

Summit-to-Sea mapping and change detection using satellite imagery: tools for conservation and management of coral reefs

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Abstract: Continuous summit-to-sea maps showing both land features and shallow-water coral reefs have been completed in Puerto Rico and the U.S. Virgin Islands, using circa 2000 Landsat 7 Enhanced Thematic Mapper (ETM+) Imagery. Continuous land/sea terrain was mapped by merging Digital Elevation Models (DEM) with satellite-derived bathymetry. Benthic habitat characterizations were created by unsupervised classifications of Landsat imagery clustered using field data, and produced maps with an estimated overall accuracy of >75% (Tau coefficient >0.65). These were merged with Geocover-LC (land use/land cover) data to create continuous land/sea cover maps. Image pairs from different dates were analyzed using Principle Components Analysis (PCA) in order to detect areas of change in the marine environment over two different time intervals: 2000 to 2001, and 1991 to 2003. This activity demonstrates the capabilities of Landsat imagery to produce continuous summit-to-sea maps, as well as detect certain changes in the shallow-water marine environment, providing a valuable tool for efficient coastal zone monitoring and effective management and conservation.

Key words: remote sensing, benthic habitats, change analysis, Landsat, coral reefs, mapping.

While concern is growing about the state of the earth's shallow water (<30 m) coral reefs, projects to quantify the extent or condition of these ecosystems at global or regional scales are limited by cost, accessibility, and magnitude of the study area (Mumby *et al.* 1999). Satellite imagery is very efficient for large scale surveying because it can collect consistent data for large geographic scales, over both land and water areas, and is capable of simultaneously mapping terrestrial and marine ecosystems from summits-to-seas, while covering a variety of habitats and environments.

In addition to many studies on land, large-scale surveys based on remotely sensed imagery have been performed, and often include satellite mapping and inventory of coastal resources (Mumby *et al.* 1997). Bathymetry and benthic cover maps for reef areas can be particularly useful in determining the quality and type of habitats, ecologically significant boundaries,

or locating study sites, which aid conservation planning and monitoring (Liceaga-Correa and Euan-Avila 2002). When this information is merged with any number of readily available land map products, the result is a seamless, continuous spatial data set from summits to seas, which can provide managers, stakeholders, and users with valuable information needed to manage land, coasts, and marine environments, which are intrinsically linked, and benefit from being managed as a ecosystem.

In recent decades, a number of satellite sensors with similar spectral resolutions have been put into orbit for visualizing the Earth. The moderate-resolution (30 m) Landsat Thematic Mapper (TM) sensor provides very low-cost imagery useful for mapping coral reefs (Palandro *et al.* 2003). In addition to surveying land with multi-spectral (including thermal) capabilities, this satellite can depict the ocean floor at a depth of up to ~ 37 m in

clear water. This sensor also benefits from a long-term acquisition plan, which has produced a very large inventory of imagery spanning three decades. This makes it feasible to perform change detection, and study the dynamics of both land and marine environments over time. This is Landsat's most powerful asset, making it a very effective tool for assessing change in ecosystems over long and short time frames. The purpose of this study is to demonstrate that Landsat is worthwhile for regional mapping of both land and water ecosystems at moderate resolutions, as well as demonstrating the capability to detect changes in coral reefs over time.

MATERIALS AND METHODS

Study area

The study area for this analysis is Puerto Rico and the U.S. Virgin Islands (U.S.V.I.) located in the Caribbean Sea, extending from (68°W, 19°N) to (64°W, 17°N). This area was selected for its wealth of field data and auxiliary information, which eased the verification and testing of this methodology, in addition to

a set of clear imagery from two time periods to permit a change analysis from 1991 to 2003.

Used data

All data used in this project are listed in Table 1. Landsat (ETM+) 7 imagery was used for the satellite derived bathymetry and benthic habitat mapping. Imagery was selected for minimal clouds, glint and wave effects, and maximum water clarity and were either purchased from the United States Geological Survey (USGS) Earth Resources Observation System (EROS) data center, or acquired from government partners, such as the National Aeronautics and Space Administration (NASA) and the University of South Florida (USF). Additional Landsat TM and ETM+ imagery pairs were selected for the St. Croix change analysis. Land use/Land cover datasets were obtained from the National Aeronautics and Space Administration (NASA) GeoCover- LC project, which contracts Earth Satellite Corporation to purchase, position Landsat imagery and create 13-class land cover products (Tucker *et al.* 2004). Additional point data were provided by the Benthic Habitats of Puerto Rico and the U.S. Virgin Islands project (Kendall *et al.* 2001).

