 26° Off-Nadir	1.0 meter panchromatic; 4.0 meters multispectral
Image Swath	11.3 kilometers at nadir; 13.8 kilometers at 26° off-nadir
Equator Crossing Time	Nominally 10:30 AM solar time
Revisit Time	Approximately 3 days at 40° latitude
Dynamic Range	11-bits per pixel
Image Bands	Panchromatic, blue, green, red, near IR

Information from Satellite Imaging Corporation
http://www.satimagingcorp.com/satellite-sensors/ikonos.html

APPENDIX II.

Product Metadata for IKONOS Imagery 77850

Version Number: 1.5
==
Company Information
Address
Space Imaging
12076 Grant Street
Thornton, Colorado 80241
U.S.A.
Contact Information
On the Web: http://www.spaceimaging.com
Customer Service Phone (U.S.A.): 1.800.232.9037
Customer Service Phone (World Wide): 301.552.0537
Customer Service Fax (World Wide): 301.552.3762
Customer Service Email: info@spaceimaging.com
Customer Service Center hours of operation:
Monday - Friday, 7:00am - 11:00pm Eastern Standard Time
==

Product Order Metadata

Creation Date: 09/19/05
Product Work Order Number: 00103690
Product Order Number: 177850
Customer Project Name: St John
Ground Station ID: PGS
License Type: Tier 3
Product Order Area (Geographic Coordinates)
Number of Coordinates: 24
Coordinate: 1
Latitude: 18.3556995733 degrees
Longitude: -64.8414778050 degrees
Coordinate: 2
Latitude: 18.3625702013 degrees
Longitude: -64.8395685254 degrees
Coordinate: 3
Latitude: 18.3695264483 degrees
Longitude: -64.8103506743 degrees
Coordinate: 4
Latitude: 18.3751267860 degrees
Longitude: -64.7905655703 degrees
Coordinate: 5
Latitude: 18.3764476549 degrees
Longitude: -64.7650656382 degrees
Coordinate: 6
Latitude: 18.3749059244 degrees
Longitude: -64.7365124672 degrees
Coordinate: 7
Latitude: 18.3743505840 degrees
Longitude: -64.7181747529 degrees

Coordinate: 8
Latitude: 18.3655995557 degrees
Longitude: -64.6878507327 degrees
Coordinate: 9
Latitude: 18.3551767080 degrees
Longitude: -64.6624268410 degrees
Coordinate: 10
Latitude: 18.3435649810 degrees
Longitude: -64.6488993456 degrees
Coordinate: 11
Latitude: 18.3321689042 degrees
Longitude: -64.6449002973 degrees
Coordinate: 12
Latitude: 18.3125603401 degrees
Longitude: -64.6471061672 degrees
Coordinate: 13
Latitude: 18.3025106933 degrees
Longitude: -64.6556851249 degrees
Coordinate: 14
Latitude: 18.2954025559 degrees
Longitude: -64.6730878497 degrees
Coordinate: 15
Latitude: 18.2914808480 degrees
Longitude: -64.7005400812 degrees
Coordinate: 16
Latitude: 18.2941771476 degrees
Longitude: -64.7154916465 degrees
Coordinate: 17
Latitude: 18.2998146065 degrees
Longitude: -64.7326493409 degrees
Coordinate: 18
Latitude: 18.3034912959 degrees
Longitude: -64.7478460760 degrees
Coordinate: 19
Latitude: 18.3015304272 degrees
Longitude: -64.7708863389 degrees
Coordinate: 20
Latitude: 18.2961380294 degrees
Longitude: -64.7919657325 degrees
Coordinate: 21
Latitude: 18.3132956746 degrees
Longitude: -64.8015249989 degrees
Coordinate: 22
Latitude: 18.3260413514 degrees
Longitude: -64.8172119936 degrees
Coordinate: 23
Latitude: 18.3329044196 degrees
Longitude: -64.8272614702 degrees
Coordinate: 24
Latitude: 18.3424636771 degrees
Longitude: -64.8358402872 degrees

