Sea Turtles and the Environmental Management of Industrial Activities in North West Western Australia

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I declare that this thesis is my own account of my research and contains as its main content work which has not been previously submitted for a degree at any tertiary educational institute

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Abstract

The nesting demographics of sea turtles using beaches within the Barrow, Lowendal, Montebello (B-L-M) island complex on the North West Shelf of Western Australia were examined in the context of their spatial and temporal distribution and potential for exposure to industrially based artificial light sources. The distribution of overnight turtle tracks throughout the island complex confirmed high density nesting of *Chelonia mydas* (green turtles) on deep, sandy and high energy beaches and *Natator depressus* (flatback turtles) on deep, sandy and low energy beaches, while *Eretmochelys imbricata* (hawksbill turtle) tracks were most visible on shallow, sandy beaches adjacent to near shore coral reef habitat. The three species exhibited a summer nesting peak. Hawksbill turtles commenced nesting in September and continued through to January, green turtles commenced in November and decreased in March. Flatback turtles displayed the most constrained nesting season reported to date in Australia with 86% of the animals visits recorded in December and January only.

Nesting population sizes estimated for the three species suggest that on a national scale the B-L-M complex is a moderately large green turtle and a large flatback rookery site. The hawksbill rookery is large on an international scale. While none of the green turtle nesting beaches fell within a 1.5 km radius of industrially based artificial light sources an estimated 42% of nesting flatback turtles and 12% of nesting hawksbill turtles were potentially exposed to these light sources.

Testing of green turtle and hawksbill hatchling response to different wavelengths of light indicate that hatchlings from the B-L-M region respond to low wavelength much like hatchlings tested in North America (Witherington 1992a). Flatback hatchlings displayed a similar preference for low wavelength light however their responses to

discrete light wavelengths between 400 nm and 700 nm suggest that this species may not discriminate well between wavelengths that lie between 450 nm and 550 nm. This response may be related to the rapid attenuation of visible light that occurs in the turbid near shore habitats favoured by this species.

Field based arena studies carried out to investigate hatchling behaviour on nesting beaches with light types commonly used in industrial settings found green turtle and flatback hatchlings are significantly attracted to these lights compared to controls. Lights that emit strongly in the low wavelength range (i.e. metal halide and fluorescent) caused hatchling misorientation at lower intensities than the test light that emitted relatively poorly in this range (high pressure sodium vapour). Hawksbill hatchlings tested *in situ* under the influence of actual oil and gas onshore and offshore facility based lighting were disrupted from the most direct line to the ocean by these light emissions. Emergence fan mapping methods that measure hatchling orientation on nesting beaches were refined and are proposed as an alternative monitoring tool for use on beaches that are logistically difficult to access for large scale experimental orientation studies. The hatchling behaviour was clearly complicated by beach topography and moon phase.

Satellite tracking of post nesting female green and hawksbill turtles from North West Shelf rookeries has identified the Western Australian location of migratory corridors and foraging grounds for these species while Scott Reef turtles migrate from their south Timor Sea rookery to Northern Territory waters. Green turtle nesting on Barrow Island and Sandy Island (Scott Reef) forage at feeding grounds 200 – 1000 km from their nesting beaches. Hawksbill turtles nesting at Varanus Island and Rosemary Islands forage at locations 50 – 450 km from their nesting beaches. While all of the nesting beaches within the B-L-M island complex are protected under the Barrow-Montebello

Marine Conservation Reserves, the only foraging ground similarly protected is the Northern Territory foraging ground used by Scott Reef green turtles. None of the foraging grounds used by North West Shelf green or hawksbill turtles is currently protected by conservation reserves.

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Acknowledgments

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Chapter 1 Introduction

1.1 Context of research

Six species of sea turtles occur within Western Australia; *Chelonia mydas* (green turtle), *Nattator depressus* (flatback), *Eretmochelys imbricata* (hawksbill), *Caretta caretta* (loggerhead), *Dermochelys coriacea* (leatherback) and *Lepidochelys olivacea* (olive ridley). Global populations of all six species are declining as a result of human activities (Lutcavage *et al.* 1996). Internationally this decline in global sea turtle populations is recognized by the protection of the species under IUCN and CITES agreements which prohibit trading of animals or animal parts across international boundaries (EA 1998). The IUCN red list of species that require protection includes hawksbill and leatherback turtles as 'Critically Endangered', green turtle, loggerhead and olive ridley are listed as 'Endangered' while flatback turtles are listed as 'Data Deficient' (IUCN 1996).

Globally significant green turtle, hawksbill and flatback sea turtle nesting beaches have been identified on the offshore islands of the Western Australian North West Shelf region (Prince 1994a, 1997). The importance of the marine habitats in the Barrow, Lowendal, Montebello (B-L-M) island complex to sea turtles was recognized as part of the justification for the establishment of a Marine Conservation Reserve over B-L-M island complex (CALM 2004). This, in conjunction with the release of the Commonwealth Government Draft Sea Turtle Recovery Plan (EA 1998), has focused greater attention on management of existing and proposed industrial operations in the area and identified the need for more detailed information on the impact of oil and gas activities on sea turtles both onshore and at-sea.

Threats to the long term viability of sea turtle populations occur at all stages of an individual sea turtle life cycle with the most important source of mortality being attributed to by-catch of mature reproductive individuals in trawl nets (NRC 1990). Historical commercial, and current indigenous, hunting of adults and eggs are also a major cause of turtle mortality worldwide (Shigenaka 2003). Non human predators of eggs and hatchlings include crabs, birds, Varanids, rats, raccoons, cats, dogs pigs, foxes and dingoes (Stancyk 1979). Vehicle movement on beaches can compress the sand over nests preventing hatchlings from emerging (Hosier *et al.* 1981; Salmon, M. *et al.* 1992). The ingestion of synthetic debris, plastic bags and tar balls can kill adults and hatchlings (Guinea 1990). Human presence on nesting beaches may deter nesting females during emergence onto the beach (Lutcavage *et al.* 1996) while any electric lights in the vicinity of nesting beaches may also deter adults from nesting and misorient hatchlings during sea-find (Lutcavage *et al.* 1996). An impact unique to Western Australia was the widespread death of juvenile and adult sea turtles associated with the atomic bomb testing in the Montebello Island group in the 1950's (Kendrick 2003). Industrial threats recognized in the literature include dredging, boat strikes, oil spills, explosive oil platform removal and seismic programs (Lutcavage *et al.* 1996).

Little detailed information is available in the literature on the threats to sea turtles and their habitats specifically associated with industrial activities. Most of the available information comes from brief reports in conference proceedings and focuses on dredging (Slay and Richardson 1988; Renaud 1990; Moein *et al.* 1994; Nelson *et al.* 1994; Renaud *et al.* 1996) and turtle behaviour around offshore oil and gas platforms (Klima *et al.* 1988; Lohoefener *et al.* 1989; Renaud 1990).

Threats to sea turtle populations that are specific to onshore and offshore industrial activity can be reasonably predicted from reviewing the published literature and the local (Western Australia) unpublished grey literature. These threats may occur at-sea (adult and hatchlings, male and female) or on nesting beaches (females and hatchlings). At-sea impacts include boat strike or seismic disturbance in mating aggregation areas, internesting areas, foraging grounds and along migratory pathways; mortality of adults or removal of foraging and internesting habitat during dredging operations for shipping channels and pipeline trenches; and oil spills. Nesting beach impacts may include: removal of nesting habitat during construction activity on beaches; compression of nesting sand from vehicular movements on beaches; disturbance of nesting females by staff recreational activities; and misorientation of hatchlings by electric lighting and flares.

Investigations into the interaction between sea turtles and industry in Western Australia have been confined to nesting beaches on the offshore islands of the North West Shelf. These studies have focused primarily on nesting female flipper tagging programs (Prince 1994, 1994a, 1994b; Pendoley 1999) and on the impacts of electric lights and flares associated with oil and gas construction and development activities on sea turtle hatchlings (Pendoley 1991; Hick 1995; Hick and Caccetta 1997; Pendoley 1999). While sea turtles spend approximately 1% of their lives in or on nesting beaches, this bias towards beach based studies reflects the global focus of sea turtle research with 90% of the sea turtle literature centred on beach based studies (Bjorndal 1999).