TABLE 1
Image, date and source from which all data used in the analysis were obtained

Data	Date	Source
Landsat 5 (TM) Path 4 row 48	09/03/1991	NASA
Landsat 7 (ETM+) Path 4 row 48	01/12/2002	NOAA
Landsat 7 (ETM+) Path 4 row 48	03/04/2003	University of South Florida
Landsat 7 (ETM+) Path 4 row 47	03/27/2000	US Geological Survey
Landsat 7 (ETM+) Path 4 row 48	03/27/2000	US Geological Survey
Landsat 7 (ETM+) Path 5 row 47	11/13/2000	US Geological Survey
Landsat 7 (ETM+) Path 5 row 48	11/13/2000	US Geological Survey
Geocover LC products for Puerto Rico and USVI (4 tiles)	2000	Earth Satellite Corporation
Digital Elevation Model (DEM)	1996	National Elevation Dataset (USGS)
Benthic habitats of Puerto Rico and the U.S. Virgin Islands	2001	Biogeography Program, NOAA

Analytical Methods

Landsat TM and ETM+ images were georectified using available ground control points (GCPs) and satellite ephemeris data, and geocorrected to each other using PCI Geomatica version 8.0 in Windows NT. Several derived products were created in the steps to characterize benthic habitats. First, the raw satellite images were converted from Digital Numbers (DNs) to normalized reflectance, by calibration specific to the sensor, factoring the round-trip of the signal through the atmosphere. Normalized reflectance (also called at-satellite reflectance, or albedo) results in standardized, satellite-independent, comparable values (Mumby and Clark 2000).

The normalized reflectance imagery was then transformed into water reflectance (or the signal <10 cm above the water surface) using a modified atmospheric correction algorithm derived for IKONOS (Stumpf *et al.* 2003). This process uses the near-infrared band to estimate and remove the effects of aerosols and waves on the spectral signal.

Estimated water depth was calculated from water reflectance using a modified Lyzenga model, derived by Stumpf *et al.* (2003). The model was calibrated using available point data from the Benthic Habitats of Puerto Rico and the U.S. Virgin Islands project (see Kendall *et al.* 2001). The Stumpf protocol uses a ratio transformed linear relationship between the blue, green and red attenuation corrected bands of the satellite data to estimate depth to known bathymetric points. This results in a continuous depth layer that is within $\pm 10\%$ of actual measured depth. This layer was then merged to a Digital Elevation Model (DEM), obtained from National Elevation Data set (NED), which is a seamless raster product produced by the United States Geological Survey (USGS).

The imagery was then processed for classification, by selecting areas of coastal zones that are less than ~ 37 m deep, and neither land, clouds nor cloud shadow. The blue water reflectance was clustered into 40 separate categories using an unsupervised K means algorithm

(Mumby 2000). This same classification method was performed on green water reflectance and filtered bathymetry. Using available point data from the field, the unsupervised clusters from both runs were aggregated to reflect a representative benthic habitat scheme (Table 2) appropriate for the resolution of Landsat imagery (Mumby and Harborne 1999).

An accuracy assessment was performed for each classification using a separate set of field data points, which identify primary and secondary habitat types observed at random point locations throughout the study area. Producer accuracy was calculated, describing the probability that any pixel is correctly classified, and conversely, user accuracy, which determines the probability that a classified pixel is the same class in reality (Mumby and Green 2000). Overall accuracy was estimated by a simple ratio of correctly classified sample points compared to the total. The Tau coefficient was also calculated, as it is a more accurate statistic used to describe overall accuracy, because it estimates how many pixels are correctly classified in addition to what would be expected by chance alone (Mumby and Green 2000).

The derived benthic maps were then merged with Geocover-LC land cover data. These merged products create a seamless map layer depicting land cover and benthic cover from mountain tops to near shore shallow water coral reefs.

TABLE 2
Classification of the land and benthic habitat features of Puerto Rico and the U.S.V.I.