Product Order Area (Map Coordinates in Map Units)

Coordinate: 1
Map X (Easting): 305423.88 meters
Map Y (Northing): 2030524.41 meters
Coordinate: 2

Map X (Easting): 305633.37 meters
Map Y (Northing): 2031282.85 meters
Coordinate: 3
Map X (Easting): 308729.00 meters
Map Y (Northing): 2032021.81 meters
Coordinate: 4
Map X (Easting): 310826.04 meters
Map Y (Northing): 2032620.96 meters
Coordinate: 5
Map X (Easting): 313522.23 meters
Map Y (Northing): 2032740.79 meters
Coordinate: 6
Map X (Easting): 316537.97 meters
Map Y (Northing): 2032541.08 meters
Coordinate: 7
Map X (Easting): 318475.23 meters
Map Y (Northing): 2032461.19 meters
Coordinate: 8
Map X (Easting): 321670.72 meters
Map Y (Northing): 2031462.60 meters
Coordinate: 9
Map X (Easting): 324346.94 meters
Map Y (Northing): 2030284.26 meters
Coordinate: 10
Map X (Easting): 325764.93 meters
Map Y (Northing): 2028986.10 meters
Coordinate: 11
Map X (Easting): 326176.20 meters
Map Y (Northing): 2027720.99 meters
Coordinate: 12
Map X (Easting): 325923.43 meters
Map Y (Northing): 2025552.89 meters
Coordinate: 13
Map X (Easting): 325006.45 meters
Map Y (Northing): 2024448.84 meters
Coordinate: 14
Map X (Easting): 323159.47 meters
Map Y (Northing): 2023678.91 meters
Coordinate: 15
Map X (Easting): 320253.12 meters
Map Y (Northing): 2023271.69 meters
Coordinate: 16
Map X (Easting): 318675.17 meters
Map Y (Northing): 2023584.91 meters
Coordinate: 17
Map X (Easting): 316867.11 meters
Map Y (Northing): 2024226.01 meters
Coordinate: 18
Map X (Easting): 315264.38 meters
Map Y (Northing): 2024648.28 meters
Coordinate: 19
Map X (Easting): 312826.45 meters
Map Y (Northing): 2024454.74 meters
Coordinate: 20
Map X (Easting): 310592.02 meters
Map Y (Northing): 2023879.66 meters

Coordinate: 21
Map X (Easting): 309600.11 meters
Map Y (Northing): 2025788.68 meters
Coordinate: 22
Map X (Easting): 307955.81 meters
Map Y (Northing): 2027215.90 meters
Coordinate: 23
Map X (Easting): 306901.10 meters
Map Y (Northing): 2027986.16 meters
Coordinate: 24
Map X (Easting): 306004.94 meters
Map Y (Northing): 2029053.36 meters
Sensor Type: Satellite
Sensor Name: IKONOS-2
Processing Level: Standard Geometrically Corrected
Image Type: PAN/MSI
Interpolation Method: Nearest Neighbor
Multispectral Algorithm: None
Stereo: Mono
Mosaic: No
Map Projection: Universal Transverse Mercator
UTM Specific Parameters
Hemisphere: N
Zone Number: 20
Datum: NAD83
Product Order Pixel Size: 1.0000000000 meters
Product Order Map Units: meters
MTFC Applied: Yes
DRA Applied: No
Media: DVD
Product Media Format: DVD
File Format: NITF
Compressed: No
Bits per Pixel per Band: 11 bits per pixel
UTM_MGRS_Geocoding: Yes
Multispectral Files: Four Files

==

Source Image Metadata

Number of Source Images: 2

Source Image ID: 2005091814594500000011600236
Product Image ID: 000
Sensor: IKONOS-2
Acquired Nominal GSD
Cross Scan: 0.90 meters
Along Scan: 0.87 meters
Scan Azimuth: 179.98 degrees
Scan Direction: Reverse
Panchromatic TDI Mode: 13
Nominal Collection Azimuth: 60.6968 degrees
Nominal Collection Elevation: 70.86302 degrees
Sun Angle Azimuth: 130.3172 degrees
Sun Angle Elevation: 65.40851 degrees

