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RAINE ISLAND: ITS PAST AND PRESENT STATUS

AND

FUTURE IMPLICATIONS OF CLIMATE CHANGE

PROJECT REPORT

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Preface

The assessment of vulnerability to climate change of the Great Barrier Reef recently published (Johnson and Marshall, eds, 2007) focused on important fauna and flora components of the GBR and on types of environment. Close examination of this holistic review indicates that within the 350 000 km^2 of the Marine Park, there would be specific locations of high value and/or greater risk. Raine Island on the northern GBR is certainly one of these with iconic values extending from its use by Traditional Owners, its historical navigational beacon, its unparalleled importance as a turtle and seabird nesting site and its unusual geomorphological features and processes.

This report reviews what is known about the island and assesses the impact of climate change. It identifies what further research is needed for sound management decisions and provides a Strategic Plan for the island to 2050. The report contains nine appendices, separate from, but contributing to, the main text. The appendices allow more detail on specific topics putting forward hypothesis on particular processes and assesses some of the methodologies which may help to save this iconic site or, at the very least promote the survival of its most important inhabitants.

EXECUTIVE SUMMARY

1. Raine Island has a very high historical, ecological and environmental value:
    - it is a significant cultural and story place for the Traditional Owners and holders of native title rights and interests.
    - it has the oldest navigational beacon constructed around the Australian coast.
    - it has a history of nineteenth century exploitation which elucidates much about the social and industrial history of the time.
    - it is the most important nesting site in the world for the green turtle *Chelonia mydas*
    - it is probably the most important seabird nesting site on the Great Barrier Reef, with 16 species recorded as breeding there. Five of the species are uncommon or rare in Queensland, one is currently endangered in Australia and one is declared vulnerable in Australia.
    - for the Great Barrier Reef it is a unique form of reef island in which a phosphate cap formed from the downward leaching of guano plays an important part.
2. Some problems have already been identified on Raine Island including:
    - a number of demographic factors suggest that the turtle nesting population may be in an early stage of decline.
    - population decline in at least 10 of the 16 breeding birds is apparent between 1979 and 2003.
    - the island is highly dynamic and constantly changing although the overall volume of sand within the large beach berm may be relatively stable. Nonetheless, changes are affecting the nesting of both birds and turtles.
3. Projected changes in climate will almost certainly exacerbate these problems.
    - increasing temperatures will alter the sex ratios of turtle hatchlings and increase heat stress on both turtles and birds.
    - sea level rise may not necessarily result in island erosion but this already dynamic cay may become even more unstable and respond to any changes in wind patterns.
    - sea level rise will cause a rise in the water table increasing the risks of turtle nest flooding.
    - sea level rise and temperature increase may change the ecology of the reef flat and delivery of sediment to the island (possibly an initial wave of new sediment followed by a rapid decrease).
    - ocean acidification will certainly affect small organisms detrimentally, especially foraminifera which make up a large part of the current sediment budget for Raine Island.
    - El Niño Southern Oscillation (ENSO) events have been shown to have important influences on the breeding behaviour of both turtles and seabirds.

  Although the exact nature of future ENSO changes (more frequent, stronger?) are largely undetermined, there will be impacts especially on the foraging areas of Raine Island's populations.
  - less well defined changes at Raine Island's latitude are those in rainfall (higher?) and cyclone incidence (more frequent, more intense) but the impact of any change on Raine Island is likely to be negative.

4. The largest current gaps in knowledge for Raine Island relate to physical oceanography and its influence on the dispersal of turtle hatchlings and on the foraging grounds of both turtles and seabirds. More knowledge is also needed on: demographics of turtles and birds and on aspects of the physical environment including beach dynamics, sediment budgets, cemented layers and water table behaviour. In addition, future modeling of climate change cumulative impacts is vital for future management planning.
5. Three modes of management are examined:
    - status quo depending on currently in place conservation strategies and Raine Island being able to adapt as climate change factors start to impact. Risks with this option are high.
    - reactive management whereby a number of thresholds (sand volume, turtle and bird demographics, coral and foraminifera bleaching etc.) are put in place and when exceeded produce a management response. Intensive monitoring is required, and appropriate responses identified to minimise risk.
    - pro-active management, involving action as soon as possible. Further research will be needed in many of the areas but programs which may be considered include sand nourishment, breaking up cemented layers, vegetation programs, weed and insect control programs, education and increasing capacity skills of Traditional Owners. More pro-active options will be identified from research and monitoring. Risk analysis for each option will be needed
6. A fundamental change in the philosophy of the management agencies may be required given that the most appropriate management responses may involve modifying what have been regarded as natural processes, highlighting the difficulty of extracting anthropogenic `greenhouse' changes from the natural `noisy' environmental records. Interfering with the natural environment may not be normal conservation policy but the very high, iconic value of Raine Island may alter the balance in favour of direct intervention if other options are unlikely to preserve the island and its inhabitants and viable alternative sites cannot be found.
7. Research and monitoring will assist in determining management actions on Raine Island. Methods examined included:
  - assessment of turtle nesting and hatching success

- testing the bryme rock formation hypothesis
- monitoring of sand depth and sand temperature
- assessment of seabird nesting and hatching success
- use of the FORAM Index to determine the health of the reef
- use of remote sensing, either high resolution satellite imagery or digitized aerial photography using especially the near infra-red band
- maintaining a watch on carbonate productivity levels of the reef using for example the alkalinity depletion method.

8. In a changing climate the worst scenario for Raine Island, and all nearby cays, is their complete erosion and even before that, their unsuitability for turtle and bird nesting (high water tables, rainfall, cyclones). Do turtles have the adaptability to move to more permanent nesting sites, such as Murray Group (carbonate dominated beaches of the high islands especially the located in a similar position to Raine Island)?
9. The importance of Raine Island to the Traditional Owners is well recognised in the current management agreements. Any proposed climate adaptation management options should be considered in consultation with the Traditional Owners.
10. Given the potential severity of climate change related impacts on Raine Island research outcomes should be reported back to management quickly and efficiently. Targeted monitoring programs to evaluate the effectiveness of management actions will also be required to ensure that strategic plans are able to cope with increasing climate variability and cumulative impacts. To achieve the most beneficial management strategies a close link between scientists and managers will be required to recognise, as early as possible, changes to the environment and ecological reactions. Wherever possible, adaptive management actions should have a scientific basis in a fragile environment like Raine Island.

1. INTRODUCTION

1.1 Location and Report Approach

Raine Island (11°36'S) is located on a detached reef at the northern end of the Great Barrier Reef Marine Park (GBRMP) (figure 1). It is the largest vegetated cay located on the edge of the continental shelf of the Great Barrier Reef (GBR) and as such is a prominent feature for a wide range of fauna. Although only one of 300 reef islands within the Marine Park, Raine Island has a unique standing and very high environmental, historical and ecological value extending back before European discovery of Australia's eastern seaboard. However, in recent decades threats to these unique values have been identified and, at a time when changes to global climate have the potential to severely exacerbate these problems, there is a need to clearly identify the issues and come up with adaptive management options. With input from as wide a range of stakeholders as possible, the intention of this project has been to:

- provide a review of the current state of knowledge (including the geomorphology which although not the only driving force behind some of the problems, has been identified as a very influential disciplinary area) and identify the knowledge gaps in consultation with key researchers and managers.
- identify existing environmental and ecological problems.
- evaluate aspects of global climate change which may further impact on Raine Island.
- scope feasibility assessment of adaptive management options and risk assessment of current versus adaptive management strategies.
- develop a strategic plan which includes recommendations for future research, monitoring and management needs with the provision to modify the strategic plan in the light of new research findings

These topics were discussed at a workshop held in Townsville 5 – 6 June 2008, attended by a wide range of stakeholders including Traditional Owners, managers and scientists. The main focus was around issues occurring on and around Raine Island, but the importance of external factors related to the wide dispersal of the green turtles and seabirds which nest on the island was also recognised and identified as one of the more difficult issues for management. A further meeting, mainly of managers, was held in Townsville on 25 July 2008 and input from that meeting has also been included in this report.

1.2 Current Management Arrangements

The management arrangements relevant to Raine Island are depicted in figure 1 and 2.

Raine Island along with Moulter Cay and MacLennan Cay are dedicated as Raine Island National Park (Scientific), which is protected under Queensland's *Nature Conservation Act 1992*. The Queensland Environmental Protection Agency manages this area.

www.epa.qld.gov.au/publications/p02061aa.pdf/Raine_Island_National_Park_Scientific_management_statement_20062016.pdf

The vision statement from the Raine Island National Park (Scientific) Management Statement 2006-2016:

> "Following dedication of Raine Island National Park (Scientific), the management of this protected area and the adjoining marine park areas will, to the extent permitted by law, be complementary and co-ordinated across relevant agencies, to control public access and to preserve and protect the area's outstanding biological diversity, cultural resources, and the significance of the area to Aboriginal and Torres Strait Islander people(s).
>
> Indigenous cultural resources, values and practices will be recognised, respected and protected, and Aboriginal and Torres Strait Islanders, in particular those groups who assert that they are the holders of native title in relation to Raine Island National Park (Scientific) and the adjoining marine park areas, will be meaningfully involved in the planning for, and management of, these resources."

The State of Queensland and the Traditional Owners of the region (the Wuthathi people of Cape York and the Erubam Le, Meriam Le and Ugarem Le of the Torres Straits) have signed an Indigenous Land Use Agreement (ILUA) (refer to figure 1). The ILUA includes the Raine Island National Park (Scientific) and surrounding waters around the islands out to three nautical miles from the high water mark. Entry is by permit only, and limited to authorised persons undertaking management activities or scientific research or monitoring.

In 2008, the Great Barrier Reef Marine Park Authority and Queensland Environmental Protection Agency accredited the Wuthathi Traditional Use of Marine Resources Agreement (TUMRA). The Wuthathi TUMRA contains provisions for managing traditional use of marine resources within an 8 085 km^2 area in the Far Northern Management Area of the Great Barrier Reef Marine Park and the adjacent Great Barrier Reef Coast Marine Park. The areas covered by the ILUA are excluded from the TUMRA region. The TUMRA demonstrates a strong commitment to, and responsibility for, the sustainable traditional use of marine resources by the Wuthathi Traditional Owners within an area of the GBRMP in which they assert having spiritual or cultural affiliations.

The waters adjacent to Raine Island, Moulter Cay and MacLennan Cay are within a Marine National Park (Green or no-take) Zone (refer to figure 1) of:

- the Great Barrier Reef Marine Park Authority's (GBRMPA) *Great Barrier Reef Marine Park Zoning Plan 2003* (extending below low water); and

- the Queensland's *Great Barrier Reef (Coast) Marine Park Zoning Plan 2004* (waters between low water and high water).

The waters surrounding Raine Island, Moulter Cay and MacLennan Cay are declared as Restricted Access Special Management Areas under both Commonwealth and State Zoning Plans (refer to figure 1). The Restricted Access Special Management Areas extend from high water seaward 500m and also includes the airspace above the water to a height of 915m. The GBRMPA and the EPA have developed a position statement setting out access arrangements to the Restricted Access Special Management Areas. For further information go to: www.gbrmpa.gov.au/__data/assets/pdf_file/0011/11423/raine_position_statement.pdf

In addition, a Remote Natural Area covers all locations within the Far Northern Management Area. The objective of the Remote Natural Area is to ensure that some areas of the Marine Park remain in a state that is largely unaltered by works or facilities, and to provide opportunities for quiet appreciation and enjoyment of those areas. Within the Remote Natural Area, motorised water sports are prohibited and the Regulations also limit the carrying out of certain works including the dumping of spoil, reclamation, beach protection works or harbour works, and the construction of structures other than vessel moorings and navigational aids

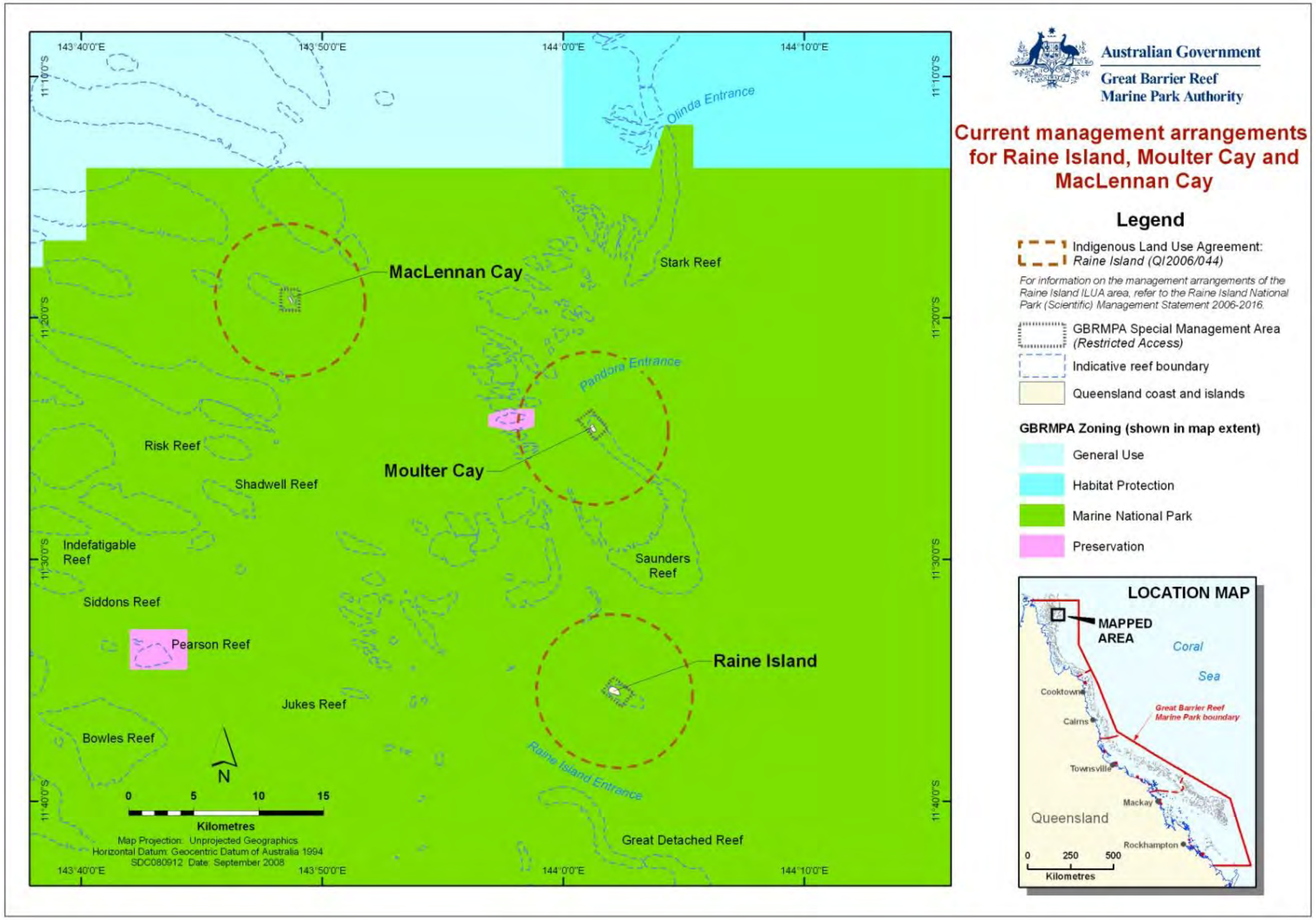


Figure. 1. **Current Management Arrangements for Raine Island, Moulter Cay and MacLennan Cay**

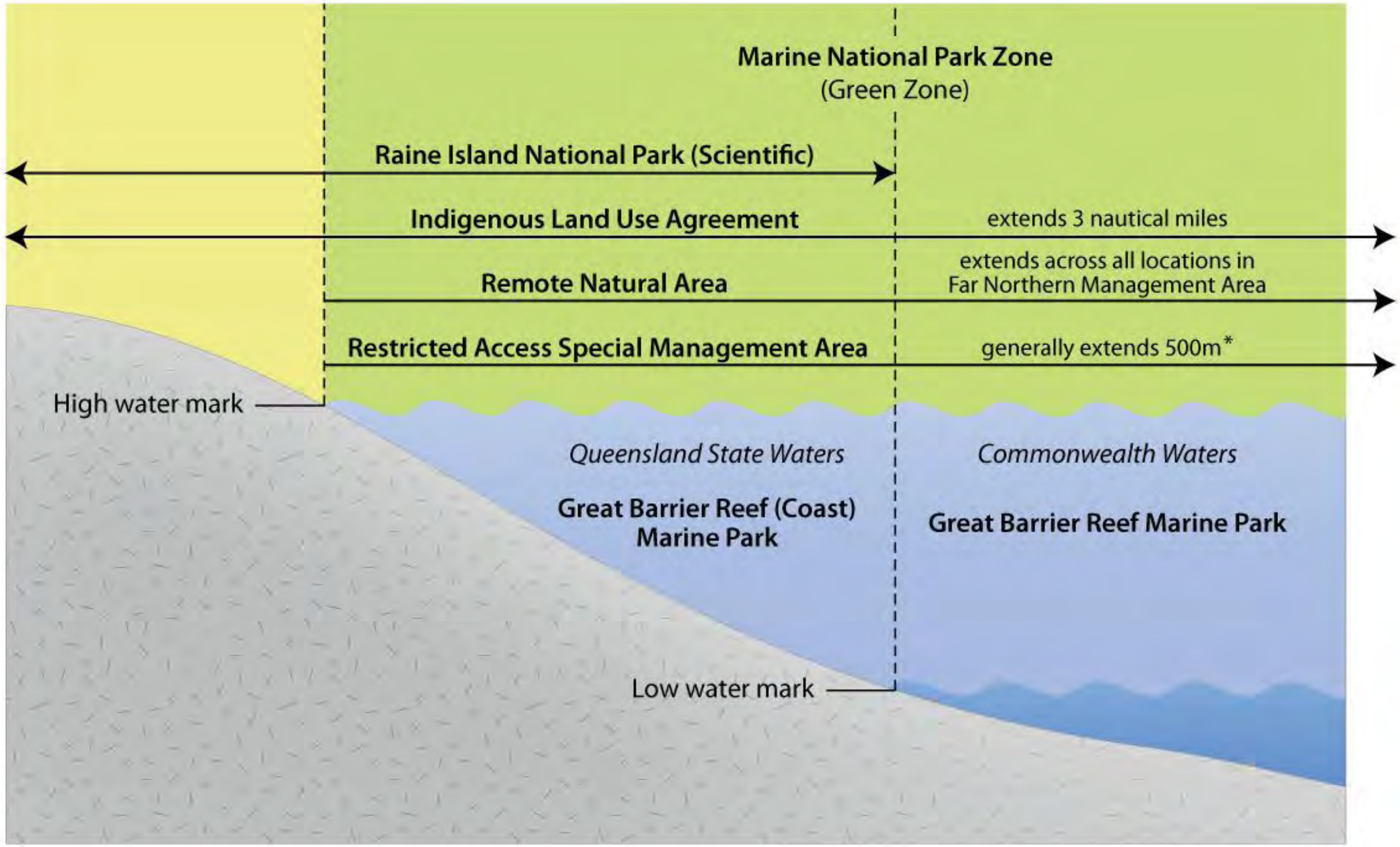


Figure 2 **Boundaries of the current management arrangements for Raine Island (* refer to *GBRMP Zoning Plan 2003* and *GBR (Coast) MP Zoning Plan* 2004 for boundary details).**

2. REVIEW OF CURRENT KNOWLEDGE OF RAINE ISLAND

2.1 The Historical and Cultural Values of Raine Island

The importance of Raine Island was acknowledged in 1981 when the Queensland Government set up the Raine Island Corporation under the *Meaker Trust (Raine Island Research) Act 1981*, highlighting historical, ecological and environmental values.

2.1.1 Indigenous Values of Raine Island

Although located 40km offshore, Raine Island is visible from the tops of continental islands such as the Sir Charles Hardy Group and pre-European use of Raine Island is recognised, (Chase, 1978). The Wuthathi people of the Shelburne Bay area identify as the Traditional Owners and holders of native title with the Erubam Le, Ugarem Le and Meriam Le peoples also having interests in Raine Island and nearby MacLennan and Moulter cays. This "sea country" provided resources such as turtles, birds eggs and shell (for ornamental purposes) as described by Schall (1985) and Smith (1987), and had significance in providing social and cultural contact between the Wuthathi people and Torres Strait Islanders. More recently (13.08.2007) the State of Queensland (represented by the Environmental Protection Agency) has negotiated an Indigenous Land Use Agreement (ILUA) with the Traditional Owners. The intention is to facilitate the meaningful involvement of the Indigenous Parties in the management of the National Park (Scientific) and adjacent marine parks and to provide a management framework within existing legislation frameworks that is consistent with their aspirations and interests (See Section 1.2).

2.1.2 Nineteenth and Twentieth Century European Impact on Raine Island

The nineteenth century from 1815 onwards was a period of major European impact on Raine Island (appendix A). Shipping losses led to the building of the first offshore beacon in Australian waters in 1844. Built from the island's phosphatic cay sandstone, the beacon still stands today as one of the most important structures on the GBR, adding to Raine Island's iconic status.

However not all the visits to the island were beneficial and even during its construction the working party used bird's eggs and turtles for provisions as did most visitors for the next 60 years. Fruit and vegetable species were also introduced as were goats for a short period seriously impacting on Raine Island's flora and fauna.

This was probably insignificant compared to the period 1890-1892 when the phosphate deposit of the island was mined with more than 100 labourers, mainly Chinese, living on the island. A tramway was built from the centre of the island to a wooden jetty for which some coral may have been removed. Ships of 1000-1500 tons exported the guano direct to Europe and Melbourne. By 1892 the extraction had ended after removing "tens of thousands of tons" (Hutchison, 1950) and most of the equipment dismantled and removed but the effect on the island has been permanent and the details of the original geomorphology and vegetation can only be surmised (see appendix A for more details).

During the following century some turtle harvesting by visiting ships still took place (Limpus et al 2003), but a 1950 Order of Council declared a year round closed season for green turtles and although reopened briefly between 1959 and 1968, Raine Island was harvested commercially only in 1959. Increasingly there was scientific interest in Raine Island and visits by film crews highlighted its important status.

Thus, over the last 30 years or so Raine Island has been given an increasing amount of environmental protection. The importance of the island was acknowledged in 1981 when the Queensland Government set up the Raine Island Corporation under the *Meaker Trust (Raine Island Research)* Act 1981 highlighting the historical, ecological and environmental values. The waters surrounding the currently proposed Raine Island National Park (Scientific) are declared *Restricted Access Special Management Areas (RA-SMA)* under both the GBRMPA *Great Barrier Reef Marine Park Authority Regulations 1983* and the Queensland Government *Marine Parks (GBR Coast) Zoning Plan 2004.* Raine Island may have been irreversibly impacted by mining and other activities, but its iconic status is recognised by the conservation protection it is now being given.

2.2 The Turtles of Raine Island

2.2.1 History of Research

First observations of Raine Island as a turtle rookery are those of Jukes (1847), since which date nearly all visitors have made some comment about the turtles and many have harvested the turtles for food (see Limpus et al, 2003 pp 361-370 for detailed historical review). Subsequent studies have shown that Raine Island and nearby Moulter Cay are the principal nesting sites of the largest remaining green turtle (*Chelonia mydas)* breeding population in the world. During the nesting season up to 15,000 females have been recorded on a single night on Raine Island and the total nesting population for Raine Island and Moulter Cay can be as high as 131 000 females (Limpus et al, 2003). The importance of the site has been highlighted in numerous research publications and reports, and in filmed documentaries, (see Limpus et al, 2003 for the most comprehensive review).