The protection of developmental habitats and nesting beaches is recognized as critical to the long term conservation of sea turtles. Within Western Australia environmental risk assessments of industrial developments have consistently identified light exposure on or close to nesting beaches as one of the greatest industrial-based threats to sea turtles (WAPET 1987; Apache 2001; ChevronTexaco 2003). Consequently this aspect of industrial sourced impact was selected for further study as part of this research project. Knowledge of the whereabouts of the sea turtles under investigation during the remaining 99% of their lives is also important to the conservation of the species. In order to put the impacts faced by nesting and hatching sea turtles on the North West Shelf into a regional perspective it was also necessary to identify the threats faced by the nesting turtles during their dispersal to, and at, their remote foraging grounds following nesting. A study to investigate the migratory pathways to, and location of, sea turtles from the study area therefore formed the second component of this research.

1.2 Objectives

The objective of this research was to investigate the impacts of industrial activities on sea turtle behaviour. The research outcomes can then be used to focus environmental objectives and activities on the key issues pertinent to sea turtle conservation both locally and internationally. The approach taken was to use the existing industrial facilities (pearling, and oil and gas) located within the B-L-M island complex as a case study to investigate the impacts of these facilities on the sea turtle nesting grounds that have been identified in the area. The behaviour of nesting females both during and after the breeding season was also investigated to identify any threats that they may be exposed to while migrating to, and at, their remote feeding grounds.

The specific objectives of this research project were to:

1. Compile information on B-L-M island complex sea turtle nesting populations, their composition, spatial variability, and seasonal distribution.

2. Identify light wavelengths most visible to green turtle, flatback and hawksbill sea turtle hatchlings.
3. Identify light types most commonly used in industrial development.
4. Examine the effects of industrial lighting on sea turtle populations on nesting beaches adjacent to industrial facilities and develop methods for ongoing monitoring of light impacts on nesting beaches potentially exposed to any artificial light sources.
5. Examine the post nesting dispersion of sea turtles and identify potential threats to the animals both en route to, from and at their foraging grounds.

1.3 Thesis outline

A brief overview of sea turtle biology is given in Chapter 2 along with background information on the conservation status of the islands and waters, geomorphology, climate and oceanography of the Case Study area. This chapter also summarised the historical and current literature on sea turtle presence and habitat use in the B-L-M island region. The spatial and temporal use of nesting beaches by sea turtles in the region is presented in Chapter 3. This data are used to identify the beach type favoured by the three species nesting in the region and provides a basis for determining the effects of industrial activity on beach use by nesting adults, and the proportion of hatchlings emerging from nests that are potentially at risk from industrial sources of impact. The key threat identified was from the electrical lighting and flares and the balance of the research program focused on the identification and quantification of this risk to local sea turtle populations.

To determine which of the industrial light types have the greatest potential to misorient hatchlings, laboratory based studies tested the preference of hatchlings for long versus short wavelength light (Chapter 4). At the same time the most commonly used industrial light sources were identified and the proportion of long and short wavelength light in each was measured (Chapter 5). These results were then used together to identify which of the specific industrial light types (including flares) were most disruptive to hatchling sea finding behaviour. The effects of industrial lights on hatchling orientation were then tested under real world conditions at an operating oil field (Chapter 6).

The final component of this research identified the location of some of the critical habitats (internesting, foraging and migratory pathways) used by green and hawksbill sea turtles nesting near the industrial facilities on the North West Shelf and in the Timor Sea (Chapter 7). The results are used to identify additional threats that these animals may be exposed to during breeding migrations and on foraging grounds.

Chapter 8 summarises this information and proposes environmental management actions to assist industry and regulatory environmental managers to protect and conserve sea turtle populations both near the industrial facilities and at their remote foraging grounds.

Chapter 2 Background

This chapter provides background information on sea turtle life cycle and developmental habitats in addition to the physical characteristics and the historical and current status of sea turtle use of habitats in the study area. The review focuses primarily on the three species of sea turtles known to utilise the marine habitats of the Barrow, Lowendal, Montebello (B-L-M) Island complex; green turtle, flatback and hawksbill. The review of sea turtle life cycle and developmental habitats includes a description of the currently recognised life cycle Types, developmental habitats and foraging ecology (Bolten, 2003) . The physical characteristics (geomorphology, climate and oceanography) of the habitats used by the sea turtles of the islands and waters of the B-L-M study area are summarised. The historical literature (1818 to 1960) was reviewed for pre-industrial development sea turtle records. Available information on the status of sea turtle populations and habitat use in the study area is reviewed. Finally, the industrial facilities present in the study area during the period of this research (1998 to 2003) are briefly described.

2.1 Sea turtle life cycle and developmental habitats

The behaviour of sea turtles in two of their critical habitats is the focus of this thesis, *i.e.* the breeding habitat (includes onshore and offshore habitat) and the foraging habitat. These habitats are described within the context of the sea turtle's general life cycle.

The ecology of sea turtles is complex and terms used to describe the various life stages frequently ambiguous. The terms used in this thesis will follow the convention proposed by (Musick and Limpus 1996) and will be restricted to hatchlings, juveniles and adults.

Hatchlings are recently hatched animals that have not commenced feeding (first few days after emergence). Juveniles are animals that have commenced feeding but have not reached sexual maturity, while adults have attained sexual maturity.

Life cycle characteristics shared by all species include a breeding migration from foraging areas to mating and nesting areas (Figure 2.1). During the breeding period, males and females migrate to mating areas which may or may not be close to the nesting beaches. Following mating the males return to their foraging grounds and the females spend several months at the nesting area laying multiple clutches. In between nesting the females move off to nearby internesting grounds while they form the next batch of eggs. After laying the last clutch of eggs the females return to their foraging area to build up fat reserves until their next reproductive migration. Most females do not nest in consecutive years (Miller 1996). Hatchlings emerge from nests after a 6-13 week (temperature dependant) incubation period. Hatchlings generally emerge onto the beach at night when sand temperature falls (Miller 1996). Hatchlings leaving their natal beaches migrate to deep water oceanic nursery habitats where they spend 5-20 years. Juvenile turtles then migrate to shallow near shore feeding grounds until they reach sexual maturity at 30-50 years. The mature adult turtles then migrate to the general vicinity of their natal beaches to begin the reproductive cycle again (Miller 1996).

Flatback life cycle varies slightly from this generalized pattern. Unlike other species they do not have an oceanic phase to their life cycle, instead juveniles grow to maturity in shallow coastal waters thought to be close to their natal beaches (Musick and Limpus 1996). There is evidence however, that some Flatback turtles engage in long distance migrations between feeding grounds and remote nesting beaches (Parmenter 1994).

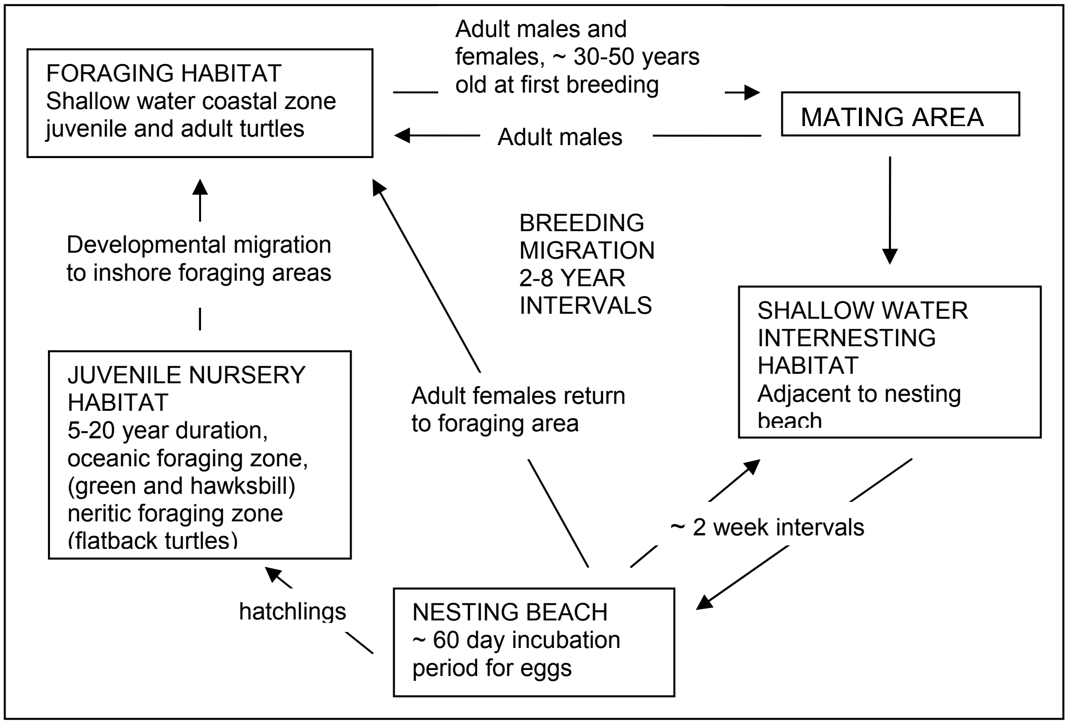


Figure 2.1: Generalized sea turtle life cycle. Redrawn from (Miller 1996)

Three developmental life history patterns (Type 1, Type 2 and Type 3) have been proposed for sea turtles (Bolten 2003). Species that complete development stages in the neritic zone (waters less than 200m deep) are classified as Type 1; the only species to exhibit this developmental pattern is the flatback turtles. The Type 2 life history pattern, characteristic of green and hawksbill turtles, show early development in the oceanic zone (> 200m water depth) followed by later development in the neritic zone. The leatherback turtle is the only extant example of a sea turtle with both developmental and adult stages common to the oceanic zone (Type 3).

