Utilizing Emerging Geo-Imaging Technologies For The Management Of Tropical Coastal Environments

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The Caribbean coastal zone is an environmentally sensitive area that is under intense pressure from a number of natural events and man-made activities. Beside the requirement to monitor these highly dynamic events and activities, there is also need for timely policy decisions to guide appropriate strategies and to ensure sustainable development. However, major obstacles in this endeavor include lack of data and understanding of factors controlling the processes involved.
This paper argues that the gap in data and information in terms of the time and space dynamics of the coastal environment can be managed through the adoption of remote sensing technology. It reviews current progress and innovative trends in the field of remote sensing theory and technology. The paper also examines the use of the new imagery data as an up to date and affordable source of information for establishing the necessary baseline information for coastal management for in the Caribbean region.

Keywords: Tropical Coastal Environment, Management, Remote Sensing, Photogrammetry.

1. Introduction

The Caribbean region is experiencing a number of events and activities that are -expected to have significant impacts on its coastal environment. These events occur at a global level (e.g., sea level and climate change) as well as at local levels (e.g., coastal development, ecosystem destruction, resource depletion, and alteration of coastal dynamics). Consequently, there is a need to introduce tools and strategies for timely decisions to ensure appropriate mitigation measures are employed for effective management (Baban et al., 2004).

A coastal management program should address the sustainable development of coastal areas, reducing vulnerability of coastal areas to natural hazards, and maintaining essential ecological processes, life support systems, and biodiversity. The sustainable development of the coastal zone aims at achieving a balance between conservation of resources and sensible development in order to ensure the optimal and most sustainable use of these unique regions for current and future generations (Campbell et al., 1997).

Maps are critical tools in the characterization, management and conservation of coastal ecosystems. Without maps, designating research areas, identifying locations, examining spatial and temporal interactions, and debating the consequences of coastal development areas would be most difficult. However, there is a severe shortage of reliable and compatible data sets in the region (Baban et al., 2004). Information needed for accurate planning is often outdated, non-existent, or

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very expensive and time-consuming to collect. Particularly in the developing nations, government data sources for domestic sites can be ten to thirty years old, if available at all. This information poverty makes planning and decision making for managing the coastal environment both challenging and error-prone.

The nascent remote sensing technologies provide an excellent alternative source for collecting primary geo-data and monitoring the health of coastal zones. Imagery of the earth's surface is becoming an integral part of today's decision-making process in coastal planning, management, conservation and monitoring of coastal resources. Advances in remote sensing technology have occurred in acquiring digital aerial photography and high-resolution satellite data. Parallel to this are new techniques for improved processing and extraction of spatial information from these new data sets. Recent improvements in computer software and hardware have allowed remote sensing and geographic information systems (GIS) to play an increasing role in the management of the coastal resources. Integrating these two sets of tools provide the way forward to collect and manage relevant data sets, and development of management scenarios to evaluate mitigation strategies.

In the Caribbean, remote sensing technology has not been meaningfully utilized in coastal development activities because of technical and financial issues (Specter and Gayle, 1990). One of the critical obstacles that have impinged on the transfer of remote sensing technology to the region is the number of trained experts. Without experienced personnel, the ability to implement projects using remote sensing is significantly curtailed. Economic constraints also play an equally major obstacle since it can affect the availability of experienced personnel, hardware, software and necessary data. The third major obstacle is the political climate in the Caribbean that may prevent long-term investments in technology and training (Specter and Gayle, 1990).

This paper reviews current progress and trends in the field of remote sensing technology and theory. It describes how remote sensing can provide a suitable alternative to collect biophysical parameters and establish baseline information necessary for meeting the spatial data needs for the effective management of coastal environments in the Caribbean region. Section two of the paper reviews the characteristics of coastal zones and the data requirements for effective management. Section three reviews the latest developments in remote sensing, while the subsequent section discusses the use of remote sensing technologies in coastal management. The conclusions are then presented.

2. *Coastal Zones*

2.1 *Coastal Habitats and Threats*

The Caribbean coastal zone contains many productive and biologically complex ecosystems. Near-shore marine habitats include coral reefs, seagrass beds, mangroves, coastal lagoons, beaches, and mud bottom communities. Their economic importance is partially tied to their value for fisheries and coastal tourism.