Data value	Class
1	Coral and colonized hardbottom
2	Submerged vegetation (seagrass and macroalgae)
3	Uncolonized hardbottom— not present in this study area or, only exists in very small locales
4	Unconsolidated sediment (sand, mud)
5	Land
6	Deep water (>37 m)
7	No data (clouds, cloud shadow)

The availability of imagery pairs from different dates allowed for an assessment of change in the benthic environment over time. This was performed using Principle Components Analysis (PCA) using the Xspace program in PCI Geomatica version 8.0. PCA is a linear transformation of the data along perpendicular axes of maximum variance between data sets (Legendre and Legendre 1998). The first eigenvector sorts pixels along an axis of highest correlation between data sets. Pixels on this axis have not significantly changed between the two images. The second eigenvector is perpendicular to the first, and therefore sorts data that lie off of the principal axis, and area pixels that are significantly different between data sets. This second eigenvalue was used to detect change between images, visualized on an eigenmap. Pixels with extreme values along the second principle axis are those that are most different between the two images, and therefore highlight areas of change.

Two different change analyses were performed to compare the technique over short and long time intervals and the efficacy of Landsat for detecting both natural and anthropogenic changes occurring at different temporal scales. The first analysis compares two images taken a year apart (March 27, 2000 and January 25, 2001). The second is over a 12-year interval, from September 3rd, 1991 to March 4th, 2003.

The seamless summit-to-sea maps derived from Landsat ETM+ imagery display a wealth of information on both land and water. Figure 1a, shows the Landsat-derived terrain and cover products from for Puerto Rico and the U.S.V.I. The digital elevation model was also used to derive watershed boundaries and out-flow points for all land areas in the study area. A continuous terrain map was created by merging estimated depth and terrestrial elevation. Figure 1b, shows the seamless cover map, which are the benthic habitats layer merged with Geocover-LC products.

The accuracy assessments for the benthic classifications of St. Croix and Puerto Rico are shown in Tables 3 and 4. Producer accuracies for St. Croix show that the probability that any pixel of sand or hardbottom is correctly classified is greater than 80%, and is slightly lower for Puerto Rico. The user and producer accuracies are slightly lower for seagrass, which is increasingly difficult to separate spectrally from hardbottom at greater depths. Overall accuracy for both classifications was >75%, and Tau coefficients >0.65.

Two change analyses for a selected area of southwest St. Croix are shown in Fig. 2. The left-hand column displays the short-term analysis (one year interval) and the long-term (12 year interval) is on the right. Both analysis show the normalized satellite reflectance at the

TABLE 3
Accuracy assessment for St. Croix benthic habitat classification

Classification	Reference points			Row total	User accuracy
	Coral reef/hardbottom	Submerged vegetation	Unconsolidated sediments		
Coral reef/hardbottom	132	13	6	151	87.4%
Submerged vegetation	14	39	9	57	68.4%
Unconsolidated sediments	11	10	55	76	72.4%
Total	157	62	65	284	-
Producer accuracy	84.1%	63.0%	84.6%	-	-

Classification created from Landsat 7 ETM+ path 4 row 48 image acquired 01/12/2002. Sample size N=284 (accuracy assessment points). Overall accuracy= 79.6%, Tau= 0.69.