The life history pattern of flatback turtles (Type 1) may be most primitive, e.g. similar to the ancestor of sea turtles that presumably inhabited coastal salt marshes, estuaries and tidal creeks (Bolten 2003). The phylogenetic pattern of green and hawksbill turtles (Type 2 life history pattern) suggests the change from a Type 1 to a Type 2 life history may have occurred in order to avoid predation in the neritic zone or to exploit food resources in the oceanic zone. The phylogenetic pattern of the Type 3 leatherback suggests they have utilised the oceanic habitat for a long time (Bolten 2003).

The developmental habitat locations described by the three life history patterns are closely aligned with foraging habitats for the various developmental stages of a sea turtles life cycle. All species are sustained by the egg yolk they resorb into their abdomen, immediately following piping from the egg, for the first few days after leaving their natal beaches (Lohmann, Kenneth J. *et al.* 1996; Musick and Limpus 1996). The foraging ecology of the three species commonly found nesting and foraging within the B-L-M island complex differs throughout their developmental stages.

Juvenile green turtles in the open ocean nursery habitat are omnivorous and may associate with downwelling zones (Witherington 2002) When they move from the oceanic pelagic habitat to the shallow water neritic habitat (30-40 cm curved carapace length) they shift to an herbivorous diet feeding on seagrass, algae and mangrove fruit (Mortimer 1979; Bjorndal 1996; Musick and Limpus 1996; Pendoley and Fitzpatrick 1999). Juvenile hawksbills may also live in association with sargassum rafts in the open ocean and appear to also be omnivorous. Juvenile hawksbills from the Indo-Pacific region move to benthic foraging habitats over coral reefs and rocky outcrops at a minimum curved carapace length (CCL) of 35 cm where they feed selectively on sponges (Limpus, Colin J. 1992; Bjorndal 1996).

Since flatback turtles do not have an oceanic phase, the juvenile and adult phases are both spent in the turbid shallow inshore waters of northern Australia where the juveniles appear to feed on planktonic (snails and siphonophores) and benthic (corals, molluscs and bryozoans) organisms. Larger juveniles and adults feed on jellyfish, sea pens and soft corals (Limpus, Colin J. *et al.* 1983; Bjorndal 1996).

2.2 Case Study area physical characteristics

This section identifies the location of the study area and describes the physical characteristics of the habitats used by sea turtles in the region. Beach types used by the three species differ and are critical to successful nesting and hatchling development. Differences in the foreshore character and beach physiography may determine which species will use a particular beach type while the subtidal habitats used by internesting and foraging sea turtles can be used to predict the potential importance of the B-L-M region to the various species.

2.2.1 Location

The B-L-M island complex study area is located in the southern region of the North West Shelf of Western Australia (Figure 2.2). The North West Shelf, including the Continental Shelf and the marginal platforms and plateaus, extends from North West Cape to the Northern Territory border and out to the 2000 m isobath. The southern component of the North West Shelf comprises extensive cemented calcareous sediments (limestone) which forms a shallow, gently inclining seabed extending from the coast to some 40 km offshore where water depths reach 20 m. Seaward of the study are the substrate slopes towards the edge of the Continental Shelf which drops sharply into deep water.

The study area, encompassing the B-L-M complex is located in shallow (average 15m deep) near shore waters of the Pilbara region of Western Australia. The region is characterized by numerous islands ranging in size from small rocky outcrops measuring several meters across to Barrow Island which covers an area of 286 km^2.

The B-L-M complex lies 120 km west of the Dampier Archipelago and 50 – 90 km north of the WA coast at its closest point. The island group is located between 20° 21’ S and 20° 57’S and 115° 35’E and 115° 18’E, extending 71 km from the northern end of the Montebello Islands to Boodie Island south of Barrow Island and 16 km across from Varanus Island to the western boundary of Barrow Island. Within this region 315 islands are recognized: 265 in the Montebello Group, 40 in the Lowendal Group and 10 in the Barrow Group (Osborne *et al.* 2000).

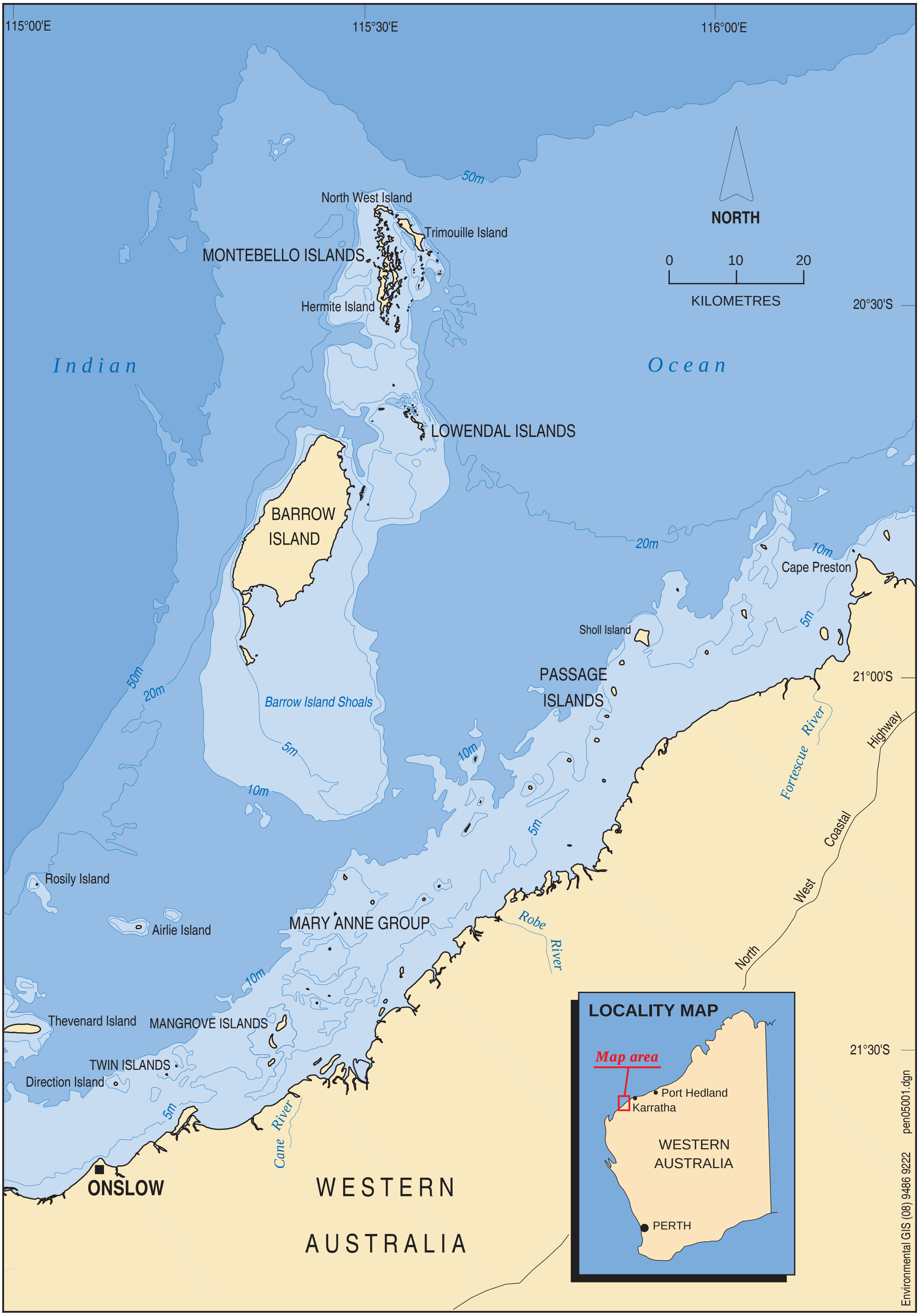


Figure 2.2: Location map of the Barrow, Lowendal, Montebello Island complex, study area

2.2.2 Geomorphology and marine habitats

The islands that make up the B-L-M complex emerge from the surface of the 'Montebello, Lowendal, Barrow Subtidal Ridge' which extends from the WA mainland coast from just south of Onslow (IUCN 1988; Osborne *et al.* 2000). This ridge is characterized by an extensive area of shallow subtidal pavement, sand banks, and the three main island complexes.