Mangrove wetland is the dominant coastal ecosystem in the tropical and subtropical regions of the world. Mangrove forest habitats are critical for healthy coastal ecosystems in the tropics as they provide habitat, nursery and food for aquatic life and protect the coastline from flooding and erosion, in addition to their economic values for coastal residents (Al-Tahir and Baban, 2005). Coral reef is the other important coastal ecosystem that occurs along most shallow, tropical coastlines. In order to survive, corals need warm, relatively clear, and nutrient-free waters with constant salinity. Corals provide food, shelter and nursery areas for many fishes and crustaceans. Reefs protect coastal areas from storms and erosion by forming natural breakwaters (CEP, 2000).

Global climate change affects the physical, biological, and biogeochemical characteristics of the oceans and coasts, modifying their ecological structure, their functions, and the goods and services they provide. It also leads to increases in sea level and sea-surface temperature as well as changes in salinity, alkalinity, wave climate, and ocean circulation (McCarthy et al., 2001). Additionally, higher rates of erosion and coastal land loss are expected in many small islands because of the projected rise in sea level.

At the regional and local levels, coastal habitats are threatened by human activities and economic development. Population growth and unsustainable land use practices along the coast and inland; including landfill and solid waste dumping, reclamation, alteration of natural drainage patterns, pollution by factory and domestic effluents have a direct impact on the health of the coastal areas (Al-Tahir and Baban, 2005). As the result of collective influence of all these factors, erosion, dredge and fill, impoundments, toxic pollutants, and excessive turbidity and sedimentation are destroying coastal wetlands and submersed habitats.

These changes collectively will have profound impacts on the status, sustainability, productivity, and biodiversity of the coastal zone and marine ecosystems. Tropical and subtropical coastlines, particularly in areas that are already under stress from human activities, are highly vulnerable to global warming impacts. Furthermore, vital infrastructure and major concentrations of settlements are likely to be effected by more severe and frequent storm damage and flooding, recession of barrier beaches and shoreline, and loss of coastal structures, both natural and man-made (McCarthy et al., 2001). Sea level rise may lead to the destruction and drowning of coral reefs and atolls, disappearance or redistribution of wetlands and lowlands, reduction in biological diversity and possible collapse of coastal ecosystems and associated fisheries (CEP, 2000).

2.2 Coastal Management

Successful coastal zone management must account for a wide range of parameters and data. The set of required physical information includes topography and terrain, soil types, watershed/catchments, and forestry (e.g., forest reserves, forest types, and vegetative species). Another set would include variety of physical, chemical and biological oceanographic data, bathymetry, morphological data, inventory of shore protection structures, and fisheries. Essential environmental data must be available regarding point pollution sources, water quality data, industrial site locations, and sensitivity analyses. Ultimately, coastal management requires socio-economic data (housing location, valuation data, demographic structure, census information) as well as land use information, administrative boundaries, coastal hazard zones, development pressure, land use capability, environmental constraints (O'Reagan, 1996).

Furthermore, accomplishing and maintaining a successful coastal zone management program demands a long-term monitoring scheme that accounts for changes over time as well as to quantify key cause-and-effect relationships within individual ecosystems (Herring et al., 2002). As such, there is a need to map the coastal zone and the spatial distribution of its habitats and resources, as well as a scientific understanding of the linkages of coastal and submersed wetland habitats with adjacent uplands. This information allows managers and scientists to evaluate and ultimately to predict cumulative direct and indirect effects of natural events and coastal development on wetland habitats and living marine resources.

3. Advancement in Geo-Imaging Technology

Remote sensing of tropical coastal environments involves the measurement of electromagnetic radiation reflected from or emitted by the Earth's surface and relating these measurements to the types of habitat or the water quality in the coastal area being observed by the sensor (Green et al., 2000). Furthermore, spectral information can capture and map factors and themes acting as possible surrogate indicators for environmental degradation; such as deforestation and development.

