Chapter 29
A Geographic Information Systems Approach to Mitigating Sea Level Rise: Examples from Bermuda

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Abstract 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. Projected sea level rise could seriously damage the socioeconomic growth of smaller island states, with practically every social and economic sector being disrupted. Smaller, low elevation islands might not have the physical size to deal with rising sea levels, and residents might be forced to relocate to other countries, which could have dire socioeconomic costs. The objective of this study is to demonstrate that a Geographic Information System (GIS) is an efficient instrument for conducting surveys and inventories to assess those small islands at higher risk and to develop mitigation strategies. 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. The results of this research reveal that GIS techniques and applications play an integral role in defending small islands from climate change and other threats.

Keywords Climate change · Sea level · Tropical storms · GIS · Bermuda · Storm surge · Aviation

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Short Introduction

A geographic Information System (GIS) is an effective way to organize large amounts of information, while allowing the user to complete a spatial analysis that readily identifies patterns. Depicting the impacts associated with climate change, such as sea level rise and the ability to determine the best way forward, make GIS an appropriate tool for decision makers. For this research, data were collected and analyzed for the Bermuda International Airport with the purpose of finding a practical solution to ensuring a sustainable aviation infrastructure into the future, while taking into account projections of sea level rise and storm surge.

Assessing Vulnerability

Since 1961, measurements demonstrate that the oceans absorb more than 80 % of the heat added to Earth's climate system, with this warming occurring to depths of at least 3,000 m (IPCC 2007). From 1955 to 1995, the global ocean warmed 0.7 °C with more than half of the heat stored in the uppermost 300 m (Levitus et al. 2000). This warming results in the thermal expansion of ocean waters and contributes to a rise in sea level. The observed rate of sea level rise due to thermal expansion was 0.42 mm per year from 1961 to 2003, and that rate was highest during the latter decade of that period (1993–2003) averaging 1.6 mm per year (IPCC 2007). When modeling thermal expansion to make predictions, there is a projected sea level rise of 0.1–0.4 m by 2100 (Mann and Kump 2009).

Presently, 20 % of the people in the world live within 30 km of a coastline (Cohen et al. 1997). Most island inhabitants, along with their infrastructure and socioeconomic activities, are situated just a few hundred meters from the shore, and, as a result, they are likely to experience the most resounding repercussions from rising sea levels (Burns 2000). The destructive effects will likely include inundation of properties, loss of wetlands, sea water encroachment into fresh water supplies, increased erosion, higher storm surges, and dislocation. Simultaneously, these impacts will affect many smaller islands worldwide due to certain shared traits such as dependence on tourism as their primary means of income, limited access to natural resources, small geographic size and little local topographic relief, and infrastructure that is often concentrated along coastlines (Leatherman 1997). The projected rise in sea level would seriously damage the socioeconomic growth of smaller island nations (Granger 1997). On the smaller, low elevation islands, residents are, and will continue to be, displaced from their homes and forced to relocate to other locations (Nicholls and Mimura 1998).

Bermuda resides in the North Atlantic Basin of tropical cyclone (hurricane) activity. This area is at its highest exposure to tropical cyclones between the months of June and November. The naturally developing weather occurrence is particularly dangerous in low lying coastal regions; however, it affects inland areas

Fig. 29.1 Bermuda international airport on St. David's island

as well. Wave energy of high intensity, produced by hurricanes, has been found to affect the coastline of Bermuda. The highest wave energy was found to be along the south shore, specifically in two regions. The two regions include the central south shore and the entrance to Castle Harbour. Erosion susceptibility around Bermuda is divided into four categories: low, moderate, high, and very high. Areas around Bermuda International Airport are susceptible to erosion in the high, moderate, and low categories. The eastern portion of the airfield is considered to have the highest vulnerability to erosion, although the direction of an approaching storm will determine the rate of erosion. The runway dimensions are 2,961 m long and 46 m wide (Fig. 29.1). The coastline, which comes into contact with the southern portion of the airfield, is Castle Harbour, and is considered an area of low erosion probability. However, wave energy has been known to pass through and around Castle Islands at the southern entrance of Castle Harbour. This wave energy can then continue to cause erosion issues for the current terminal and the southern coastline of the airfield, which is rated in the moderate erosion susceptibility category.