Acquisition Date/Time: 2005-09-18 14:59 GMT
Percent Cloud Cover: 19

Source Image ID: 2005091814595830000011600235
Product Image ID: 001
Sensor: IKONOS-2
Acquired Nominal GSD
  Cross Scan: 0.87 meters
  Along Scan: 0.84 meters
Scan Azimuth: 359.98 degrees
Scan Direction: Forward
Panchromatic TDI Mode: 13
Nominal Collection Azimuth: 83.9952 degrees
Nominal Collection Elevation: 75.59476 degrees
Sun Angle Azimuth: 130.5683 degrees
Sun Angle Elevation: 65.52139 degrees
Acquisition Date/Time: 2005-09-18 14:59 GMT
Percent Cloud Cover: 0

==

Product Space Metadata

Number of Image Components: 2
  X Components: 1
  Y Components: 1
Product MBR Geographic Coordinates
  Number of Coordinates: 4
    Coordinate: 1
    Latitude: 18.3757214901 degrees
    Longitude: -64.8416902394 degrees
    Coordinate: 2
    Latitude: 18.3775208300 degrees
    Longitude: -64.6453044766 degrees
    Coordinate: 3
    Latitude: 18.2919543177 degrees
    Longitude: -64.6444950946 degrees
    Coordinate: 4
    Latitude: 18.2901639331 degrees
    Longitude: -64.8407843743 degrees
Product Map Coordinates (in Map Units)
  UL Map X (Easting): 305423.88 meters
  UL Map Y (Northing): 2032740.79 meters
Pixel Size X: 1.0000000000 meters
Pixel Size Y: 1.0000000000 meters
Product Order Map Units: meters
Columns: 20756 pixels
Rows: 9472 pixels
Reference Height: -26.4203586578 meters

==

Product Component Metadata

Number of Components: 2

Component ID: 0000000
Product Image ID: 000
Component File Name: po_177850_pan_0000000.ntf po_177850_red_0000000.ntf po_177850_grn_0000000.ntf po_177850_blu_0000000.ntf po_177850_nir_0000000.ntf
Thumbnail File Name: po_177850_rgb_0000000_ovr.jpg
Country Code:
Component Geographic Corner Coordinates
Number of Coordinates: 4
Coordinate: 1
Latitude: 18.3757214901 degrees
Longitude: -64.8416902394 degrees
Coordinate: 2
Latitude: 18.3766881545 degrees
Longitude: -64.7389441809 degrees
Coordinate: 3
Latitude: 18.2966185696 degrees
Longitude: -64.7381435610 degrees
Coordinate: 4
Latitude: 18.2956564075 degrees
Longitude: -64.8408423779 degrees
Component Map Coordinates (in Map Units)
UL Map X (Easting): 305423.88 meters
UL Map Y (Northing): 2032740.79 meters
Pixel Size X: 1.0000000000 meters
Pixel Size Y: 1.0000000000 meters
Product Order Map Units: meters
Columns: 10860 pixels
Rows: 8864 pixels
Percent Component Cloud Cover: 21

Component ID: 0010000
Product Image ID: 001
Component File Name: po_177850_pan_0010000.ntf po_177850_red_0010000.ntf po_177850_grn_0010000.ntf po_177850_blu_0010000.ntf po_177850_nir_0010000.ntf
Thumbnail File Name: po_177850_rgb_0010000_ovr.jpg
Country Code:
Component Geographic Corner Coordinates
Number of Coordinates: 4
Coordinate: 1
Latitude: 18.3759480717 degrees
Longitude: -64.7565661728 degrees
Coordinate: 2
Latitude: 18.3769426195 degrees
Longitude: -64.6452989924 degrees
Coordinate: 3
Latitude: 18.2919543177 degrees
Longitude: -64.6444950946 degrees
Coordinate: 4
Latitude: 18.2909646865 degrees
Longitude: -64.7557079755 degrees
Component Map Coordinates (in Map Units)
UL Map X (Easting): 314419.88 meters
UL Map Y (Northing): 2032676.79 meters
Pixel Size X: 1.0000000000 meters

Pixel Size Y: 1.0000000000 meters
Product Order Map Units: meters
Columns: 11760 pixels
Rows: 9408 pixels
Percent Component Cloud Cover: 0

==

APPENDIX III.