Systematic turtle research commenced on Raine Island in 1975 was initially part of exploratory studies by the Queensland Conservation Agency, which became the Queensland Parks and Wildlife Service. Between 1979 and 1985 the Queensland Turtle Research Project undertook the development of new methodologies to address marine turtle population dynamics. In 1985 a priority was placed on these studies after recognition of potential threats to breeding populations posed by large scale harvesting within the Australasian region. It is from these studies that the present large scale knowledge base has developed. It includes numerous reports to the Raine Island Corporation and in recognised scientific journals, a high proportion of which are referenced in Limpus et al (2003), which is the primary but not only source of information for this report.

2.2.2 Chelonia mydas on Raine Island

The green turtle *Chelonia mydas* appears to be the only species nesting on Raine Island although the remains of one hawksbill turtle (*Eretmorchelys imbricarta*), have been recorded from the central flat. Raine Island is probably the most studied turtle nesting site in the world with more than 130 years of observations. DNA analysis has indicated that there are three genetically identifiable populations off eastern Australia with that centred on Raine Island (with Moulter Cay, Bramble Cay, Murray Island and Number 7 and 8 Sandbanks) making up the largest. The three populations do not interbreed although their foraging areas may overlap. Tagging has indicated that the feeding range for the Raine Island population extends from Indonesia to New Caledonia and Vanuatu.

Radio carbon ages from clam shells on Raine Island indicate that a nesting population was present prior to 1200 years ago and possibly as much as 5000 years B.P., a reef flat date beneath the cay coming from the margins of the island which may have accumulated much of its mass prior to 4700 years B.P. (see appendix B). Although there is evidence of older fringing reef development around the margins of the reef as deep as 90 m. The conclusion by Limpus et al (2003) that beach areas were not available for nesting during the post-glacial transgression, appear sound.

2.2.3 Nesting and Nesting Success

From the far flung foraging grounds, where turtles from other populations may also be feeding, the Raine Island female turtles return to the island for nesting between September and January, an extended period compared to elsewhere, probably because of the numbers involved. Different foraging areas can be used by the Raine Island nesting population and distance does not appear to be a significant factor. Nesting success in a single night may not be high but an individual may try several times on successive nights. The mean egg count is about 100 with up to 90% hatchling success. Predation of the hatchlings is high, especially by rufous herons and only 6.7% may reach the sea.

Several factors impact on the success of nesting including:

- trapping of the nesting turtles on the island, especially in the low lying swale of the island. Trapped turtles die of heat exhaustion within 24 hours
- turtles dying when they fall off the phosphate cliff (section 2.6.4) whilst attempting to return to sea
- disturbance of females attempting to locate a suitable nesting site
- interference with previously laid nests because of the density of nesting sites
- nest collapse in the dry sand. Mean depth of the nest is between 50 and 80cm and collapse may be common
- flooding of the nest in periods of high rainfall producing surface pools or rises in the water table (see Guard et al, 2008). Exceptionally high tides may also cause the water table to rise. Eggs may be drowned within a few minutes
- harvesting of turtles in Australian and waters of neighbouring countries.

2.2.4 Fluctuating Numbers and Indicators of Decline in Turtle Population

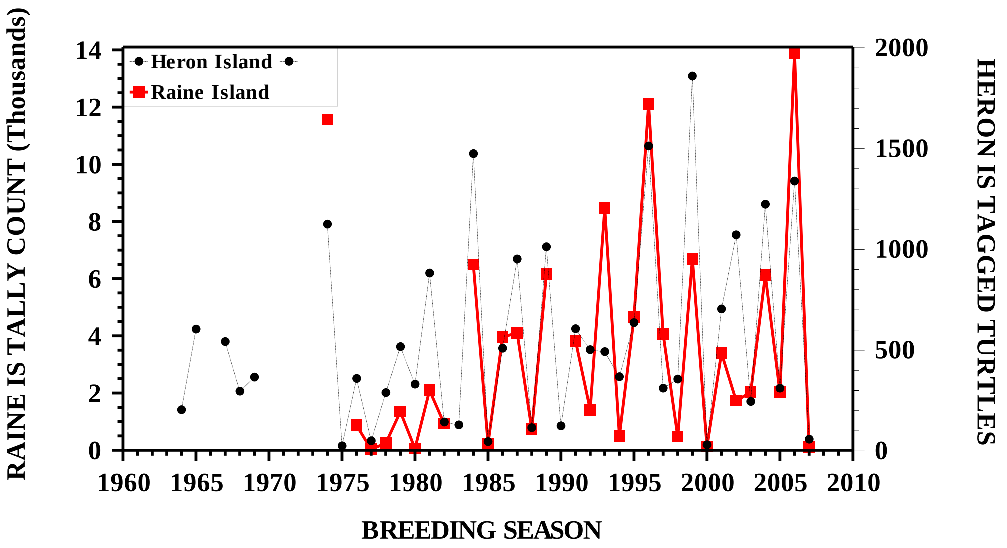
Large fluctuations in numbers of nesting green turtles have been recorded (see figure 3). Limpus and Nicholls (2000) have demonstrated that these fluctuations are a function of the El Niño Southern Oscillation climate events. There is a significant correlation to the mean SOI value approximately 1.5yrs before the breeding season commences with high numbers after El Niño events and very low numbers after La Nina. A nutritional basis is suspected for this fluctuation. This is then determined by the deviation of the sequence of physiological processes that culminate in egg production. There is therefore a problem in quantifying the stability of the green turtle nesting population. Several decades of detailed monitoring is required to obtain meaningful trends.

The long life cycle and logistical difficulties of making observations on more than an expeditionary basis on Raine Island have been noted by most authors. Natural variability in the size of the female green turtle population is illustrated by figure 3 in (Limpus et al 2003). Hamann et al (2007) suggest that there has been no significant decline in the population to date. However, a number of demographic factors analysed by Limpus et al (2003) led to the conclusion that "this large population is in the early stages of decline as a result of loss of adult turtles", (Limpus et al, 2003 p436). Factors include:

- decline in the average size of breeding females
- increasing remigration intervals
- declining population of older adult turtles

With remigration intervals of 5-8 years and strong influence of ENSO these trends may be further defined in the future.

Attempts to identify reasons for decline are also influenced by the very wide foraging range of the turtle which takes it outside Australian waters and beyond the protection of Australian legislation. Traditional hunting does take place in the Northern Great Barrier Reef and Torres Strait, with females at the courtship phase being targeted (Miller and Limpus, 1991). However, there appears to be little data on the size of the harvest. Probably more significant are the numbers of the Raine Island population again mainly large females, taken in Indonesian waters. This harvest has increased since a major decrease in Indonesian stocks in 1988. Major markets are Bali, Ujung Pandang and Dobo where increasing pressures on all marine resources are problematic (for review, see Hopley and Suharsono, 2000). Even in 1991, Limpus et al (1993) suggested that the rate of harvesting was not sustainable.



Raine Island census data, extending the data in Limpus et al. 2003 figure 21.

Figure 3 Raine Island Green Turtle Census Data from Limpus et al (2003 and Limpus (pers comm.)

2.3 The Seabirds of Raine Island

2.3.1 Species and Foraging Areas

Raine Island is one of, if not the most important tropical seabird nesting sites on the GBR and probably has been since the island was first formed. Avifauna recorded between 1843 and 2003 comprises 84 species, with 16 species recorded as breeding on the island. It is visited by migratory birds and is the focus for seabird activity within the northern GBR region (Batianoff and Cornelius, 2004).

Observations and studies of the birds range back to the first European visitors and most parties who landed on the island reported some qualitative information on the birds as reviewed by Stoddart et al (1981). However the first quantitative records come from Warham (1961) made in 1959. Systematic records from between 1979 and 1985 come from B.R. King whose methodology was continued by QPWS staff in subsequent years (See Batianoff and Cornelius, 2004, 2005) up to the present day. Numerous reports, mostly to the Raine Island Corporation are listed in Batianoff and Cornelius (2004, 2005) and recommendations from a 1991 workshop organized by the Corporation in Taplin and Blaber (1993). These are the resource references for this report.

Each of the 84 species of bird observed and recorded on Raine Island can be assigned to one of these major habitat groupings:

i. Pelagic seabirds – 24 species, mainly marine carnivores making up 28.6% of the total. 14 of these breed on Raine Island.
ii. Water birds – 31 species (37.5%) of shorebirds and birds which depend on the presence of fresh or saline water bodies for their food supplies. Twelve of these species are known to migrate to Australia as non-breeding summer migrants from the northern hemisphere.
iii. Land birds – 28 species (34.1%) dependant on terrestrial food supplies such as insects, seeds etc. At least 15 are known to be migratory especially from Papua-New Guinea. However, 13 of the 28 are land birds, probably weather blown or lost stragglers.

A list of the breeding species is given in Table 1, together with data on numbers and population dynamics (from Batianoff and Cornelius, 2005).

The extent of the foraging area of Raine Island birds was indicated in a figure in the Raine Island Corporation First Annual Report (p5) with recovery of banded birds from the southern shores of Papua-New Guinea and as far north as New Ireland. Most recently Dobbs (1999) has reported on the recovery of banded birds not from Raine Island but from nearby McLennan and Moulter Cays, and Sandbanks 7 and 8. Distances travelled ranged from 265 km (near Daru) to Tuvalu 3800 km away.

It is not just the numbers of seabirds at Raine Island which makes it such an important site but also the status of many of the species. Five are uncommon or rare in Queensland including the Herald Petrel, Red-tailed Tropic Bird, Red-footed Booby and the Great and Lesser Frigate Birds. Currently the Herald Petrel is listed as Critically Endangered in Australia under the *Environment Protection and Biodiversity Act 1999*, and the Red-tailed Tropic Bird as Vulnerable in Queensland under the *Nature Conservation (Wildlife) Regulation 1994-ScheduleB*. The Nankeen Night Heron which breeds on Raine Island is also uncommon on the GBR and the Wedge-tailed Shearwater colony has been shown to be reproductively isolated from other GBR populations (Peck and Congdon, 2002).

2.3.2 Fluctuating Numbers of Seabirds

Natural fluctuations in numbers of birds are to be expected for a number of reasons including site availability and climatic conditions:

> "Natural pressures on breeding colonies include cyclones, localized floods and seasonal scarcity of prey such as fish or squid. Nest disruption by the green turtle's nesting in summer is a regular and important limiting factor for all birds on Raine Island, particularly for breeding terns on the strand plain and beach."
>
> (Batianoff and Cornelius 2005, p2).

Cyclone activity and heavy monsoonal rainfall in particular appear to influence the variation in mortality of the eggs with reports also of drowning of chicks in the central depression after heavy rains (Taplin and Blaber, 1993).

Although there is strict regulation of human visitors to the island this has obviously not always been so. The two years of phosphate mining must have been a period of major disruption and even brief visits may have impacted the nesting populations - much of it deliberate. For example, when *HMS Bramble* visited the island in 1845, 36 dozen eggs per day were taken for food. Other visitors, on landing, would break all visible eggs to ensure that those they collected subsequently were fresh (Stoddart et al, 1981).

The seabirds of Raine Island, like the turtles, have a wide foraging range, extending far into the Gulf of Papua and possibly as far north as New Ireland (see map, p5, Raine Island Corporation, 1982). Whilst not subjected to the same harvesting impacts they do lie at the upper end of the food chain and therefore reflect changing oceanographic and trophic conditions (Congdon et al, 2007). Many are important environmental indicator species. A high natural variability in population numbers may be expected and causes are reviewed by Congdon et al (2007). Relationships with ENSO events seem notably strong, for example a decline of between 6 and 7% in frigate birds was noted in 1998 after the particularly strong ENSO. Cyclones and nest flooding are also factors.

At Raine Island, however, superimposed over this natural variability there appears to be a progressive decline in the breeding populations (Batianoff and Cornelius, 2004, 2005). Between 1979 and 2003 estimates of breeding bird species suggest significant population decline in at least 13 of the 16 species. In descending order of reduction they are: Common Noddy (95.5%), Sooty Tern (84.4%), Bridled Tern (69.1%), Red-footed Booby (67.9%), Lesser Frigate bird (67.6%), Brown Booby (40.4%), Red-tailed tropic bird (38.5%), Nankeen Night Heron (33.3%), Masked Booby (26.9%), Wedge-tailed Shearwater (18.6%).

Table 1; **Raine Island breeding bird populations (Mean population data includes free-flying, breeding and non-breeding birds. The data presented is inclusive of all seasons. In brackets are the total numbers of visits/recordings) (from Batanioff and Cornelius, 2005).**

Species	**Yearly Estimates** **1979 to 1993** **(22 visits)**	**Yearly Estimates** **1994 to 2003** **(22 visits)**	**Population changes** **(1979-93 and 1994-03)**
1. Herald Petrel	5 (9)	2 (1)	3 (-60.0%)
2. Wedge-tailed shearwater	1,247 (14)	1,015 (8)	232 (-18.6%)
3. Red-tailed Tropicbird	104 (20)	64 (21)	40 (-38.5%)
4. Masked Booby	1,457 (21)	1,065 (20)	392 (-26.9%)
5. Red-footed Booby	467 (18)	150 (22)	317 (-67.9%)
6. Brown Booby	4,435 (21)	2,642 (20)	1,793 (-40.4%
7. Great Frigatebird	7 (15)	7 (6)	No changes
8. Lesser Frigatebird	1,851 (21)	599 (21)	1,252 (-67.6%)
9. Nankeen Night Heron	990 (11)	660 (18)	330 (-33.3%)
10. Buff-banded Rail	37 (11)	23 (17)	14 (-37.8%)
11. Silver Gull	27 (20)	22 (18)	5 (-18.5%)
12. Crested Tern	29 (13)	48 (7)	19 (+39.6%)
13. Black-naped Tern	65 (14)	85 (12)	20 (+23.5%)
14. Bridled Tern	191 (15)	59 (11)	132 (-69.1%)
15. Sooty Tern	840 (17)	131 (8)	709 (-84.4%)
16. Common Noddy	11,693 (20)	526 (20)	11,167 (-95.5%)
Mean annual population	23,445 (9-22)	7,098 (1-22)	16,347 (-69.7%)

Although there may be anomalies in the data, Batianoff and Cornelius (2005) believe that the trends are so strong that they do indicate the real situation. Congdon et al (2007) commenting on these figures, note that there is no evidence of human disturbance and no deterioration of nesting habitat or habitat loss over the period of decline.

> "This lack of other mechanisms and the fact that the species which commonly form foraging associations at sea have similar declining trends, highlights depletion of marine food stocks linked to changing climate and oceanographic regimes and/or human influences such as trawling as the most likely possible driving factors."
>
> (Congdon et al, 2007, p438).

Within the context of this report differentiation between causal factors on and beyond Raine Island itself will be important in assessing future risks which can be managed locally.

Declining numbers of seabirds at other nesting sites on the GBR have also been noted with a strong relationship to ENSO events (Congdon et al, 2007)

2.4 Vegetation of Raine Island (figure 4).

Although there appears to be nothing remarkable about the vegetation of Raine Island,"the island's flora is an integral ecological factor in maintaining the island's soil stability and in providing appropriate nesting environments for turtles and birds"(Batianoff et al, 1993 p33)

There are no long term climate records for Raine but various authors have estimated total annual rainfall at about 1000 mm, highly seasonal and variable.

Thus unlike many other GBR cays which have accumulated guano deposits, a woodland vegetation (perhaps of *Pisonia grandis*) does not appear to have existed here, with all early observations noting only a low shrubby vegetation (e.g. Juke, 1847). Natural disturbance by turtle nesting contributes to a high turnover but examination of long term observations and records by Batianoff (1991); Batianoff et al (1993) and Batianoff and Cuff (2004) also highlights the anthropogenic impacts on the vegetation especially the introduction of goats in the 1840s and most especially by the phosphate mining in the 1890s. Although there may be gaps in collections the earliest observations in the 1840s suggested that there were about 20 species of vascular plants but these had reduced to only 11 by 1874 and by the 1950s and 1960s to only six, (Batianoff et al, 1993). Stoddart et al (1981) list 10 species, with 12 species recorded in 1987 (Hacker, 1990). Harsh climate, turtle nesting and disturbance by humans produce a high turnover of the plants most of which are annuals. Most appear to be dispersed by flotation with Hacker (1990) identifying 19 species of drift seeds on the beach in 1987. Of these one, *Pangium edule* is not known in northern Australia but seems to have originated from Papua-New Guinea. A full list of all species of vascular plants observed at various times on Raine Island is given in Table 2.

Batianoff and Cuff (2004) defined 8 map units (figure 4):

1. Beachrock (0.65 ha)
2. Sandy strand plain (5.69 ha)
3. Succulent sparse herbland (1.3 ha)
4. *Lepturus* sparse to open tussock grassland (5.31 ha)
5. *Lepturus* open-tussock to tussock grassland (2.19 ha)
6. Mixed open herbland (3.4 ha)
7. *Abutilon-Achyranthes* dwarf open-heath to herbland (5.75 ha)
8. *Abutilon-Ipomoea dwarf* open-heath (0.7 ha)

Although it is more than 100 years since mining operations ceased on Raine Island it would appear that many plants have not returned to the island. Continued vegetation monitoring has been recommended (Batianoff et al, 1993) especially of the most important stabilising grass *Lepturus repens* which may play an important part in island stability/erosion studies. The *Abuliton asiaticum* var. *australiense* taxon on Raine Island has a unique prostrate growth habit and tolerance to a wide range of soil conditions and also has the potential to be used for future coral cay revegetation programs (Batianoff and Cuff, 2004).

2.5 Geomorphology of Raine Island and its Ecological Significance

2.5.1 Basic Morphology and Holocene History

Whilst there are no totally unique features on or beneath the Raine Island reef the combination of features are not common on the GBR.

> “Raine Island is, in fact, interesting not only in itself but also as a representative of small, semi-arid guano and phosphate islands in the reef seas”
>
> (Stoddart et al, 1981, p1).

The Raine Island reef is one of a series of detached reefs found on the northern GBR separated from the outer shelf slope by water depths of > 300 m. It is a platform reef about 3.5 km long and 0.75 km wide with an area of 210 ha. The cay lies at the western end of the reef with an area estimated in 1973 as 273 000 m^2, a length of 860 m and width 420 m (Stoddart et al, 1981). The vegetated area was estimated as 163 300 m^2 or 60% of the total island area.

Figure 4 Vegetation of Raine Island From: Batianoff and Cuff (2004)

TABLE 2: Number of recorded plant species and dispersal mechanism on Raine Island. (1959-2003) From: Batianoff and Cuff (2004)

Species (Family)	**Lifeform**	**Dispersal**	**1959**	**1961**	**1973**	**1981**	**1987**	**1991**	**2003**
Abutilon asiaticum var. *australiense (Hochr. ex Britten) Fosberg,* (Malvaceae)	S	B	P	P	P	P	P	P	P
Achyranthes aspera L. (Amaranthaceae)	Ha	B/H	N	P	P	P	P	P	P
Amaranthus interruptus R.Br. (Amaranthaceae)	Ha	B	P	N	P	P	P	P	P
Boerhavia albiflora Fosberg var. *albiflora* (Nyctaginaceae)	Hp	B	N	P	P	P	P	P	P
Cleome viscosa L (Capparaceae).	Ha	B/H	N	N	N	P	P	P	P
* *Dactyloctenium aegyptium (L.) Willd* .(Poaceae)	Ha	H	N	N	N	P	P	P	N
* *Eleusine indica (L.) Gaertn.* (Poaceae)	Ha	H	P	N	P	P	P	P	N
Ipomoea macrantha Roem. & Schult. (Convolvulaceae)	V	O	N	N	N	P	P	P	P
* *Lepidium englerianum (Muschl.) Al-Shehbaz* (Stoddart 1973) (Brassicaceae)c	Ha	O	N	N	P	N	N	N	N
Lepturus repens (G.Forst.) R.Br. subsp. *repens* (Poaceae)	Hp	B/O	P	P	P	P	P	P	P
Portulaca oleracea (Portulacaceae)	Ha	B	P	N	P	P	P	P	P
Sesbania cannabina (Retz.) Poir. var. *cannabina* (Fabaceae)	Ha	B/H	N	P	P	P	P	P	P
Tribulus cistoides L. (Zygophyllaceae)	Ha	B/O	P	P	P	P	P	P	P

Plant data: J. Warham (1959), K.A. Hindwood (1961), D.R. Stoddart (1973),
B.K. King (1981), J.B. Hacker (1987), G.N. Batianoff & M.A. Card (1991) and G.N. Batianoff (2003).
Dispersal: B = Birds, H = Humans, O = Ocean currents
Life forms: S = Shrub, Ha = Annual herb, Hp = Perennial herb, V = Vine
P = Present, N = Not recorded or absent
* = Introduced exotic plant species.

Raine Island has been the focus of a number of physical studies over the last 40 years (Stoddart et al, 1981; Gourlay and Hacker, 1991; Gourlay, 1995, 1997; Hopley and Rasmussen, 1989; Hopley et al, 2007; Neil et al 2000; Neil, 2003, 2005; Guard et al, 2008; Dawson, 2008) and these form the basis for this section of the report.

2.5.2 Significance of Holocene Evolution

The Holocene evolution of the reef and cay is outlined in appendix B. It shows that changes in sea level, or probably more importantly, changes in the depth of water over the reef flat have had very important implications for the delivery of sediment to the island. Also important has been the morphology of lagoon or reef flat with an uneven reef flat producing a frictional effect on wave energy and also reducing sediment delivery. Thus it is not surprising to find that both erosional and progradational periods are recorded in Raine Island's history, the change from one to the other apparently possible within a few hundred years. Cementation in the form of beach rock and phosphatic cay sandstone appears to have been a process over a long period of the island's history. The extent of the older cay sandstone can be approximated but beach rock may underlay many parts of the island and will retard any future erosion or other responses such as changing sediment delivery as the result of climate change.

2.5.3 Reef Flat Zonation and Sediments (see figure 5)

The reef flat zonation is described by Gourlay and Hacker (1991) and by Clegg et al (1997) commencing from the reef margin:

- a reef rim zone of dense coral growth (42 species) dominated by Acroporids. Stout growth forms reflect the high energy of this environment.
- algal pavement dominated by large areas of turf and sand at about 0.9 m H.A.T. with living foraminifera (*Baculogypsina sphaerulata* and *Marginopora* sp). Small *Porites* heads also exist here.
- a branched *Acropora* zone in the central reef flat formed in a slightly lower area
- a micro atoll zone, mainly *Porites* sp close to the island with an elevation of 0.5 m to 0.6 m L.A.T. Unconsolidated sediments are mainly *Halimeda* and foraminifera with some sea grass (*Thalassia hemprichii*) growing on these sediments. 44 species of hard corals are recorded for this zone.
- an 'eroded' reef surface at the western end of the reef at 0.3 m to 0.4 m L.A.T.

Neil et al (2000) observed the sediment zonation over the reef flat noting that it is very thin veneer, a reflection of the high energy levels experienced by this very exposed reef. The eastern end of the reef may have little or no cover except in occasional depressions. In the west it is rarely more than 5 cm and exceeds 10 cm only adjacent to the cay and between microatolls. The sediments range from 100% gravel to 100% sand with no fines. They are coarsest around the margins of the reef. Coral and coralline algae are the major constituents with lesser *Halimeda* and foraminifera (*Marginopora* and *Calcarina* can be up to 80%). Three sediment zones were recognised by Neil et al (2000):

- an outer well-rounded coarse *Marginopora* rich facies
- a central angular fine mixed facies
- an intermediary coarse foraminiferan – medium *Halimeda* facies.