The geomorphology and habitats of the region have been summarised by Osborne et al (2000), Deegan (1992) and CALM (1994) and include:

- rocky shores, shoreline reef platforms and offshore intertidal reefs;
- intertidal mud/sand shoals and beaches;
- mangrove communities;
- coral communities, and;
- subtidal sand/silt/rubble and limestone pavement with macroalgae and seagrass

These are discussed within the context of each island group's physiography

Barrow Island

Barrow Island is the largest of the islands within the B-L-M island complex, measuring 26 km long and 11 km wide and covering ~28,600 hectares. The coastline is dominated by low headlands and cliffs (2-10 m) of Pleistocene coastal limestone on the east coast and high (30 m+) Miocene limestone cliffs on the west coast (Osborne *et al.* 2000). Sandy beaches comprise 45% of the estimated 89 km of Barrow coastline.

The east coast shoreline is characterised by sandy beaches interspersed between notched limestone cliffs or headlands. The sandy beaches are an average of 453m long and 11m wide. The beaches have relatively low slope angles and are dominated by fine-grained sand reflecting the low wave energy experienced by this coast (Plate 2.1).

Plate 2.1: Narrow, low profile sandy beach, east coast Barrow Island (Yacht Club Beach).

The primary dune line backing the east coast beaches range from 0m (south east coast) to 5+m (north east coast) and is typically covered with *Spinifex longifolius*, backed by *Acacia coriacea* and *Triodia angusta (WAPET 1988)*.

The intertidal zone seaward of the high tide line is broad and flat (Plate 2.1). The platform is up to 1200m wide in places and slopes gently with a fall of 1- 3 cm per meter (Murex and BBG 1997). The platform typically grades into the subtidal zone with no distinct drop-off. The intertidal platforms are either bare or covered by thin veneers of sand and silt (Murex and BBG 1997). Leafy algae, such as *Sargassum,* occur on the deeper outer edge of the platform while low density turfing algae dominates the middle section of the platform. Close to shore, algae levels drop off and silty sand sediment veneer characterise the inner platform.

The west coast of Barrow Island is more rugged with sandy beaches dissecting the tall limestone cliffs and headlands of the north-western coast (Plate 2.2). The height of these limestone cliffs and headlands gradually diminishes towards the southwest where low rocky limestone ledges and cliffs, more reminiscent of the east coast, dominate. A wave-cut rocky platform in the lower intertidal zone separates the sandy and rocky shorelines of the west coast from the subtidal zone (Murex and BBG 1997). This platform ranges in width from a few meters to 300 m. The wave cut platform has a discrete edge that drops abruptly into deep water. These platforms support dense bands of leafy brown algae (*Sargassum*), short dense turfing algae, coralline red algae and green algae (*Halimeda* and *Caulerpa*). Green turtles are frequently observed feeding and resting within this habitat.

Plate 2.2: Broad steeply profiled sandy beach on the west coast of Barrow Island (Petal Beach).

The white calcareous sandy beaches of the west coast average 407m in length and 25m in width and are backed by limestone cliffs or white calcareous foredune 0 m – 5 m tall. Dune blow-out areas up to 2 km long by 0.2 km wide separate the foredune from the secondary dune line behind most of the west coast sandy beaches between Cape Dupuy and the South End. The high wave energy of this coast produces steep beach slopes. Exceptions are on beaches where the shallow sand depth allows underlying rock to emerge from the beach. Seaward of the west coast intertidal zone water depths fall rapidly as the seabed drops over the edge of the Continental Shelf break.

The biggest concentration of coral reef habitat around Barrow Island occurs on the west coast. This reef (Biggada Reef) is a fringing coral reef that extends in a 1.5 km long arc north from Biggada Creek enclosing a shallow lagoon (CALM 1994). Scattered coral bomboras and small patch reefs occur on the shallow limestone and sandy banks separating Barrow Island from the Lowendal group (Deegan 1992).

Barrow Island mangrove communities are restricted to the sheltered bays of the south and east coast (Osborne *et al.* 2000). Most are small stunted isolated trees growing from thin sandy sediments overlying the limestone platform. The most luxuriant stand occurs at the mouth of the Donald River where deep red mud has accumulated (WAPET 1988). The most northerly stand is found at Square Bay.

Montebello Islands

These are the most oceanic and remote of the island groups. The geomorphology of the group has been described by Deegan (1992) and CALM (1994). The group comprises 170 islets and stacks in addition to 95 islands larger than 50m in length. The islands form two arms with the western arm running from Ah Chong Island northward through and beyond Hermite Island. This line of islands is a relict of a drowned Pleistocene landform that has eroded into numerous islands with intricate and convoluted shorelines that are characterised by lagoons, channels and intertidal embayments. Deep narrow channels separate the islands. The islands forming the eastern arm include North West, Trimouille and South East Island. These are composed of accumulated sand over a limestone base.

The largest island in the group is Hermite Island (970 ha), followed by Trimouille (450 ha) and North West (120 ha). These islands comprise 4%, 30% and 73% sandy shoreline while Alpha, Primrose, Crocus and Bluebell are among the larger of the islands that are almost entirely surrounded by rocky shorelines. Sandy beaches are absent on most of the small rocky stacks and islets. However, they are present on two of the smaller islands, Ah Chong (22%) and South East (32%). The total shoreline length for the entire Montebello group is 210 km and consists primarily of rocky cliffs and wave cut platforms (CALM 1994). Approximately 17 km are sandy beaches, 8% of all Montebello Islands shoreline.

The coastal processes acting on the sandy beaches of the Montebello islands are influenced by two different metocean regimes. Beaches on the outside of the islands face the open ocean and are exposed to higher wave energy than the beaches on the protected inner shores of the island complex. The high energy beaches occur on the west coast of Hermite, the western, northern and eastern beaches of North West Island and the eastern coast of Trimouille Island. These beaches are bounded by limestone headlands, backed by foredunes 2-5+m tall (Plate 2.3) and are shorter (average 355m) and broader (average 30 m) than the inner lagoon facing beaches which are long (average 1.8 km) and narrow (3-4 m) with little foredune development (2.4).


Plate 2.3: Example of large open ocean facing beaches, east coast Trimouille Island (Beaches 5,6 and 6a)

Plate 2.4: Long narrow low energy inner (lagoonal) beach within the Montebello Island group (Beach #6, North West Island)

The islands have a low topographic profile with limestone and sandstones topped with sand dunes up to 40 m high. *Spinifex longifolius* dominates the dunes and terrestrial flora of the islands. Most of this coastline is low undercut limestone rocky shoreline, however some of the ocean facing shorelines on the three largest islands (Trimouille, North West and Hermite) drop abruptly off 20 m tall cliffs onto rocky intertidal platforms.

A 12 km long barrier reef (denoted West Montebello Barrier Reef herein) provides some protection to the Montebello group from large oceanic swells and waves to the west (Osborne *et al.* 2000). This barrier reef is wide, flat, and composed of coral rock slabs, interspersed with sand and loose boulders. Patch reefs are common in and around the islands of the archipelago and extend south to the Lowendal Island group along a broad shallow limestone ridge. This ridge is covered mainly in algal turf, thin sand veneers, mobile sand dunes and small patch reefs. Extensive algal beds occur on the sub littoral pavements of the group, especially towards the southern end.

The best developed stands of mangroves in an oceanic setting occur at the end of Stephenson Channel on Hermite Island (Deegan 1992). These mangals are contained within a circular embayment accessed via an inlet 10 m wide and cover 15 ha.