Geo-Imaging techniques are becoming increasingly cost-effective, given the rapid pace of innovation in computer technology, information networks, and improvements in sensing systems for satellites (Campbell et al., 1997). The following sections detail the advancements in the geo-imaging technologies and theory of photogrammetry and satellite remote sensing.

3.1. Digital Photogrammetry

The field of photogrammetry is a rapidly changing one with new technologies and protocols being developed constantly. In a relatively short period of time, the practice of photogrammetry has gone from the analog to digital (softcopy) with the advent of computing and imaging technology. The main driving premise in developing digital photogrammetry was that it would enhance the performance, speed and accuracy in the execution of photogrammetric tasks (Crystal, 2003). Progress has occurred along two tracks; developing commercial digital cameras for direct capturing of digital images as well as developing digital photogrammetry systems for data processing and information extraction.

3.1.1. Digital Aerial Cameras

One of the most obvious requirements for digital photogrammetry is the digital image. While this can be obtained by scanning aerial photographs, an emerging trend is the use of digital airborne cameras. Digital photography is capable of delivering photogrammetric accuracy and coverage as well as multispectral data at any user-defined resolution up to 0.1m ground sampling distance (Keating et al., 2003). As such, the new digital cameras combine photogrammetric positional accuracy with multispectral capabilities for image analysis and interpretation. As no chemical film processing is needed, the direct digital acquisition can provide image data in just a few hours after the mission is flown, compared to several weeks using the traditional film-based camera (Keating et al., 2003). Another advantage over the traditional film is the ability to assess the quality of data taken directly after the flight is completed.

Two digital mapping cameras, ADS40 by Leica Geosystems and DMC from Z/I Imaging, were first presented to the market in 2002 to address requirements for extensive coverage, high geometric and radiometric resolution and accuracy, multispectral imagery, and stereo capability. These two cameras, and the successive ones from other companies, employ one of two different technologies to accomplish an airborne digital recording system; one-dimensional linear or two-dimensional CCD arrays (Ehlers, 2004).

The Leica Geosystems ADS40 Airborne Digital Sensor utilizes triplet linear arrays to implement the three-line-scanner concept. This concept generates one image looking forward, another one looking vertically down, and a third one looking backward from the aircraft (Figure 1). The ADS40 simultaneously captures data from three panchromatic as well as four multispectral bands that receive information from exactly the same portion of the earth's surface through a special beam splitter and filter. These concepts have the benefits of reducing the ground control requirements, producing high quality digital elevation models (DEM), and a perfect RGB co-registration (Leica, 2002). However, on the downside, the airborne line-scanning system requires incorporating inertial navigation system and real-time kinematic GPS positioning to improve the geometric accuracy of the final scene (Loedeman, 1999).

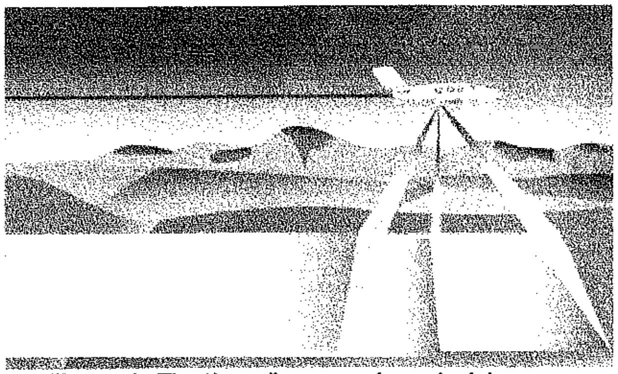


Figure 1: *The three-line scanning principle in ADS40 (Leica, 2002)*

The second camera, the Digital Modular Camera (DMC) developed by Z/I Imaging, makes use of two-dimensional arrays and a set of coupled nadir-looking lenses to emulate a standard frame camera's central perspective(Loedeman, 1999). The DMC's recording system comprises of up to eight individual, yet synchronously operating, CCD array cameras that can be put together in different ways in a modular design (Figure 2). The high-resolution panchromatic channel contains four converging 7k x 4k large area chips and high-performance lenses that provide a single digitally-mosicked image of 7,680 pixels along track and 13,824 pixels across track. For the simultaneous collection of true and false color images, four multispectral channels are incorporated in the camera electronics unit; each of which features a separate high-performance wide-angle lens with a 3k x 2k CCD chip (Z/I Imaging, 2003).