Notably for the Raine Island cay and its future, the reef flat is not a store of sediment which can be rejuvenated by sea level rise and increased reef flat wave action as may take place on other reefs (see 3.6.1).

2.5.4 Geomorphological Components of the Cay (see figure 6)

Raine Island has a concentric zonation apart from at the eastern end where beachrock and phosphate rock are contiguous with little beach. Most detailed descriptions are by Stoddart et al (1981) and Neil et al (2000). The zones are:

- the beach rising steeply from the reef flat with a width of between 18 and 20 m and rising to a 4 to 5 m berm, generally higher in the north-east than south-west. It contains approximately 0.68 ha of beachrock dipping seawards at between 5^0 and 12^0 especially along the north-eastern shore.
- a swale which Neil et al (2000) indicates is underlain by an undefined cemented "bryme" rock at a depth of about 1.0 m. The swale is 30 to 80 m wide, with a partial tussock grassland. This and the berm are major turtle nesting sites.
- a phosphate cliff, fronted by isolated outliers and boulders. It surrounds more than 60% of the island. The cliff is undercut and cavernous 1.0 to1.5 m high. The upper level is very uniform and cementation is greatest here with stalactite like a densely vegetated unconsolidated sand ridge rising to 8.0 m in the south-west, 6.5 m in the north-east. It almost encircles the island and is 25 to 100 m wide.
- an interior central depression, largely unvegetated but with a fresh white guano covering. Rich organic soils were described in this area by the early explorers but it is from here that most of the guano was mined. Nonetheless, a depression did exist prior to mining. Elevation today is about 6.0 m but appears to be tilted to the south-east. This is the major bird roosting and nesting site.

The phosphate rock, cliff and newly described 'bryme rock' have a strong influence on the turtles and to a lesser extent the birds. A hypothetical model of development is given in appendix C (see especially figure C1).

2.5.5 Raine Island Sediments

Several studies have included investigations of the sediments of Raine Island but by far the most comprehensive is that of Gourlay and Hacker (1991). Except for a small amount of pumice (common on other GBR cays) all sediments are derived from the reef top. They include coral, algal, molluscan, foraminifera and *Halimeda* fragments, generally in the coarse sand size fraction. Typically coralline algal values are 10.0 to 23.6%, *Halimeda* 5.4 to 53.8%, molluscs 8.8 to 14.0% and foraminifera 20.4 to 53.8%. The foraminifera include *Baculogypsina sphaerulata* (up to 50%) and *Marginopora* and *Amphistegina* sp. The foraminifera are the most important component of Raine Island's beaches but also very susceptible to climate change (see Section 3.6.2 and appendix D).

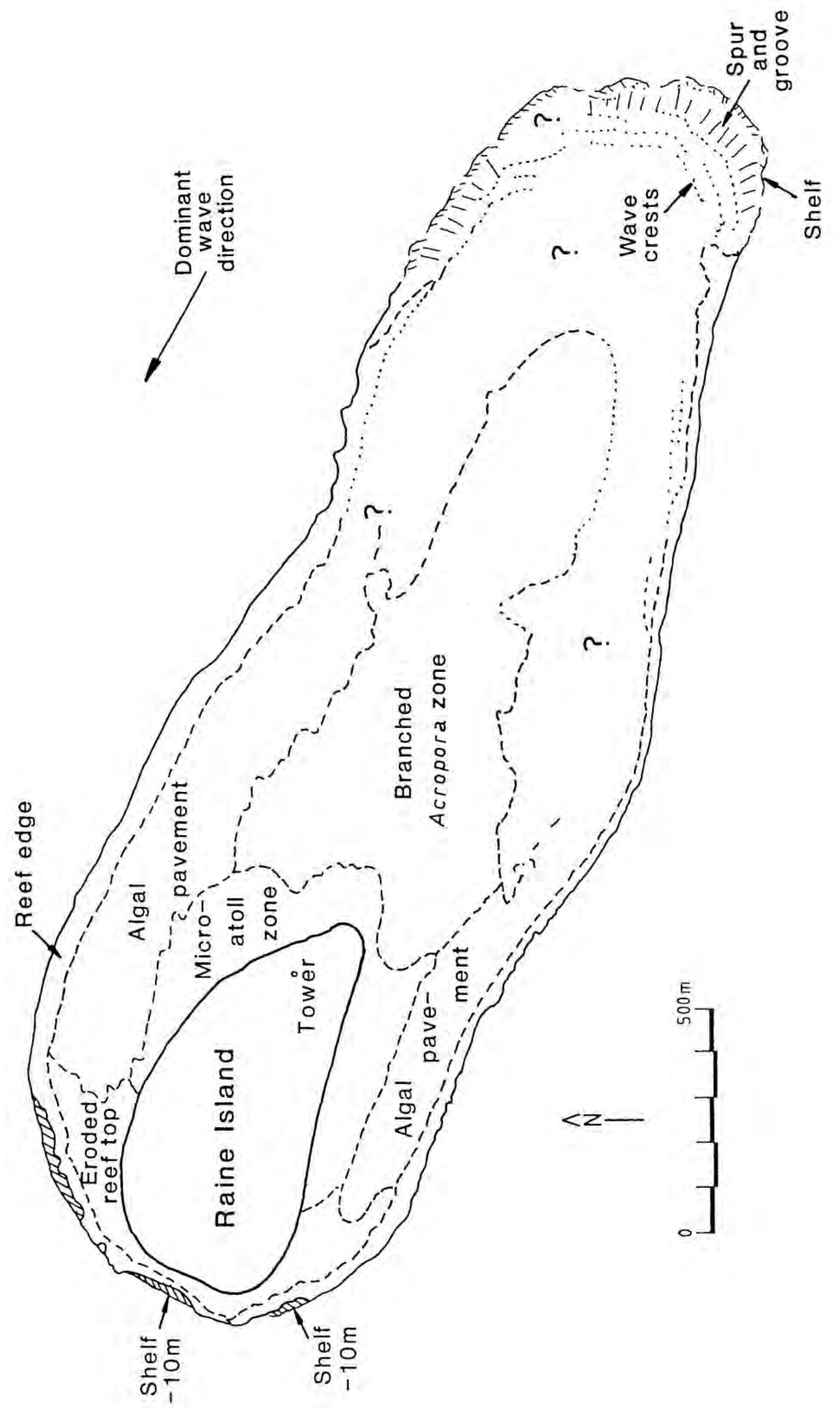


Figure 5 Raine Island reef (from Gourlay, 1995)

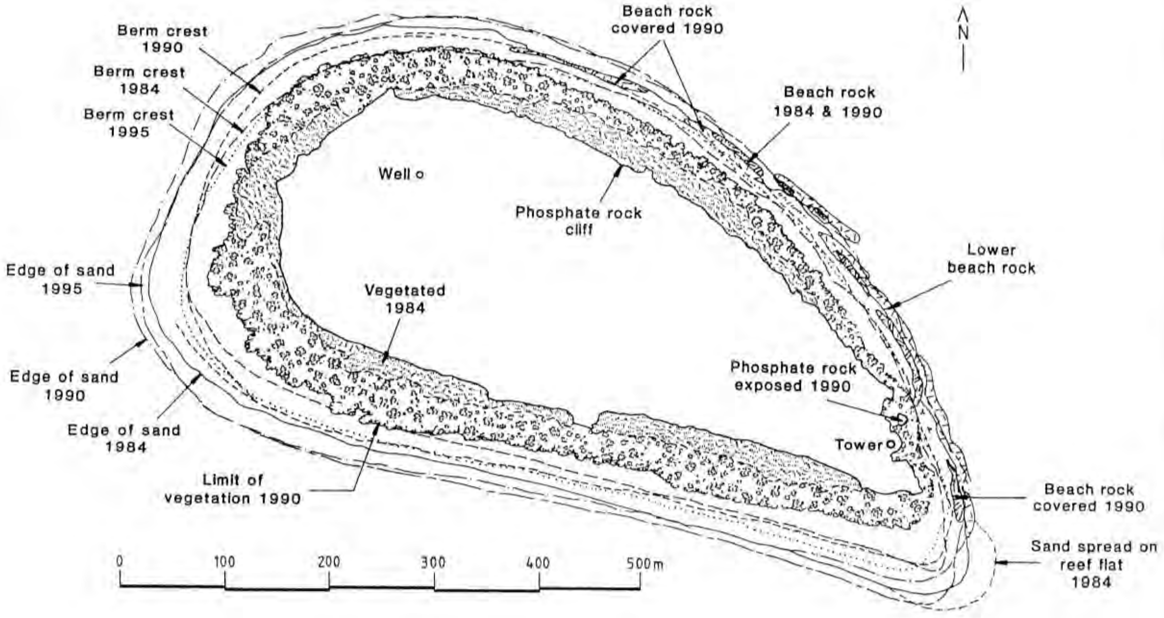


Figure 6. Island geomorphology and comparison of shoreline and berm crest position, Raine Island – 1984, 1990 and 1995. (Adapted from Gourlay and Hacker 1991, figure 5.13)

2.5.6 The Phosphate Rock of Raine Island (see figure 7 and appendix C)

Although not unique to Raine Island, the capping of phosphate rock has been the focus of many observations in the papers quoted and especially in Baker et al (1998). The material has formed from avian guano over the last 1200 years (based on ages from the juxtaposed beach rock). Cementation is highest at the surface and rarely extends below 2.0m. The cap over the island is planar but the lower cementation level has a stalactite relief. The phosphatic mineral has been identified as dahllite (carbonate hydroxyapatite).

Baker et al (1998) regard the Raine Island deposit as classic and not unusual. They describe the formation as the result of rainfall descending vertically through the overlying layer of guano and soil. The hardpan formed below the evaporative zone where porewaters could undergo $^{18}0$ enrichment creating intense phosphatisation and total replacement of most bioclasts.

This groundwater model, which enlists the basic Ghyben-Herzberg freshwater lens, (figure 7, lower figure) is important in possibly explaining the present morphology. The fresh/brackish lens can have an elevation above that of the surrounding ocean and if Raine Island has been larger in the past, erosion into the domed water table at which cementation took place would explain the prominent scarp of phosphate rock today and possible slope of the interior of the island. It also disposes with any need for a higher sea level in the formation of the phosphate cap.

The 'bryme rock' around the outer zone of Raine Island may be a recent addition to the phosphatic cay sandstone as discussed below and in appendix C.

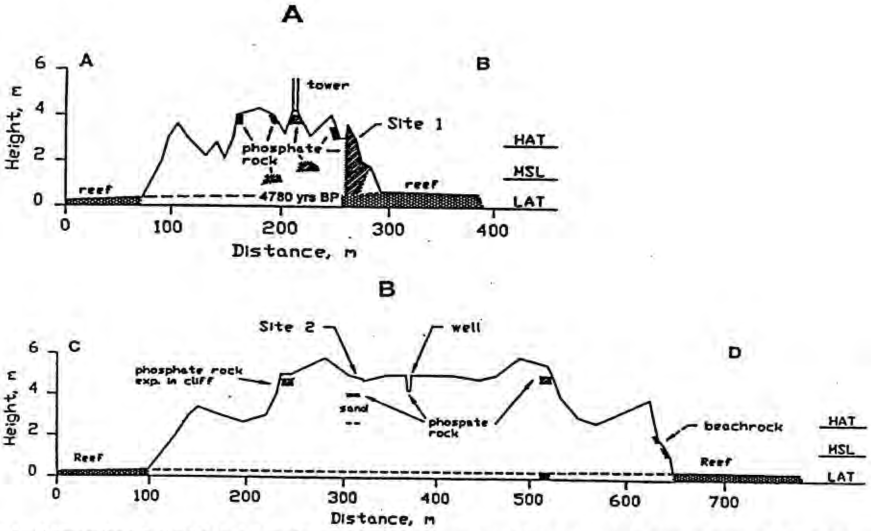


FIG. 3.—A) Cross section A–B, showing Site 1, from where 1A, 1E, 1G, and 1H were collected. Note the existence of phosphate rock down to 0.5 m above LAT at Site 1. B) Cross section C–D, showing Site 2 from where 5A was collected. Cross sections were prepared from photogrammetric map 1991 (based on 1990 and 1991 aerial photography). Date of 4780 ka shown in cross section C–D is for cemented coral material underlying phosphate rock at 0.1 m LAT (D. Hopley and C. Rasmussen, personal communication 1991). LAT = lowest astronomical tide; MSL = mean sea level; HAT = highest astronomical tide; height is relative to LAT.

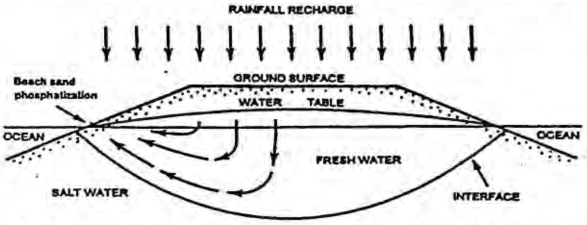


FIG. 8.—Groundwater flow model for an oceanic island. Note that in shoreline areas, the freshwater-seawater interface can be well below sea level. Modified after Todd (1980).

Figure 7. Cross section of Raine Island showing phosphate rock and Ghyben-Herzberg groundwater model both (from Baker et al, 1998)

2.5.7 Impacts of the Physical Features of Raine Island

Although Raine Island is already attractive for nesting activities of both turtles and birds, there are many aspects of the geomorphology which cause problems. These have been discussed by Neil et al (2000) and Neil (2005). and include:

- the phosphate cliff restricts access to the internal parts of the island and causes the mortality of turtles if they fall over it on their return to the sea.
- the lithified sediments in the major nesting area of the beach berm and swale.
- inundation of nest sites laterally by tide waters.
- freshwater run-off from the central depression through the nesting sites.
- over wash of the berm by strong waves

The most serious problems are:

a. Flooding of turtle nests – resulting from pools of water forming on the less permeable central phosphate flat but also from rising water tables after rain, especially beneath the swale in which many nests are built. Limpus et al, (2003) provide an example of the problem. One of the largest nesting populations was recorded in December 1996. However, instead of thousand of hatchlings crossing the beach the following February elevated water tables resulted in only hundreds being observed. Both rainfall and exceptionally high tides can produce this elevation which intercepts the critical ~80 cm depth of the turtle nests.

b. Shoreline changes – Raine Island is very dynamic as indicated by the analyses of Gourlay and Hacker (1989), Gourlay (1997, 1998, 1999), Neil et al (2000) and Dawson (2008). Appendix E summarises their conclusions which include:
    i) although periods of erosion have been most noticeable over the past 40 years there has actually been a net gain of ~14,000 m^3 and, over the last 10 years a gain of ~45,000 m^3.
    ii) these figures, however, are small within the context of the island as a whole which is in a very delicate state of balance between sediment supply, from the reef flat, and sediment loss off the reef top.
    iii) the major beach changes have been related to changing wind patterns and ENSO events. Major changes in the 1970s are comparable to those described on Warraber Island in Torres Strait (Rasmussen and Hopley, 1995), and in the Bunker-Capricorn Group by Flood

These changes may provide insight into the response of Raine Island to climate change (further discussed in later sections).

3. Projected Climate Change Impacts on Raine Island and Inhabitants

3.1 Sources of Information

> "There is now no scientific doubt that human activities have changed the composition of the atmosphere and the oceans. The change in the heat balance of the earth is now causing observed changes in global and regional climate".
>
> (Lough, 2007, p17)

Current climate trends and future projections have been summarized comprehensively elsewhere, and this review draws on a number of these recent reports, some specifically related to the GBR. The latest global projections have been derived primarily from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007, a, b, c, d). Projections specific to Queensland and the GBR are drawn from the relevant chapters in Johnson and Marshall (2007) and a recently released assessment from the EPA (2008), which evaluates the IPCC projections in conjunction with modeling by the CSIRO and Bureau of Meteorology.

The source of much of the following section is the major vulnerability assessment carried out by the Great Barrier Reef Marine Park Authority in 2007 (Johnson and Marshall, eds. 2007), utilising the relevant chapters:

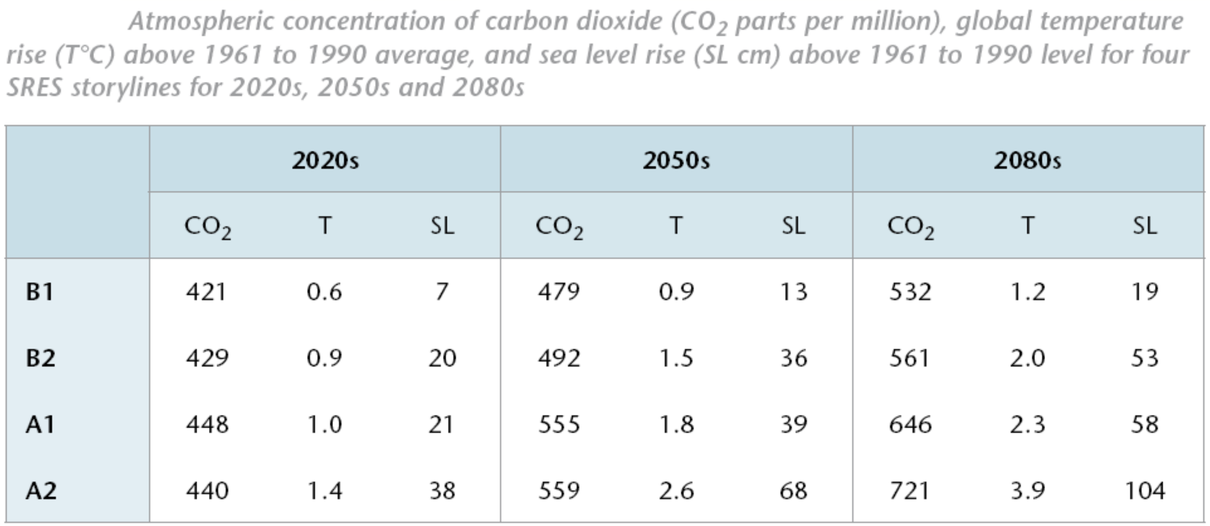
- climate change projections (Lough, 2007)
- turtles (Hamann et al, 2007)
- seabirds (Congdon et al, 2007)
- geomorphology (Smithers et al, 2007)
- physical oceanography (Steinberg, 2007)
- coral reefs (Fabricius et al, 2007)
- island flora and fauna (Turner and Batianoff, 2007)

3.2 Projected Climate Changes (table 3, 4 and figure 8)

The IPCC assigns uncertainty ranges to projections based on expert judgement and statistical analysis of a body of evidence (IPCC, 2007d). There has been increasing confidence in many climate projections in the latest reports, especially for those climatic components most directly related to the proportion of greenhouse gases in the atmosphere. Unfortunately, considerable uncertainty remains about future changes in components with more complex feedbacks such as those related to El Niño events. Climate projections of greatest relevance to Raine Island include:

Atmospheric temperature: since the end of the 19th century average global air temperatures have risen by 0.7 ^{0}C.The eleven warmest years since the beginning of the instrumental record have all occurred since 1995 (NASA, IPCC 2007). .. Temperatures in Queensland coastal areas are projected to increase by an about 0.9 °C (range of 0.7–1.2 °C) by 2030 (EPA, 2008) and as much as 4 to 5°C by 2070 (Lough, 2007). Projections for Cairns suggest an average increase of 0.9 ^{0}C (0.6-1.2 ^{0}C) by 2030 and 1.5 ^{0}C (1.1-2.0 ^{0}C) to 2.9^0 (2.0-3.9 ^{0}C) by 2070 depending on future emissions pathways. Whilst lower than further south, these changes will still have implications for both bird and turtle populations and also the sediment budget of Raine Island as discussed below.

Table 3 Projected global atmospheric CO_2 concentrations, temperature rise and sea level rise for four IPCC SRES storylines.



Atmospheric concentration of carbon dioxide (CO_2 parts per million), global temperature rise (T°C) above 1961 to 1990 average, and sea level rise (SL cm) above 1961 to 1990 level for four SRES storylines for 2020s, 2050s and 2080s

	2020s			**2050s**			**2080s**		
	CO_2	T	SL	CO_2	T	SL	CO_2	T	SL
B1	421	0.6	7	479	0.9	13	532	1.2	19
B2	429	0.9	20	492	1.5	36	561	2.0	53
A1	448	1.0	21	555	1.8	39	646	2.3	58
A2	440	1.4	38	559	2.6	68	721	3.9	104

† *Climate Change and the Great Barrier Reef: A Vulnerability Assessment*, p.50

i) Sea surface temperature: the GBR has already warmed significantly with the last 30 years being 0.4^{0}C higher than at the end of the nineteenth century (Figure 8). Coral core records take this warming period back a further 200 years (Lough, 2007). Projections are for a further warming of 1^{0}C by 2050 and 1^0-3^{0}C by 2100. Unless corals exhibit substantial adaptive capability, mass bleaching of corals will become regular events over coming decades (e.g. Hoegh-Guldberg, 1999).

ii) Rainfall: projections are less certain, though greater extremes appear likely, with high intensity events in northern Australia. There are implications for turtles and seabirds nesting on Raine as nest flooding is more likely (refer to table 4).

iii) Cyclones: Interpretation of trends in tropical cyclone frequency and intensity is complicated by their high variability across multidecadal timescales, but recent patterns suggest an increase in intensity if not frequency (Fuentes et al, in press; see also EPA, 2008; Puotinen et al, 1997; Puotinen, 2004). This is consistent with the likelihood that cyclones in a warming world will be more intense with higher maximum wind speeds and greater rainfall (Lough, 2007). However, the latitude of Raine Island is such that there may be insufficient Coriolis force for there to be much effect at this low latitude.

iv) Sea level: (table 3) Global average sea level is projected to increase by 18-59cm by 2100 (IPCC 2007d), though this range does not into account possible increased ice sheet melting. Regional sea level can vary depending on many factors and sea level rise on the Australian east coast may be slightly greater than the global average (EPA 2008). Most sea level rise recorded to date is a response to thermal expansion rather than ice melting. Global average sea level is currently rising at 1-2 mm per year and has increased by 195 mm between 1870 and 2004 (Lough, 2007). . The observed trend at Cape Ferguson, near Townsville is 2.9mm per year (1991-2006) (Lough, 2007). The response of sandy shorelines such as that of Raine may be complex, not necessarily involving erosion (see Gourlay and Hacker, 1991; Hopley et al, 2007) but other impacts, such as rising water tables may be of concern.

v) Ocean acidification: Ocean uptake of carbon dioxide has already resulted in a reduction in ocean pH from 8.16 to 8.05 since the start of the industrial revolution, and this is projected to decrease to between 7.91 to 7.76 by 2100 depending on future emissions pathwars (Kleypas et al, 2006). Resulting changes to ocean carbonate chemistry will will have a major impact on calcifying organisms, slowing down growth rates and/or resulting in more fragile skeletons (e.g. Fabricius et al, 2007; Kleypas et al, 2006). The impact on small organisms such as foraminifera, an important component of Raine Island's beaches, will interfere with sediment budgets though other impacts may produce short term increase in sediment yield to coral reef cays (refer to figure 9)

vi) El Niño/Southern Oscillation (ENSO): ENSO is a critical driver of inter-annual climatic variability in the GBR region. There is no obvious trend in ENSO events and projections are uncertain (Lough, 2007; EPA, 2008). Whether or not El Niño and La Nina events will be more frequent or more intense (important as they again relate to erosion and accretion and to turtle and bird behaviour on Raine Island) may only become clear in the next few decades.