Lowendal Group

The Lowendal Island group lies to the south of the Montebello Islands and east of Barrow Island. They are made up of over 40 islands, most of them small low-lying bare rocky stacks and islets with no sandy beach accumulations. The rocky shorelines are typically less than 5 m high with a vertical notched seaward face. The base of the notch supports a thick cover of oysters. Narrow (10-20 m) wave cut rocky platforms extend into the intertidal zone of the smaller islands. Shallow embayments of fine sediments occur off the larger islands.

The five largest islands of the group include Abutilon, Varanus, Bridled, Beacon and Parakeelya. These islands all have sandy beaches comprising 18% of their coastlines. The sandy beaches are composed of fine white sands and range in length between 10m to 290m. The sandy beaches form embayments between rocky headlands. Beach slopes in the group are low while widths tend to be narrow in the shallow protected embayments and wider on higher energy beaches.

With the exception of Mangrove Beach the foredune is typically 3 – 5 m tall and is vegetated by *Spinifex longifolius*. (Plates 2.5 - 2.7).

Plate 2.5: Wide, deep sand, low profiled sandy beach within the Lowendal Island group (Harriet Beach, Varanus Island)

Plate 2.6: Example of a small cove beach on Varanus Island (Pipeline Beach)

Plate 2.7: Narrow sandy beach with exposed rock within the Lowendal group (Anderson Beach, Varanus Island)

Coral reefs in the area are almost exclusively small patch reefs or individual bomboras. There is no extensive reef development (Osborne *et al.* 2000). Isolated mangrove trees occur on upper intertidal zone of several sheltered sandy beaches of Varanus and Bridled Island (Deegan 1992).

2.2.4 Climate

The climate of the study area is a function of its arid tropical location with high summer temperatures, periodic cyclones and associated summer rainfall. The rainfall in the region is generally low with evaporation exceeding rainfall throughout the year. Intense rainfall may sometimes occur during the passage of summer tropical cyclones and thunderstorms (NSR 1995).

The area experiences two seasons, a warm winter from May to September and a hot summer from October to April. Winters are characterized by clear skies, fine weather, predominantly strong east to southeast winds and infrequent rain. Summer winds are more variable, with strong afternoon south-westerlies dominating. Three to four cyclones per year are typical, primarily between December and March (WNI 1995).

2.3 Status of sea turtles in Western Australia and the study area

2.3.1 Regional Western Australia

A recent review of the status of sea turtles in Australia concluded that significant nesting populations of green, flatback and hawksbill turtles occur in Western Australia however the population size estimates are based upon sparse census data. The review further concluded that the status of the nesting populations is currently undetermined for green turtles (Limpus, C. J. 2006a in prep) hawksbill turtles (Limpus, C. J. 2006b in prep) and flatback turtles (Limpus, C. J. 2006c in prep). The review also confirmed a total lack of information on hawksbill and flatback foraging grounds and limited information on green turtle foraging grounds. Internesting locations were not addressed in the review.

This section summarizes the current knowledge of the genetic relationships and size estimates within the Western Australian sea turtle populations, and the location of internesting, mating, foraging and migratory habitats that are utilized by green, hawksbill and flatback turtles found in Western Australia.

Regional nesting populations and habitat use

The green turtle population in Western Australia is from a single genetic stock that nests from the North West Cape to the Lacepede Islands (Fitzsimmons, Moritz, Limpus, Pope and Prince 1997). The large size of this population (estimated to be in the range of 1,000's – 10,000's, population makeup is not reported) is significant on a world scale and thought to be the largest in the largest in the Indian Ocean (Prince 1994; Fitzsimmons *et al.* 1997; Limpus, C.J. 2002; Limpus, C. J. 2004a in prep, 2006a in prep).

The largest hawksbill population in the Indian Ocean is represented by a single genetic stock that is centred on Rosemary Island in the Dampier Archipelago and extends south to North West Cape (Figure 2.4). The size of the annual nesting population is estimated at 10's – 100's (Prince 1994). The northern extent of the population has not been confirmed but may extend into the Kimberley (Broderick *et al.* 1994; Prince 1994; Limpus, C.J. 2002; Limpus, C. J. 2004b in prep, 2006b in prep).

Flatback turtles are endemic to subtropical and tropical Australian waters. Approximately 30% of the total Australian breeding population occurs in Western Australia, split into two genetically distinct stocks. The northern stock nests during winter in Western Arnhem Land in the Northern Territory, while the southern, summer breeding stock, nests from North West Cape to the Lacepede Islands and is estimated at 100's to 1000's of individuals nesting annually (Prince 1994; Fitzsimmons *et al.* 1996; Limpus, C.J. 2002; Limpus, C. J. 2004c in prep).

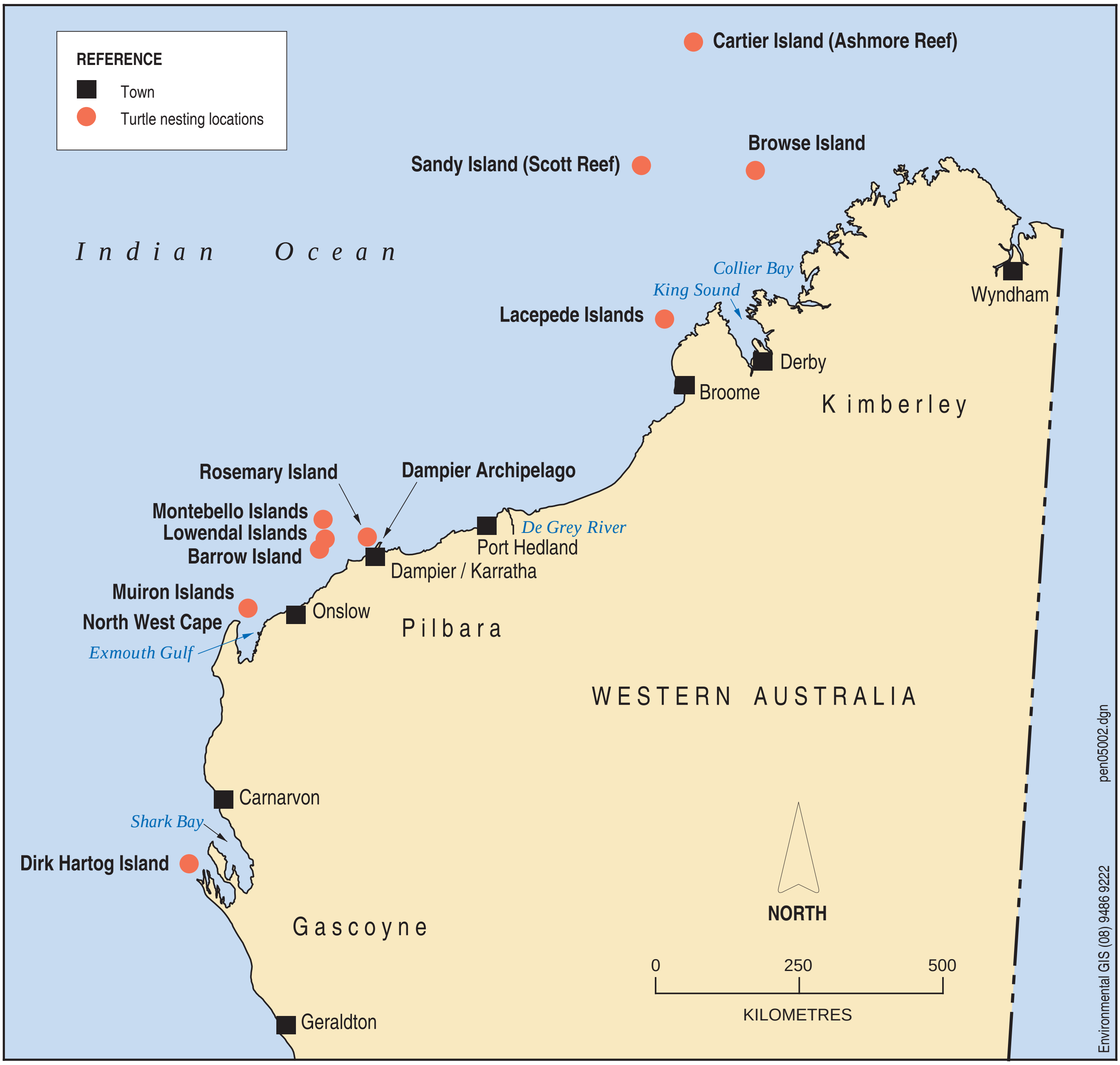


Figure 2.4: Regional nesting locations documented for Western Australian sea turtles

Mating aggregations and Internesting grounds

The location of green, flatback and hawksbill turtle mating aggregations and migratory pathways within Western Australia have not been confirmed in the literature.

