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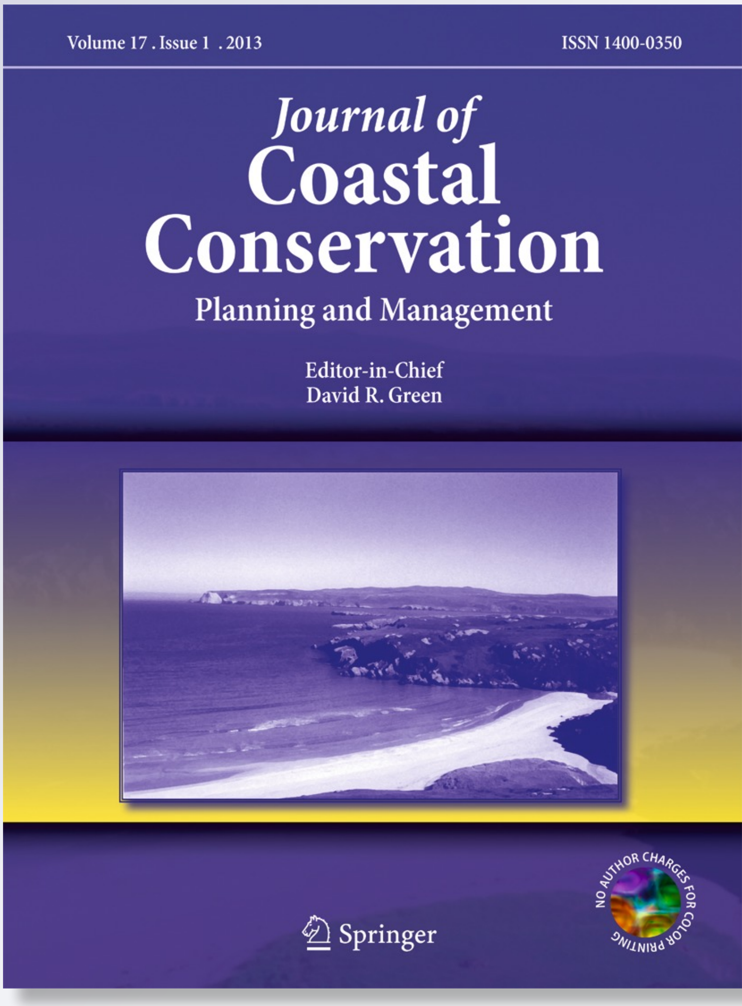

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Abstract Caroni Swamp Ramsar Site, the largest mangrove dominated wetland in Trinidad and Tobago, continues to be impacted by human activities. This study examines changes in land cover and land use from 1942 to 2007 using remote sensing technology, geographic information systems (GIS) and extensive field surveys. Land cover maps were produced for 1942, 1957, 1986, 1994, 2003 and 2007 from aerial photos and high resolution satellite imagery. Caroni Swamp's hydrology was altered in the 1920's to facilitate rice cultivation. This resulted in the formation of large tracts of freshwater marsh. From 1942 to 1957, freshwater marsh and agriculture lands increased, but after this period there was a steady decline in both, as freshwater was diverted away from the wetland and salt water intruded further inland. Although mangrove forest was cleared for built development, its coverage has consistently increased in the Swamp from 1957, with the exception of 2003 when there was a decrease by less than 100 ha. This is in contrast to most areas in the tropics where mangrove coverage continue to decline. In this case, the mangrove trees are out-competing/shading marsh vegetation, causing shift in the wetland communities. In the Caroni Ramsar Site, the natural wetland communities generally increased from 1942 to 2003, but declined in 2007, as built development more than doubled. The paper provides spatial coverage, and quantifies land cover from 1942 to 2007. It also identifies reasons for the changes in land cover and uses, and the implications for management.

Keywords Mangroves · Agriculture · Remote sensing · GIS · Land cover · Hydrological alteration

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Introduction

Human transformation of land to yield goods and services represents the most substantial changes to ecosystems worldwide (Millennium Ecosystem Assessment 2005; Worm et al. 2006). Material demands of production and human consumption alter land use and land cover, biodiversity, and hydro-systems locally to regionally; and waste discharge affects local to global biogeochemical cycles and climate (Grimm et al. 2008). While it is difficult to quantify alterations to marine ecosystems, changes are substantial as about 60 % of the world population lives within 100 km of the ocean (Vitousek et al. 1997). Coastal wetlands that mediate interactions between land and sea have been altered over large areas; approximately 50 % of mangrove ecosystem globally have been transformed or destroyed by human activities (World Resources Institute 1996; Valiela 2006; Valiela et al. 2009).

Wetlands were once considered wastelands which would better serve nations when filled for built development or drained for agriculture (Field 1995). This perception is changing as research conducted during the past four decades have highlighted the value of wetlands and the services they provide. The Millennium Ecosystem Assessment (2005) classified wetland services as provisioning (food, water and fuel), regulating (erosion, flood control, climate regulation), cultural and supporting (tourism and recreation), and has acknowledged their tremendous economic benefits (Blumenfield et al. 2009). Yet, wetland coverage worldwide continues to decline as human population increase.