Actions Homeowners Can Take to Minimize the Impacts of Impervious Surfaces

IMPERVIOUS SURFACES:
ACTIONS YOU CAN TAKE TO REDUCE POLLUTION

What are impervious surfaces?

Impervious surfaces are surfaces covered with impenetrable materials, such as concrete, asphalt, and roofing material. Hard packed soils, such as unpaved roads and driveways, are also very impervious.

Roads and houses are common impervious surfaces that prevent rainfall from filtering through the ground to remove pollutants, such as soil runoff, fertilizers, and pesticides. Instead, these pollutants end up in coastal waters where they damage coral reefs and seagrass beds. This photograph from Google Earth (2008) shows the town of Coral Bay, St. John.

What's wrong with impervious surfaces?

These solid surfaces prevent rainwater and other surface water from infiltrating into the ground. As a result:

- Increased runoff can kill vegetation and cause soil erosion.
- Pollutants, such as animal wastes, fertilizers, pesticides, oily wastes and other debris, are often not filtered through the soil before the runoff reaches guts, wetlands and the sea. These pollutants can severely degrade water quality and harm aquatic life.
- Hard surfaces prevent rainfall from seeping into the soil to recharge groundwater.
- Hard surfaces have high heat conductivity so raise the temperature of water runoff and the surrounding air temperature.

How can you help limit impervious surface effects?

1. Use pervious material, such as gravel, porous concrete, porous pavers or vegetation for driveways, patios, sidewalks, roads and parking areas and allow water to seep into the ground.

2. Create depressions known as 'swales' next to impervious surfaces to collect runoff. Fill these with gravel to help slow down flow or plant these with native trees and shrubs to help soak up standing water.

3. Avoid over-watering. Use native plants that don't require much water, use drip irrigation whenever possible and adjust sprinklers to minimize over-spraying.

4. Sweep driveways and walkways rather than spraying down.

5. Protect the soil by maintaining plant cover rather than bare ground.

6. Prevent soil compaction by reducing tillage and by avoiding the use of machinery when the soils are wet.

7. Keep vehicles on the road or on a porous surface rather than on the ground and prevent rutting the ground by following the same wheel tracks when off the road.

8. Protect the island's salt ponds and wetlands. These are important in reducing pollutant loads that could enter the ocean.

About this project

This brochure has been produced as part of the study "Impervious Surface Analysis of Terrestrial Watersheds of the U.S. Virgin Islands" which was funded by the University of the Virgin Islands Water Resources Research Institute (WRRI). The study developed a GIS-based methodology for using impervious surface analysis to monitor, quantify, and manage water quality and habitat health of a watershed. The Coral Bay watershed, St. John, was used to develop the methodology. Contact the WRRI for a copy of this report (http://rps.uvi.edu/WRRI/wrri.htm).

Information in this leaflet has also come from the following sources:
Helvarg, D. 2006, 50 Ways to Save the Ocean, Inner Ocean Publishing; Barnes, K.B. et al., 2000-2001, Impervious surfaces and the quality of natural and built environments; Natural Resources Defense Council Stormwater Strategies, http://www.nrdc.org/water/pollution/storm/stoinx.asp; EPA, 1999, Urban Stormwater Best Management Practices Study, http://www.epa.gov/waterscience/guide/stormwater/

The research on which this report is based was financed in part by the U. S. Department of the Interior, United States Geological Survey, through the Virgin Islands Water Resources Research Institute. The contents of this publication do not necessarily reflect the views and policies of the U. S. Department of the Interior, nor does mention of trade names or commercial products constitute their endorsement by the United States Government.