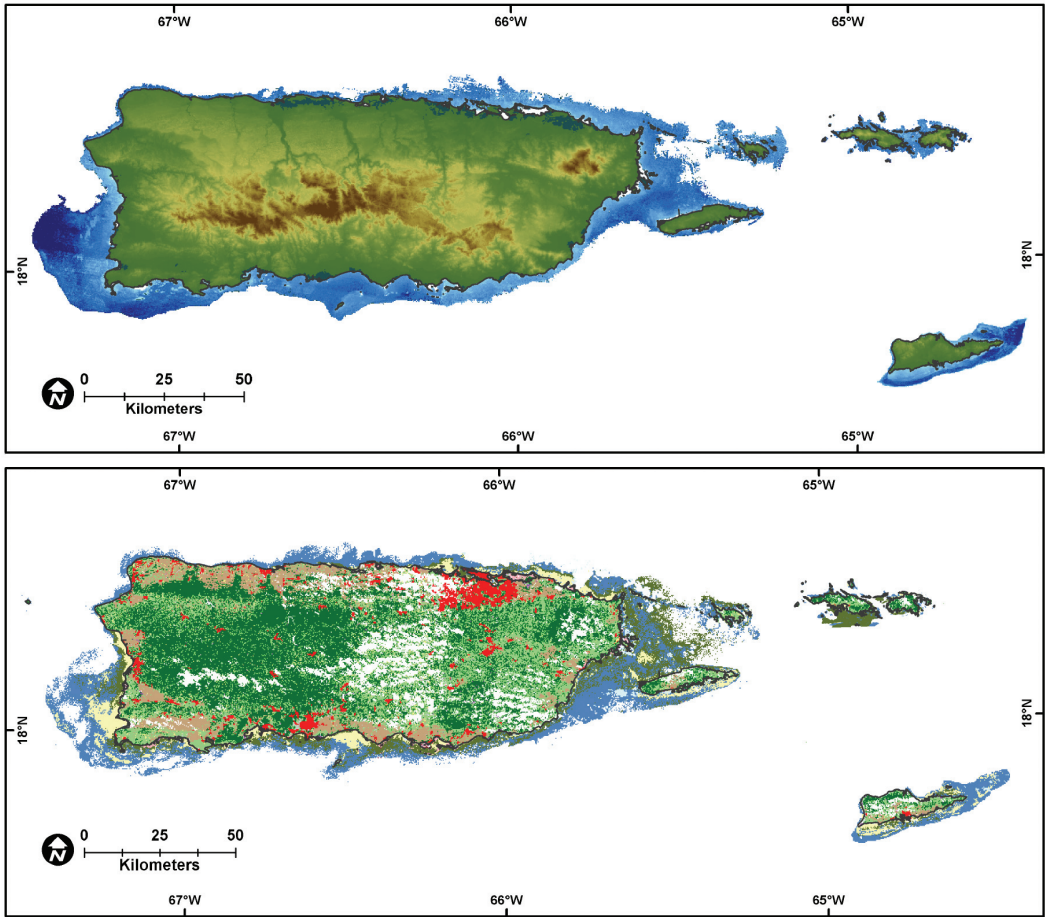


Fig. 1a.

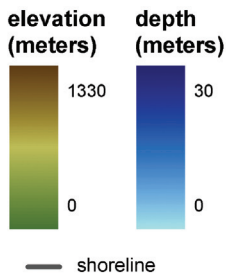


Fig. 1b.

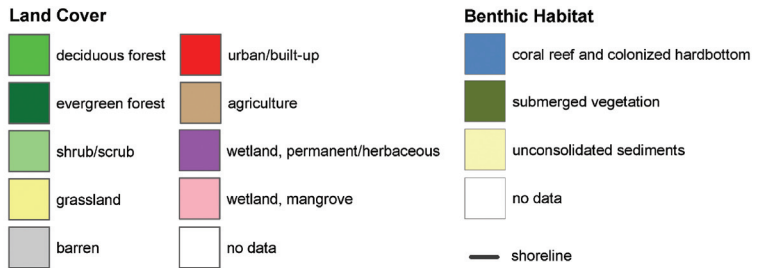


Fig. 1. (a) Bathymetry and elevation (terrain) and (b) Land cover and benthic habitat (cover) mapping for Puerto Rico and the U.S. Virgin Islands.

early date, followed by the later date directly below it, and finally, the second eigenmap for each analysis, including watershed boundaries and outflow points are in the bottom row of the figure.

In the first analysis column showing the annual pair of images, certain changes are apparent between the two dates. For one, a dark linear plume is seen along shore to the left in the 2001 image. There is also a bright blue

TABLE 4
Accuracy assessment for Puerto Rico benthic habitat classification

Classification	Reference points			Row total	User accuracy
	Coral reef/ hardbottom	Submerged vegetation	Unconsolidated sediments		
Coral reef/ hardbottom	117	27	3	147	79.6%
Submerged vegetation	25	134	22	181	74.0%
Unconsolidated sediments	17	19	108	108	75.0%
Total	159	180	133	472	-
Producer accuracy	73.6%	74.4%	81.2%	-	-

Classification mosaic created from four Landsat 7 ETM+ images (path 4 rows 47 and 48 acquired 3/27/2000, path 5 rows 47 and 48 acquired 11/13/2000). Sample size N=472. Overall accuracy= 76%, Tau= 0.68

area around the jetties to the right, near the port area. This distinct change is highlighted in the second eigenmap showing extreme eigenvalues in red and blue. The blue arrow points to the area of change representing the dark plume, which are areas that have changed from brighter in 2000 to darker in 2001. The red arrows show areas that are significantly brighter in the later date. In the second change analysis, the same plume is visible in 2003 (blue arrow), as well as the brighter areas along shore and near the port (red arrows). There is an additional red area close to the port that represents an area in the bay that has increased in brightness in 2003, and has an extreme eigenvalue.