Trinidad and Tobago, like other Small Islands Developing States (SIDS), has a small land mass, high population density and concentrated economic activities along the coast. In addition, development activities within these smaller river basins have an almost immediate impact on the coast. In almost all Caribbean watersheds, population growth threatens to overwhelm any attempt to implement rational coastal management

(Mosher 1986; Kjerfve et al. 2002). In Trinidad and Tobago the population has almost doubled from 600,000 in 1950 to 1.2 million in 2000 with approximately 70 % living on the west coast of Trinidad (CSO 2000). As local populations have increased across the decades, there have been parallel changes in land cover and extensive re-working of the landscape.

The Caroni River Basin, the hydrometric area that encompasses the Caroni Swamp, is situated in northwest Trinidad and covers about 883.4 km^2, equivalent to 22 % of the land surface area of the island (Juman et al. 2002) (Fig. 1). This River Basin is the most populated part of the country (density = 439 persons km^{-2}), housing 33 % of the national population (CSO 1995) and contains some of the most fertile land in the country (Brown et al. 1966). Increased competition for lands in the flatter areas of the basin has led to built development on the fertile lowlands, encroachment into the wetland area and additional development on steeper slopes.

The Caroni and associated Rivers discharge into the Caroni Swamp, the largest mangrove forest in Trinidad and Tobago, but the second largest wetland after Nariva Swamp (Juman et al. 2002). The Swamp is situated southwest of the capital, Port of Spain. The mangrove forest is a mixed system of the *Rhizophora-Avicennia-Laguncularia* association. *Rhizophora mangle* (L.) is the dominant species, with a few small stands of *R. racemosa* (G.F.W. Meyer) and *R. harrisonii* (Leechman). The more landward areas are dominated by *Avicennia germinans* (L.) Stearn, with isolated patches of *A. schaueriana* (Stapf & Leechman). *Laguncularia racemosa* (L.) Gaernt is ubiquitous, but nowhere common (Juman et al. 2002). The eastern borders of Caroni Swamp are occupied by saline marshes, dominated by sedges (Cyperaceae) in association with grasses (Graminaea and Poaceae) and the fern *Acrostichum aureum* (L.) which grades into rice fields (Bacon et al. 1997). The swamp is important economically for oyster and fish harvesting, for hunting and for ecotourism, particularly birdwatching. Major commercial fisheries are based on demersal stock in the adjacent eastern Gulf of Paria.

Caroni Swamp was altered in the 1920's under the Cipriani Reclamation Scheme which was initiated to facilitate rice cultivation. The scheme involved hydrological alterations to the swamp; embankments were built, channels were cut, and two tide exclusion sluices were constructed (Bacon 1970; Fig. 2). The Reclamation Scheme was officially abandoned in 1954 by which time the canals and embankments were already in a state of disrepair (Bacon 1970). Further flood protection works which began in the 1950's and the construction of the Caroni Arena Dam resulted in an overall reduction of freshwater inflow into the Caroni Swamp (Phelps 1997). This has reduced freshwater storage in the wetland and caused salinity levels to