There are no published data on green turtle internesting grounds in Western Australia. However, studies elsewhere suggest internesting grounds are located close to nesting beaches, in 10-18m of water (Stoneburner 1982; Mortimer and Portier 1989; Meylan 1995a; Tucker *et al.* 1995). Flatback internesting grounds are also unknown for Western Australia. They are thought to favour nearby soft bottom habitat. Similarly there is no published information available on Hawksbill interesting habitat in WA. However, studies overseas suggest hawksbill internesting is similar to other species in that the females remain within several kilometres of their nesting beaches during this period (Starbird and Hillis 1992).

Foraging grounds

Limited information on green turtle foraging grounds in WA is available from flipper tag returns. Of the 11,471 flipper tagged turtles at Western Australian rookeries, 73 returns have come from locations that include West Australian, Northern Territory and Indonesian locations (Prince 1997). The limited flatback dispersal data (3 tag returns from 741 tagged turtles) suggest the animals disperse to feeding grounds between Exmouth Gulf and the Northern Territory (Prince 1997). None of the 1050 flipper tagged hawksbills have been reported from discovery at sea. Aggregations of unidentified sea turtles were mapped during an aerial marine fauna survey of the region of the North West Shelf situated between the De Grey River and Exmouth Gulf, carried out in April 2000 (Prince *et al.* 2001). The aggregations, presumed to be on foraging grounds, given the mid winter timing of the survey, were concentrated in warm shallow waters of the offshore islands. The results must be interpreted with caution since they have not been ground-truthed to confirm the habitat usage and the high natural turbidity of the shallow coastal waters would have precluded accurate enumeration of turtles in these areas.

2.3.2 Case Study area – Barrow, Lowendal, Montebello (B-L-M) island complex

Historical sea turtle records

This section summarises the historical records that referred to sea turtle presence in the B-L-M island complex. These anecdotal records are important as there are no published empirical data on sea turtle populations in the region. The records provide an indication of sea turtle activity, and the pressures the populations were under, prior to 1980. The value of historical records in assessing the current and future vulnerability of ecosystems is recognised by modern conservation biologists (Caughley and Gunn 1996; Jackson *et al.* 2001). Since ecological research on sea turtles in the Case Study area is limited in spatial and temporal scope, the historical documents from the area provide some perspective on the size of sea turtle feeding and breeding aggregations in the region. From 1980 onward, the activity of oil and gas operators in the regions provided greater opportunity for scientists to access the islands. The available historical documents on visits to the B-L-M island complex have been reviewed for reports of sea turtle presence or absence and general population sizes. This information is summarised in the following section.

Barrow Island

In 1818, Lt Phillip Parker King, sailing aboard the *Beagle*, named Barrow Island for John Barrow, a second secretary to the British admiralty. The area was revisited by the *Beagle* in August and September, 1840, captained by John Clements Wickham, to make observations of the fauna of Barrow Island (Stokes 1846; Cox 1977). Sea turtles were plentiful at the time and 7 tons were taken for food. A journal entry by a transport vessel captain in December 1864 noted the numerous turtle tracks on the eastern coast of Barrow Island and that “the bays were swarming with them” during a night-time turtle hunt (Jarman in Cox 1977).

Between 1871 and 1880, applications to hunt turtle for meat, oil and shell at Barrow Island were made to the Surveyor General for export to overseas and interstate markets (Cox 1977). The applications noted that Barrow Island was “a major breeding ground for the edible green turtle from which oil, meat and fertilizer can be extracted, and the hawksbill turtle which produces shell plates called tortoise-shell”. Government fisheries annual reports from the time note an abundance of green and hawksbill turtle on the North West coast of Barrow Island (Saville-Kent 1893; Gale 1901).

John T. Tunney carried out the first dedicated biological survey of Barrow Island. He spent 3 months between October and December 1900 collecting specimens on Barrow Island. The single letter remaining as a record of his time on Barrow Island does not include any reference to sea turtle presence or activity (Saville-Kent 1893; Cox 1977).

In 1908, largely because of the efforts of J.T. Tunney and Guy C. Shortbridge (British Museum of Natural History), Barrow Island was classified a public reserve for Flora and Fauna. In 1919, following an application to the Government to hunt turtle on Barrow Island, the reserve status was upgraded to a “Class A” nature reserve and gazetted on 18 February 1919 under the “Permanent Reserves Act, 1899”. A second proclamation under the “Game Act” of 1912 provided added protection to the reserve by requiring Government permission to visit the island in addition to an Act of Parliament to cancel the reservation status. Unauthorised visits to hunt turtle continued, however, with police reports from 1926 noting that a pearler (E. Francis) hunted on the island for ‘tortoise shell’ while carrying out “a little pearling” (Cox 1977).

The next biological survey of Barrow did not take place until 1917 and 1918 when F. Lawson Whitlock spent several weeks there in October (1917) and July (1918) collecting birds. His papers, published in the journal *Emu*, noted that during October 1917 “turtle were plentiful and my Japanese boatman brought many eggs back to the cutter”. In July 1918 the only notes he made of marine life were in reference to whales and the abundant fish and crayfish in the area (Whitlock 1918, 1919).

The island was not visited again until personnel associated with the British atomic testing program landed in 1952 and sparse natural history observations were made during a 2 hour trip to the north end of Barrow Island by Lt Frank L. Hill and Surgeon-Commander Wedd (Hill 1955). No references to sea turtles were made during this visit.

In September 1958, an expedition by the CSIRO in conjunction with the WA Museum made a 1-week trip to the B-L-M region. During the three days they spent on Barrow Island, between September 18 – 21, they noted no sea turtle activity (Serventy and Marshall 1964). Since they did make a brief reference to green turtles when they visited the Montebello group after Barrow Island it is likely there were no sea turtle present at the time.

In 1962 the restriction on access to Barrow Island (associated with the atomic testing in the Montebello Islands during the 1950's) was lifted and West Australian Petroleum (WAPET) commenced oil exploration activities on the island. Between 1964 and 1970 the naturalist W. H. Butler made five trips to Barrow Island to collect specimens for the WA Museum. Two of these trips were during the summer sea turtle breeding season, in 1966/67 and again in 1969. He reported green turtles nesting on the island with "as many as 50 turtles would be seen on a beach at one time during this process". Hawksbill turtles were reported as "small, 2 ft long turtles were commonly seen in shallow pools at low tide, or swimming in the shallows" (Butler 1970). The morphological characteristics used to identify the small hawksbill turtles is not given, and it is possible they may have been juvenile green turtles. Butler made no record of flatback turtles and the first museum record for this species was in 1973 during a WA Museum collecting trip to Barrow Island (WA Museum registration number 61344). This same year all the sea turtle fishing licenses were finally cancelled for the North West Shelf region over concern with the decline in green turtle numbers.

The presence of West Australian Petroleum (WAPET) on Barrow Island significantly improved access for biological studies from the 1960's onwards. By 1990 CALM had recognised Barrow Island as an important green turtle and flatback rookery (Prince 1994b; Burbidge *et al.* 2000) however no systematic surveys had been carried out on the sea turtles of Barrow Island until the work reported in this thesis was commenced in 1998.

Montebello Island group

The Montebello Island group was first named by the French explorer Nicolas Baudin in July 1801 to commemorate the French victory over the Austrians in 1800 at the battle of

Montebello in Northern Italy (Osborne *et al.* 2000). A second survey by Baudin in March 1803 and a third eighteen years later by Lieutenant Philip Parker King (aboard the cutter *Mermaid*) failed to record the fauna of the islands (Serventy and Marshall 1964; Cox 1977).

The first natural history records for the Montebello Islands were made by Stokes in 1840 (Stokes 1846). No sea turtles were recorded during this survey. The next biological survey of the islands was carried out 66 years later when naturalists spent 4 months on the islands between 29 May and 29 August 1912 (Montague 1913, 1914; Hill 1955). The survey's purpose was to collect fauna of the Montebello group.

Montague provides the most detailed references to sea turtle activity of any surveys published over the past 150 years. While his visit was in winter (May – August 1912), and outside the currently recognised turtle breeding season, he notes that green turtle was very abundant in the shallow seas around the islands and that the west coast of Trimouille was "great breeding localities for turtles" suggesting that nesting was occurring over the winter season. The successful nesting effort was confirmed by Montague's description of hatchling tracks from an emerged nest.