DISCUSSION

The continuous summit-to-sea maps derived in this analysis demonstrate that Landsat imagery can be used to map both land and shallow water seas. The Landsat sensor provides the ability to estimate a continuous water depth and identify benthic habitats. Merging bathymetry with land elevation, results in a seamless terrain map displaying continuous topography of land into the ocean bottom environment. The benthic habitat classifications presented here demonstrate the ability for Landsat imagery to produce bottom cover maps for this classification scheme that have accuracies that are generally consistent with other studies (Capolsini *et al.* 2003, Mumby *et al.* 1997). Because of

the numerous Landsat acquisitions over the Caribbean, it is now feasible to create consistent, regional coral maps using the same techniques. Merging these maps with available land cover data could result in a moderate resolution land-sea map for the entire Caribbean.

The Landsat sensor has a longer history compared to other satellite platforms. Coral reefs are dynamic ecosystems, and undergo significant change in both long and short-term time frames. It is therefore very important to study these ecosystems at varying temporal scales.

The PCAs performed in St Croix have shown the ability of Landsat to isolate meaningful changes between satellite images taken at varying intervals. These changes could be surrogates for sedimentation, colonization of seagrass, pollution, or other local changes in marine systems. In both analyses, two types of changes were discerned using PCA: areas that became significantly darker from one time period to the next, and areas that were clearly lighter. The former are likely to be areas of seagrass colonization or pollution, which would make the water column appear darker.

The plume detected in both change analyses is a known outfall from the Cruzan Rum distillery that flows west with the prevailing currents (Anonymous 1979). Areas that change from darker to brighter in the later image are areas of possible sedimentation or suspended sediments, shown in red in the eigenmap, could be likely inputs from land, and affected by currents. The areas of sediment around the port