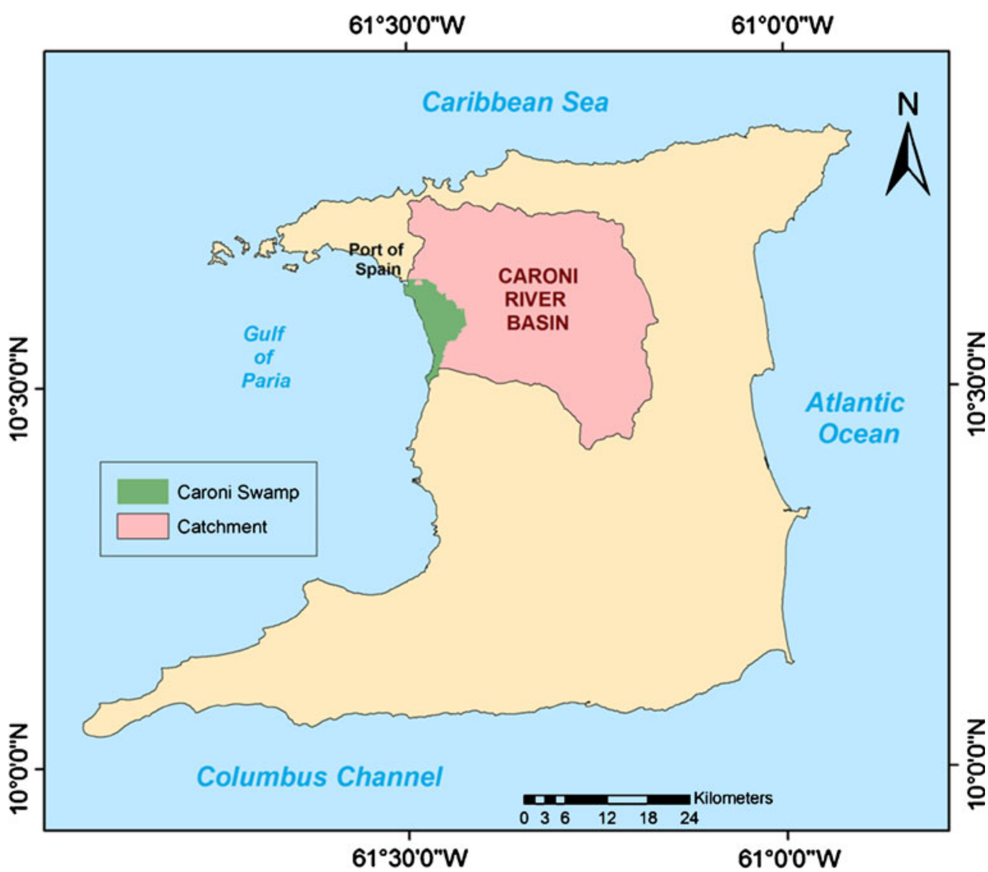

Fig. 1 Location of Caroni Swamp, Trinidad

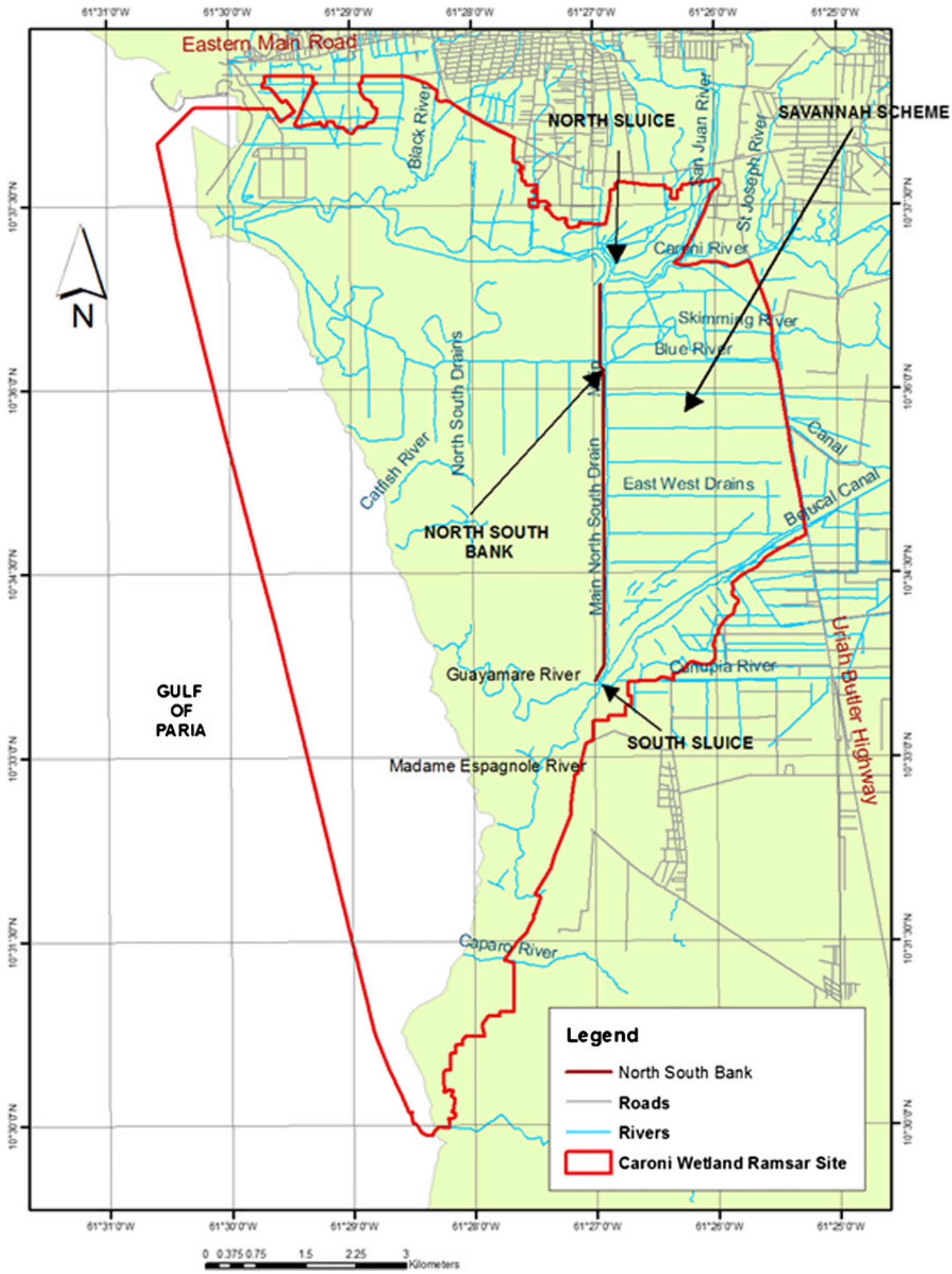

Fig. 2 Map showing channels within the Caroni Swamp Ramsar site

increase. In addition to saltwater penetration, the Caroni Swamp receives water polluted with sewage, wastewater from industry and agriculture run-off (Phelps 1997).