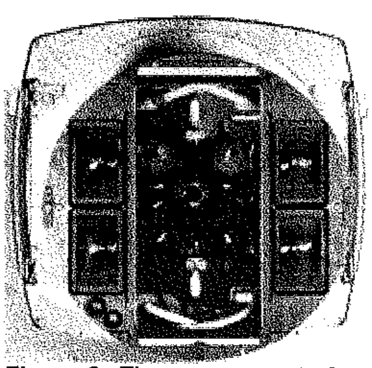


Figure 2: *The arrangement of multiple CCD cameras in DMC (Z/I Imaging, 2003)*

3.1.2. Softcopy Workstations

Digital photogrammetric workstations (DPW) are used to process digital images and are on the verge of replacing the current photogrammetric instruments. A DPW consists of hardware and software components that accept digital photographs/images, interactively and /or automatically perform photogrammetric procedures and operations, and produce digital and paper outputs. Typically, a DPW consists of a graphics workstation with a stereo viewing device and a 3D mouse (Tao, 2002). There are many ways to provide stereo viewing, including a split screen with a simple stereoscope, anaglyph (red/green display), polarization and liquid crystal methods. Digital stereo plotters are around 3-4 times cheaper than analytical stereo plotters (Crystal, 2003).

At present, a high-end DPW supports automatic or semi-automatic processing of specific functions that are otherwise extremely labor intensive. Using digital images permits vastly extended automation possibilities that enable quick and efficient production of DEM, ortho-rectified images and extracted vector features. Additionally, DPWs are equally capable of processing and extracting information from aerial and satellite imagery. The generation of DEM is practically done automatically through image matching that identifies and measures corresponding points in two or more overlapped photographs or images (Tao, 2002). A similar degree of automation has also been achieved in producing ortho-images. Ortho-images have been one of the driving forces in the adoption of DPWs as they are a preferable product for many GIS applications since features can be delineated on top of ortho-images without stereo viewing (Keating et al., 2003).

However, automation in the field of feature extraction from imagery is still limited despite it being one of most important tasks in photogrammetry. Some vendors provide semi-automated tools to help the manual process, but the performance of such tools still needs improvements in terms of reliability. The research community has devoted significant efforts through adapting higher-level image processing and image understanding techniques (Tao, 2002).

3.2. High-Resolution Satellite Remote Sensing

Remote sensing based data collection and research for the environment and coastal management has been predominantly founded on using mid-resolution satellite imagery. Three platforms are currently in orbit and obtaining data; the US Landsat, the French Spot, and the Indian IRS programs. All three systems have a swath width of 60-180 km and produce multispectral data (visible and near infrared - VNIR) and short-wave infrared (SWIR) with a ground resolution of 10 to 30 m. All operational instruments have been built and operated through government–sponsored programs.

In the late nineties, private satellite corporations started collecting high-resolution remote sensing data. The satellites from Space Imaging (Ikonos), Digital Globe (QuickBird) and Orbimage (Orbview-3) are already in orbit capturing imagery at up to 0.61m ground resolution. ImageSat International is also expected to launch EROS-B satellite in the first quarter of 2006 that will offer multispectral imagery with 0.70 m resolution. These systems share several common specifications with respect to the spectral and spatial resolutions as well as orbital details. Table 1 lists specific information about the satellite systems being discussed, including data about ground resolution, spectral coverage and swath width.

The new satellite images are recorded with 11-bit dynamic range causing the pixel values to span a gray scale of 2048 shades. Practically it means that greater detail can be extracted from scenes that are very dark (e.g., shadows) or very washed out from excessive sun reflectance (Corbley, 2000). Additionally, one-metre color imagery can be created using a pan-sharpening process that combines the high spatial resolution of the panchromatic image with the spectral information of the multispectral bands.