Hurricane Fabian

In September 2003, Bermuda was hit by a Category 3 hurricane named Fabian. The hurricane was a typical Cape Verde storm and was the first major hurricane to directly impact Bermuda since Hurricane Edna of 1953 (Miller et al. 2009). Some locations on the island reported atmospheric pressure during the event as low as 953 millibars. However, the official pressure at its closest point of approach to Bermuda was 961 millibars. Storm surges impacted the island for several days and reached estimated heights of 6–9 m along the most exposed south shore of the island with 1.8–2.4 m storm surges affecting the airport area (BWS 2003).

It should be noted that elevation of the terminal floor in the departure area of the airport is approximately 3 m above mean seal level and the runway elevation is a mere 1.8 m higher. Storm surge wave run-up created by Hurricane Fabian and impacting the airport reached approximately the same level as the runway elevation, as evidenced by debris lines left by the sea water on the runway. The terminal building was flooded by 0.91 m of seawater.

Figure 29.2 is a GIS rendering of sea level and storm surge of 1.8 m, such as was experienced as a result of Hurricane Fabian. The resulting repair work at the Bermuda International Airport was reported to have been $15 million (USD) from damages, which included damage to the passenger terminal, Instrument Landing System (ILS), radar, and debris on the runway from ocean water, completely inundating the runway during the event. No proactive damage limitation measures have been installed since that time. As sea level increases, storm surge may impact the Airport at a higher cost to the Government of Bermuda (Miller et al. 2009).

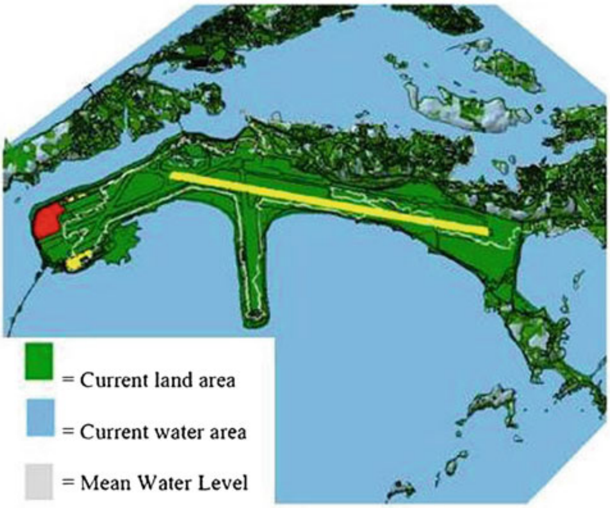

Fig. 29.2 Hurricane fabian mean water level 1.8 m

GIS Simulation of Mean Water Level

Various sea level rise scenarios and the associated threats to coastal locations can be modeled using GIS. The simulation begins with the establishment of mean sea level for a specific coastal area based on topographic quadrangle contour lines, which are the most important data source for assessing areas that might be flooded. Local mean sea level can be increased according to the elevation estimations derived by the models allowing the user to project future high water marks to reveal the areas under the greatest risk of inundation.

After demarcations of high water marks are made, the GIS can be further developed to incorporate a wide range of applications, such as surveys, inventories, monitoring, and modeling.

Surveys that are useful for assessing vulnerability near airports include navigational aids, service facilities, cargo, maintenance, aprons, taxiways, runways, civil terminal areas, and service roads. Also, the infrastructure that supports the airport's land use, such as fresh water supply, power transmission, and production were added to the GIS to approximate demands and keep disruption to a minimum. In a study conducted for the Government of Bermuda, synthetic storms were created in models that computed storm surge sea levels and did not factor in a specific directional approach of a hurricane. These models assumed a predicted global sea level rise (GSL) in the next 50 years to be 0.25 m (0.82 feet).