Prior to 1965, the eastern border of the Caroni Swamp was predominantly freshwater marsh with extensive tracts of sedges and grasses comprising *Paspalum serpentinum*

Hockst, *Cyperus articulatus* (L.), *Eleocharis mutata* (L.), *Mariscus ligularia* (L.) Urb. and *Pycreus odaratus* (L.) Urb (Beard 1946; Bacon 1970). Water lilies *Pistia stratiotes* (L.), *Eichhornia crassipes* Solms and *E. arurea* Kunth were common. From July 1966 to February 1968 surface salinity in this section of the Swamp ranged from 2.4 to 5.1‰ with a mean of 3.1‰ (Bacon 1970). Bacon (1970) hypothesized that there was likely to have been a large lagoon, bordered by freshwater marsh along the eastern border of the wetland. Distributary patterns and water movements were altered by the drainage work, leading to impoundment of land run-off to the east and influencing the location and extent of colonization by freshwater species. As the tide exclusion banks deteriorated in the late 1960's, the wetland began to revert to its former structure.

Between 1922 and 1985, more than 500 ha of mangrove forest were lost for the construction of roads, sewage ponds, landfill, and as a result of dredging to widen the River (Gerald 1985). In 2001, 170 ha of mangrove dieback were detected from Landsat imagery within the Caroni Swamp Forest Reserve. More recently, private landowners have cleared wetland and there is encroachment on the eastern boundary from illegal housing. Management of this wetland has become very challenging since most of the impacts on the wetland emanate from outside its boundaries and there are issues of land tenure. Caroni Swamp Ramsar Site has been impacted by human activities within the catchment areas and within its borders which have resulted in changes in the plant communities over time. The aim of the study is to determine decadal changes in major plant communities such as mangrove forest, marshes and agriculture within this wetland, by assessing the land cover and land use from 1942 to 2007 using aerial photography and satellite imagery. Mangrove forest is expanding at the expense of freshwater marsh communities as a result of hydrological alterations and salt water intrusion.

Methods

The boundaries of the Caroni Swamp were defined using physical and biological characteristics: topography (below 7.62 m contour), hydrology, and vegetation community. Aerial photography from 2003 along with extensive ground-truthing surveys conducted between November 2004 and April 2005 were used to delineate the boundary of the wetland and various land cover classes. Additional ground surveys conducted in October 2008 and February 2009 were used to validate land cover classes delineated from 2007 IKONOS satellite imagery. Data sources include:

- 1:25 000 Topographic Map Sheets
- 1:50 000 Aerial Photographs (1942)
- 1:12 500 Aerial Photographs (1957)
- 1:10 000 Aerial Photographs (1986)
- 1:12 500 Aerial Photographs (1994)
- 1: 25 000 Aerial Photographs (2003)
- IKONOS Satellite Imagery (2000–2007)

The data layers generated were imported into a GIS for mapping, change detection and analysis. Features mapped and assessed for changes over time include:

- Wetland plant communities: mangrove forest, marshland, open water area.
- Agricultural areas/rice lands
- Water channels/rivers
- Land use (roads, built development, landfill, treatment plant)

Visual interpretation was used to identify land cover classes from the aerial photographs by manual delineation of the boundaries separating one class from another. The major plant communities (natural and agricultural) within the system were identified, following the classification for Caribbean wetlands provided by Bacon (1993). The Caroni Swamp spans a relatively small land area. Due to its natural evolution and anthropogenic influence the area consists of large homogenous areas of different land cover types with fairly well defined boundaries. Studies have shown that visual interpretation can be used effectively for small regions (Minnich and Bahre 1995; Skinner 1995) and for regions with coarse land cover types (Turner et al. 1996; van Wyk et al. 1996). Computer aided classification techniques were not applied to the aerial photos in this study due to the inherent problem of bidirectional reflectance exacerbated by poor data quality.

Over 100 hardcopy photographs were scanned for each of the years (1942, 1957, 1986, 1994 and 2003) using a simple desktop scanner at a resolution of 300 dpi. This cheap method allowed for small workable file sizes that could be easily mosaicked and manipulated in the computer environment. Limitations to this method however included reductions in the quality of the radiometric information transferred as well as the geometric accuracy of the image. The aerial photos were re-sampled to match the 1 m pan sharpened RGB IKONOS imagery. They were then mosaicked to form complete coverage of the study area for each epoch using ER Mapper 7.0 software.