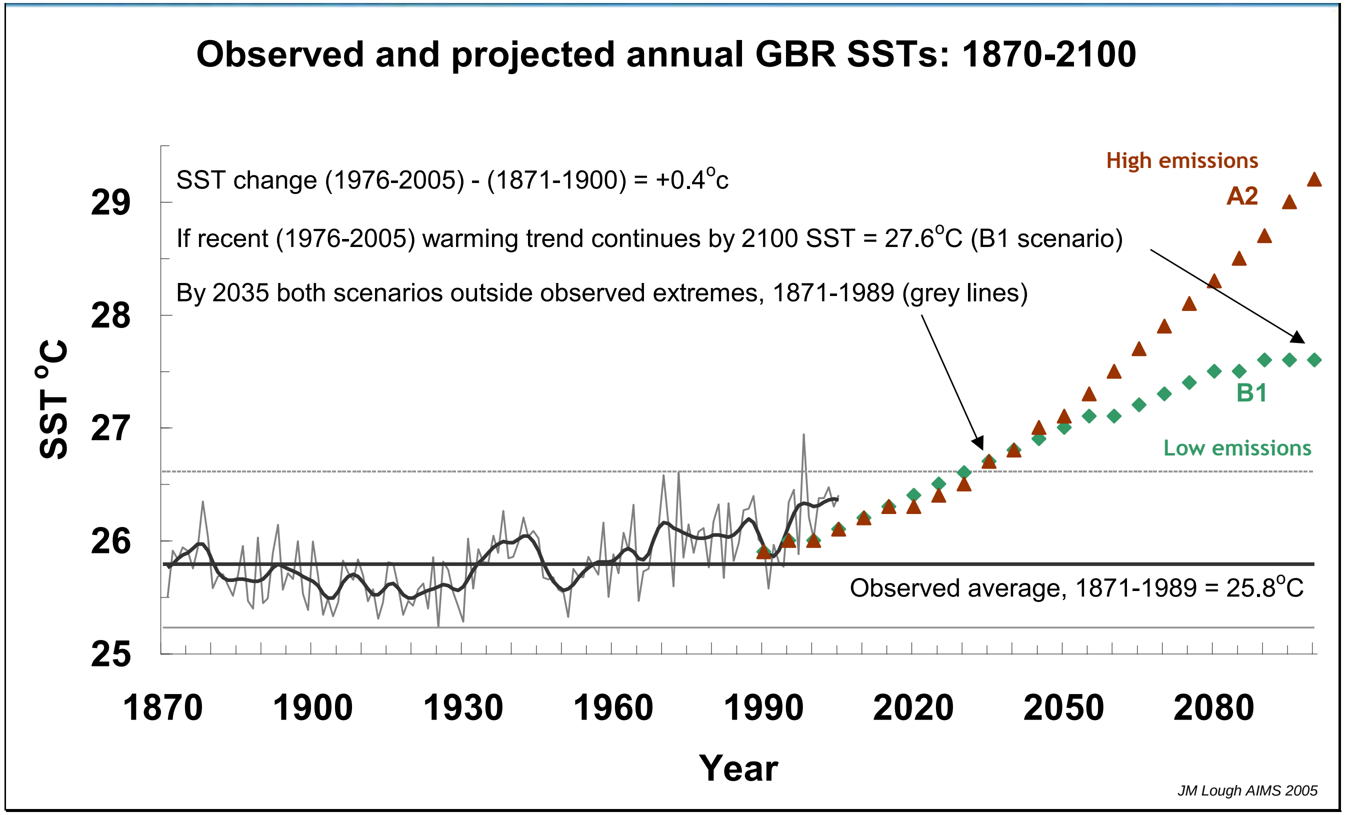


Figure 8 Observed and projected annual GBR Sea Surface Temperatures: 1870-2100.

These climate change projections and likely impacts on components of Raine Island's ecological system are summarized in Table 4.

3.3 Impact of Climate Change on the Green Turtle Population

Risk assessment for marine turtles on Raine Island has many similarities with the assessment for seabirds (see below). Both have a breeding period on the island which can be carefully monitored but both also have widespread foraging areas upon which the effects of climate change can only be surmised. However, the turtles face a further threat from increased harvesting outside of Australian waters as stocks of both turtles and other marine resources are depleted by subsistence economies.

Hamann et al (2007) focus on air and sea surface temperature rise as the most important impacts. Higher temperatures during nesting may result in greater heat stress and mortality of nesting females. Hatchling incubation and embryo development will also be affected. The present optimum range of sand temperature is 25^0 – 33 ^{0}C, the lower levels favouring the hatching of males, the upper females. Climate change may move the incubation period towards the upper end and beyond, which Hamann et al (2007), believe will increase egg mortality as well as the altered sex ratio, which could reach 4:1 in favour of the females, the sustainability of which is unknown.

However, changing climate may also affect foraging area dynamics with possible greater availability of food sources (sea grass, algae, mangrove leaves). There is the possibility of sea turtle growth rates being enhanced with shorter intervals between breeding seasons. On the negative side higher temperatures appear to result in hatchlings with poor swimming ability and hence potential for survival.

A rise in sea level will have a debatable affect on the green turtle population of Raine Island. Hamann et al (2007) suggest that the main cause of recent decline has been erosion, but the geomorphological surveys do not support this. Rather they show a very dynamic and constantly changing beach/berm system. Continued seasonal monitoring, measurement of the actual processes operating at different stages of the tide and a determination of the sediment budget under contrasting weather conditions are needed to understand projected sea level rise responses of the Raine Island nesting sites.

Rising sea level will also affect the water table at Raine Island although any rise resulting only from a higher sea level is likely to be more than compensated for by construction of a higher berm.

Table 4. Climate Change Projections Relevant to the Northern GBR and Possible Impacts on Raine Island and Its Inhabitants

		Impact			
Climate Change Component	**Projected Change by 2050**	**Turtles**	**Seabirds**	**Vegetation**	**Physical Environment**
Atmospheric temperature	+0.9 – 2.6 ^{0}C	Heat Stress sex ratio hatchlings	Heat stress	Higher evapotranspiration	
Sea Surface Temperature	+1.2 - 1.3 ^{0}C	Poor swimming of hatchlings	Impact on food resource		Coral and foram bleaching, sediment yield
Rainfall	More intense amount. uncertain	Nest flooding	Nest flooding	Beneficial if higher	Higher water table – leaching of guano
Cyclones	Probably more intense	Nest disturbance, Egg mortality	Nest disturbance Adult, hatchling and egg mortality	Greater disturbance?	Change in beaches
Sea level	+13 - +68 cm	Nest flooding Island disturbance	Possible nest flooding. Island disturbance	Salinisation of water table	Sediment supply from reef flat
Ocean Acidification pH	-0.15 – 0.25				Loss of calcium carbonate binding organisms, e.g. forams and corals Decrease in sediment yield
ENSO	More frequent, more intense	Impacts on foraging Impact on egg production	Impacts on foraging Decline in numbers		Changing wind patterns – changing orientation
Atmospheric CO^{2} and other greenhouse gases	Dependent on investigation but definitely higher than today			C$_3$ plant fertilisation	

Nesting sites 50-80 cm beneath the surface may not be affected by normal tidal pumping but the effects of increased rainfall, even in short events may be more important and need incorporating into the ongoing groundwater studies. A possible benefit of more rainfall however, may be easier nest digging with less collapse of the sand.

As noted above the incidence and severity of tropical cyclones is not clear at Raine Island's low latitude. The topic is the focus of research by Fuentes et al (in press), who indicate the high vulnerability of the Raine Island green turtle population if cyclonic patterns remain the same or change according to the projections of one model. Timing of the nesting season, as well as location in an area of high cyclone risk are the determining factors.

Relating the response of green turtles at Raine Island to climate change projections involves a complex system of energy thresholds. The turtles may have an adaptive capacity with the ability to shift nesting season (the Gulf of Carpentaria population nest in winter to avoid high summer temperatures). Hamann et al (2007) indicate that by 2050 one to two generations will have been adversely affected, the main impact being on the embryo development phase, but the longevity of the turtles reinforces the need for continuous long term monitoring.

3.4 Impact of Climate Change on Seabirds of Raine Island

Congdon et al (2007) highlight the dependence of seabirds on marine food and suggest they are one of the best indicators of environmental change. Reviewing the data on fluctuating seabird numbers they suggest that ENSO events have a major impact on the time of breeding, year to year recruitment, numbers of breeding pairs and hatching success. In particular, the 1982-3 ENSO created widespread reproductive failure and mortality with the slowest recovery in populations of brown booby, red footed booby, and great frigatebirds. In the Coral Sea the 1998 ENSO event produced significant declines of 6-7% populations of great and lesser frigatebirds and possibly black noddies which appear not to have returned to pre 1998 levels. As noted, earlier on Raine Island a decline in the breeding population of at least 10 of the 14 breeding species has been recorded. The increase in sea surface temperatures occurring during ENSO events appears to cause a decline in food availability and subsequent impact on the birds. Any increase in the frequency or intensity of ENSO in the future will thus impact detrimentally on Raine Island's breeding bird stocks.

Similarly, the uncertainty about cyclones is also problematic as these too impact on the seabirds, destroying eggs, increasing mortality of chicks and adults and impacting nest sites by wave inundation and erosion. Also the availability of the breeding habitat may be reduced by sea level rise, although the geomorphological projections suggest that the overall area may not be reduced. Nonetheless, any re-orientation of the island may involve loss of specific vegetation zones. Sand and rubble added to the island as suggested by the geomorphological projections will increase early colonising vegetation and woody shrubs favouring some species over others. Also on Raine Island Congdon et al (2007) note that rising sea level may flood the cavernous phosphate rock areas, the only nesting site available to the red tailed tropic bird. They also note that disturbance to the turtle nesting areas may move the turtles into areas now mainly used by the birds only resulting in further disruption. Overall, climate change may have negative impacts on both nesting sites and, via ENSO frequency and increased sea surface temperatures, reducing foraging efficiency and reproductive potential. However, the increased height of the beach berm and possible minimal change to the central depression should ensure suitable nesting sites until at least the middle of this century.

Turner and Batianoff (2007) indicate that many seabirds return to nest on familiar beaches, but if these disappear they have some capacity to find alternate sites, given they have the appropriate conditions and are not already occupied. Ground nesting shorebirds and seabirds that nest on bare ground close to the intertidal mark are adapted to dynamic landscapes and frequently select new sites each year. However, some seabird species such as Raine Island's brown booby show strong nesting site fidelity and whilst they may move a short distance to another site their potential for moving to distant islands is uncertain. This would appear to apply to most of Raine Island's seabird population.

3.5 Impact of Climate Change on the Vegetation of Raine Island

The vegetation of Raine Island is already depauperate after 150 years of disturbance in addition to the effects of turtle nesting. Change in rainfall will influence change in the plant community on the island. Increase in storm/cyclone intensity and frequency may impact of the vegetation. There are no deep-rooted trees or shrubs which could be affected by a rising saline water table and it is possible that if there is a reduction in turtle nesting then Raine Island may acquire greater diversity. Any change to ocean currents may have an influence. At the present time the vegetation is derived almost exclusively from drift seeds, probably from the Coral Sea islands rather than the GBR, with one (*Pangium edule*) originating from Papua-New Guinea (Hacker, 1990). Any change to ocean current patterns in the northern Coral Sea could result in more plants from the north drifting to GBR islands.

Whilst any addition of new material to the beaches will require colonization by pioneering species, small positives may be increased growth rates with increased CO_2 levels in the atmosphere, especially as the plants are growing in nutrient rich (guano) soils which, gives them a greater ability to withstand drought.

3.6 Geomorphological and Other Environmental Responses to Climate Change on Raine Island.

3.6.1 Sea Level Rise

Increased water depth will allow the passage of higher energy waves over reef flats which may have been inert for thousands of years and the general conclusion about cays in general is that they will continue to exist in the short term though with modifications (e.g. McLean, 1989; Parnell, 1989; Hopley, 1993; 1997 a,b; Kench and Cowell, 2002). Gourlay and Hacker (1991) in particular provide a detailed modelling study applied specifically to Raine Island. Their model showed a small rise in sea level without any responding build-up of the height of the reef flat would result in the attainment of greater berm height under most weather conditions, i.e., a build-up of the island by an amount which could exceed the amount of increase in water level. For example, at Raine Island, Gourlay and Hacker (1991) suggest that with a 0.6m rise in sea level, the larger 1.6 m waves would increase berm height by a factor of 0.8m, and 0.5m waves would increase the height by 1.2 m, i.e., to 4.8 m and 5.2 m respectively from the initial 4.0 m height.

Water depth over the reef flat is critical. At Warraber Island in Torres Strait, Kench and Brander (2006) have shown that the reef flat is geomorphologically inert for most of the time with waves above 0.05 m occurring on the outer reef < 30% of each Spring to Neap tidal cycle. With a higher sea level rise, larger waves will propagate further across the reef flat and over a larger proportion of the tidal cycle. However, re-invigoration of sediment movement on the Raine Island reef flat may be very limited as the sediment cover is so sparse (5-10 cm). Figure 9 shows projected changes to the reef flat with rising sea level and other environmental changes to 2080 for Raine Island.

3.6.2 Thermal Stress and Ocean Acidification

Both thermal stress and ocean acidification will produce weaker corals and widespread mortality. These corals, especially the branching species will be broken in catastrophic storms, producing a new wave of sediment delivery to the focal point of refracted waves, i.e., Raine Island. The reef rim zone is the most likely area for this impact, especially as Acroporids make up 62.7% of the coral cover (21.5% of substrate). (Clegg et al, 1992). The micro atoll zone may also be affected in the same way, as Acroporids also occupy 7.7% of the total area of the central reef flat including *Isopora palifera*, *Seriatopora hystrix* and *Pocillipora damicornis*.

Ocean acidification may also affect the more regular supply of sediment to the Raine Island beach. As noted, small foraminifera tests are an important component of both reef flat and island sediments. Calcification of these tests in the future will be difficult and foraminifera may disappear completely from the Raine Island reef flat impacting negatively on the sediment budget. The part played by benthic foraminifera in cay sediments of the GBR and their likely adverse response to thermal stress and ocean acidification is outlined in more detail in appendix D.

The beach rock on Raine Island will slow down any changes to the beaches but future cementation may be retarded by the reduction in pH thus decreasing long term beach stability.

3.6.3 Water Table Modification from Sea Level Rise and Changes to Rainfall Patterns.

It is unlikely that a permanent fresh or brackish water lens exists on Raine Island. Which of the two groundwater models applied to coral cays is most applicable to the island is also uncertain. The Ghyben-Herzberg lens, producing a freshwater lens in the form of an upturned saucer with a water table depth to height ratio of 40:1 may help to explain the surface morphology of the phosphate cemented upper surface (figure 7) but a minimal island width of 300 m is required, perhaps indicating the minimum size of Raine Island before the erosional phase which ate into the phosphate margins and formed the present phosphate cliff.

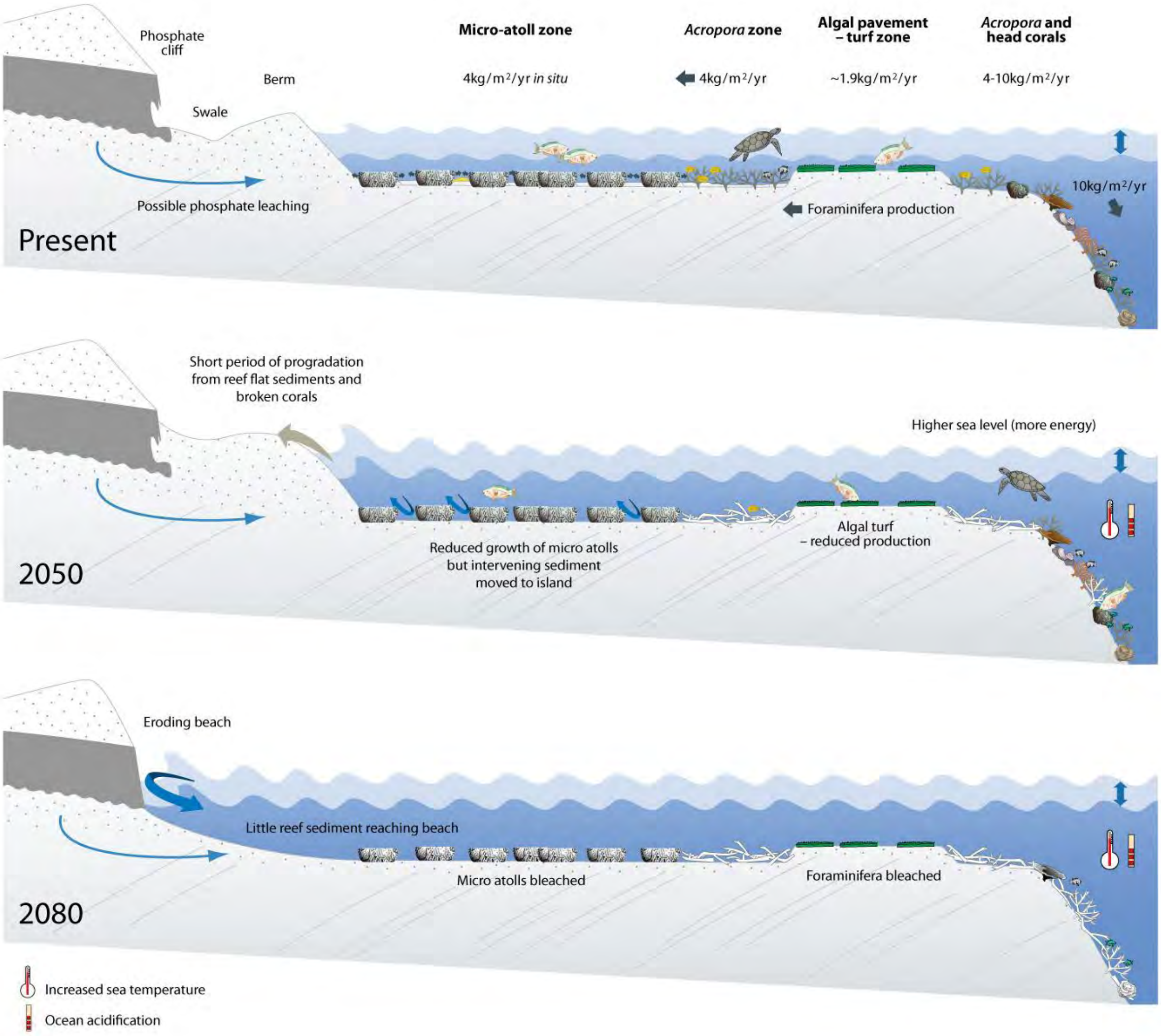


Figure 9 Projections for Raine Island reef flat benthic ecology and sediment delivery from the present to 2050 and 2080. (see below for extended caption).

Raine Island Beach and Reef Flat.

Present: the reef and reef flat are producing a healthy carbonate budget which can be estimated as about 10kg m^2 yr^{-1} on the reef front, dropping to about 4kg m^2 yr^{-1} for the reef margin Acropora zone. Production from the foraminifera in the turf zone is about 1.9 kg m^2 yr^{-1}. The microatoll zone may produce at about 4kg m^2 yr^{-1} but most of this will remain in situ.

water levels around 1.5 m only at high tide and this together with the frictional effect of the microatoll zone, limits the effectiveness of waves. Only the most easily moved sediments – the foraminifera tests will be responding to the centripetal wave section on a regular basis. Other sediments will be lodged between the Microatolls, though the sediment cover in this zone is very thin.

There may be some loading of phosphate from the cay if renewed movement as the result of the 1890s mining is taking place (see appendix C).

2050: acidification , more regular bleaching and a rise in sea level of about 36 cm will have a major affect on the reef. Carbonate productivity may remain relatively high on the deeper reef front but the *Acropora* zones will be largely dead and breaking up to provide a new wave of sediment to the island. Foraminifera production will have almost totally ceased but with water depth over the reef flat being at least 36cm higher than present wave effectiveness will have greatly increased and capable of moving the *Acropora* shingle to the island as well as sediments previously lodged between the Microatolls. The new shingle addition to the berm is unlikely to produce a site favourable for turtle nesting.

2080: by 2080 the full effects of climate change will be felt. Bleaching and acidity will have reduced levels where no new carbonate sediments are being produced. Indeed there may be a negative budget in some areas. Sea level may be ~53 cm higher but there is little new sediment to transport to the island. Erosion is now the dominant process, first of all stripping the beach berm from the island, then eating into the phosphate cliff. These are the first stages of total erosion of Raine Island.

The alternate layered aquifer model (Buddemeier and Oberdorfer, 1990; Oberdorfer et al, 1990) is less sensitive to island size with a threshold width of only 120 m. It depends on two layers of contrasting porosity (the Holocene cap over the cemented and diagenetically altered Pleistocene reef limestone). A rise in sea level actually enlarges the aquifer as more of the low permeability layer is incorporated. Given the additional of more intense rainfall more regular nest flooding of both birds and turtles would appear likely.

3.6.4 Cyclones.

Raine Island already experiences cyclones although they are generally small and have insignificant storm surges. Although more numerous and more intense cyclones are projected by some climate models, the effect on Raine Island may not be great because of its low latitude. However, any increase in activity would accelerate any beach changes. The risk is assessed in Fuentes et al (in press).

3.6.5 Raine Island Response to Changing Weather Patterns.

Raine Island has been shown to be highly dynamic responding to both major El Niño/La Nina oscillations and smaller changes to wind directions and energy. Whilst details of any changes into the future are not available, analysis of wind records from the nearest weather stations (Thursday Island, Willis Island) and correlation with Raine Island beach changes may strengthen these relationships.

However, the response on island beaches is highly dependent on the state of the tide when the cyclone hits (Flood and Jell, 1927). Erosion occurs if water levels are high or deposition if tide levels are low (see Hopley et al 2007 for examples).

4. Gaps in Knowledge with Respect to Assessing Raine Island's Response to Future Climate Change

4.1 Gaps in Knowledge and Future Climates

Although Section 2 outlined considerable data bases for Raine Island, it also highlighted many unanswered questions for which information will be needed to provide sound management decisions. This section reviews current information versus outstanding questions from the scientific perspective based around each of the disciplinary areas represented or highlighted at the 2008 Townsville Workshop and the possible impacts of climate change in the foreseeable future.

Unfortunately, although there is now a high confidence in the general concept of climate change there is uncertainty about the specific response of each of the affected environmental variables due to differences between individual climate models and understanding of the physical processes of the climate system. Uncertainties also relate to predictions of future greenhouse gas emissions as future mitigation policies take effect (Lough, 2007). Thus for most components of global change reports such as that of IPCC give a range of possible projections. As noted this range is relatively narrow for components directly related to atmospheric gas concentrations, such as temperature but the range becomes wider the more links there are in the environmental component (e.g. rainfall, as pattern and intensity will change not just total amount). At the end of the chain are components such as ENSO events for which projections are particularly difficult.

Sea level is another complex component depending on melting of glaciers but also on thermal expansion of surface waters which has been responsible for a large part of sea level rise over the past century. Sea level is also an example of what may happen if certain thresholds are passed. During the post glacial period there have been times when particular ice sheets have collapsed with 'meltwater pulses' in sea level resulting. Within the relatively near future, collapse of the Greenland ice cap or the East Antarctic shelf could cause a rapid rise of sea level of up to 7 m, catastrophic for low lying coastlines and islands such as Raine. The following sections outline the identified gaps in knowledge. These are addressed in the form of more specific research projects in Section 6.4.

