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Richard Snow
Embry-Riddle Aeronautical University, snow4fc@erau.edu

Mary Snow
Embry-Riddle Aeronautical University, snowm@erau.edu

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GIS modeling and mitigation of coral reef damage

R. Snow[1], M. Snow[2]

1) Embry Riddle Aeronautical University, 600 S. Clyde Morris Blvd., Daytona Beach, Florida 32114, USA
2) Embry Riddle Aeronautical University, 600 S. Clyde Morris Blvd., Daytona Beach, Florida 32114, USA

Abstract. The objective of this study is to demonstrate that an efficient instrument for conducting surveys and inventories of coral reefs to assess those ecosystems at higher risk and develop mitigation strategies is through the use of a Geographic Information System (GIS). Efficient monitoring requires the assessment of various coastal data baselines and the evaluation of subsequent alterations in spatial patterns. While monitoring involves real-time components, among the most powerful tools of a GIS are its modeling capabilities, which allow simulation of various climate change scenarios. Relevant aspects include changes in coastal land use, wetlands, and shoreline configuration. Using Caribbean coral reef examples, the results of this research reveal that GIS techniques and applications play an integral role in defending coral reefs from climate change and other threats. Planners and politicians require the ability to analyze risks, assess impacts, and consider alternatives based on input from researchers across diverse disciplines. GIS provides the collective tool that integrates multifaceted data and transforms it into a meaningful medium for informed decision-making.

Key words: Geographic Information Systems, reef monitoring, reef management

Introduction

According to the most recent assessments from the Intergovernmental Panel on Climate Change (Mann & Kump 2009), as a result of climate change and sea level rise, the planet's coasts are exposed to multiple risks including coastal erosion, changes in sediment and nutrient transport, and additional coastal flooding. Heavily populated, low-lying areas, which already face other challenges such as tropical storms or local coastal subsidence, are especially vulnerable. Coastal wetlands, including mangroves and salt marshes, will be impacted by sea-level rise especially in places where they are inhibited from migration as a result of natural or anthropogenic barriers. Despite their diversity, coral reefs are highly susceptible to thermal stress and have low adaptive capacity. Increases in sea surface temperature of 1 to 3 degrees Celsius are projected to result in more frequent coral bleaching events and widespread mortality with increasing human-induced pressures on coastal areas aggravating these negative effects. A Geographic Information System (GIS) is a tool that can create, analyze, and display sea level rise scenarios helping managers address the negative effects of elevated sea levels by allowing them to identify coral reef communities that are at risk, assess the situation, and develop mitigation strategies.

Coastal Ecology and Economy

According to Cohen et al. (1997), 20% of the people in the world live within 30 kilometers of the coast and it is predicted that by the year 2100, approximately 600 million humans will live on coastal floodplains lower than the 1000-year flood stage (Nicholls & Mimura 1998). Burns (2000) reached similar conclusions regarding island populations reporting that most island inhabitants, along with their infrastructure and socioeconomic activities, are situated just a few hundred meters from the shore and as a result, are likely to experience negative impacts from rising sea-levels. The destructive effects could include coastal flooding, loss of wetlands, saltwater intrusion, increased erosion, and higher storm surges. Additionally, these impacts have the potential to affect many of the smaller islands in the Caribbean due to certain similar traits these islands share such as limited funds, natural resources, geographic size, and infrastructure (Leatherman 1997).

Granger (1997) states that the projected sea level rise could seriously damage the socioeconomic growth of smaller island states while Leatherman (1997) asserts that practically every social and economic sector will be disrupted. Smaller low islands might not have the physical size to deal with rising sea level, and residents might be forced to relocate to other countries, which could have dire socioeconomic costs (Nicholls & Mimura 1998). For example, the IPCC (2001) projects that on the island of Cuba a 1-meter rise in sea level would displace 50,000 people. Nicholls et al. (1999) suggest that 22% of coastal wetlands could be lost as a result of rising sea levels by the year 2080 and that the Caribbean Islands along with those of the Pacific and Indian Oceans will experience the greatest relative rise in frequent flooding. Over the past 15 years, some beaches on Trinidad and Tobago have reported annual erosion rates of 2-4 meters, which is primarily attributed to rising sea levels (Singh 1997).

Flooding and erosion also could adversely affect the tourism industry, which is a major economic sector on many islands of the Caribbean through the loss of beaches, saltwater intrusion, infrastructure damage, and other forms of degradation. Most of the islands with economies based primarily on tourism tend to concentrate their resources and infrastructure along the coasts where rising sea levels will have the greatest impact. The problem will be compounded by the fact that many existing tourist facilities currently are not adequate and frequently experience problems such as water shortages.