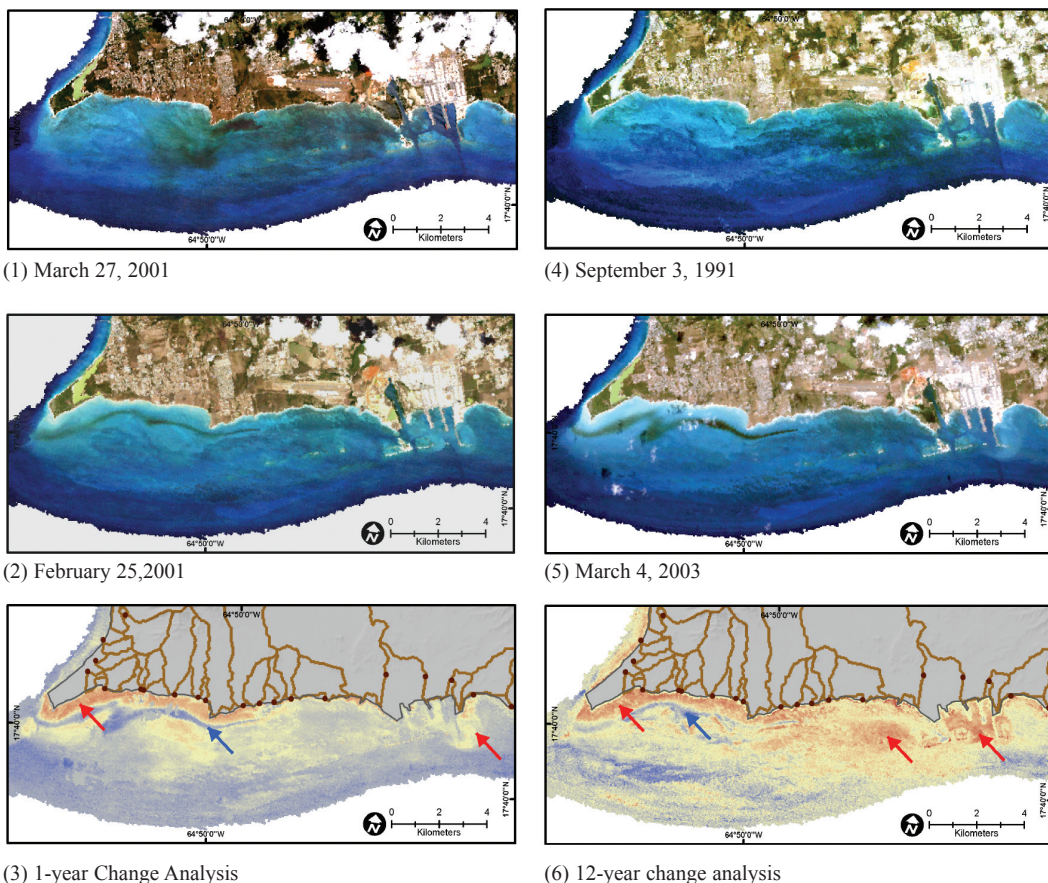


Fig. 2. Time change analyses using PCA in southwest St Croix. The shorter time interval from March 27, 2000 to February 25, 2001 is shown in the left column starting with the raw imagery for each date respectively in boxes 1 and 2. The final box 3 shows the delineated watersheds and outflow points (potential sources of land based pollution), and areas of change shown by the second principal component with extreme eigenvalues in red and blue, highlighting a dark plume that appears in 2001 (blue arrow), and brighter areas along the shore and near the port (red arrows). The long-term time change analysis shows the areas of change between September 3, 1991 and March 4, 2003. The raw images are shown in boxes 4 and 5. The second principal component in box 6 shows a similar plume along-shore (blue arrow), and sedimentation around the port, as well as an area of relative brightness west of the port area (red arrows).

area could be likely due to trapped currents from jetties, dredging, or ship traffic. Areas of sedimentation close to shore may be related to watershed outflow points.

According to the cover map, the southwest corner of St. Croix is mainly farmland, which makes run-off from land likely to be contributing to near shore turbidity. The Landsat sensor has shown that both short-term and long-term

changes are apparent in marine ecosystems, and this imagery can be used to detect meaningful changes, which is a useful tool for consistent coral reef monitoring at a regional scale.

The principal components analysis using Landsat has proven to be useful in detecting certain changes the marine environment at varying temporal scales, though it should be noted that neither the type of change, nor its frequency

can be determined from the PCA. Long-term changes such as seagrass colonization look the same in the PCA as short-term phenomena. Further studies and field verification are required to relate change identified by PCA to a specific type of change in the marine environment. Potential research includes studying imagery before and after large storm events, and groundtruthing areas of significant change. Given the large database of Landsat imagery available, additional analyses at small time intervals may show that some areas experience repeated or persistent change over time – such as the Cruzan rum plume, which appears and disappears in the Landsat time series. This could help identify particularly vulnerable reef areas for conservation and management.

The PCA demonstrated in this study can provide an important analysis tool in studying the dynamics of Caribbean reefs and the consequences of local anthropogenic effects in coastal environments and aid the mitigation of land-based sources of pollution on near-shore coral reefs. Given the capacity of Landsat to map both coral reefs and land areas and its current cost to process, this imagery will remain valuable for regional scale summit-to-sea mapping. In addition, these analyses are applicable to higher resolution imagery. Combining analyses from different sensors could add significant detail in target locations. With the continuously increasing data sets other sensors, satellite remote sensing of coral reefs will continue to play a vital role in mapping, monitoring and conservation.

RESUMEN

Se elaboraron mapas de Puerto Rico y las Islas Vírgenes Estadounidenses que muestran la cobertura del suelo y el fondo en arrecifes de coral (“mapas cima-mar”) con imágenes del año 2000 del Enhanced Thematic Mapper (ETM+) del satélite Landsat 7. Se fusionaron Modelos de Elevación Digital con batimetría satelital. Se caracterizaron hábitats bentónicos con clasificaciones “no supervisadas” de imágenes de Landsat, agrupando mediante datos de campo, y produciendo mapas con una precisión superior al 75% (coeficiente Tau >0.65). Estas caracterizaciones se combinaron con datos de Geocover-LC (uso /cobertura

del suelo) para hacer los mapas. Comparando pares de imágenes mediante Análisis de Componentes Principales se logró identificar las zonas de cambios en los ambientes marinos en dos periodos: 2000 a 2001 y 1991 a 2003. Se demostró la capacidad de las imágenes del satélite Landsat para producir mapas continuos cima-mar y para detectar cambios en los ambientes marinos someros, proveyendo así una valiosa herramienta para el monitoreo, el manejo y conservación efectiva de la zona costera.

Palabras clave: Sensores remotos, hábitat béntico, análisis de cambios, Landsat, arrecifes coralinos, mapeo.

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