4.2 Knowledge Gaps Affecting Turtle Nesting

There are a number of major questions related to turtle nesting on Raine Island. These include:

- Problems associated with nest digging and the 'bryme rock'. Raine Island has two clearly recognised cemented materials: beach rock and phosphatic cay sandstone. There is also the cemented layer of unknown origin but termed `bryme rock' by Neil et al (2000) which underlies much of the swale area and, at least in recent decades has restricted nest building by the turtles (ca 25% of the swale area underlain by this material, Neil 2005). The material appears to be different to both beach rock and phosphatic cay sandstone as its upper level follows the overlying topography, which may be constantly changing, and does not appear to be related to a near horizontal water table. But it may also be a second generation of phosphate cementation in an early phase of formation following the disturbance caused by the mining more than 100 years ago, (see appendix C). Mapping of all the cemented deposits and a full understanding of the processes involved in the formation of the `bryme rock' are needed. Coring and Ground Penetrating Radar (GPR) studies will indicate 'bryme rock' distribution. This information is important for future changes to the island if it is to undergo a serious erosion phase as the cemented formations will form the `headlands' to which any retreating beaches will be attached. Extent, depth, thickness, degree of lithification and processes involved in the formation of the `bryme rock' may lead to possible management actions e.g. if only lightly lithified it may be possible to break up. A possible hypothesis for the formation of bryme rock is given in appendix C, but much more research is needed to verify or reject this idea.

- water table flooding of turtle nests is a serious problem which may be related to the formation of the `bryme rock'. It may be a relatively recent phenomenon and thus be playing a role in the long term decline in turtle numbers. Neil (2005) and Guard et al (2008) have indicated the behaviour of the tidally controlled water table beneath the berm but more information is needed especially during and after heavy rainfall events when outflow from the island is superimposed over tidal pumping. As much of the turtle nesting season coincides with the wet season, such observations should have high priority.
- A further major question relates to what would happen to the Raine Island green turtle population, were the island to disappear completely. Although there appears to be some nesting site fidelity, if the turtles would migrate to other sites then continued viability of the northern GBR population appears possible. Alternative sites are discussed in appendix F which concludes that Raine Island would outlast any other northern sand cay but that the sandy carbonate beaches of the Murray Island would provide viable long term nesting sites.

Other questions relating to the turtles include:

- the size of the loss to traditional harvesting and as fisheries by-catch
- dispersal of hatchlings
- areas of foraging and density of turtles in these areas
- demographics on both Raine Island and in the foraging grounds, especially age structure and genetics
- aspects of the physical environment including the dynamics of the cay berm which appears to be restricting the area available for nesting, the behaviour of the water table and the soil moisture index above it which influences the stability of nests
- reaction of turtles to several unsuccessful nesting attempts
- qualify hatchling success
- possible changes to sand composition over time making nest building more difficult
- sand depth thresholds
- the amount of sand turtles may remove from the island after nesting
- further work is required on the relationships between ENSO and turtle nesting numbers

4.3 Knowledge Gaps Affecting Seabirds

The major questions for seabirds are similar to those for turtles, i.e. behavioural patterns away from Raine Island and the possible impacts of climate change. Specific gaps identified include:

- the adaptive capacity of the birds, especially those breeding on Raine Island, to major environmental change such as reduction in size of the island or even complete erosion. Are there other sites which may be more resilient or new islands form on the outer reef which will attract the birds?
- the birds have complex interactions with the turtles, the vegetation and the physical features of the island (such as the undercut beneath the phosphate scarp) which need better definition before any adaptive management is considered
- investigate links between food availability for seabirds with climate change factors and fishing
- determine the breeding periods of various seabird species on the island
- identification of foraging areas is a high priority item, together with an assessment of the food reserve and impact of fisheries
- although records of bird counts exist they are irregular, mostly confined to the summer season and not fully definitive. More comprehensive work is required to assess the identified decline in numbers
- a program is required which will re-evaluate existing data. This data bank still has the capacity to elucidate the causes of decline
- further work is required on the relationships between seabird behaviour and demographics and ENSO.

4.4 Knowledge Gaps Affecting Vegetation

Low biodiversity and general robustness of the flora of Raine Island limit the questions being raised but these still include:

- how should the vegetation be managed e.g. weed management, introduction of more stabilising plants etc.
- could shade trees be introduced to aid turtle nesting in the future?
- plants have an influence on bird behaviour and this needs further definition especially for the roosting species
- what is the propagation potential of *Abutilon asiaticum var. australiense* (an important seabird roosting and nesting habitat on the island)? Important species if revegetation is required post storm/cyclone activity.
- analysis of the seed bank
- a question re the impact of insects both native and introduced on the vegetation has been raised
- vegetation mapping in all seasons is required for a more comprehensive understanding.

4.5 Gaps in Understanding the Physical Oceanography

To date only one study (Bode et al, 1995) has been undertaken in relation to physical oceanography and turtle and bird foraging and hatchling dispersal. This study used desk top numerical modeling to examine the dispersal of turtle hatchlings. Although producing general patterns, results were inconclusive. New methods, including the use of satellite imagery combined with ground truthing, may better define the dispersal patterns. Requirements include:

- Detailed tide measurements and data from a weather station located on the island
- Reef flat sea surface temperature records to indicate susceptibility to bleaching and beach temperatures as they effect turtles (e.g. sex ratios)
- Reef margin monitoring to determine the extent of local upwelling of nutrient rich water
- Determination of northern Coral Sea oceanic current patterns and the part they play in turtle hatchling dispersal
- Mapping the oceanographic conditions of the northern Coral Sea to identify possible foraging grounds for turtles and seabirds

4.6 Gaps in Benthic Ecology Knowledge

The only detailed survey of the Raine Island reef flat ecology is that of Clegg et al (1997). It has reasonable detail and more than 10 years later, and after several severe ENSO events, a comparative survey could answer questions about the health and robustness of the reef flat. Further, deployment of an ROV or equivalent could also determine the depth and characteristics of reef slope coral cover and its possibility as a future refuge site. Because of their importance as beach sediments far more information is needed on the calcification rates of benthic foraminifera and their susceptibility to various aspects of climate change, especially ocean acidification (see appendix D).

4.7 Gaps in the Understanding of Geomorphology and General Environment of Raine Island

Many of the questions relating to geomorphology and the general environment have already been discussed (e.g. the formation and extent of 'bryme rock' and the behavior of the water table) as they relate especially to turtle nesting. However, further information is needed on the following:

- a detailed sediment budget is a high priority item given its current delicate balance. The berm is dominated by benthic foraminifera, especially *Baculogypsina sphaerulata*, the source of which is the algal turf zone around the reef margin. There are few studies of calcification rates in such zones but what there are suggest rates of between 0.3 and 1.9 kg $m^2 yr^{-1}$, relatively low within the reef system as a whole (Hallock, 1981; Kinsey, 1985). Thus a critical question for Raine Island is the productivity and rate of transport of this sediment source to the island. This becomes even more critical during future climate change and especially ocean acidification as the small size and delicate structure of the *Baculogypsina* tests make them out of the most susceptible organisms (See appendix D).
- more information is required on the physical response of Raine Island to climate change, especially sea level. Mathematical and physical modeling, by Gourlay

and Hacker (1991) and Gourlay (1995) have provided some insight (for example suggesting that a higher sea level will produce a higher berm rather than erosion) and Dawson is presently undertaking field research to elucidate processes of sediment movement and beach changes. These studies need to be extended into both summer and winter conditions when contrasting wind speeds and directions are encountered. Equally informative will be studies at different times during the lunar tidal cycle especially at high spring tide levels which may model aspects of the Raine Island reef flat at a higher sea level.

- as indicated many of the problems for turtles and birds, are related to the physical environment. Raine Island's beach is so dynamic, with 40m or more of erosion between surveys, that it is easy to see how the impression of the island eroding as a whole has arisen. However, progradational events of up to 30m have also occurred and the general assessment at present is that the island is in a delicate balance, but undergoing changes in orientation in response to weather patterns. Gaps in knowledge relate to the long term evolution of the island which may provide information on how it will respond to future climate change. For example can dating of foraminifera from the berm give an indication of past pulses of sediment delivery or indicate that little or no sediment is currently being provided to the island from the reef flat.

5. Risk Assessment and Feasibility of Current and Adaptive Management Options.

5.1 Risk Assessment, Research and Management

Changes to the ecology of Raine Island are already taking place and impacting both turtle and seabird populations. The legacy of anthropogenic activities on the island (such as guano mining in late 1800s) continues to influence the island's ecology. As discussed in Section 3, climate change will have an effect on Raine Island and the surrounding reefs. However, assessing the exact extent of future impacts on the island is challenging because of the uncertainties in timing and dimensions of the changes (as outlined in the IPCC reports).

Warnings from turtle researchers suggest the northern population of the green turtle (*Chelonia mydas*) could be decimated in 25+ years. Further, the already dramatic decline in the number of breeding seabirds is cause for concern. There is urgency to understand what is impacting on those populations and what potential adaptive management strategies can be implemented to assist their resilience in the face of a changing climate. As Raine Island is a critical breeding and nesting site for both green turtles and seabirds, it is important this habitat continues to support turtles and seabirds into the future. Further, it is recommended a risk assessment be conducted on the northern green turtle population and seabirds, which assesses the additional pressures beyond Raine Island.

At the Townsville Workshop, the following research areas were identified as having highest priority for predicting the bird and turtle populations:

- physical oceanography related to turtle and bird foraging and hatchling dispersal.
- island features interfering with nesting
- demographics of both turtles and birds.
- impact of harvesting on turtle numbers

Also of direct management relevance but requiring longer term programs were:

- investigation into the adaptive capacity of turtles and assessment of alternative sites if Raine Island disappears (see appendix F).
- reef flat benthic ecology and sediment budget
- physical processes associated with wind, wave and tidal currents with data from both winter and summer seasons, and at extreme tidal levels.
- vegetation interactions and the role of plants in stabilising Raine Island

Results from the programs will have a strong influence on the way management may tackle the problems. Three common approaches, discussed in the next section, can be considered.

5.2 Possible Management Approaches Applied to Raine Island

5.2.1 Retain Present Regime – Status Quo

There are conservation policies already in place which provide Raine Island with protection from a number of activities and give protection to the turtles, with some level of traditional harvest permitted. However, even under such comprehensive management arrangements, declines in turtles and seabirds have been observed. There are concerns that further declines in the green turtle population and seabird populations are likely, especially as the effects from climate change become more apparent. Under the pressures from climate change, the risks associated with the status quo approach to managing Raine Island and its inhabitants need to be considered.

The status quo approach would only work with any success if Raine Island were not fully eroded or if alternative nesting sites became available before it disappeared. Even though it is highly likely that coral cays would survive through the early period of `Greenhouse' induced sea level rise, the majority would not be vegetated and would be overtopped at high tides thus making them unsuitable for both turtle and bird nesting. Risks appear to be high for this option which depends on the length of time between the disappearance of current environmental niches, like Raine Island, and the formation of new ones as nature catches up with environmental change or Greenhouse mitigation measures take effect. The time period would be decades at least, possibly centuries, and survival of many species in limited refuges may be tenuous. For the turtles, only adaptability to nesting on high island beaches would seem to be a viable option (appendix F).

5.2.2 Reactive management:

Reactive management has a high dependency on research and monitoring. It involves having a number of threshold values in place which, when exceeded, will lead to implementation of previously considered options. Threshold figures would include:

- turtle, seabird numbers and demographics. This approach has already picked out alarming trends. The long life span of the turtles and remigration intervals of 5-8 years highlight the need for an extended period of monitoring and for a clear understanding of the signals indicated by changing demographic balances
- There are on island impacts which appear to be negatively affecting nesting success and need to determine the thresholds such as optimal sand depth, sand temperature, and impact of nest flooding
- Adult mortality - Phosphate cliff contributing to adult mortality
- Also important to consider what other factors beyond Raine Island are driving the decline in turtle population. A risk assessment of the northern GBR green turtle population is recommended.

  What on island management options could be considered? Potential options include:

    - Shading structures/vegetation
    - Sand replenishment
    - Breaking up the bryme rock
    - Move turtle eggs to another part of the island
    - Flip overturned adult turtles and move them to water's edge
- for the sea birds there is also the El Niño factor to take into consideration and, as most surveys to date have been in the summer season a better

understanding of fluctuating populations may come from the inclusion of regular winter surveys in the monitoring program.

- similarly for the turtles, need to ensure nesting habitat remains viable for seabirds. Should consider revegetation options (or alternative nesting habitat structures) if seabird nesting habitat is compromised by insect infestation, storm events etc. Risk assessment needs to consider beyond Raine Island. What factors are driving the decline? Is it linked to fisheries activity? Do their foraging grounds require different management arrangements?
- island erosion, changes to sand volume. Monitoring over the last 40 years indicates that Raine Island sediment budgets are in a delicate state of equilibrium. Although short periods of gross sand loss have been noted these have been more than balanced by sand gain within the same decadal period. A problem of continuous sand loss over e.g. a 5 year period could act as a critical threshold for management action. Is the sand moving to other parts of the island and is it feasible to move turtle eggs to those areas?
- disruptions to the sediment budget. As the foraminifera dominate the beach sands, careful monitoring of the reef flat zone from which they come (the algal turf zone) could provide figures contributing to a critical threshold value. Several methodologies are possible. The simplest is straightforward counts of individual numbers (standing crop) and this has been undertaken (e.g. Chave et al, 1972; Muller and Hallock, 1974; Hallock, 1981). However, with densities of up to several 100 000 per m^2 reliance on numbers alone would be tedious (Sakai and Nishihira, 1981; Hohenegger, 2006). Probably more reliable for the general testing of the health of foraminifera production is the use of the FORAM Index (see appendix D and Hallock et al, 2003). Other methods which could be applied to Raine Island to test the health of the turf zone and its production of foraminifera include the use of the alkalinity depletion technique (see appendix G), which has been successfully applied to north west Pacific reef flats to specifically determine the calcification rates of foraminifera (Fujita and Fujimura, 2008). Unfortunately, this may be difficult on Raine Island because of the time and number of people required. An alternative is the use of remote sensing, either aerial or satellite, analyzing in particular the near-infra red band which has an ability not only to define reef flat zonation but also the distribution and health of reef flat organisms, especially those carrying algal symbionts such as foraminifera (see appendix H).
- thresholds of seawater carbonate chemistry. Some data has allowed the identification of “tipping points” or thresholds when ocean acidification will cause net calcification rates to be less than net distribution rates in coral reef systems (Yates and Halley, 2006; Guinotte and Fabry, 2008). Given the susceptibility of Raine Island’s major beach constituent, foraminifera, monitoring for such a threshold may be highly relevant.
- major bleaching events in corals and foraminifera. As already noted using the FORAM Index (appendix D) may provide early warning of major bleaching events which in turn may not only detract from Raine Island’s reefs iconic status, but also interfere with ‘normal’ sediment supply.

- single low frequency, high intensity events such as major cyclones or tsunami. Raine Island has already experienced many cyclones but most have been in the category 1-3 range. Higher energy events, may well produce irreversible changes to the island and require specific management responses. Raine Island sitting on the edge of the GBR is highly susceptible to tsunami generated on the edge of the Pacific plate within the Vanuatu trench.

Setting the level of a threshold would be critical and it could be argued that the observations on turtle and bird populations indicate that the critical threshold may have already been reached or exceeded. Further research will clarify this.

Other examples of threshold values may also be found in Raine Island's sediment budget. At present this is in a delicate state of equilibrium but examining the results of surveys over the last 15 years suggests that specific thresholds precipitating management responses may be:

- decline in total volume of sand at critical rates (e.g. > 10 000 m^3 per year over a 3 year period)
- exposure of beach rock in areas it has not been previously reported
- increase in the area or decrease in the depth of the `bryme rock'

These examples emphasise the importance of research to identify the significance of these changes and of monitoring more frequently than on an annual scale basis to pick up the early stages of a detrimental uni-directional change.

Recognising the breaching of a threshold is only the first stage as management responses are needed as quickly as possible. Many of the options will be the same as those outlined in Section 5.2.3 and may involve a basic change in the philosophy of the management agencies in that the most appropriate action may involve modifying what have been regarded as natural processes, highlighting the difficulty of extracting anthropogenic `Greenhouse' changes from the natural `noisy' environmental records. Interfering with the natural environment may not be normal conservation policy but the very high, iconic value of Raine Island may alter the balance in favour of direct intervention if other options are unlikely to preserve the island and its inhabitants and viable alternative sites cannot be found.

5.2.3 Pro-active Management:

Reactive management strategies depend on research results yet to be gathered, and monitoring programs that have been running for sufficient time to be able to extract long term trends from naturally noisy data. However, once it has been decided that intervention into the natural environment is acceptable, then, actions may be taken as soon as is feasible. For each intervention ideally the risk should be balanced against the benefit that will be achieved. Close examination of each of the examples given below, however, suggests that for most, further research and monitoring is needed to provide more confidence in the outcome.

Examples of pro-active management actions specific to the turtles and seabirds which were discussed at the Raine Island workshop are included in the Strategic Plan

(Section 6). As can be seen many of the potential management actions require further research and/or monitoring e.g. on the food available to the seabirds, essentially a major oceanographic remote sensing project to determine changes to patterns of upwelling.

Other measures are similar to those in many protected areas, for example imposing quarantine regulations on all visitors to reduce the introduction of exotic weed and insect species. Also included in this category would be education programs for the Traditional Owners, setting size limits for the harvested turtles and involving them in the guardianship of Raine Island and its environs.

Some of the on-island measures suggested could only be applied on a non continuous basis because of Raine Island's remote location. Rescuing stranded female turtles however successful could probably be carried out only opportunistically rather than as a targeted program.

The final group of actions can be classified as soft and hard engineering projects. If these management options are required, the risks associated with any machinery used should be assessed so to reduce the impact on the surrounding area. As the 'bryme rock' appears to have such a negative impact on the island, once its origin is ascertained then a way of removal may be found. Options could include mechanical breakup or alteration to water table conditions with wells. Similarly, removal of the rock and sand ramps which give the turtles access to the central depression where most of the birds nest. Low impact techniques should be considered.

Although Raine Island is not eroding at present there is some possibility that it may in the future. Sand replenishment or sand manipulation on Raine Island may need to be considered as an adaptive management option, if factors such as sand depth are determined to be a critical to turtle nesting success. Nearby cays may be little more than intertidal sand banks but before they disappear their value may be in providing the sand for any replenishment on Raine Island. This will be a no loss position, as within a few years as sea level rises, these cays will disappear completely and their sand resource lost forever. Raine Island is likely to be the last cay to disappear in the northern GBR.

Alternatively, sand could be moved from one part of the berm to another, but if it were to come from elsewhere, then it would have to be a biogenic carbonate sediment similar to the attributes of the beaches of Raine Island, and even then there is no guarantee that it would stay in the place deposited. This has been a recognised problem on tropical beaches, especially cays as noted on Green Island (Hopley 1982; Hopley et al, 2007) and in the Indian Ocean as noted by prominent reef conservation expert Barbara Brown (1997). Carbonate sands generally react to physical forces in a very different way to the more common quartzose sands (Orme, 1977). Sands composed of foraminiferan tests have a very low specific gravity and their shape facilitates movement (Hohenneger, 2006). These sands are even more mobile and would not combine well with any other type of sediment. Also damage to the individual sand grains (foraminiferan tests) is probable if heavy machinery were operating on the beach and berm. Damage would reduce sediment particle size and almost certainly enhance subsequent loss from the beach.

Hard engineering such as rock walls, tetrapods and groynes are also no longer generally accepted solutions to erosion on coral islands (Kraus and McDougal, 1996; Maragos, 1993; Kench et al, 2003). More detail is provided in appendix I., but essentially hard engineering on small islands cannot accommodate the circulatory movement of sediment, nor the annual exchange of sediment between beach and reef flat and wave reflection from hard structures results in scouring and accelerated loss of beach sand.

5.3 Risk Assessment of Current Versus Adaptive Management Policies

Outlined above are the framework of present conservation measures and two forms of intervention management. The present regime is tried and trusted and is an excellent focused example of the policies of both GBRMPA and the Queensland EPA which have provided the GBR with more protection than any other reef system in the world. Unfortunately, this has not prevented serious declines in both turtle and bird nesting numbers on Raine Island. What the current management policies have not been able to do are cope with changes both environmental (oceanographic and ENSO related) and anthropogenic (turtle harvesting) happening outside the waters of the GBRMP. Nor are there any specific policies in place to deal with the changing environment of a ″greenhouse″ world.

An adaptive policy, possibly incorporating aspects of both the re-active and pro-active strategies outlined in Section 5.2.2 and 5.2.3 would not be without risk but it would include specific action to detect meaningful changes and have in place strategies to alleviate their impact. A combination of the policies outlined under both re-active and pro-active management would appear to be the best scenario for Raine Island (and elsewhere on the GBR). Monitoring programs would identify specific changes and trigger optional responses. Research is still required to identify the most accurate and meaningful monitoring schemes, the determination of thresholds and the response required, but low risk policies, such as education with the involvement of the Traditional Owners of Raine Island could be put in place very quickly. Actions, such as sand nourishment and breaking up the bryme rock, may require a few years of research before action is taken.

However well Raine Island and its environs are managed there is still the problem that many of the changes which have or will take place are in waters outside Australian jurisdiction, and/or on a global scale beyond the capacity for one nation to handle. Mitigation measures to reverse the accumulation of Greenhouse gases in the atmosphere are also needed on a global scale and until this happens there will be no guarantee for the existence of Raine Island or similar habitats beyond the next century.

6. A Strategic Plan for Raine Island Incorporating Targeted Science.

6.1 Adopting a Management Strategy and Framework.

Raine Island is already showing signs of impact, possibly due to human activity on the island since the 1900s, which is affecting its iconic status as a green turtle and seabird nesting site. Whilst continued provision of a high conservation status for the island is essential, further actions are required. As discussed in the previous two sections, changes on the island are affecting its inhabitants, and there are off-island changes which are also having an impact. Early stages of climate change are evident and are predicted to become more prominent in the near future.

Establishing thresholds in the context of climate change, including impacts on the turtle, seabirds and island processes is an important part of the process. It is likely, resulting management actions, which may result in their own impact on the island, will require monitoring. This will be facilitated by having in place a framework in the form of a strategic plan developed specifically for the island.

6.2 Vision Statement

Participants at the Townsville Workshop put forward a large number of ideas on what they hoped Raine Island would be in future years and how their aspirations could be achieved. From these ideas the following strategic plan has been drawn up comprising a proposed Vision Statement for the island up to 2050, objectives which complement the Statement and Strategies outlining the actions required.

Management of Raine Island will continue to actively involve the Traditional Owners (Wuthathi, Erubam Le, Meriam Le and Ugarem Le Peoples), within the framework of the Raine Island National Park (Scientific) Land Use Agreement. It will also involve the close co-operation of scientists and managers. By 2010 there will be a full understanding of the physical, chemical, biological and ecological processes which maintain the Raine Island environment and its population of turtles and seabirds, and methodologies will be in place to identify and react to change. By 2050, this unique cay will have been maintained as an iconic location for the nesting of the green turtle Chelonia mydas and for a range of seabirds. It will have returned to a robust ecology with special geomorphological features.

6.3 Objectives and Strategies

1. Continued co-operative management with Traditional Owners (Wuthathi, Erubam Le, Meriam Le and Ugarem Le Peoples) in maintaining their aspirations and interests.

Strategies:

- accompany research, monitoring and management visits to Raine Island
- supply rangers to help oversee Raine Island
- involve rangers in community education programs
- provide feedback for plans for sustainable harvesting of green turtles

2. Develop research and monitoring programs for management needs

Strategies:

- target science to inform adaptive management
- identify key links in the ecology and physical environment of Raine Island
- monitor nesting and hatchling success of turtles and seabirds

- ascertain the impacts of cementation layers/byrme rock formation on turtle nesting and hatchling success
- identify seabird and turtle foraging grounds
- identify critical areas which may indicate early stages in a changing environment (e.g. coral and foraminifera bleaching, island orientation)
- maintain an awareness of the most up to date data on global climate change as applied to northern Australia and project the possible effects on Raine Island.