This prediction is on the conservative side of forecast sea level rise and could be as much as approximately 0.6 m (1.97 feet) more or less depending on the impact of climate change in the near future. A GSL of this magnitude or higher will have a significant impact on the aviation infrastructure in Bermuda due to the storm surge water levels reaching unprecedented heights in a 1-in-150 year event. To assess the vulnerability of Bermuda's airport, multiple factors such as the inverse barometric pressure rise (IBR), GSL, tide heights, intensity of the storm, effects of inland regions of water, and the nearshore environment need to be taken into account. Previous studies have compiled values that will be used to predict a worst-case scenario storm surge in the Castle Harbour north region in a 1-in-50 year hurricane event. The values also include a predicted worst-case scenario storm surge in the Castle Harbour north region with a 1-in-150 year or major hurricane event. IBR is dependent on the pressure inside the storm. The deeper the low pressure inside of the hurricane, the less weight is exerted on the ocean causing it to increase the water level in that specific region. The closer to the center of the low pressure, the higher is the effect of IBR, which may create a dome of water. Tide heights were calculated by using mean higher high water (MHHW) measurement above mean sea level (MSL) around Bermuda based on recorded data (NOAA 2010).

The GIS simulation included expected normal high tide level and expected tropical cyclone storm surge plus a wave setup factor from extreme wind. The Bermuda Coastal Erosion Vulnerability Assessment (2004) calculated static storm surge data by using a model to simulate waves, named Simulating Waves

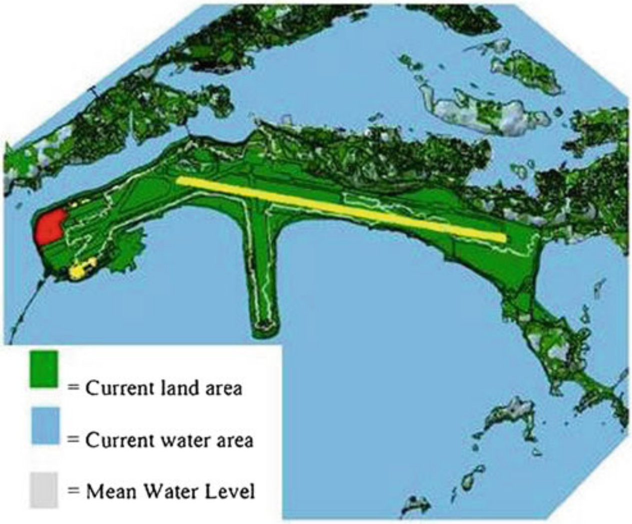

Fig. 29.3 Mean water level 2.25 m

Nearshore (SWAN). Using SWAN, interpolation, and data attained from previous hurricanes, static storm surge was given a value for each category of hurricane under a proposed sea level rise of 1.5 m by 2100 (Grinsted et al. 2009). Finally, the combination of factors was used to graphically represent the mean water level (MWL) at specific regions of coastline around the airport. Figure 29.3 depicts an MWL of 2.25 m, which is equivalent to a Category 4 hurricane striking Bermuda today, or a Category 2 making landfall in 2075, based on the suggested sea level rise of 1.5 m by 2100. Under this scenario, the new terminal, old terminal, and much of the operational runway would be underwater and most likely damaged beyond repair.

Taking the simulation to the worst case scenario, Fig. 29.4 depicts MWL of 3 m which could be associated with a Category 5 hurricane striking in 2100 under the suggested sea level rise. The only areas of the airport not completely inundated in this extreme case are the land reclaiming facility, roofs of the civil air terminal, and the mail center. The area for the future air terminal would also be underwater.