Many of the Caribbean Islands meet their water demands through an exclusive source such as rainwater, groundwater, importing, or surface reservoirs, which makes them vulnerable to a disruption in supply. For those islands that rely on precipitation stored during the rainy season, any variation in climatic patterns could be critical. The IPCC (2001) points out that on Barbados three months of the rainy season account for all of the groundwater recharge and, just 15% to 30% of the yearly precipitation actually makes it to the aquifer.

However, perhaps the most critical concern is the threat of saltwater intrusion, which is occurring on some islands, such as Barbados, due to over pumping. With an increase in sea level, intrusion could take place at pumping stations further inland as well as along the coasts. On Trinidad and Tobago, over pumping, which has been aggravated by rising sea levels, has contributed to a significant salinity increase among some coastal aquifers (Singh 1997).

Mangrove forests are an integral component of the island ecosystem offering protection from high tides and storm surges, while providing feeding grounds for numerous species juvenile fish and products. However, many mangrove habitats in the Caribbean are suffering from human exploitation and will face further stress with rising sea levels. According to the IPCC (2001), 62% of the mangroves in Puerto Rico have been eradicated due to anthropogenic activity, and a 1-meter sea level rise in Cuba could destroy 30% of that island's mangrove ecosystems. Alleng (1998) reports that due to the inability to migrate, Jamaica's Port Royal mangrove forest could be totally devastated with rising sea levels. Consequently, the loss of mangrove forests will have negative effects on local wildlife. For example, Sattersfield et al. (1998) observe that the forested areas of the Caribbean are home to most of the threatened bird species in the region.

Likewise, coral reefs supply food and shelter for marine flora and fauna while providing a natural barrier as well as income in the form of tourism and fishing for the Caribbean islands. However, a global inventory of Earth's coral reefs estimates that already nearly 60% are at risk due to the actions of humans (Bryant et al. 1997), and 90% of all living reefs have been damaged by coral bleaching (Goreau & Hayes, 1994). Regionally, the occurrence of coral bleaching will be the highest in the Caribbean and could take place on an annual basis over the course of the next 30-50 years (Hoegh-Guldberg 1999).

GIS Modeling and Mitigation

Among the steps that can be taken toward informing the public of these threats is the modeling of various sea-level scenarios using GIS. Beginning with the establishment of mean sea level for a particular location based on topographic quadrangle contour lines, which are the most valuable data for determining which locations might be inundated, it is possible to adjust sea-levels according to estimated rates of increase. As a result, the user can project future high water marks revealing areas under the potential threat of flooding.

The Environmental Protection Agency (EPA) has created a GIS using the United States Geological Survey's (USGS) 1-degree digital elevation series and the National Oceanic and Atmospheric Administration's (NOAA) digital shoreline data to produce a series of maps illustrating coastal areas below the 1.5-meter and the 3.5-meter contours for the eastern United States. The results suggest that approximately 58,000 square kilometers of coastline along the Atlantic Ocean and the Gulf of Mexico lie below the 1.5-meter contour and face the possibility of being flooded within the next two hundred years if sea level rises at a rate of 0.75 meters per century.

A similar GIS has been developed for south Florida that incorporates elevation and land use data to depict those areas with elevations of less than 5 feet and 10 feet. The GIS reveals that significant urban areas in Miami-Dade County could undergo flooding during high tide or storm surge events. A large portion of the Florida Keys have elevations below 5 feet that are at risk of inundation should sea levels increase at the rates predicted by the IPCC and other researchers.

Digital Elevation Models (DEM) and Triangulated Irregular Networks (TIN) also are being used to create three-dimensional GIS of areas that might be at risk as a result of rising sea levels. Three-dimensional visualization of such models allows the user to zoom and rotate the scene from a variety of angles for a better comprehension of the negative impacts associated with sea level rise. This technique can be especially effective when presenting inundation scenarios to administrative officials and the public.

Once the potential high water areas have been delineated, a GIS can be further developed to integrate a variety of related applications, such as surveys, inventories, monitoring, and modeling. Surveys and inventories of coastal ecosystems, including coral reefs, mangrove forests, and other biota can be incorporated into a GIS to assess those ecosystems at higher risk. Other surveys that are useful for determining vulnerability along coasts consist of population distribution such as residential, commercial, and recreational areas. Similarly, the infrastructure that supports these centers such as power generation and fresh water sources should be added to the GIS.

Efficient monitoring requires the assessment of various coastal data baselines and the evaluation of subsequent alterations in spatial patterns through the use of GIS. Relevant aspects might include changes in coastal land use, wetlands, and shoreline configuration. While monitoring involves real-time components, perhaps the most powerful tool of a GIS is its modeling capabilities allowing the user to simulate sea level rise scenarios while offering complete control over the conditions of the simulations which are made affordable and manageable through the use GIS.