The IKONOS satellite imagery used for this study was supplied minus the Near IR band, effectively limiting the usefulness of computer aided classification. Satellite image tiles were mosaicked using ER Mapper software to produce a complete coverage of the study area. Initial trials of unsupervised classification on the RGB IKONOS image yielded results that were less accurate than results from the visual interpretation-manual delineation method.

Both sets of mosaics (aerial photos and satellite image) were georeferenced and registered to the Naparima Datum–UTM projection using digital versions of spatially referenced maps. Orthorectification using a DEM was not carried out since the study area was topographically uniform, with its highest point being less than 8 m above sea level, (implying that distortions in the image due to relief were minimal). The ground control points (GCPs) used for the rectification process involved elements such as road intersections, fixed man made features, and water course junctions, which are all difficult to be determined at accuracy levels higher than 2–3 m. A further correction based on a third order polynomial transformation was applied to reduce the total error and improve the spatial matching between mosaics to 4 m.

Once coincident mosaics were produced, land cover classes were derived through visual interpretation and manual delineation using ArcGIS 9.3 software. Land cover types were identified based on texture and ancillary data such as historical maps, ground truth data (for 2003 and 2007) and local knowledge. The boundaries of the land cover classes were then vectorized in ArcGIS to produce polygon shapefiles. Following this, the spatial statistics function in Spatial Analyst (ArcGIS) was used to calculate areas of each land cover class for each epoch. Evaluations of the changes among different epochs were then carried out based on a quantitative assessment of the changes in areas of the respective classes.

Independent ground data was used to verify the boundaries of delineated classes and assess the accuracy of the overall visual interpretation for the 2003 and 2007 vector maps produced. Overall, an accuracy matrix produced 95 % true values. This is exceptional when one considers that ground points were collected with a hand held GPS device that had a positional error of 3–5 m and that the mosaics had their intrinsic locational error as well. It must be noted that the accuracy of the vector maps produced for 1942, 1957, 1986 and 1994 could not be accurately assessed. However, considering that the visual interpreter was the same throughout and trained in discerning the vegetation types, particularly in this region, there is no reason to suspect any critical differences in accuracy between both sets of outputs.

Results

Knowledge of Caroni Swamp's current and past extent, condition and uses is essential so that managers can make effective interventions, so as to maintain and if necessary, restore ecosystem services. Caroni Swamp is a mangrove dominated wetland that has undergone major land cover/land use changes (Figs. 3 and 4). In 65 years (1942–2007), mangrove coverage in the swamp increased by 1,105 ha while marshland decreased by 523 ha and agriculture decreased by 393.5 ha (Fig. 3). Built development increased by 835 ha while a solid waste landfill expanded from 47.5 ha in 1986 to 73.7 ha in 2007 (Fig. 3). Generally, natural wetland communities (mangrove, marshes and open water/pond) increased between 1942 and 2003, as agriculture lands reverted to marsh and mangroves colonized new areas: mudflats and deposited dredged spoilt. However, between 2003 and 2007, natural wetland coverage declined by about 346 ha as built developed and agriculture lands increased (Fig. 5).

Discussion

In 1942, a larger portion of the Caroni Swamp was covered with freshwater marsh vegetation and agriculture; primarily rice fields (Fig. 4). Bacon (1970) provided a detailed description of this marsh community comprised of extensive

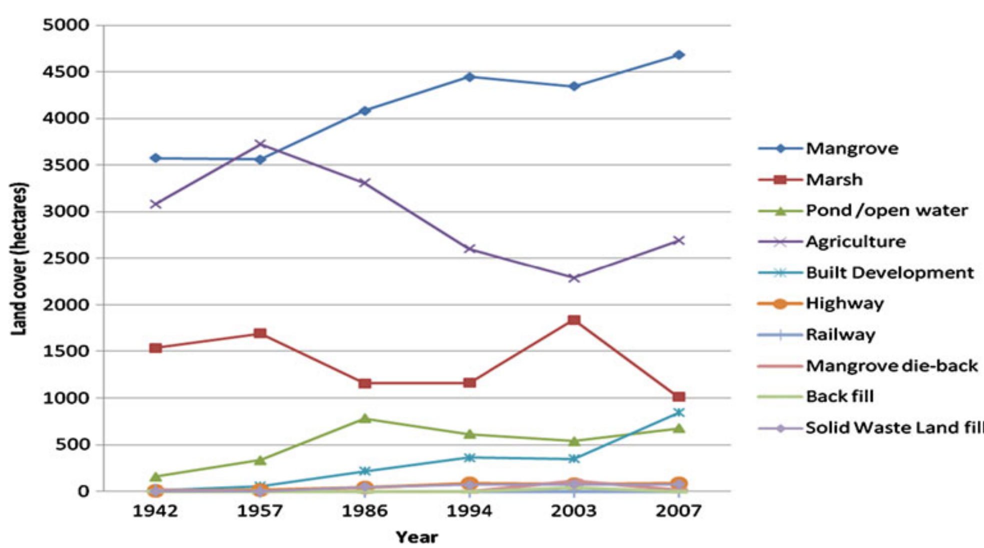

Fig. 3 Changes in land cover in the Caroni Swamp from 1942 to 2007

tracts of sedges and grasses. Beard (1946) and Bacon (1970) postulated that the construction of the tidal exclusion embankment (N-S Embankment) in the 1920's may have led to the development of the freshwater marshland, and therefore this section of the swamp may have developed artificially. In the 1942 image, mangrove forest was found mainly west of the N-S embankment, except in the south along the banks of the Madame Espagnole River (Fig. 4).