Montague also noted a decline in hawksbill populations in the area. He reported that Mr Louis Williams hunted "Hawksbill turtles, which formerly came up in large numbers to breed, though are now nearly extinct in that neighbourhood". He further notes the exploitation of the sea turtle natural resources. "When Hawksbill were abundant on the islands in the north of the group, Malays were stationed on the various islands to watch the sandy shores during the breeding season, and an attempt was also made by a storekeeper in Onslow to ship green turtle, alive or canned, and a small canning factory was established. This, however, came to nothing, and the project proved a financial failure."

The next visit was by K. Sheard in August 1950 while on crayfish survey with CSIRO (Sheard 1950). His brief report includes the following reference to turtles. "Green and Hawksbill turtles very numerous in the shallows chiefly on the eastern, sandy beaches of Trimouille Island. Mating was in progress. The males were half to two-thirds the size of the females." This report does not state how the species were identified.

Professional biologists did not survey the islands prior to or following the British testing. Instead lay personnel were asked to make incidental observations along with their main duties. Observations made between August and October, 1952, were compiled by Hill (1955). His detailed report included lists of flora and fauna species for the islands. However, there is no reference to sea turtle activity(Hill 1955).

Three nuclear devices were detonated in October 1952, May 1956 and June 1956. The first aboard the HMS *Plym,* anchored off Main Beach, Trimouille Island, resulted in radioactive contamination of the northern 2/3 of Trimouille Island. The second and third were detonated on 30m tall towers on the north western tip of Trimouille Island and near Burgundy Bay on Alpha Island (Acaster 1995). While no official account of biological impacts arising from the nuclear explosions exist, personnel involved with the testing program report "within one week of the detonation (in October 1952) there were 1000's of turtles piled up dead on the North Western beaches of Trimouille Island." (pers comm. Bill Plewright, 4 Oct 2003). A year later (October 1953) Max Kimber, a seaman on board the

HMAS Karangi, reported ‘tens of thousands’ of dead and rotting turtles on the same beaches (Kendrick 2003).

In September 1958 a CSIRO/WA Museum survey of the region included 3 days on the Montebello group. The only reference to sea turtles was of two green turtles observed copulating in Benedictine Bay, Trimouille Bay and 2 others sleeping on beaches at Hermite Island (Serventy and Marshall 1964). Restrictions associated with the 1950’s atomic testing program limited further scientific surveys of the area for ~40 years. The Montebello Islands were officially a prohibited area under Commonwealth control until 1992, when they were returned to State control and declared a (terrestrial) Conservation Reserve (Burbidge *et al.* 2000).

Burbidge *et al* (2000), in summarizing biological surveys of the Montebello group noted that sporadic surveys had been carried out by Butler (1967), Burbidge (1971) and CALM staff since the 1990s. However, little of this information is readily available (Burbidge *et al.* 2000). Burbidge *et al* reported that turtles were common in waters around the Montebello group and that significant turtle nesting beaches occur “on the Montebello group and nearby island groups”. They concluded that “…while turtle nesting occurs on islands of the Montebello group, detailed information regarding species and locations is not available”.

Lowendal group

The Lowendal group was named by Nicolas Baudin in March 1803 and probably commemorate Marshall Ulrich-Frederick Walderman de Lowendal, a prominent member of the French Academy of Science, who died in 1755 (Butler and Butler 1985). The Lowendal group was sporadically visited by turtle hunters, guano seekers and fishermen up to the mid 1900s. However, there are no natural history accounts from the island group (Butler and Butler 1985). The islands were visited during the operations for the British nuclear testing in the Montebello group though no account of it was included in Hill's 1955 report. The CSIRO/WA Museum expedition in 1958, which included 2 days on Varanus Island in the Lowendal group, made no reference to sea turtle presence (Serventy and Marshall 1964; Butler and Butler 1985).

Following the declaration of the islands as a Nature Reserve in the early 1980's, the islands were visited by officers of the Department of Fisheries and Wildlife who documented the existence of bird and sea turtle rookeries (Butler and Butler 1985). They reported on the presence of Hawksbill turtle tracks and "green turtle nests" on the five largest islands. The report does not detail how these identifications were made, nor is there any indication of turtle numbers.

Current status reports

Status reports on sea turtles in WA acknowledge the lack of detailed information on nesting habitats and specifically identify the B-L-M region as requiring further study to quantify potentially major green turtle and flatback rookeries (Prince 1994; Limpus, Colin J. 1995).

Prince (1994) suggested green, flatback and hawksbill turtles would be found in the B-L-M region at similar relative abundances as seen elsewhere in Western Australia, *i.e.* green turtle populations > flatback populations > hawksbill populations. Since these estimates were based upon mostly anecdotesl and unpublished snapshot surveys by oil industry and

CALM personnel (G Oliver, T Robinson, K Morris, R Prince) Prince acknowledged the need for systematic surveys to confirm nesting species and estimate their numbers.

The rookeries in the B-L-M complex identified by these surveys included green turtles on the west coast of Barrow and on Trimouille and North West Islands within the Montebello group. The largest Flatback rookery in the B-L-M region was identified on the east coast of Barrow Island with 25-30 turtles per night nesting.

Prince (1994) identified an "important" hawksbill rookery on Varanus Island. Unpublished data suggest hawksbills also nest in the Montebello Islands and on Lowendal Islands other than Varanus (G Oliver, R Prince and T Robinson in Prince 1994). Regular low frequency nesting of flatback turtles (Prince 1994b; Burbidge *et al.* 2000), green turtles (Burbidge *et al.* 2000) and significant numbers of hawksbills (Prince 1994b) have also been reported for the Lowendal island group.

Of the 50+ islands that occur in the southern Pilbara region of the North West Shelf, Barrow Island (John Wayne Beach, green turtle rookery) and Varanus Island (Hawksbill rookery) are the only locations currently supporting regular sea turtle tagging programs. None of the other islands in the B-L-M complex have been routinely surveyed for sea turtle nesting activity.

Specific detail on foraging grounds for turtles nesting in the Barrow-Lowendal-Montebello region is limited to two Barrow Island green turtle tag returns from the west Kimberley (Prince 1997). Barrow Island is also a foraging ground for green turtles that nest elsewhere. Male and female adult green turtles are regularly seen feeding on turfing algae on the near shore rocky platforms along the west coast of Barrow Island (pers. obs.)

2.4 Industrial activity (1998 – 2003)

Human activity in the B-L-M region consists of pearl culturing, oil and gas exploration and production and tourism.

Pearl culture

Morgan Pearls Pty. Ltd. has been based in the Montebello Island group since 1981. Their pearling leases cover a large area of the shallow protected waters of Hermite Island, south of North West Island and west of Trimouille Island (CALM 2004). Their facilities are all marine based and are located within Faraday Channel (Hermite Island). The infrastructure includes an accommodation houseboat, pearl shell processing, holding pontoons and grow out areas (Figure 2.5).

Cossack Pearls Pty. Ltd. carried out a two year pilot programme between 2000 and 2002 to grow pearls in the Lowendal group. This pearl lines were installed north of Parakeelya Island. However the associated accommodation and support vessels were moored in the sheltered waters of the eastern bay of Bridled Island and in the channel between Beacon Island and Varanus Island (Figure 2.5).