3. Maintain a viable Northern GBR turtle population, including sufficiently sustainable to allow for harvesting by Traditional Owners

Strategies:

- continued research and monitoring to specifically ascertains trends
- identify foraging areas and possible problems related to them
- identify information required to conduct a risk assessment of adaptive management options aimed at optimising nesting conditions on Raine Island e.g. breaking up the cemented layer to lower the water table, sand replenishment to deepen the profile available for nest digging, planting shade trees, operating a rescue program for moribund turtles (especially in major nesting years)
- incorporate Traditional Owners into management processes and develop educational programs on the islands – reduce take of mature females
- identification of possible alternate nesting sites such as Murray Island and Bramble Cay (see appendix F).

4. Protect and maintain viable seabird populations

Strategies:

- continued research and monitoring, expanded into all seasons of the year
- determine if the decline observed on Raine Island is part of a larger GBR phenomena and what is driving the decline
- determine what impacts climate change will have on Raine Island seabirds and identify potential adaptive management options to improve their resilience
- identify foraging grounds and possible impacts on them
- identify interactions between birds, turtles, vegetation and geomorphology
- reduce human and seabird interactions and stop unauthorised visits

5. Maintain the vegetation as an effective and functioning part of the ecosystem

Strategies:

- continued research and monitoring, again, extended into all seasons
- evaluate and diminish existing threats such as weeds and insects
- introduce quarantine measures for visitors
- determine the impacts of climate change on Raine Island's vegetation and identify adaptive management options that will ensure these vital seabird nesting habitats are persist in the future.

6. Fully understand the physical environment and the processes responsible for it: now and into the future

Strategies:

- extend research and monitoring –
- determine formation of `bryme rock' (see appendix C.)
- determine extent and depth of all cemented deposits on Raine Island
- determine the present sediment budget
- evaluate the susceptibility of both corals and benthic foraminifera to bleaching events and ocean acidification
- reciprocate the processes which may operate at a higher sea level by undertaking measurements during high Spring tides.

7. Rapid transfer of research and monitoring results and information to management and other researchers

Strategies:

- dedicated committee for Raine Island established
- limited access web site available for posting results
- regular cycle of workshops to discuss progress.

Many of the strategies out lined above overlap with the previously identified research programs which reinforces the fact that there are major gaps in knowledge which need to be filled before actions can be taken. These are specified below.

6.4 Research Programs Resulting from and Related to the Strategic Plan

6.4.1 Critical questions for management

As discussed above (section 5 and section 6.2, 6.3) numerous knowledge gaps have been identified. At the Townsville Workshop participants from GBRMPA and the EPA raised a number of *specific questions for resolution by scientific research. They included:*

- what changes are taking place on Raine Island?
- what causes these changes – anthropogenic impacts and what further changes will occur on Raine Island due to climate change – and are there achievable solutions?
- can these changes be monitored and are there critical thresholds which should precipitate action?
- what responses can management take and what are the risks of such actions?

Attempts to provide answers to all these questions are included in the strategies associated with each objective of the Strategic Plan. Each strategy can be identified with one of the specific questions posed and linked to focused research projects. The following are developed from the Townsville Workshop and from subsequent discussion. The project timing indicated is approximately:

- immediate 1-3 years
- mid term – to 6 years
- long term – to 10 years

6.4.2 Research projects related to green turtle nesting

a) As short term rapid decline in the nesting population will not allow for adaptation, with a 50% reduction in recruitment requiring 150 years for recovery, intense monitoring over at least the next two nesting seasons is required to get a better understanding of the mechanics behind nesting decline. Various methods such as tagging may need researching but the requirement for monitoring is of very high priority. *Timing – immediate.*

b) Risk assessment of northern green turtle population. *Timing – immediate*

c) Turtles nesting on Raine Island are having difficulties digging their nests because of the cemented layer, termed 'bryme rock' in this report, and because of an apparent increase in nest collapse in recent times and flooding of nests. The 'bryme rock' problem is discussed in appendix C and required research includes

    i) identification of the cement and cementing process

    ii) experimentation with methods to remove it including alterations to the water table using wells etc., geochemical processes or because of the damage to beach sands which may occur, mechanical breakup.

    Problems with nest collapse may be related to recent changes in sand constituents which may be identified by research into sand budgets (see 6.4.5c). Also need to determine critical nest depth. *Timing – immediate to mid term.*

d) Little is known about the dispersal of hatchlings from Raine Island (only a single oceanographic modeling study – Bode and Dight, 1995). Further oceanographic studies on the northern Coral Sea possibly using satellite imagery are required. *Timing – mid term*

e) Harvesting in Torres Strait is having an impact on the breeding population of green turtles but more research is needed on numbers taken and size of the turtles. *Timing – immediate*

If Raine Island suffers severe erosion then alternate nesting sites will be required.

Because of its size and cemented deposits Raine Island will outlast other cays such as the outer sandbanks and Moulter Cay and high islands with carbonate beaches such as the Murray Islands would appear to be the most suitable as discussed in appendix F. Further research and a risk assessment of the northern green turtle population are required. *Timing – immediate to midterm.*

6.4.3 Research projects related to Raine Island seabirds.

a) Other seabird breeding sites on the GBR have much longer records (Michaelmas since 1984; Swains since 1984; Heron since 1910) and there is a place for examining the applicability of these results, which show a similar decline to Raine Island, to the Raine Island situation. *Timing – immediate.*

b) Identification of foraging areas, food resources and amounts required is needed specifically for Raine Island. Elsewhere depletion of marine food stocks has been related to ENSO. A temperature increase of 2^0 – 3^0 sees chicks of all species receiving little or no food (Congdon et al, 2007). Only limited data for Raine Island is available and extension of this research to the northern GBR is needed. *Timing - immediate.*

c) Identification of seabird nesting territory is possible using satellite transmitter tracking (Congdon et al, 2007, p 458). This would be very useful research for Raine Island, the birds effectively acting as proxies for the oceanography. *Timing – mid term.*

d) Research programs on the preferences of seabirds for vegetation types and interactions with them, is needed. *Timing – immediate.*

e) More specific information is required on anthropogenic impacts such as fishing. *Timing – immediate.*

f) There is some debate about the adaptability of seabirds to changing environmental conditions (see Congdon et al, 2007; Turner and Batanioff, 2007). Until further research is carried out the reaction of the Raine Island colonies to climate change factors will be unknown. *Timing – mid term.*

g) Disturbance by turtles is a problem for many of the birds. Access to the central depression is via the phosphate rock ramps and concrete ramp. An assessment into the impact and risks of removing these (which may also lessen the number of turtles being stranded) is needed. *Timing – mid term.*

6.4.4 Research projects related to the vegetation of Raine Island.

a) Monitoring of the vegetation of Raine Island has not had a high priority and an organised program involving both summer and winter surveys and aided by remote sensing, either low level digitised aerial photography or satellite imagery using a multi-spectral approach is needed (see for example appendix G). *Timing – immediate and continual.*

b) The monitoring of weeds and exotic insects which seem to have periodically plagued Raine Island and testing the effectiveness of management actions such as quarantine measures is needed. *Timing – immediate.*

c) What seed bank exists on Raine Island and what is the propagation potential of *Abutilon spp*? Vegetation is an important habitat for nesting and roosting seabirds. In the face of climate change pressure on the island vegetation may occur.

6.4.5 Projects related to geomorphology and the general environment (Oceanography,Meteorology, Benthic Ecology).

a) Although Raine Island is in a delicate state of stability at present changes in orientation and to sand distribution on the beaches over the last 40 years (appendix E), clearly indicate that change will take place in the future as sea level rises and weather patterns change. Continuous monitoring is needed (probably using remote sensing) and refinement of the understanding of reef top processes such as wave generated currents required. Mathematical modelling can help but field studies are essential. *Timing – immediate.*

b) A detailed study of the sediment budget of Raine Island will help to identify important thresholds and management responses. Methods can include remote sensing especially using the near infra-red part of the spectrum (appendix G), the alkalinity anomaly method (appendix I) or a concentrated study of the foraminifera of the algal zone (appendix D) and further identifying important thresholds via the FORAM Index. *Timing – mid term.*

c) Important changes to the supply of foraminifera which make up such a large proportion of Raine Island's sediments, may have already taken place. This may be identified by the radiometric dating of individual tests from the beach and reef flat. Results would form an excellent early warning system. *Timing – immediate*

d) Similarly, monitoring of the acidity of the waters around Raine Island will identify the important "tipping point" (Yates and Halley, 2006; Guinotte and Fabry, 2008) of this component of climate change. *Timing – mid term.*

e) Sand nourishment for Raine Island should be considered (see Section 5.2.3). Sources of sand such as nearby outer reef sand banks which, by this time may be in danger of complete erosion need investigating, together with the least damaging ways of delivering it to Raine Island. A risk assessment should be conducted to identify any potential impacts associated with the management action. Small scale studies (such as 25 m of beach using dyed sand) could be implemented first. *Timing – long term.*

f) Only one study of the benthic ecology of Raine Island's reef flat has been undertaken (Clegg et al, 1997). This needs repeating and a continuous monitoring program put in place to detect, for example, coral bleaching or the effects of eutrophication on reef flat organisms by renewed leaching of phosphate enriched groundwater from the island (see appendix C). As some outer reef slopes have been identified as having coral cover to depths greater than 100m (e.g. Myrmidon Reef) an ROV survey around Raine Island would be useful to identify possible future refuge sites. *Timing – immediate to mid term.*

g) Much of the research requires more environmental data and installation of sophisticated telemonitoring devices for oceanographic and meteorological conditions is a basic but essential part of the research to be carried out on Raine Island, as is the long term installation of a tide gauge. *Timing – immediate to mid term.*

h) Research is already underway into short-term high intensity events such as cyclones (Fuentes et al, in press) and this work should be continued, especially as projections become more certain. *Timing – immediate.*

i) Over the last 40 years changing patterns on coral reef cay beaches have been correlated with global scale weather patterns such as ENSO. This work includes Raine Island (Proh, 1995; Proh and Gourlay, 1997). Further analysis may help formulate projections for the behaviour of Raine Island in the future. *Timing – immediate to mid term.*

6.5 Provisions for Management to Modify the Strategic Plan in the Light of Any New Research Findings.

Once a strategic plan is in place and research programs as outlined start to produce results, it is recommended regular contact between managers and researchers be maintained. This will ensure research that will inform management is conducted and ensure the most up to date information is available to guide adaptive management options. Several methods of reporting were discussed at the workshop including:

- lodging of annual reports from researchers with the Raine Island committee (n.b. all reports to go through a review process).
- listing of research findings on a restricted access web site
- a regular cycle of workshops at 3 to 5 year intervals

With monitoring programs for turtles, seabirds, vegetation, island morphology, reef flat ecology and eventually sediment budgets in place, important threshold values should be identifiable (and revised as further research results are available and climate change variability identified) which will set in motion the optimal management response.

Assessing management effectiveness should also be part of the monitoring programs. Each component should relate to the management requirements retaining the focus of researchers on specific goals. By 2020 success will be indicated by:

- Raine Island is still in existence, retaining its iconic values
- turtle nesting will be at sustainable levels
- turtle harvesting in Torres Strait will also be at sustainable levels
- seabird populations will be increasing
- the seasonal vegetation cycle will be fully understood and any long term problems identified
- the benthic ecology of the reef flat will be healthy though not necessarily identical to that of the 1990s
- the sand volume of the island will be stable though the shape may change
- cementation and water table processes will be fully understood and measures in place, if possible, to improve turtle nesting conditions

Easy flow of information and adequate communication between research and management are an important component of the plan. If these targets are met, then in 2020 Raine Island will be in a good position to respond to accelerating global change parameters such as SST, acidification and sea level rise, the impacts of which will increasingly become the focus of management in the near future.

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Appendix A

Nineteenth Century Activities on Raine Island

There are several historical accounts of Raine Island including Stoddart et al (1981), Lavery (1988) Lawrence and Cornelius (1993) and Cornelius (2001). First European siting of the island was by Thomas Raine on the vessel Surry in 1815. Openings in the outer barrier reef at nearby Great Detached Reef saw this area develop into a major shipping route for ships sailing from the Pacific through Torres Strait. This was a dangerous passage and on the 15th August 1834 the English barque *Charles Eaton* struck the reef with partial loss of the crew. The incident precipitated the British Admiralty in 1841 to commission Capt. F.P. Blackwood in the corvette *Fly* to survey the area and as the result of his recommendations, plans were put together to erect a navigational beacon on Raine Island.

> "In late May 1844 *HMS Fly* in the company with *HMS Bramble* and colonial revenue cutter *Prince George* had landed a working party of 20 picked convicts, chiefly masons and quarrymen, with guards and supervisors on Raine Island to build the beacon. The ships lay off some 20 kilometres to the south-west in sheltered waters behind Great Detached Reef while the small tender *Midge* acted as supply vessel"
>
> (Lavery 1988, p21).

The party lived in pre-fabricated wooden huts and tents. Building materials were an obvious problem on a coral island but it is here that the unusual geomorphology of Raine plays a part (discussed in more detail below). Much of the island consisted of phosphatic cay sandstone derived from the downward leaching of guano (Baker et al, 1998). The rock is soft but does have sufficient structural strength for use in construction and it is easily hewn into shape. Lime was obtained for mortar by burning clams and other shells and brackish water suitable for mixing was added from wells put down on the island. Ironically, timber for the beacon's roof and internal fittings was collected from the *Martha Ridgway*, a Liverpool registered barque wrecked on a reef 40 kilometres to the south in 1842.

The beacon was completed in mid September 1844, the first such structure on the Australian continent, and whilst shipwrecks continued to occur the value to the increased amount of shipping was obvious. There were many visits to the island and as early as 1880 Capt. Denham on *HMS Salamander* reported damage, especially to the roof. In 1874 *HMS Challenger* visited Raine by which time most of the timber had collapsed and much of the lower walls covered by inscriptions carved into the rock by visitors (see Bairstow,1983 for a full list of inscriptions). Some of the more notable visits up to 1973 (The Royal Society-Universities of Queensland Expedition) are listed in table A 1.

A century after the tower was built serious deterioration of the rockwork was taking place. In 1959 *HMAS Gascoyne* affected some poor quality repairs. As noted by Lavery (1988), in 1982 the late Professor David Saunders during a visit concluded that the tower was special as a heritage item of national significance. In Mid 1987 the Raine

Island Corporation placed restoration in the hands of a Scottish stone mason, Ian Watson and restoration was commenced in July 1987. Investigations into the island stability were undertaken by University of Queensland engineers and into the nearby reef structure by James Cook University scientists (see appendix B).

Whilst the beacon is the most important artifact of historical importance on Raine Island there has been considerable anthropogenic impact elsewhere. Both turtles and bêche de mer were harvested and most landing parties gorged themselves on bird's eggs and Blackwood in 1844 left gardens in the centre of the island with several introduced fruit and vegetable species. However, goats introduced in 1845 probably destroyed them. The goats bred for a number of years but there are no records after 1850 (Stoddart et al, 1981). A small bêche de mer fishery was located on Raine from the early 1870s (Ellis, 1937).

However, phosphate mining had the largest impact on the island. The deposit was first mentioned when Raine, with other islands was included in a lease taken out for 7 years in Hobart in 1862 but most of the early digging took place in the more accessible Bunker-Capricorn Islands (Tryon, North-west, Lady Elliott and Fairfax). However, the J.T. Arundel Company, which had been mining central Pacific islands during the 1880s transferred its operations to Raine in 1890. Prior to moving his operations there he discussed the site probably with bêche de mer fishermen and was told of a "massacre of 12 men by natives" in the 1870s an indication at the very least of traditional owner access to Raine Island in spite of its distance from the coast.

Phosphate extraction may have commenced as early as 1882 (Saville Kent, 1893) but the major operation commenced in 1890 with a manager (Albert Ellis), a staff of 9-10 Europeans and 100 Asian (mainly Chinese) labourers. A tramway was built from the centre of the island to a wooden jetty for which some coral may have been removed. Ships of 1000-1500 tons exported the guano direct to Europe and Melbourne. By 1892 the extraction had ended after removing "tens of thousands of tons" (Hutchison, 1950) and most of the equipment dismantled and removed but the effect on the island has been permanent and the details of the original geomorphology and vegetation can only be surmised. A sad reminder of the mining days is the grave of Annie Elizabeth Ellis, wife of George C. Ellis, next to the beacon, who died on June 29th 1891.

Table A1: Visitors to Raine Island 1815-1973 from Stoddart et al, 1981)

Date	Vessel	Visitors	Notes	References
1815	Surry	Thomas Raine	First recorded sighting	
1843 29-30 July	H.M.S. Fly	Capt. F.P. Blackwood, J.P. Jukes	Short visit	
1844 29 May-mid September	H.M.S. Fly	Capt. F.P. Blackwood, J.P. Jukes, J. MacGillivray (June only), Lt. J.M.R. Ince	Shore party camped to build beacon; vegetable gardens established. Geological botanical and zoological work	Blackwood 1844a, b, c, Jukes 1847, 1871; J. MacGillivray 1846
1845 25 January	Heroine	Capt. M.MacKenzie	Short visit, goats introduced	Mackenzie 1845
1845 April-May	H.M.S. Bramble	J. Sweatman	Short visit	Sweatman, MS
1846 5 August	Heroine		Short visit	Anon. 1846
1850 24-25 July	Enchantress	Capt. I'Anson	Wrecked	Lack 1953
1860(-)	H.M.S. Salamander	Capt. Mangles Denham, A. Rattray	Short visit	Rattray 1869
1862	H.M.S. Salamander		Raine & other islands leased for guano digging	Crowther 1939
1865 March	H.M.S. Herald	Capt. Mangles Denham		
1874 31August	H.M.S. Challenger	Capt. G. Nares, with H.N. Moseley, J.Murray, J.Y. Buchanan	Short visit, botanical and zoological collections	Campbell 1876; Spry 1876; Swire 1938; Buchanan 1874; Forbes 1878; Sclater and Salvin 1878; Moseley 1879; Miers 1886; Murray 1895
1870s		Beche-de-mer fishery	Shore camps	Ellis 1936
1890-1892	Guano digging	Guano digging	Shore camps	Ellis 1936; Arundel, MS; Hutchinson 1950
1910 30 October		W.D.K. Macgillivray, E.H. Dobbyn	Ornithology	Macgillivray, 1910; North 1912
1911 9-15 July		W.R. M'Lennan	Ornithology	Macgillivray, 1914, 1917, 1918
1913 4-12 December		W.D.K. Macgillivray, W.R. MacLennan	Ornithology	Macgillivray, 1914, 1917, 1918
1957 July		D. Attenborough	BBC film unit on Raine for 4 days	
1959 7-14 & 22nd February		J. Warham	Ornithology; plants	Warham, 1959, 1961,1963

APPENDIX B

Holocene Evolution of Raine Island Reef and Cay

Reef Evolution.

Considerable data have been acquired over the last twenty-five years about the Holocene evolution of reefs of the GBR based on drilling and dating results (see Hopley et al, 2007 for comprehensive analysis). The modern Holocene reef has grown over older Pleistocene last interglacial foundations which typically on mid and outer shelf locations is between ten and twenty metres below modern reef flat level. The Holocene veneer was added during the latter part of the Holocene transgression, the Pleistocene foundation first being inundated about 9000 years ago. Most reefs lagged a little behind the sea level rise but many including the outer ribbon reefs, had commenced reef flat development by about 6000yrs. B.P. (Hopley, 1977) as indicated for example by figure 24 of Neil et al (2000). Hole five drilled in 1988 provides supplementary information. It commenced on the cay just north of the beacon and intercepted the reef flat at about 4m. To fifteen metres the core was mainly through sand and shingle with occasional corals possibly *in situ*. At fifteen metres cemented *Halimeda* was encountered and continued for at least 1.5m. Radio carbon dates were obtained from this core (Hopley et al, 2007, figure 9.3) establishing the cemented *Halimeda* at 15m (11m below reef flat level) as the top of the Pleistocene. An anomalous date of 6300±130 yrs B.P. comes from coral at 14.0m, possibly rubble which has fallen into the drill hole but the other dates indicate colonization of the Pleistocene well prior to 7000yrs ago and reef flat development sometime after 6.300 yrs ago. Initiation of the cay is suggested by a basal date of 4740±130.

This date for Raine Island Reef is very similar to that from other outer shelf reefs of the northern GBR (Hopley, 1977; Hopley et al,2007) and whilst hydro isostatic warping of the shelf may have uplifted inner shelf reefs (e.g. the low wooded island reefs) by approximately 1m there is no evidence of a higher Holocene sea level on shelf edge and detached reefs as mooted by some of the early reports and as late as Fairbridge (1950), (see Nakada and Lambeck 1989; Lambeck and Nakada, 1990; Hopley et al 2007, Ch. 7).

There are several other radio carbon ages which provide a minimal age for Raine Island. A *Tridacna* shell from the beach rock surface near the beacon and overlain by the phosphatic sandstone provided an age of 1180±65 B.P., (Polach et al, 1978). Other clam shells provided conventional ages of between 1040 and 1640yrs B.P. being older toward the western end of the island (Limpus, 1987). Significantly for the Raine Island turtle population the remains of probably a green turtle *Chelonia mydas* was found at 60cm below the oldest clam, a minimal indication of the use of the island as a turtle rookery.

Cay Age and Formation

Gourlay's (1988) model of reef island formation as the result of focusing refracted wave energy on the leeward end of the reef is classically illustrated by Raine Island. It is generally agreed that the radio carbon age of 4740± 130 yrs B.P. at about reef flat level beneath the sand ridge just north of the beacon indicates the approximate age of the island. However, this borehole is not centrally located and some accumulation may have taken place prior to this. The age of clam shells (see above) also suggests that the phosphatisation and emplacement of the modern berm post-date about 1200 yrs B.P.

From the high level of the clam shells, which obviously could not be wind borne, Gourlay and Hacker (1991) hypothesized a higher sea level in the last 1000 years. There is no supporting evidence for this anywhere on the GBR (see Hopley et al, 2007, Ch.3 for discussion), nor for tectonic activity or hydro-isostatic tilting of the scale proposed on Raine Island Reef. Coarse deposits including clam shells are found on most northern GBR islands with actual depositional episodes during cyclonic activity witnessed. Further, the larger micro atolls on the Raine Island reef flat are of such a size that they will have been growing over many centuries, yet their surfaces which can detect sea level variations of less than 1cm show no evidence of sea level change.

Neil et al (2000) also review ideas on the formation of Raine Island and also dismiss the sea level change model. Instead they favour the original evolution as put forward by Jukes (1847) and endorsed by Stoddart et al (1981):

- cay formation at the leeward end of the reef (ca 5000 yrs B.P.).
- formation of the phosphate cemented layer by solution and redeposition (1200 yrs B.P.
- erosion and scarp formation in the lithified sediments (ca 1000 yrs B.P.).
- sand accumulation to form the modern berm (since 1000 yrs B.P.).

Questions still remain including when was the guano first deposited, why was leaching apparently so recent and what were the dynamics behind changes from deposition to erosion? Answers may lie in determining when birds first started nesting on Raine Island, whether or not there have been wetter and/or drier periods of climate in the past which would have influenced the hydrogeology of the island and what part tropical cyclones have played in both constructional and depositional phases. Changes in the morphology of the reef as it evolved from lagoonal (4000yrs B.P.), to shallow lagoonal (2000yrs B.P.?).and, finally planar (since 1000yrs B.P.) may also explain changes to sediment yield as explained below.