GIS Coral Reef Applications

Numerous environmental organizations already make use of GIS as a principal tool in their protection arsenal. According to the website of the Center for Coastal Monitoring and Assessment (CCMA) at http://ccma.nos.noaa.gov, the mission of the CCMA is to assess and forecast coastal and marine ecosystem conditions through research and monitoring. The CCMA assesses the impacts of climate change on coastal ecosystems through various means such as remote sensing and GIS. Projects include habitat mapping, especially in coral reef environments. The GIS is used to assess the baseline conditions of each coral reef and monitor any changes. Among the goals of the CCMA is to develop a GIS of the benthic habitats of all coral reefs within U.S. waters, including territories as well as an assessment of reef fish ecologies. The CCMA already has mapped essential fish habitats of the U.S. Caribbean and provided color aerial photographs of near shore waters of Puerto Rico and the U.S. Virgin Islands.

However, perhaps the greatest contribution by the CCMA is the production of comprehensive, detailed maps of 2,360 sq km of the shallow-water benthic habitats of the Northwestern Hawaiian Islands. The products include a web site and CD-ROM that provide access to digital GIS data, maps, and satellite imagery depicting the location and distribution of shallow-water coral ecosystem habitats. The GIS maps are characterized by unprecedented detail and represent the first comprehensive assessment of benthic habitats of the shallow water environments of the islands. Efforts also are underway to update the coral ecosystem habitat maps of Florida. The CCMA is an outstanding example of an organization using GIS to provide the best available scientific information for resource managers and researchers as well as offering technical advice and easy accessibility to data.

Similarly, ReefBase is the official database of the Global Coral Reef Monitoring Network (GCRMN), as well as the International Coral Reef Action Network (ICRAN). The ReefBase Project is housed at the WorldFish Center in Penang, Malaysia, with funding through ICRAN from the United Nations Foundation (UNF). According to their website at http://www.reefbase.org, ReefBase gathers available knowledge about coral reefs into one information repository. It is intended to facilitate the analyses and monitoring of coral reef health and the quality of life of reef-dependent people, and to support informed decisions about coral reef use and management.

The website outlines numerous objectives of ReefBase which include developing a relational database and information system for structured information on coral reefs and their resources that will serve as a computerized encyclopedia and analytical tool for use in reef management, conservation, and research. Additionally, ReefBase collaborates with other national, regional, and international databases, and GIS facilities relating to reefs to provide a means of comparing and interpreting information at the global level.

The ReefBase online Geographic Information System (ReefGIS) allows the user to display coral reef related data and information on interactive maps. The ReefGIS offers layers with data related to the location of reefs by type such as barrier reef, fringing reef, patch reef, and shelf reef as well as reef geomorphology and reef depth. Other layers depict coral diseases, coral bleaching, and sea surface temperatures. There is even a layer of reefs that are currently being monitored and the name of the organizations charged with the task.

Among the most noteworthy undertakings by ReefBase is the development of the Millennium Mapping GIS. Using high-resolution Landsat images, ReefBase is collaborating with NASA and other partners to create the first global uniform map of shallow coral reef ecosystems. The full image archive and the GIS shapefiles are available through ReefBase to provide high-quality information about reef location, distribution, and extent.

The Caribbean Reefs at Risk map server at http://coralreefs.nbii.gov/reefsatrisk provides spatial information about coastal areas and human threats to coastal ecosystems for the wider Caribbean Region. Most of the data come from the Reefs at Risk in the Caribbean project sponsored by the World Resources Institute and from the University of the West Indies Caribbean Coastal Data Center. Reefs at Risk supports a GIS map analyzer, which allows interactive viewing of a wide range of spatial data on coral reefs, population, development, physical components, and is capable of modeling threats to the Caribbean reefs.

The Reefs at Risk in the Caribbean project was initiated to raise awareness about threats to coral reefs and to provide detailed information about threats in specific locations across the Caribbean region. These data are available on the map server along with an index of integrated threats. The Reefs at Risk in the Caribbean project also includes an assessment of the economic benefits associated with coral reefs and of economic losses as a result of coral reef degradation. Additionally, the project offers recommendations for preserving coral reef ecosystems.

Conclusion

Long-term studies are needed in order to develop a full understanding of the composition, structure and functioning of coral reefs. Such research includes the monitoring of coral reefs and enables the tracking of changes in the health, species composition, and functioning of these diverse and delicate ecosystems.

The optimal means of managing spatial data is through a GIS, which is capable of producing maps that incorporate numerous layers of interdisciplinary data. Data gathering, modeling, and dissemination through the use of GIS offers a tool for decision-making concerning coral reefs at every level. The small representative sample of organizations and institutions dedicated to coral reef conservation presented in this paper is intended to support the claim that GIS is a powerful tool with extensive spatial data analysis capabilities that can reinforce the process of coral reef protection and policy-making, as well as long-term integrated resource management.

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