Implications for the Bermuda International Airport

With rising sea levels and possible increased storm surge and erosion, the distance to the Atlantic Ocean and the runways and taxiways will decrease. The International Civil Aviation Organization (1999) requires, where practical, to have a runway strip area of 150 m either side of the centerline and 60 m beyond the end

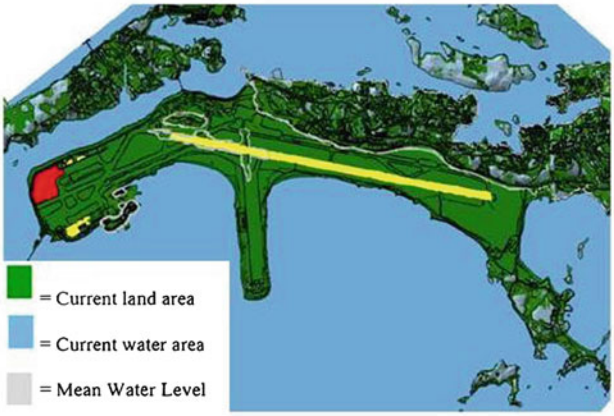

Fig. 29.4 Mean water level 3 m

of the runway. Also, the runway end safety area (RESA) should be at least 90 m from the end of any runway strip totaling 150 m. For the length of Bermuda's runway, the RESA is a code number 4 and is suggested to be 240 m or as far as practicable. The purpose of the RESA is for aircraft overshooting or undershooting a runway, and they have been proven to greatly increase the safety at a particular airport. Due to the Bermuda airport's position in relation to Castle Harbour, the Atlantic Ocean, and being on St. David's Island, it may prove difficult to create a sufficient RESA due to the site of the runway and taxiways.

With more tropical cyclones impacting Bermuda with increased intensity, storm surge levels will become higher than ever before due to increased sea level. This could lead to MWL higher than witnessed during hurricane Fabian at Bermuda's airport. Increased MWL would lead to more damage to facilities from floating debris, wave forces, water weight, and erosion of surface features. Areas reached by Fabian's storm surge made portions of the airport and the island's infrastructure unusable after the hurricane had passed. Examples of the storm surge destroying or damaging Bermuda's infrastructure during hurricane Fabian include much of the causeway bridge, the civil air terminal, and area service roads on the Castle Harbour side of the airfield. This type of damage could reach the only currently active runway and cause increased damage to the civil terminal at the Bermuda International Airport. Damage felt by increased storm surge would lead to a crippled aviation infrastructure in Bermuda.

Although navigational aids are shifting to more space based technologies for instrument approaches such as GPS/RNAV approaches, Very-high frequency Omni-directional radio Range (VOR) approaches are still used. Airport lighting in the ground would also be damaged during storm surge inundation. Damage to Bermuda's ground-based facilities and equipment due to the increase in major hurricanes would reduce the airport's redundancy and safety measures for aircraft landing in Bermuda. Instrument approaches, lighting for night operations, and visual aids for approaches such as the PAPI are aids used by airports to conduct safe and effective operations for the users.

Other ground based facilities and equipment at the airport are already vulnerable to damage from major hurricanes and may be more significantly and frequently damaged as sea level rises. Bermuda's airport will be more likely to experience damage into the future as more major hurricanes affect the island, combined with sea level rise due to elevation and location of the ground facilities and equipment. The VOR is located in an area less than 2 m above sea level and is continually vulnerable to inundation by passing hurricanes. Significant damage to Bermuda's only operational runway due to a higher storm surge during tropical cyclone events in the future, would lead to a slower and more difficult recovery effort for the island.

GIS depictions of storm surge inundating much of the airport show that it could become a more common occurrence with increased sea level and a more active yearly hurricane season. Medical aid, food supplies, and outside assistance would have to find different sources of transportation to reach people in a relief effort. The delay in assistance could lead to slower economic and social recovery from the tropical cyclone event. Hurricane Katrina's effect is still being felt over five years after it plowed into the gulf coast. Fabian's cost to repair Bermuda's airport and the Government of Bermuda would be dwarfed if a category 3, 4, or 5 hurricane struck in the future due to higher MWL. Bermuda's fastest link to the rest of the world would be crippled with the next closest means of transporting goods then being marine transportation. The longer the airport is not operational in bringing goods, services, people, and business to and from Bermuda, the greater will be the impact on the island's economic well-being. The cost of a lengthy airport shutdown to Bermuda's public and private sectors must not be underestimated. Ripple effects would further impact the island's economy due to Bermuda's heavy reliance on aviation for international business, tourism and perishable goods being transported. Runway repair would be costly and difficult to accomplish in a short amount of time without outside assistance and services, due to limited access to supplies and specialized workers in Bermuda.