Reef Flat Evolution and Controls on Sediment Supply and Cay Depositional and Erosional Episodes

The models of Gourlay and Hacker (1991) and Neil et al (2000) are based around only two radio-carbon dates. The first is a date (uncorrected) of 4740 ± 130yrs B.P. (ANU 6623) for coarse material at reef flat level near the edge of the cay and thus probably added late in the first period of Raine Island development. It is quite possible if not probable that the centre of the cay had been deposited 1000 years earlier. The second date, on a Tridacna shell at 1640 ± 110yrs B.P. (SUA – 1906) has been used as indicating the maximum age for the phosphate rock (e.g. Gourlay and Hacker, 1991). However, the age of the sediment into which the clam shell was washed and the age of the cementation process may be very different. Further research is required to determine this but the process as described by Baker et al (1988) seems to require appropriate groundwater conditions which may change with island migration or with wetter climate conditions. Nonetheless, the age of 1180 ± 65 yrs B.P. (ANU 1591) for another clam shell from the surface of the beach rock near the beacon and also partially overlain by phosphate rock (sample collected in 1973 by this reviewer) possibly indicates the time when the modern berm began accumulating (it coincides well with Dawson's (2008) estimate of 1260yrs from sediment budgets).

This brief review has been added to indicate that both cay and reef are constantly changing. Hopley et al (2007, Ch. 8, pp 265-270) discuss rates of reef development based on both dated drill cores and carbonate budgets. If the depth to the Pleistocene of about 10m below reef flat level is taken to be the depth of the lagoon as Raine Island Reef developed then based on the size of the reef (3 km x 1 km) Raine Island would have changed from a lagoonal reef to a planar reef (today's morphology) in between 5000 and 2000 years B.P. Changing sediment budgets can be related to these changes in morphology with the following being a hypothesis of Raine Island's development:

1. reef first reaches sea level c. 6000 years B.P. and, possibly influenced by the shape of the Pleistocene foundations and the need for some protection for reef flat development on such a high energy reef, develops an area of reef flat on the leeward western end.
2. sufficient area of reef flat is available on this part of the reef for refracted waves to form a high energy (shingle)cay by 5000 years B.P. The remainder of the reef remains lagoonal with a surrounding reef flat area. Lady Musgrave Reef in the Bunker-Capricorn Group is a good modern analogy.
3. for ca 3000 years there is a slow lagoon infilling period with most sediment from the productive margins going to infill the lagoon with only small additions to Raine Island. The modern equivalent could be Heron Island reef with its shallow largely in-filled lagoon. This is probably a period of erosion or instability on the island which extends into the period of phosphatisation, forming the distinctive cliff.
4. by about 2000 years ago the lagoon was largely in-filled, the resulting reef flat relatively smooth and sandy with sediments well within the range of sand moving waves. Parts of the reef flat of Redbill Reef are like this and are delivering sediment to Bushy Cay (Hopley, 1981). For Raine Island this was the period of accumulation of the large beach berm, the sediments of which are clearly of reef flat and reef margin origin.
5. possibly by 1000 years ago this delivery of sediment was largely cut-off. Examination of the present reef flat (see Clegg et al, 1997) provides the reason. It is a micro-atoll zone, providing a plate over the underlying lagoonal sediments but also with a relief of 30-40cm it is a highly frictional surface which does not aid movement of sediment.
6. present studies suggest that this delivery of sand from the Raine Island reef is in a delicate balance but attempts at reconstructing past variations may provide insights into how the reef may respond to future sea level rise.

Evolution of the cay over the last 3000 years is also discussed in appendix C. in relation to the formation of the phosphatic cay sandstone and more recent "bryme rock" and is illustrated in figure C1.

Appendix C

Possible Process for the Formation of “Bryme Rock”

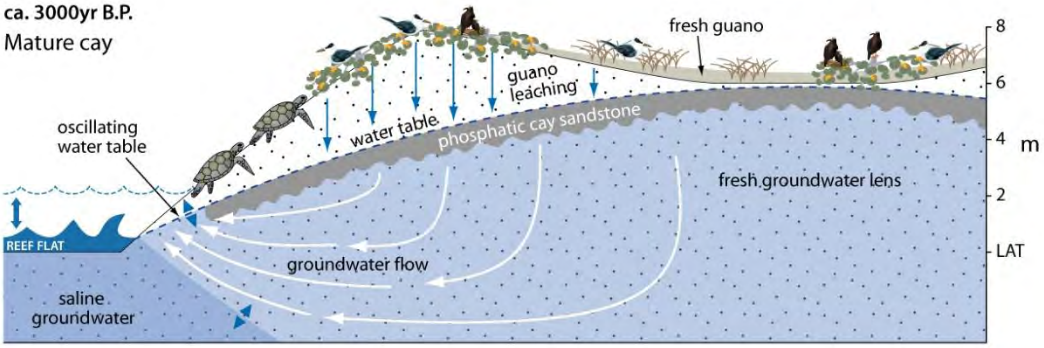
The bryme rock on Raine Island is a major problem for turtle nesting and little seems to be known about its formation. It appears to be recent and the cement is almost certainly either calcium carbonate (as for beach rock) or dahllite derived from the phosphatic guano (Section 2.5.6) Both are common on Raine Island but a phosphatic origin is favoured in the following hypothesis which follows the sequence of events from the formation of the initial phosphatic cay sandstone cap:

1. After the initial formations of the cay and extensive bird nesting, guano is leached downwards to the water table which is presumed to have the up-turned saucer shape of the Ghyben-Herzberg Lens (figure 7)
2. A period of erosion follows, forming the scarp and subsequently having the berm deposited in front of it.
3. Initially at least there may have been little new downward leaching of the guano but the mining of the 1890s may have caused changes to the groundwater level and behavior on the cay, and a new Ghyben-Herzberg lens may have formed at a lower level to make allowance for the material moved by mining, but superimposed over the older cay sandstone and the newer berm.
4. If a new Ghyben-Herzberg lens formed it would still have its highest level in the centre of the island but, still presuming the upturned saucer shape, be a relatively thin layer towards the beach where lateral movement of groundwater would bring the dissolved phosphate and deposit it relatively close to the ground surface.
5. This new phase of phosphate rock formation would be unnoticeable in the centre of the cay as it would be superimposed on the zone already cemented. Only close examination and analysis may differentiate it from the earlier phase cementation.
6. Another factor of the deposition along the top of the freshwater table which matches the observations of the bryme rock on Raine Island is that especially close to the sea it may oscillate in response to tidal influences and give the impression of following the ground contours.

This is only a hypothesis which can be proven (or disproven) only by fieldwork. What needs to be identified is the nature of the cement and if survey of the bryme rock surface can show that it is a new phase of cementation superimposed on the older cemented core of the island and the newer berm. If the mining of the phosphate in the 1890s remobilized the leaching process down to the water table then problems for reef flat corals may be developing. As a nutrient, phosphate is highly detrimental for corals but over the past 1000 years or so most of the guano has remained on the island which has acted as a filter for the nutrient. Lateral movement within the water table from the cay to the reef flat has been investigated by Charley et al (1990) and Chen and Krol (1997) and eutrophication effects on corals of the surrounding reef flat demonstrated. This is another area in which further research is needed on Raine Island.

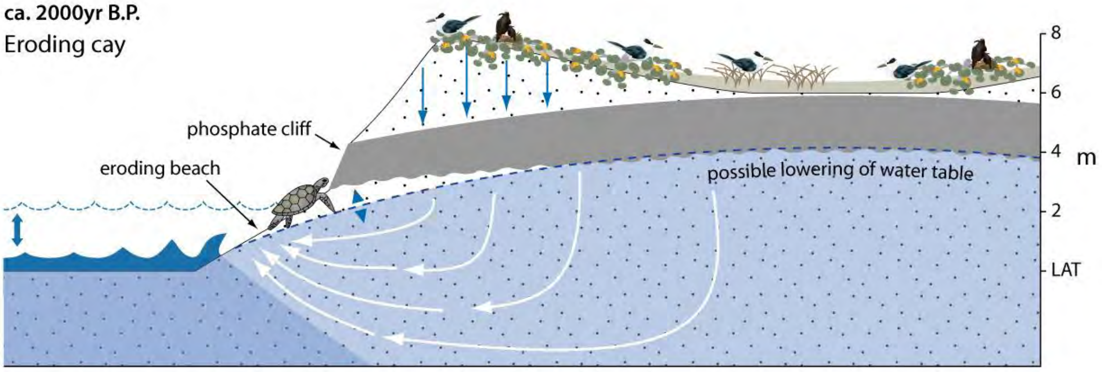
ca. 3000yr B.P.

Mature cay



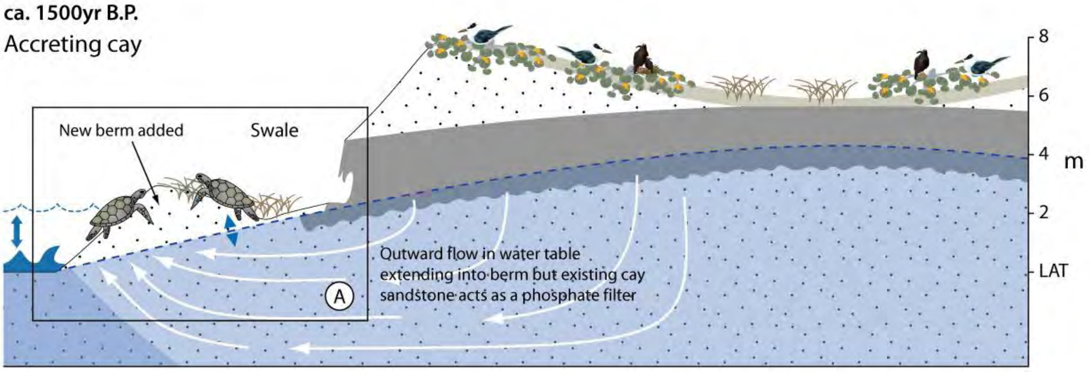
ca. 2000yr B.P.

Eroding cay

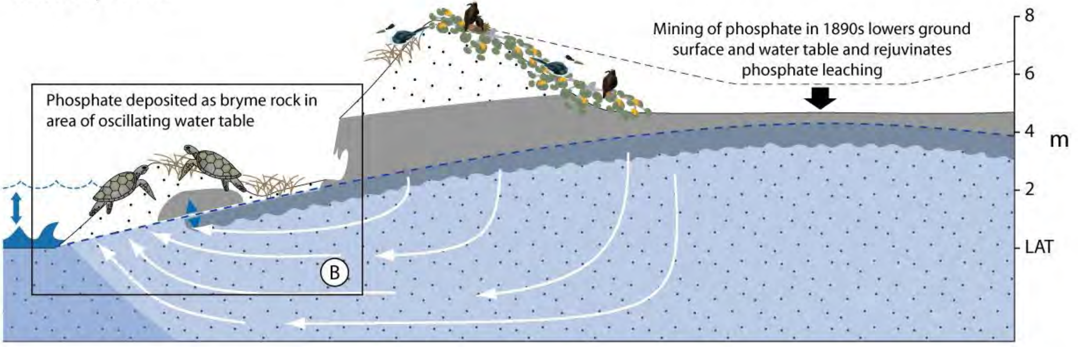


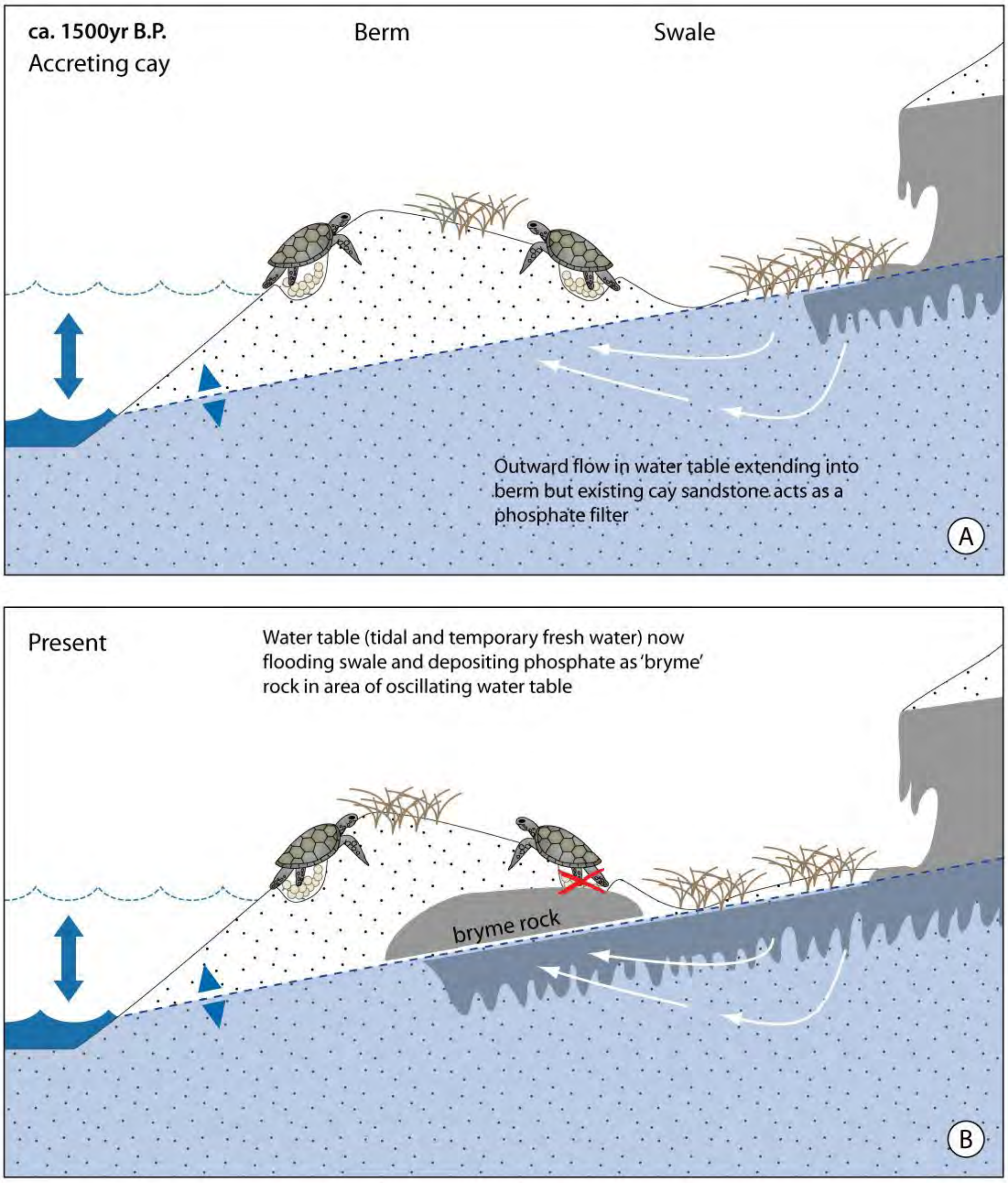
ca. 1500yr B.P.

Accreting cay



1890s to present





Outward flow in water table extending into berm but existing cay sandstone acts as a phosphate filter

Water table (tidal and temporary fresh water) now flooding swale and depositing phosphate as 'bryme' rock in area of oscillating water table

Figure C1 Sequence for the development of the phosphatic cay sandstone, cliff and berm over the last 3000yrs and hypothesis for more recent formation of the "bryme rock" since phosphate mining in the 1890s

Appendix D

The Importance of Benthic Foraminifera to Raine Island

The importance of spheroidal foraminifera in the sediments of Raine Island has long been recognised (Stoddart et al, 1981) and was quantified by the work of Gourlay and Hacker (1991). They report a range of 20.4 to 53.8% of benthic foraminifera in the beach sediments with the most prominent being *Baculogypsina sphaerulata* (10-50%), *Amphistegina lessonii* and *Marginipora* sp. Sediments on the adjacent reef flat may contain up to 80% foraminifera (Neil et al, 2000) with the source identified as the reef marginal turf zone (Clegg et al, 1997).

These figures are not unusual on the GBR. Maxwell (1968) described foraminifera components of the outer Reefal areas (*Marginipora* and *Operculina)* as up to 30% with figures from the sands of the algal rims and reef flats of reefs he surveyed being as high as 95%. Hopley (1981) in a study of the dynamics of reef flat and island sediment movement reported that on Redbill Reef, in the south central GBR, Bushy Island beach contained 12-38% foraminifera (mainly *Baculogypsina sp.)* and the adjacent reef flat up to 88%. Similar figures came from Green Island near Cairns (Yamano et al, 2000), with foraminifera making up to 30% of cay beach sediments and 50-70% sanded reef flat sediments. These figures compare with those elsewhere as Hohenneger (2006) quotes figures between 20% and 95% for the foraminiferan content of West Pacific carbonate beaches.

Globally, foraminifera (including planktonic) account for 25% of carbonate production of the oceans with the larger symbiont bearing foraminifera contributing about 5% to the carbonate production of reefs and shelves (Langer, 2008). *In situ* productivity has been calculated from standing counts and by alkalinity anomaly measurements (e.g. Hallock, 1981; Fujita and Fujimura, 2008). In the north-west Pacific Fujita and Fujimura show that *Baculogypsina* sp. and *Calcarina* sp. can make up to 2-7.5% of gross primary production of reef crest communities and *Marginipora* up to 11% in the back reef area.

Quite clearly benthic foraminifera are an important component of coral reefs and are very susceptible to climate change, illustrating the possible fragility of the sediment budget of Raine Island. Unfortunately in the otherwise excellent comprehensive review on climate change and the GBR edited by Johnson and Marshall (2007) there is very little mentioned about benthic foraminifera, a review of which is recommended to assist in future management in the face of global climate change.

Benthic foraminifera, like corals, have symbiotic zooxanthellae which are lost under stress. Nutrification as a stressor has long been known (Hallock, 2000) but it is over the last 30 years that bleaching as a response to changing radiation has been studied (Hallock, 2000; Hallock et al, 2006 a, b,). Unlike corals which expel their symbionts, foraminifera digest the zooxanthellae, producing a similar bleaching. Major events occurred in 1992, 1998 and 2005 (Hallock et al 2006a). This response is not to thermal stress but is light induced especially in the 300-490 nm range. UVB has had increased penetration over the last 30 years with depletion in the ozone layer.

Because even the larger foraminifera are small and fragile, fears have also been expressed about their reaction to ocean acidification. Changing chemistry of the ocean has been shown to have an influence on the formation of shell which responds by changing its composition (more Mg^{2+}) but resulting in a weaker structure which may break down as the foraminiferan sediments are moved (Hallock, 2000). Anomalies, which have been noted as the result of acidification include:

- microborings
- microbial bio-films
- pitted surfaces
- dissolution
- calcification anomalies
- growth anomalies

However, foraminifera have the potential (Crevison and Hallock, 2007) to forecast coral bleaching and susceptibility to disease (Hallock et al, 2006 a, b.).

> "Response of *Amphistegena* populations can provide managers worldwide with a relatively quick low cost method to make informed decisions about when to employ more expensive technology such as δ ^{15}N assessment, cellular or molecular biomarkers or other specific detection protocols to determine the sources of stress".
>
> (Hallock et al, 2006a).

A protocol termed the FORAM Index has been developed (Hallock et al, 2003) which is based on the proportions of three functional foraminiferan groups. It has been shown to have the ability to differentiate between local and global impacts, including for example on Low Isles Reef where agriculture on the local mainland was shown to have had a negligible impact (Schueth and Frank, 2008). The FORAM Index appears to have many advantages and its application to Raine Island deserves consideration. Its advantages include:

- it is now a widely used environmental and palaeoenvironmental indicator
- reef building corals and other reef organisms have similar water quality requirements
- the relatively short life span compared to corals facilitates differentiation of long term water quality decline and episodic stress events
- foraminifera are relatively small and abundant making them easy to collect and sample
- collection has a minimal impact on reef resources

Undoubtedly as sea surface temperatures rise and the ocean becomes more acidic, the foraminifera of Raine Island will be negatively impacted. Close scrutiny of these organisms which are so important to the sediment budget is needed but if carried out through, or in association with a FORAM Index monitoring program a more holistic monitoring of Raine Island's environment may be achieved. Hohenneger (2006) recognises that beaches dominated by foraminifera, such as Raine Island, are highly mobile, a result of the density and hydrodynamic shapes of tests. Understanding the ecology, especially population dynamics of larger foraminifera in combination with factors influencing the transport of empty tests, is essential to preserve the balance between deposition and removal of sand on carbonate beaches. His analysis of the carbonate budgets and mobility of foraminifera is directly applicable to Raine Island.

Appendix E

Changing Shorelines on Raine Island

i) Cay Dynamics (figure E1)

Erosion of Raine Island has been noted in numerous reports but this may be an oversimplification of the geomorphological changes on the island (see appendix B). Coral cays are highly dynamic landforms and whilst the internal area with organic soils or, as in the case of Raine Island phosphatic cay sandstone deposits may have been stable for thousands of years, more recently added beach berms may be more mobile apart from areas of cemented beach rock. In fact it is almost certain that sand is being added to and eroded from the island continuously, the balance between the two processes resulting in erosion or aggradation. Carbonate sediments are produced from the different zones of the reef margin and reef flat as discussed in Gourlay and Hacker (1991). Production rates can be as high as 10kg m^2 yr^{-1} (Kinsey, 1988; Kinsey and Hopley, 1991) but the nature of the Raine Island reef flat, with little sediment cover suggests that the yield to the island may currently be very small. Loss of sediment is over the reef margin and general reports e.g. Neil et al (2000) have noted sediment plumes close to the location of the 1890s jetty on Raine Island. First indications are that the present sediment budget on Raine Island is close to balanced though further detailed studies are required.

That this has not always been so is indicated by Raine Island's major beach berm which appears to have accumulated over the last 1000 years (appendix C, figure C1). This feature also points out the importance of analysing cay sediment budgets from a three dimensional approach. Planimetry may change but sediment apparently lost may be built vertically into features such as berms. Gourlay and Hacker (1991) in particular describe the processes which allow such construction. However, the main berm on Raine Island may have formed when the Raine Island reef was different to today. Hopley et al, (2007) have demonstrated that the rates of geomorphological change on relatively small reefs of the GBR can take place in short periods of time. It is well within the known rates of geomorphological development for Raine Island until 2000 years ago having a central highly productive shallow lagoon, the source of the berm sediment, which over succeeding centuries has become in-filled and largely overlain by the micro atolls of today, the diameter of which suggest that the lagoonal phase did not go beyond 500 yrs B.P., (see appendix B).

Further caution is needed when examining shoreline change on cays as erosion in one area may be matched by progradation elsewhere. The result is a re-orientation of the cay, usually in response to changing wind patterns. Such re-orientations have been documented in nearby Torres Strait (Rasmussen and Hopley, 1995). Changes to wind speeds and wind strengths in the 1970s were correlated to re-orientation of Warraber Island and other cays in Torres Strait. A similar analysis of Thursday Island wind records by Proh (1995) and Proh and Gourlay (1997) also recognised a link with strong ENSO years and hindcasted erosional events in 1950-56 and 1970-76 related to westerly wind anomalies and 1958/59, 1965-69 and 1977-87 related to easterly anomalies. Changes to Raine Island and to islands in Torres Strait appear to correlate with ENSO events. Flood (1986) recognised similar correlations between wind shifts and island re-orientation in the Bunker-Capricorn Group.

ii) Mathematical and Physical Modelling of Raine Island Processes.