The U.S.A. Commercial Remote Sensing Space Policy released in 2003, called for the commercial firms to provide finer resolution to effectively replace the government spy satellites. Consequently, the U.S.A. National Geospatial-Intelligence Agency (previously National Imagery and Mapping Agency (NIMA)) awarded contracts (called the NextView agreements) to DigitalGlobe and to Orbimage for more than $500 million each over four-year period. The two NextView acquisitions assure the source for 0.5-meter commercial imagery to mitigate a potential gap in availability of commercial imagery that support the implement the U.S. commercial remote sensing space policy.

In addition, the agreements provide both companies with long-term commitments and capital for their satellite development and to substantially improve resolution, collection capacity and revisit capabilities with the next generation systems. Already, Digital Globe and Space Imaging have applied for licenses for 0.25 m resolution follow-on satellites. This means that images and information of higher resolution will soon be in the hands of the customers, researchers, and eventually, end users in the field of coastal zone management.

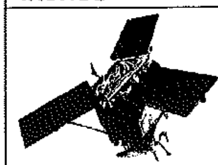
		Ikonos	QuickBird	OrbView-3
				
Sponsor		Space Imaging	Digital Globe	Orbimage
Launched		Sept 1999	Oct 2001	June 2003
Spatial Resolution (m)	Panchromatic	1.0	0.61	1.0
	Multi-Spectral	4.0	2.44	4.0
Spectral Range (nm)	Panchromatic	525 - 928	450 - 900	450 - 900
	Blue	450 - 520	450 - 520	450 - 520
	Green	510 - 600	520 - 600	520 - 600
	Red	630 - 690	630 - 690	625 - 695
	Near Infrared	760 - 850	760 - 890	760 - 900
Swath width (km)		11.3	16.5	8
Off nadir pointing		±26°	±30°	±45°
Revisit time (days)		2.3 - 3.4	1 - 3.5	1.5 - 3
Orbital Altitude (km)		681	450	470

Table 1: *Satellite parameters and spectral bands (Space Imaging, 2003; Digital Globe 2003; Orbimage, 2003)*

The new high-resolution sensors pose new challenges for automated interpretation, extraction and integration information. Finding features in sub-metre imagery is a new challenge since most feature extraction techniques have been developed for lower resolutions. It is therefore essential that new techniques be developed that allow automated processing of high resolution and multisensor images as well as accurate interpretation results. One of the promising approaches is the use of auxiliary spatial (contextual) information besides the multispectral information in the processing and classification steps (Ehlers, 2004).

4. Geo-Imaging in Coastal and Marine Applications

Spatial data have been customarily acquired by converting existing thematic maps and other data into a digital format. However, maps generally depict one specific theme; hence contain subjectively selected features that, additionally, are cartographically modified (shifting, generalization, exaggeration, use of symbols). The most significant shortcoming of these maps is that they generally are out-dated and, hence, cannot facilitate continuous monitoring. In contrast, satellite imagery and aerial photographs are viable sources for up-to-date information. Remote sensing allows the acquisition of repetitive, non-intrusive, and synoptic data quickly and at little cost. Consequently, satellite remote sensing data have the potential to guarantee data currency, sufficient accuracy, and uniform and comprehensive coverage (Al-Tahir and Ali, 2004). While it is true that remote sensing can be of comparatively little cost when compared to in-situ field data collection, however, the cost of the imagery can still be prohibitive in its purchase and use, especially for the high-resolution sensors.

Remote sensing can play a major role in coastal zone management because it overcomes the difficulties associated with obtaining information on natural resources and the environment. In addition to identifying and defining the spatial extents and the environment. In addition to identifying and defining the spatial extents of coastal habitat such as wetlands, coral reef and sea grasses, the spectral components of these images provide additional thematic information essential for mapping and monitoring the changes of different physical and biophysical parameters (Cracknell, 1999). The most widespread use of satellite imagery has been mapping the land use/cover types and monitoring their changes, as well as inventories of coastal resources, environmental monitoring, and coastal hazards (Campbell et al., 1997). Land cover change is a direct measure of the extent of habitat loss or gain, and is also a measure of increases or decreases in factors that determine habitat quality.