Some engineering measures have been taken to protect the civil air terminal since Fabian, but it has not been tested by a hurricane of similar intensity and proximity to Bermuda. Increased damage to the civil air terminal due to increased exposures to tropical cyclones or increased intensity could lead to extreme costs for repair or replacement. Factors of erosion and corrosion, from increased exposure to the ocean due to climate change, could increase operational costs for the Government of Bermuda.

Recommendations for Mitigating Sea Level Rise

GIS depictions show that the airport is already at risk of being inundated from storm surge. As time progresses, the GIS depictions show less powerful hurricanes having increased impact on the airport. Although most scenarios do not expect sea level to increase a significant amount in the next half century, Bermuda's long-term airport plan should consider solutions to sea level rise due to climate change in advance to prevent a heavy burden on tax payers in the future.

With Bermuda's new civil air terminal still in its planning stage, adjustments may have to be made to current plans. Adjustment may include increased elevation of the planned height above sea level for the future terminal. The new terminal will not be built for some time, as the priority of Bermuda's citizens is currently with the construction of the new hospital. Due to the current economic climate, the project may not happen for quite some time. Considering possible future outcomes of climate change, such as sea level rise, an assessment into the elevation and vulnerability of the new civil air terminal should be accomplished to ensure a strong aviation infrastructure into the future.

Possible solutions should start with a more in depth hazard assessment of the potential damage and costs versus the cost to prevent damage. It may take an extreme event for action to be taken for prevention solutions to justify the costs of seawater protection. Further research should examine the cost of a major hurricane impacting Bermuda's airport in the future. The total toll on the economy should be assessed for factors such as the transportation of goods, services, and people being completely cutoff from the outside world. The cost of unplanned repair of the runway, taxiways, civil terminal, navigational equipment, and other essential services should be included.

Engineering solutions should be further researched to ensure that the people and government of Bermuda are prepared, protected, and secure from the threats to the airport from storm surge and sea level rise. Engineering seawater protection should consider short and long-term solutions including breakwaters, revetment, and raising airport elevation. A long-term airport plan of land reclamation efforts at Bermuda's airport should be instigated to optimize efficient use and protection of the airport. Environmental impacts of land reclamation to Bermuda's marine life and Castle Harbour should be examined to prevent negatively influencing the area through pollution.

The Government of Bermuda should consider using a seaplane access for emergency relief efforts in future extreme events. Areas that are limited to exposure should be investigated as possible areas for seaplane docking. Since the former flying-boat stations are available, an assessment of the use of these facilities for relief efforts and emergencies in the future should be considered for additional options to Bermudians. Finding the exact height of wave-up action during storm surge inundation of the Bermuda International Airport should be further studied. This would give indications of possible impacts to other areas of Bermuda besides the airport, which includes residences, businesses and infrastructure. Other infrastructure besides aviation that may be affected by the increased sea level and storm surge due to climate change could be electricity, water, and marine and ground transportation.

Lastly, additional research should be done on the cost of building up the elevation of the airport for long-term implications of climate change. An example of other airports being elevated is the artificial island airport in Japan, named Kansai

International Airport. Although the scale of Kansai International Airport construction is much larger than Bermuda's elevation rise and land reclamation project will need, lessons could be learned from the project (KALD 2008). For efficient planning to occur, an effective policy is needed that assesses the numerous coastal databases and projections of both global temperature and sea level rise. GIS can be an important planning tool for this task due to its ability to speed the decision-making process by allowing easier management of data, modeling various climate change scenarios, and graphically depicting the impacts.

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