A valuable insight into Raine Island's sedimentary processes has been provided by the work of Gourlay and colleagues (comprehensively reported in Gourlay and Hacker, 1991; Gourlay, 1995). The modeling included in the initial report was directed at island formation and beach profile development. As noted in Section 3.6.1 it was shown that sea level rise may not cause erosion on Raine Island, rather the change to waves as they cross a deeper reef flat may produce accretion of the beach berm. This work, including detailed sediment analysis is one of the most valuable contributions to understanding the behaviour of GBR cays in response to higher sea levels, and, as noted in section 3.6.1 confirms other geomorphological conclusions.

The later report (Gourlay, 1995) focused on wave generated currents which are responsible for continually re-shaping Raine Island. The model produced a westward flowing current over the reef top, as the result of wave set-up on the eastern end of the reef where the larger waves break. These currents are greater than any tide or wave induced currents, and are responsible for the mechanical transport of sand from the windward to leeward reef, including along the cay beaches even when breaking crests are parallel to the shore. Further Raine Island reef's simple planar reef top geometry means that tidal height does not affect the process. Nonetheless, Gourlay (1995) has the following recommendations:

- further modeling using different wave direction approaches
- better topographic survey of the reef top (and windward reef margins where spur and groove systems may occur.

and

- confirmation of processes from fieldwork (already underway (J. Dawson, JCU) within a field program as outlined by Kench et al (2003, 2006).

iii) Driving Forces of Shoreline Change.

The exposed location of Raine Island makes it very susceptible to changes in energy conditions which in turn will impact upon the shoreline. Both Gourlay and Hacker (1991) and Neil et al (2000) discuss the driving forces behind Raine Island's beach changes. Factors include:

- periods of negative sediment budget when more sand is lost from the reef top than is provided by the contributing reef flat and reef front areas. Of particular note are plumes of sediment reported moving off the reef under strong south-easterly conditions, especially via a re-entrant in the reef margin near the beach. This is close to where the jetty for phosphate export had been constructed and there is some speculation that the re-entrant was artificially cut at that time

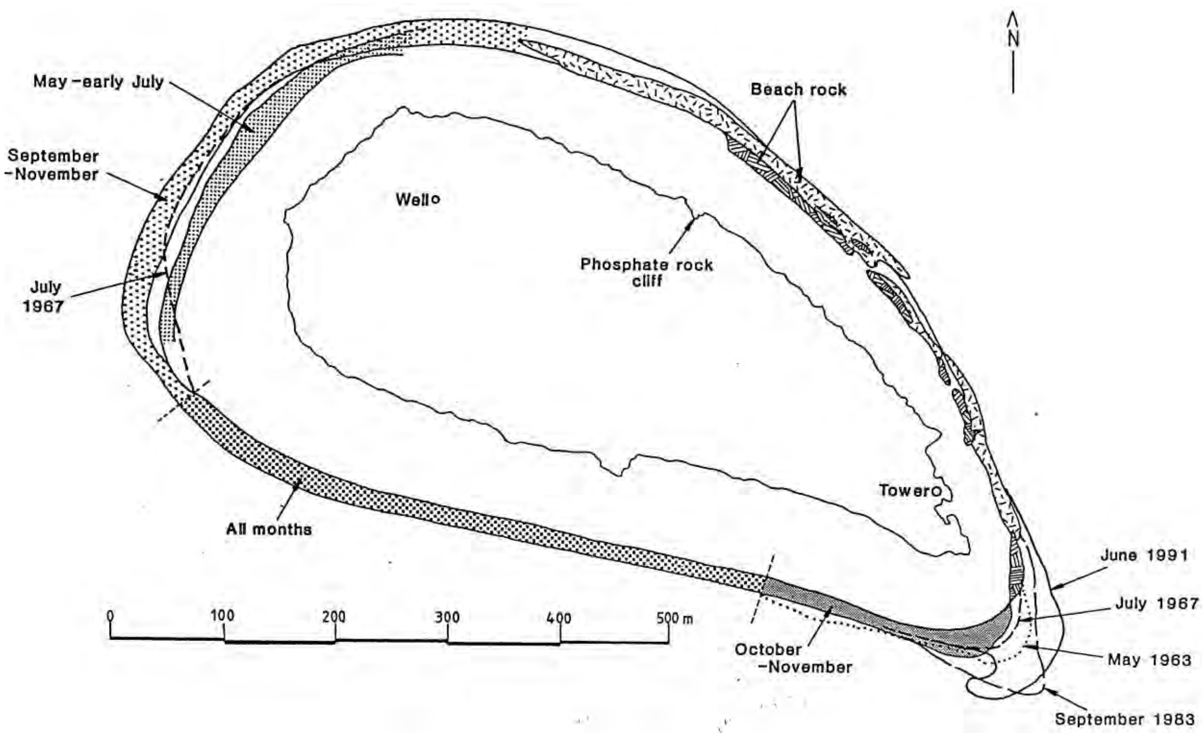


Figure E1. **Comparison of shoreline positions, Raine Island – 1963 to 1995. (Adapted from Gourlay and Hacker 1991, Figure 5.12).**

- this is one example of the effects of human activity but removal of the phosphate deposits and probably sand for purposes such as ballast will have reduced the island's total store
- a loss of sand on the backs of nesting turtles has been observed (Limpus, pers. comm.) but this is unlikely to be a major factor as the sand would be washed off the backs of the turtles as they returned to the sea and returned to the beach during the next high tide.
- occasional high energy events such as cyclones, bringing winds and waves from unusual directions. Cyclones Dawn (1970) and Faith (1972) which passed close to Raine Island have been suggested as factors in shoreline changes at about that time. Extremely strong cyclones are not common in the northern Coral Sea and

storm surges at Raine Island will be limited to the "inverted barometer" wave only (<1 m) without the shoaling and funneling effects of storms making landfall

- longer term changes to wind and wave patterns. As noted Dawson (2008) reports a correlation between strong El Niño conditions and accretion and strong La Nina and erosion. These global events were also involved in the changes observed in the 1970s in wind strength and direction at Thursday Island (Rasmussen and Hopley, 1995).
- changes in sea level have been a major driving force in the construction of both the Raine Island reef and its island as outlined by Neil et al (2000). However, more recent changes may be involved. Micro-atoll evidence on the Raine Island reef flat suggests a period of relatively stable sea level over several centuries. Whilst tide gauge records are non consistent along the Queensland coastline, recent studies have concluded that the best estimate of global averaged sea level rise between 1950 and 2000 is 1.8± 0.3 mm yr^{-1} (see Hopley et al 2007 for discussion).

iv) Conclusions on Shoreline Change.

Conclusions about erosion of Raine Island have been expressed on a number of occasions over the last 40 years. Undoubtedly the cay is highly dynamic and its beaches constantly changing. As with many cays on the GBR the narrower eastern and western ends have shown the largest changes with up to 30 m of erosion or progradation. The main northern and southern beaches are more stable with changes between surveys generally within 5 to 10 m. The southern beach appears to be the most stable in the long term but no part of the island has changed in a uniform direction (erosion, progradation) over the period of the surveys. However, a migration of the cay from east to west has been occurring together with an elongation in shape. Raine Island appears to be in a delicate equilibrium, the estimated 14 000 m^3 of gain in sand over the last 40 years being negligible compared to inter-annual (and even intra-annual) changes.

Many of the changes appear to be contributing to a long term re-orientation of the island possibly ENSO driven and commencing in the 1970s. Climate change, incorporating frequency of El Niño/La Nina events and sea level rise are important components of projected climate change and if links between these phenomena and shoreline changes on Raine Island can already be established, forecasting the island's response into the future may be possible.

Appendix F

Alternative Nesting Sites for the Green Turtle, *Chelonia mydas*

The worst case scenario for Raine Island is the complete erosion of the island as sea levels rise and weather patterns change. Turtles and other marine life have clearly adapted in the past as they accommodated the rapid rise in sea level and other environmental changes during the Holocene transgression. Whilst the rates of change over the next 50 years will be more rapid than the average rate of sea level rise during the Holocene transgression there were times when short periods of accelerated rise were experienced. The conservative range of 18 to 59 cm rise in sea level by 2100 alone should not impact significantly on turtles. However, it is the effect of the rise on the nesting beaches which is of much more concern and, at the Townsville Workshop the possibility of the Raine Island turtles being able to adapt by moving to a more stable site was suggested.

That turtles have been adaptable in the past has already been demonstrated. Their adaptive capacity includes changing the time of breeding to avoid times of higher temperature or shifting to beaches which do not absorb solar radiation as much as the ones they previously used (Haman et al, 2007). It has also been shown that within the large nesting areas of each of the three discrete breeding populations of eastern Australia (Limpus et al, 2003), if Raine Island were to become untenable as a nesting location the turtle population would migrate to a more suitable nesting site.

However, will there be more appropriate sites available on the northern GBR? Favoured nesting sites for the northern GBR breeding population are composed of well sorted, medium coarse carbonate sand. The beach is well drained without any extensive cementation. A location close to the shelf edge also seems to be favoured. A search for suitable locations immediately highlighted the many advantages which Raine Island has over potential rivals. It is the largest vegetated cay on the outer GBR, at the focal point on the reef flat for wave refraction and, although close to the reef edge, does not appear to be losing large amounts of sand into deeper water. Further, as a “capped” cay it has extensive areas of cemented deposits including phosphate cay sandstone, beachrock and “bryme” rock (see Sections 2.5.6 and appendix C) all of which will slow down any erosion. Such an array of cemented features is not found on any other island in the northern GBR with the exception of Moulter Cay.

Alternative sites for turtle nesting can be classified into 4 groups:

- capped cays – Moulter is the only example
- sand cays with no vegetation or only ephemeral vegetation cover e.g. Sandbanks No 7 and 8, Anchor Cay and the numerous vegetated and unvegetated cays of central Torres Strait.
- islands with volcanic rock core (but without vegetation) surrounded by carbonate sands e.g. Bramble Cay, Black Rocks, Stephens Is.

- Continental islands with fringing reefs and stable bayhead carbonate beaches e.g. Darnley, Mer, Waier, Dauar, (Murray Islands).

Although Moulter is very similar to Raine, its smaller size will almost certainly result in it responding to climate change more rapidly and possibly more severely. The sand cays, at least in the next 100 years or so, may not disappear as rejuvenation of reef flats (section 3.6.1) and increasing fragility of corals and other carbonate organisms lead to increased sediment supply. However, it is unlikely that the cays will be built to significant heights and tidally driven water tables are likely to intrude into the zone of egg laying (80 cm).

Islands with a volcanic rock core will be more stable but where this consists of a few outcrops only 2 or 3 m above HWM, the attached carbonate beach will be highly mobile especially if the present climatic regime of winter south-easterlies and summer north-westerlies remains.

However, the bayhead beaches of larger islands such as those in the Murray Group will not only be more permanent but will also be in the position to capture the new waves of sediment which will result from climate change. There are many examples on North Queensland continental islands of relatively fresh bayhead carbonate beaches, the most common including broken fragments of *Acropora*. Whilst coarse beaches are more common adjacent to the bayhead fringing reefs, sandy beaches (often a mix of carbonate and quartzose sediments) are also found (e.g. the lee-side beaches of most Palm Group Islands). Further assessment of the sustainability of beaches in the Murray Islands (and elsewhere) for accommodating a significant increase in *Chelonia mydas* breeding females is needed but these sites would appear most appropriate and be in a position to resist sea level rise at least in the foreseeable future. Some *Chelonia mydas* nesting on these islands has already been noted.

Appendix G

The Alkalinity Anomaly Method For Calculating Calcification Rates.

Fujita and Fujimura (2008) claim that whilst there is much data on calcification rates of foraminifera in general, figures for symbionts bearing reefal foraminifera such as those contributing to the Raine Island sediment budget are not common. They therefore carried out studies on three species. *Baculogypsina sphaerulata*, *Calcarina gaudichaudii* and *Marginopora kudakajimensis* all of which at least at the generic level are found in the turf zone of Raine Island (Neil et al, 2000). Whilst Fujita and Fujimura (2008) applied the alkalinity depletion method in closed laboratory conditions, they did show that the method could be applied to these small but numerous organisms and its application to the turf zone on Raine Island is possible.

The alkalinity depletion methodology was developed in the 1970s (Smith, 1978, 1983; Kinsey, 1978, 1985; Smith and Kinsey, 1978). The method depends on the rate at which $CaCO_3$ production depletes the overlying water column with respect to some $CaCO_3$-related dissolved constituents. Measurements of magnesium or strontium are too small to be useful but $CaCO_3$ precipitation lowers alkalinity in the overlying water column. For each mole (100g) of $CaCO_3$ precipitated from a given volume of water, the total alkalinity is reduced by two equivalents. The volume of water will be in contact with the reef for a given time. Therefore, $CaCO_3$ productivity equals the decrease in alkalinity ($\Delta\, T.A.$ in eq m^{-3}) times 50 g $CaCO_3$ eq^{-3} times the water volume per unit area (which equals the mean water depth in m) divided by the period of time the water remains in the system (γ in days or other useful units). Application is limited by the resolution of $\Delta\, T.A$ and γ. Smith applied the method to a body of water flowing over a reef top whilst Kinsey applied it to still water at low tides especially in reef pools or, by fencing off an area of reef (Kinsey, 1978).

Noise is introduced into the calculation by rainfall or evaporation and a minimum width of reef flat. Maximum water depth and maximum rates of flow are critical in achieving optimal results. However, results have been consistent for specific reef zones throughout the world. Daily figures show maximum rates at midday and effectively no deposition at night (the influence of photosynthesis). Also there are seasonal variations which suggest that if this methodology were applied to Raine Island measurements would have to be made during at least one daily cycle and over contrasting seasonal conditions. Nonetheless, if care is taken in the measurements, accuracies to within >0.1 kg m^2 yr^{-1} can be achieved. Dense coral cover rates are up to 10 kg m^2 yr^{-1}. Figures obtained from algal turf areas, where the main calcifying organisms were almost certainly foraminifera, are in the range of 0.3 – 4.0 kg m^2 yr^{-1}. With such a range, the determination of the exact figure applicable to the Raine Island turf zone is important.

Appendix H

Application of Near Infra-Red Imagery to Coral Reefs.

The application of near infra-red imagery to coral reefs goes back to the 1970s when oblique aerial photographs were taken from light planes over a number of reefs north of Cairns (van Steveninck, 1976; Hopley and van Steveninck, 1977; Hopley, 1978). Four types of film were used including normal colour, normal black and white, near infra-red (IR) colour and near IR black and white to determine which was the best to distinguish between up to 16 defined reef top zones chosen from ground truthing. Differentiation was undertaken objectively by using a scanning densitometer. Colour IR was shown to be the most effective of the emulsions. Ground truthing, using colour IR film indicated that strong reflection came not only from algae but also from corals and other reef flat organisms such as *Tridacna* sp. which hosted microalgal zooxanthellae. That this was the source of the reflectance was confirmed by grinding up a living coral specimen and separating the coral polyp tissue, zooxanthellae and coral skeleton using a centrifuge. Only the zooxanthellae reflected in the near IR wave lengths.

Although there is a problem of water penetration by IR wavelengths (ideally water depth should not be greater than 0.5 m), the advantages for reef mapping and monitoring was clearly shown. However, as LANDSAT imagery became available the focus of remote sensing changed from aerial photography, even though the initial resolution of satellite images was 10m, far too coarse for most coral reef projects (Kuchler, 1984, 1986, 1987). The introduction of multispectral scanners and satellite imagery with better resolution (e.g. SPOT ~ 1m) helped in lifting the usefulness of satellite sensing for differentiating reef zones (see Mumby and Green, 2000 for discussion). Nonetheless, greater resolution was still needed for some projects and the exchange of methodologies between satellite and aerial photographic imaging, which was now digitized and able to be analysed with many of the techniques developed for satellite imagery, has continued. Aerial photography from altitudes as low as 500 feet were processed to provide a pixel size of 5.9 cm in a project designed to monitor the effects of *Acanthaster plancii* off Townsville (Hopley and Catt, 1994). Further development of the processing was made by monitoring of the fringing reef at Iris Point on Orpheus Island which has an algal turf zone similar to that on Raine Island (Linfoot and Thamrongnawasawat, 1993; Thamrongnawasawat, 1996). The research was then applied to managing coral reefs in Thailand, and identifying snorkeling trails (Thamrongnawasawat and Hopley, 1995). The technology was also applied to a project assessing the impact of sewage outfall on Great Palm Island (Withey, 1996).

Thus over a period of more than 30 years both satellite imagery and aerial photography, have improved in their ability to map and assess reef zones. Some satellite imagery now has a resolution of ~ 30 cm whilst aerial photography can be analysed using a wide spectral signal, (Mumby and Green, 2000). Best results appear to be from the compromising Compact Airborne Spectrographic Imager (CASI). For aerial photography a combination of near infra-red film (Kodak Aero colour infrared 70 mm 2443 false colour reversal film) and true colour (Kodak Aerocolour Negative 70 mm film

2445) proved to be optimal for mapping reef zones at Iris Point, Orpheus Island (Linfoot and Thamrongnawasawat, 1993; Thamrongnawasawat, 1996). Although the problem of water penetration remains, the addition of analyses of blue, green and red wavelengths resulted in greater discrimination. For example, on Surin Island in Thailand, identification of living coral areas was >89% and at nearby Chang Kard, reef user accuracy for classifying massive corals was 94.35% and for branching corals 84.47%.

On Raine Island, the main target for monitoring using remote sensing will be the algal turf zone, although the early detection of coral bleaching will also be possible. If digitized aerial photography (DAP) is the chosen technique, then the methodology for turf zone discrimination is already in place (Thamrongnawasawat, 1996) with accuracies ranging from 81 to 94% for enhancement and subtraction techniques but as high as 100% for supervised classification (table G1). The new high resolution satellite imagery currently being ordered for the Raine Island project will have all wavelengths used by DAP and this should be able to equal or excel the aerial photography results. Both satellite imagery and DAP should have the ability to detect changes to the reef flat brought about, for example, by the projected sea level rise, as discussed by Hopley and Catt, (1988). The effectiveness of Thamrongnawasawat's analytical techniques is shown in table G1. Note that the small macro algae classification is in fact an algal turf zone very similar to that on Raine Island. The test site used for ground truthing was the Iris Point Reef on Orpheus Island.

Table G1: Mapping accuracy for algal zones on Iris Point Reef, using the image analysis techniques developed by Thamrongnawasawat, (1996).

Image Analysis	Macro algal	Fossil reef	Small macro algae (algal turf)	Large macro algae	Fossil reef
Enhancement	87%	86%	81%	94%	83%
Subtraction*	94%	93%	94%	97%	92%
Supervised	100%	100%	100%	100%	100%

Exercise 1 – N° samples = 52
Exercise 2 – N° samples = 59
*Subtraction transformation (IR-R)

Appendix I

Assessment of Hard Engineering Works on Coral Cays

Comparison with Other GBR Cays.

In a detailed statistical analysis of GBR cays Aston (1995) identified Erskine Island (Bunker-Capricorn Group) as the most stable and Maclennan Cay (northern GBR) as the most unstable of GBR cays. Of the 50 cays he analysed (Aston, 1995, Table 5.4), Raine Island was the 8th most stable. If Raine Island had been the site of a tourist resort (planned with some knowledge of the short term beach changes) it is highly unlikely that any major problems would be currently identifiable. It is the turtles and seabirds which give Raine its special status and given the relative stability as identified by Aston (1995) and in the detailed analysis presented in appendix E the introduction of engineering works such as, walls or groynes would not only be superfluous but would almost certainly have a negative effect in the birds and turtles.

Engineering Works on GBR Cays

Significant engineering works have occurred on only two cays on the GBR. At Green Island attempts to halt man made erosion on the western end of the island using rock and sand bag groynes in the 1960s and 1970s merely moved the focus of erosion to another area (Kuchler 1978, Hopley, 1982). Between 1974 and 1976 the Beach Protection Authority tried to resolve the problem by pumping 18,000 m^3 from deeper water off the reef to the area of the cay which was eroding. This also failed as the sand was too mobile and relocated to the north-west corner of the island where it is now a permanent feature going through early stages of vegetation succession. A wall has now been built at the erosion hotspot and in combination with the other minor works appears to be finally stabilizing the problems which were initially aggravated by the groynes

The other site on the GBR is Heron Island. A boat channel was blasted through the reef in 1945 and deepened in 1966, 1987 and 1988, providing sediments with a routeway to leave the reef top aggravating problems associated with changing wind patterns (Flood, 1986). Similarly, the construction of a retaining wall on the north-western end of the cay has enhanced the erosive capacity of waves from the northern quadrant. Although spoil from the harbor has been dredged and placed near the north-western beach (20,000 m^3 in 1972) the sediment has subsequently migrated westward along the beach and has again re-entered the harbor. Between 1960 and 1972 approximately 2900 m^3 was lost from the western end of the cay (Flood, 1977, 1986; Hopley, 1982; Gourlay and Flood, 1981).

Engineering Works on Cays Elsewhere

The processes around a coral cay are very different to those along a mainland shoreline. There is a constant exchange of sediment between the beach and the adjacent reef flat. Seasonally the direction of movement around a cay may change and unvegetated spits at the ends of cays (especially elongated ones) are a very important part of the annual sediment budget. Engineering works more often than not interfere with these processes. Nowhere are there more examples of the poor application of a wide range of engineering works than on many of the tourist resort cays of the Maldives.

As noted by Kench et al (2003) engineering structures on coral cays often have a short life span, do not stop the erosion problem and often exacerbate the erosion problems and can degrade reef productivity. Although the problems in the Maldives are in part due to lack of high quality technical input, the study by Kench et al (2003) highlighted the fact that it is very difficult to provide engineering solutions to coral cays and especially where seasonal reversal of wind patterns were experienced. There are clear indicators that engineering solutions to Raine Island problems are unlikely to succeed, as well as being superfluous, as the island is currently stable.

> "The unique circulatory nature of coastal processes around islands has a number of implications for use of engineered structures. First, conventional engineering practices resulting from an understanding of onshore/offshore and alongshore processes are not necessarily appropriate. Second, it requires reconsideration of notions of passive erosion and placement loss. Effects of structures that are usually transferred alongshore are contained within the 360^0 coastline and act to compound island instability and erosion"
>
> Kench et al (2003), p1.

Whilst sand nourishment as a last resort using sediments from nearby reefs may be in the processes of being lost permanently from the reef top, may be considered (see Section 5.2.3), it is almost certain that hard engineering on Raine Island would accelerate sediment loss or, if rock walls were used, lead to the removal of sand beaches upon which the turtles depend.

Plate 1: Raine Island from the air. The wide berm surrounding the island and central depression dominate the island. © EPA

Plate 2:The historic 1844 beacon, constructed from phosphatic cay sandstone © D. Hopley

Plate 3: The cliff of phosphatic cay sandstone showing the columnar structure
© D. Hopley

Plate 4: The wide berm, a recent addition to Raine Island and constructed of sediments dominated by the foraminifera *Baculogypsina sphaerulata*. Bryme rock is thought to underlie this feature. © D. Hopley

Plate 5: The largely bare central depression resulting from phosphate mining in the 1890s. Numerous rubble piles are found across the depression. © D. Hopley

Plate 6: A green turtle *Chelonia mydas* about to nest on Raine Island. © D. Hopley

Plate 7: Colony of immature lesser frigate birds on the edge of the central depression.

© D. Hopley

Plate 8: Masked booby nesting in the central depression of Raine Island.

© D. Hopley

Plate 9: High islands such as Dauer and Waier in the Murray Group have sandy beaches which are already the site of limited green turtle nesting and may become more important in the future as climate change impacts on Raine Island. © D. Hopley

Plate 10: Hard engineering works produce more problems than they solve on coral cays as exemplified by this example of Bolifushi, Maldives. © Mohammed Ali