By 1954, the N-S embankment and the enclosing polder embankments constructed in the 1920's to reclaim swampland for rice cultivation were already in a state of disrepair, allowing saline water to enter the reclaimed area once again (Bacon 1970). A new swamp drainage channel constructed under the reclamation scheme provided a conduit for saline water to enter (Phelps 1997) and mangrove began colonizing the marsh area (Fig. 4). By 1957, agriculture had increased by 639 ha and there were slight increases in built development and marsh vegetation (Figs. 3 and 4). There was a small decrease in mangrove coverage as more drains were cut and pond and open water areas increased. While the agriculture land expanded on the eastern edge of the swamp taking up marsh area, agriculture land on the northern edge reverted to marsh, and mangrove area on the southeastern edge was colonized by marshes. The Uriah Butler Highway was constructed and it partially blocked the free flow of flood waters of the Caroni River arriving

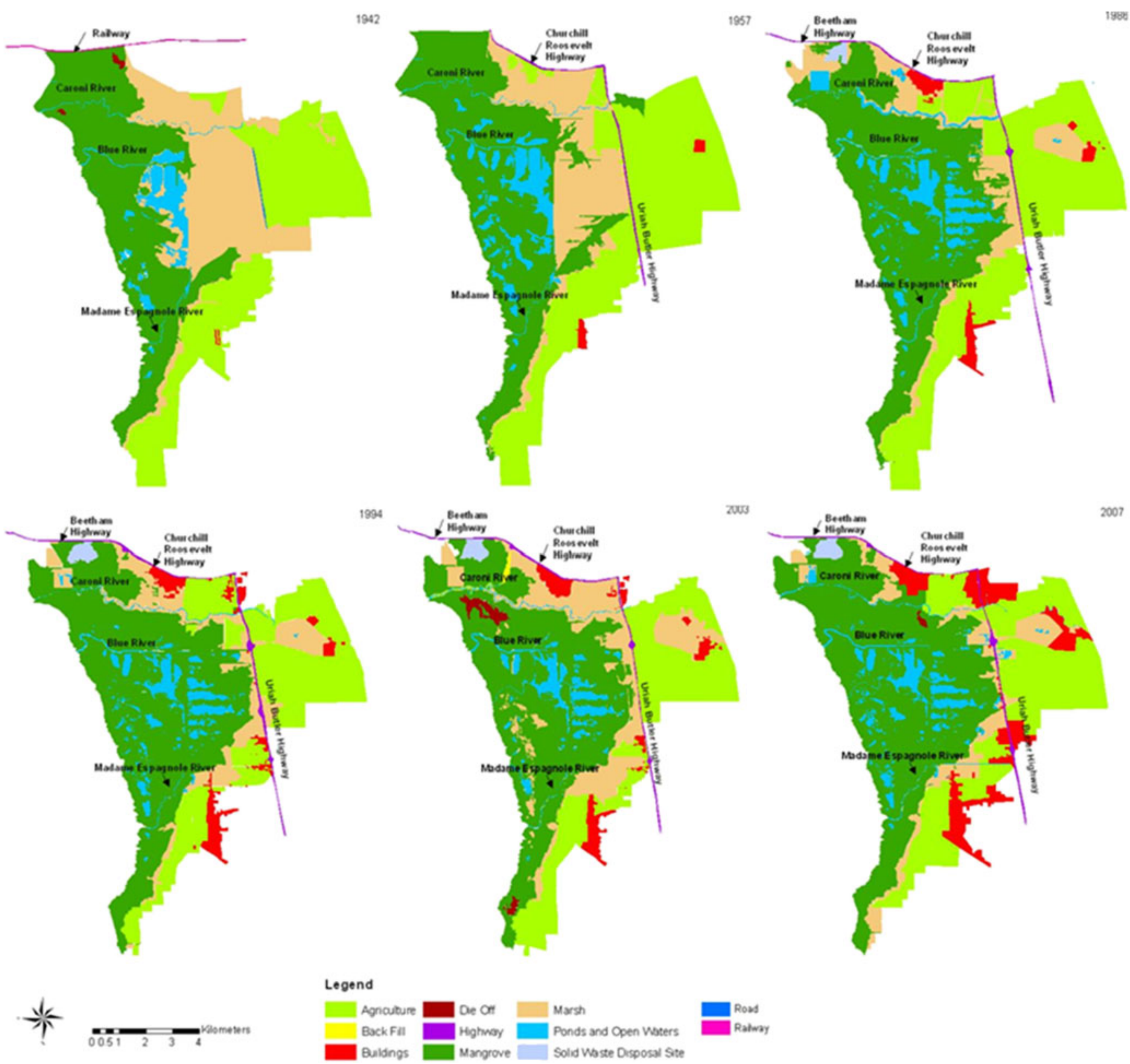

Fig. 4 Land cover maps for Caroni Swamp for 1942, 1956, 1986, 1994, 2003 and 2007

from the east; thereafter drainage in the swamp could take place only through culverts and under the bridges provided integrally with the new highway (Phelps 1997).