Another application for multi-spectral and thermal sensors onboard satellites is monitoring of near shore and marine habitats, where satellite images provide quantitative information on a number of environmental and ecological variables associated with these habitats. The list of such variables includes sea surface temperature, water clarity, circulation, aquatic vegetation, bathymetry, chlorophyll concentration, suspended sediment concentration, algal blooms, and point sources of pollution (O'Reagan, 1996; Lavender, 2001). The downwelling solar irradiance that penetrates the water surface interacts (through scattering and absorption) with the water body and part of it is reflected back towards the sensor. For example, the variations in the concentrations of phytoplankton pigments and suspended particulate matter influence the spectral composition of the water-leaving radiance (Lavender, 2001).

One pertinent engineering application is related to coastal hazards, such as coastal erosion, flooding, storms, and salt-water intrusion. These are natural phenomena that have the potential to impact natural resources, property, and the quality of human life. Satellites provide imagery that can help managers identify natural resources and property at risk through a time series of such imagery. Consequently, local patterns of shoreline erosion and/or accretion can be identified; damages to property and resources can be quantitatively assessed; and most significantly, response priorities during emergency situations can be determined.

The advent of very high-resolution satellite programs and digital airborne cameras with ultra high-resolution offers new possibilities for very accurate mapping of the environment. The advancement in satellite remote sensing has occurred in the improvement of the spectral resolution through the use of hyper-spectral technology in space (hundreds of narrow wavebands). The first commercial hyper-spectral satellite OrbView-4 (200 spectral channels with a spatial resolution of 8 m) was launched on September 2001 but did not reach its orbit (Ehlers, 2004).

The increase in the spatial resolutions is the other aspect of the recent developments in the satellite remote sensing. The new space-borne sensors generate data of a resolution of 0.6-1.0 m black-and-white and 2.5 m multispectral images. Parallel to this, the advancement trend in the aerial photogrammetry is in developing new methods for direct capturing of ultra high-resolution geospatial data in digital format using commercial digital cameras and digital photogrammetry systems (Mondello et al., 2004). Sensor technologies capable of collecting elevation information and direct geo-registration (e.g., Light Detection and Ranging (LIDAR) and Interferometric Synthetic Aperture Radar (IFSAR)) has opened up new opportunities for urban mapping and infrastructure inventory and analysis, as well as engineering applications that require of superior geo-positioning and terrain information (Mondello et al., 2004).

Due to the improved spatial characteristics, the high-resolution aerial and satellite sensors are capable of capturing data that would be suitable for mapping at scales of 1:5,000 or better, as compared to 1:50,000 scale mapping from existing mid-resolution satellites. Using ground control points for referencing the images, a horizontal accuracy of 2 m and vertical accuracy of 3 m are achievable; this is equivalent to 1:2,500 scale map standards (Corbley, 2000). This may require the availability of sufficient high quality ground control points that can be obtained through the relatively expensive survey quality GPS equipment.

Increased detail adds an entirely new level of geographic knowledge to image-based environmental maps and GIS databases. The high spatial resolution allows users to identify and map small objects (e.g., individual trees, vehicles and sidewalks) that were previously not detected in the coarser satellite imagery. A clear, accurate, and high-resolution image of the earth can enhance land use and infrastructure planning, natural disaster assessments and recovery efforts, resource exploration and management, and support environmental applications such as habitat analysis and wetlands characterization, as well as change detection.

In one aspect, the high spatial resolution would simplify the process of epoch-to-epoch image registration and reduce the error of registration to at least ten times less than in the case of satellite imagery, thus further enhancing the accuracy of change detection (Al-Tahir and Ali, 2004). Accordingly, the delineation of land cover classes would be at higher spatial accuracy and reliability, and hence, would improve the accuracy of the detected changes. Figure 3 depicts the use of high-resolution digital images in investigating the changes in coastline and land cover/use in Lisas Bay and Couva Bay, west coast of Trinidad, between the years 1966 and 1994. Such information provides detailed and accurate assessments of the changes that are shown in Figure 3c. Numerically, the study revealed that about 260 ha of vegetated land (mainly sugar cane) and about 70 ha of natural mangrove were lost in the period through mainly industrial and commercial uses. The coastline had gone through several stages of change as about 130 ha were claimed from the adjacent water body (Gulf of Paria) (Ali, 2005).