Between 1957 and 1986 more than 1,000 ha of mangroves spread into marshland, while approximately 500 ha were cleared on the northern edge for the construction of a solid waste landfill, a sewage treatment plant, a highway and while widening the Caroni River (Fig. 4). Overall, mangrove coverage increased in the swamp by 523 ha while marshland coverage decreased by more than 500 ha. Marshland was over grown by mangroves and marshes on the northern end of the wetland were cleared for an Industrial Estate. Agriculture coverage decreased by 413 ha; some was left to lie fallow and reverted to marsh, while some were converted into built development. Built development increased by 159 ha (Fig. 3).

Between 1986 and 1994, mangrove forest increased in coverage by 361 ha as mangroves spread further eastward into marshland, and recovered on the northwestern side around the sewage ponds and landfill (Fig. 4). Ponds and open water areas were overgrown by mangroves and these areas decreased by 170 ha. Dredged spoilt that was deposited at the mouth of the Caroni River, was also colonized by mangroves. Although marshlands were lost to mangrove, marsh coverage in the swamp increased slightly by 6 ha, as some agriculture lands reverted to marsh, and the sewage ponds were covered with marsh vegetation. Agriculture decreased considerably in the swamp during this period by more than 700 ha. Built development increased by 148.2 ha as new developments were built along the fringes of the Uriah Butler Highway on land that was previously used for agriculture (Fig. 3).

By 2003, the agricultural land on the northeastern side of the wetland, and between Caroni and Blue Rivers, west of the Uriah Butler Highway had reverted to marshland (Fig. 4). Between 1994 and 2003, marshland increased by 674.2 ha while agricultural land decreased by 314 ha. Marsh vegetation also occupied areas that were once built up as built development decreased by 14 .1 ha. During this same period, the Caroni River was straightened and widened, and mangroves along the banks were cleared. An island was created as a result of the hydrological work and an area of dead mangrove approximately 110.7 ha was observed south of the Caroni River. Overall, mangrove coverage decreased by 101.2 ha, even though mangrove dieback accounted for 110.7 ha. This indicates that there were about 9.5 ha of new growth. Mangrove continued to extend into marshes on the eastern side of the wetland, west of the Uriah Butler Highway.

Between 2003 and 2007, mangrove coverage increased by 338 ha, built development more than doubled (increased from 346.4 to 842.1 ha), and agricultural land increased by 403.3 ha (Figs. 3 and 4). The area of mangrove dieback observed in 2003 had re-grown, however some new dieback was observed further east on the southern side of the Caroni River. During the same period marshland decreased by 824 ha and open water area decreased by 140 ha. Mangrove forest extended further east overgrowing marshland, and filled in some of the open water/pond. Marshland was converted into built development and agriculture lands. Built development continued to encroach upon marshland along the Uriah Butler Highway.

Prior to the 1960's, the major changes to Caroni Swamp were hydrological in nature; East–West and North–South channels were cut, the North–south embankment was built (Fig. 2), water was diverted away from the wetland, and the Caroni River was dredged and widened. A freshwater marsh habitat was created on the eastern side of the N-S embankment but as the embankment fell into disrepair in the 1950's, the same conduits that were constructed to drain the wetland, carried saline water upstream into the freshwater environment. Highways (Churchill Roosevelt and Uriah Butler) were constructed and this also impeded the flow of the rivers into the wetland.

These hydrological changes eventually led to saltier conditions in the eastern marshes, east ward of the N-S embankment and colonization by mangroves. From July 1966 to February 1967, the salinities reported ranged from 2.4 to 5.1‰ (Bacon 1970) while between December 1977 and June 1978 salinities ranged from 10 to 34‰ (Deonarine 1980) and from November 1995 to May 1997 salinities ranged between 23 and 38.5‰ (Bacon et al 1997). Cuffy (1999) reported hypersaline conditions in the eastern marsh for several week during the dry season of 1996 despite regular tidal flushing. In May 2004, minor repair works were done on the North–South embankment; breached areas were filled in with backfill material transported into the area. Salinities from February 2004 to July 2005 ranged from 1 to 45‰ with lowest salinities being reported after heavy rainfall (Nathai-Gyan 2006).

Prior to the 1950's there were minor changes in the natural wetland communities (Fig. 5), while agricultural land increased and built development started. Beyond, the 1950's there were major land cover/land use changes in the

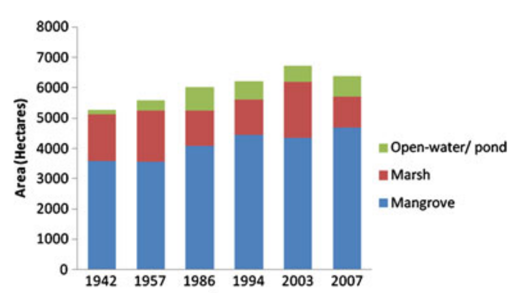

Fig. 5 Changes in coverage by natural wetland communities in the Caroni Swamp 1942–2007

Caroni Swamp. The mangrove forest on the northern side of the Caroni River was reclaimed for the construction of a solid waste landfill, sewage treatment ponds, and unplanned housing. Built development expanded along the fringes of the wetland and while agriculture land reverted to marshes, marshlands were overgrown by mangroves. In 2007, there was a small increase in agriculture land (≈400 ha), which had consistently declined form 1957–2003.

The Caroni River Basin also experienced extensive land-use/land cover changes within the past few decades and this has serious consequences for the Caroni Swamp; the receiving environment for the land-based runoff. In addition to saltwater penetration, Caroni Swamp receives sediment laden water polluted with sewage, wastewater from industry and agriculture run-off (Donawa 1976; Deonarine 1980; Siung-Chang et al. 1987; Phelps 1997; Institute of Marine Affairs (IMA) 1999; IMA (unpublished)). This has affected the quality of the habitat, and the shellfish harvested in the swamp (per comm. Christine Bullock). Fish kills and mangrove dieback seem to be a regular occurrence in Caroni Swamp (Bacon 1970; Siung-Chang et al. 1987). Major mangrove die-off events were reported by Bacon (1970) and observed in 2001 Landsat Imagery. In 2001, 170 ha of dead mangroves were recorded and although the cause of the die-off was undetermined, it coincided with the widening, deepening and straightening of the Caroni River, the raising of the southern bank (IMA unpublished) and hypersaline conditions. Interstitial salinity in the dead area was recorded at 82‰.

Frequent hydrological work in the Caroni Swamp to mitigate flooding in the associated catchment have negatively impacted the wetland, since channels are widened and dredged, mangrove trees are removed, and the dredge spoilt placed on the bank inhibits the natural flushing of the system. Mangrove productivity is a function of water turnover in the forest (Pool et al. 1975); reduced tidal flushing results in higher soil salinity (Cintrón et al. 1978; Santos et al. 1997), decrease in nutrients and/or the accumulation of toxic substances such as hydrogen sulphide (Nickerson and Thibodeau 1985). Mangroves have an optimum salinity range for maximum growth; at extreme level mangrove species suffer damage and even mortality (FAO 1994).

In 1953 under the Forest Act Chap 66.01, 3,033 ha of Caroni Swamp were designated a protected area. Part of this area is a Wildlife Sanctuary for breeding Scarlet Ibis (*Eudocimus ruber* L.); the National Bird of Trinidad and Tobago (Bacon and Ffrench 1972). The number of breeding pairs has declined and this has been attributed to the fact that Scarlet Ibises shift their feeding to freshwater prey during the breeding season and freshwater habitat in the Caroni Swamp has been declining as saltwater intrudes further inland (ffrench 1984; Bildstein 1990; Bacon et al 1997). Designation as a Wetland of International Importance under the Ramsar Convention in 2005 was expected to bring much needed attention and conservation intervention, yet between 2003 and 2007, built development within the wetland doubled and no attention has been placed on preserving the marshlands. There are privately owned land within the Ramsar Site and development of these lands continue to negatively impact the wetland, especially along the Uriah Butler Highway.

The Forestry Division is the government agency with responsibility for managing the Caroni Swamp and while they provide game wardens to patrol the swamp to discourage poaching, there is no comprehensive management plan for the conservation and restoration of this wetland. A management plan for the Caroni Ramsar Site is urgently needed to address impacts emanating from outside the wetland that affect water quantity and quality, human activities within the wetland including hydrological alterations, land tenure issues and restoration of freshwater habitats which is critical for maintaining biological diversity within the wetland. Expansion of mangrove forest inland due to hydrological changes brought about by human intervention, and whether this expansion is being exacerbated by relative sea level rise associated with global climate change impacts, needs to be given careful consideration in any management strategy. This trend of expanding mangrove forest into marsh land has not been documented in other wetlands in the region.

Conclusion

This study quantifies the changes in the land cover/land uses within the Caroni Swamp Ramsar Site since 1942. Lands used for agriculture particularly rice farming, and freshwater marshland that developed as a result of hydrological alteration in the wetland in the 1920's have declined. Mangrove forest has expanded and continues to over grow marsh vegetation as salt water intrudes further inland. Salt water intrusion is due to human activities, and may be compounded by relative sea level rise associated with global climate change. There is a definite need for management intervention in the Caroni Swamp Ramsar Site to address these factors and to protect and restore the diverse plant communities within the wetland.

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