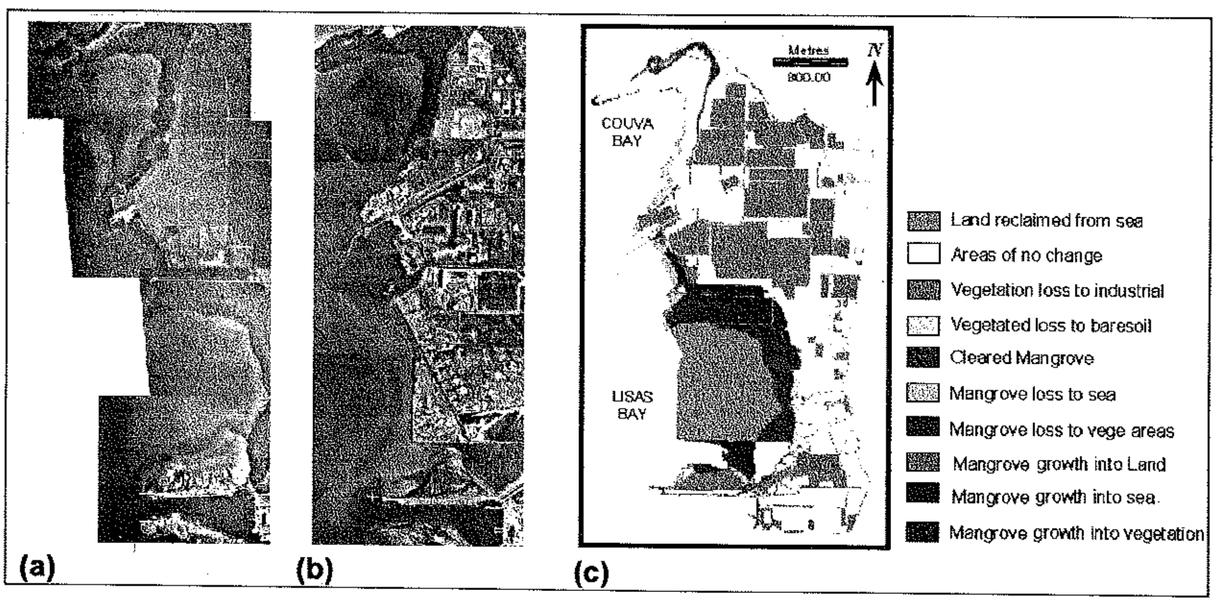


Figure 3: *Aerial photographs depict part of Trinidad's west coast in 1966 (a) and 1994 (b) Changes in land use and coastline over this period is shown in (c) (after (Ali, 2005))*

5. Conclusion

The paper has provided an overview on recent developments in acquiring geo-information using aerial and satellite-based remote sensing technologies, and their utilization for assessing, managing, and protecting coastal resources. It has also highlighted their promise as a cost-effective in the Caribbean region.

It is evident that as high-resolution images, created by high-resolution satellite sensors (e.g., 0.6 - 1.0 m) and ultra high-resolution airborne digital cameras (e.g., 0.05 - 0.2 m), are becoming available and affordable, remotely sensed data provides real opportunities for applications at resolutions and scales that were deemed impossible just a few years ago.

The Caribbean region may be characterized as mountainous small islands with fast rates of development that can perpetuate rapid environmental degradation on the coastal environment, besides having little or no up-to-date information as the information base is on average some 30 years old. Therefore, the fore mentioned technological developments are critical for the region as they provide opportunities for bridging the gaps in data and information needed for coastal planning and management in terms of the time and space dynamics of the coastal environment. More specifically, they provide effective means for surveying, inventorying, mapping and monitoring developments and the environmental both on land and coastal marine domains. Furthermore, they can be utilized to provide the necessary land and coastal parameters to run conventional coastal management mathematical models as well as developing plausible scenarios to simulate environmental response to different natural events and development activities in coastal environments.

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