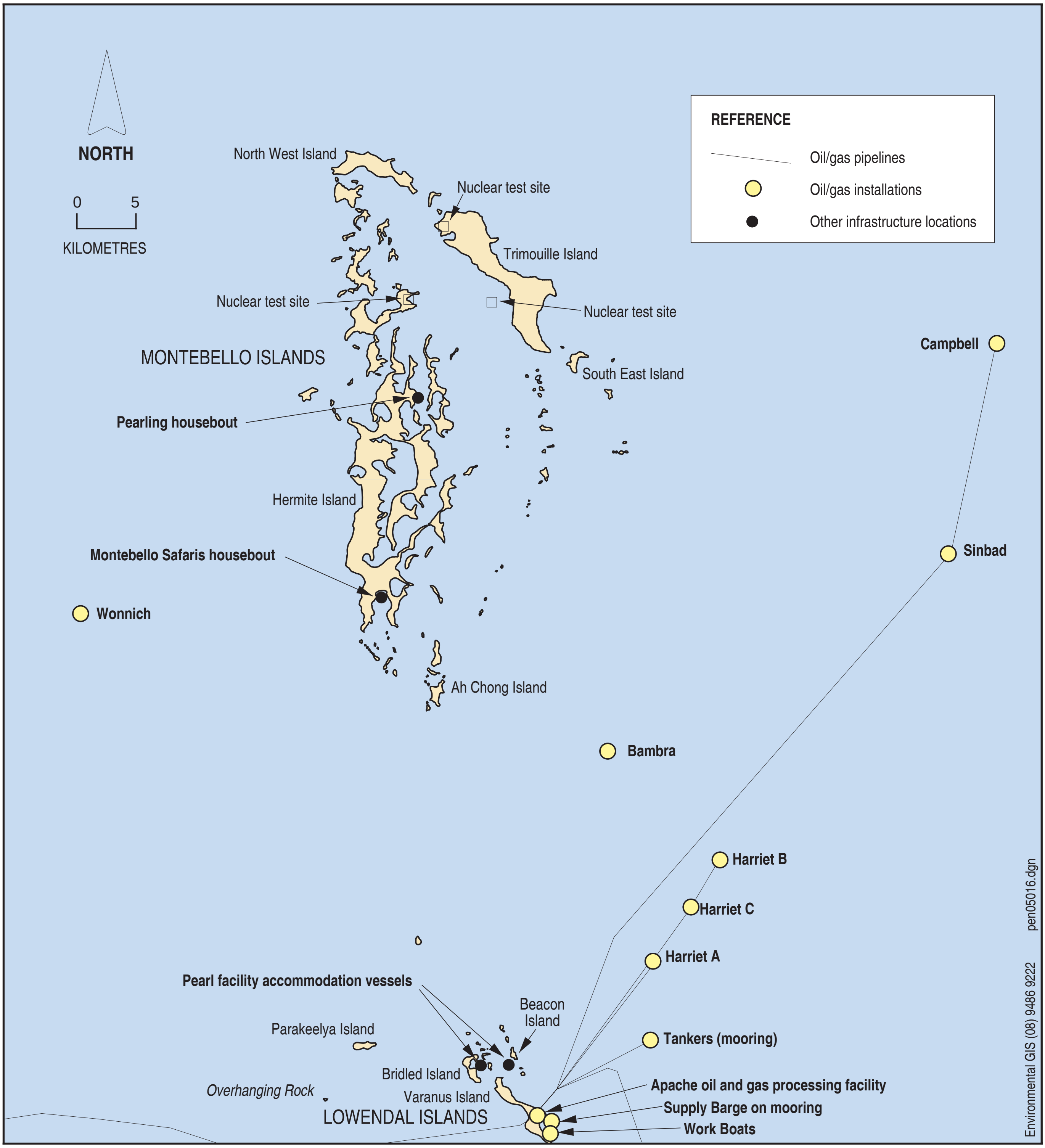


Figure 2.5: Montebello and Lowendal Island complex, industrial infrastructure locations

Tourism

Tourism in the area is limited by the presence of oil and gas operations on Barrow and Varanus Island, and until recently, by the residual radiation risk in the Montebello group. Much of the tourism is currently based around the Montebello Island group. A houseboat operated by the Montebello Safaris Pty. Ltd. is moored in Claret Bay at the southern end of Hermite Island between approximately March and August each year. Tourists are ferried from Onslow by boat. Charter fishing vessels and diving groups, private cruising vessels are increasingly using the area as a destination (APPEA 1997).

Oil and gas

Western Australia is recognized both nationally and internationally as a significant hydrocarbon bearing area. The 55 producing oilfields within the State are worth one third of the states $A30 billion mineral and energy revenue (DoIR 2004a). The region of the North West Shelf that was the focus of this study encompasses the B-L-M island complex which currently supports two major oil and gas developments based on and around Barrow Island and Varanus Island (in the Lowendal Island group, Figure 2.6). These developments contributed 10% of oil , 6% of condensate and 7% of gas to the total Western Australian production totals in 2004 (DoIR 2004b). A producing oil field has been based on Barrow Island since 1964. Barrow Island is also the site of the proposed A$40 billion Gorgon Gas processing facility which has a predicted production life of 20 years (ChevronTexaco 2003)

Oil and gas activities can be divided into exploration, construction, and production phases, which are typically operated 24 hours a day. Exploration comprises drilling for oil using an onshore or offshore oil rig. The rig may remain on a drilling location for weeks or months

Figure 2.6: Barrow Island, industrial infrastructure locations

at a time. The drilling operation offshore is supported by work boats that are required to remain with the rig 24 hours a day (APPEA 1997; Apache 2001).

Following the discovery of oil or gas, a field is developed by installing flow lines linked back to a central processing plant. Marine pipelines are installed using pipe lay barges supported by numerous smaller vessels. Pipe lay barges are typically large and extremely well lit vessels and may remain on site for weeks to months at a time. The number of vessel movements increases substantially during the construction phase of an operation.

Oil and gas production facilities separate out the oil, water and gas. The water is disposed either into the ocean or into disposal wells. The oil is collected and stored in large terminal storage tanks on site until collected by oil tankers. The gas is either burnt or piped to the mainland. All facilities have on site gas flares for use during process upsets. Production operations require supply barge and work boat support to service the processing facilities on a regular basis. The oil is collected by oil tankers on a weekly or monthly schedule (Osborne *et al.* 2000).

Oil and gas activity in the region commenced in 1947 when a permit to explore for oil was granted to the Australian Motorist Petroleum Company for Barrow Island and environs. It was not until 1964 that the first commercial oil discovery in WA was made on Barrow Island (Wilkinson 1988). Since that time over 800 wells have been drilled on Barrow Island and over 400 million barrels (63.5 billion liters) of oil have been produced from the island. The Barrow Island oil field is confined to onshore wells and include three short causeway leases at the southern end of the island (WAPET 1988).

Infrastructure on Barrow Island include a barge landing area, crude storage tanks and load out line, accommodation facilities for several hundred people, hundreds of kilometers of roads, an all weather airstrip and terminal facilities, office and workshop facilities, and 7 separator stations (Figure 2.6). Barges transport materials and equipment to the island and operate on a year round schedule constrained only by tides (APPEA 1997)

Preliminary approval to develop onshore processing facilities on Barrow Island for the offshore Gorgon gas field was granted in 2003 when 300 ha of the Barrow Island Nature Reserve were excised by an Act of Parliament (ChevronTexaco 2003). The ERMP for this development is in preparation and will be released for public review in mid 2005.

The Harriet oilfield was discovered 10 km east of Varanus Island in 1983 (Figure 2.5). In 1986 it was the first offshore oil field in WA to be brought into production. Since 1983, Bond Petroleum, Hadson Energy and now Apache Energy have discovered and developed numerous new oilfields centered around the Varanus Island based processing facilities. This development is ongoing (APPEA 1997; Osborne *et al.* 2000).

Chapter 3 Sea turtle beach usage and beach light exposure

3.1 Introduction

3.1.1 Background

The review of the historical, anecdotal and published sea turtle literature in Chapter 2 identifies the limitations of our knowledge of sea turtle nesting seasonality, distribution and abundance in Western Australia, particularly in the Barrow, Lowendal, Montebello (B-L-M) region. In order to quantify the impact of anthropogenic light on sea turtles in this region it was first necessary to document the spatial and temporal distribution of nesting activity (as represented by tracks left on the nesting beaches (Miller 1996) for the three species that use the beaches of the B-L-M Island complex. The size of the B-L-M complex and its remoteness made it difficult to systematically visit the area to conduct biological surveys. It was therefore necessary to develop methods for surveying the beaches for sea turtle nesting actively that were both simple and reliable to use. Consequently the early focus of this component of the project section was to develop methods to identify turtle species from both adult and hatchling tracks so that demographic surveys could be conducted in the absence of actual animals. This data was then used to investigate the beaches favoured by the different species and their exposure to light on those beaches.

3.1.2 Research questions

The research questions addressed in this chapter were:

1. What species of sea turtle nest within the Barrow, Lowendal, Montebello island complex?

2. How much nesting habitat is available and what are the physical characteristics of the beaches these turtle use for nesting?
3. What beach types do the different species favour?
4. What is the nesting season length and peak?
5. How are the different species distributed *between* the three island groups (*I.e.* Barrow, Lowendal and Montebello islands)
6. How are the different species distributed *within* the three island groups?
7. How many turtles use the nesting beaches close to industrial artificial light sources?
8. What proportion of the nesting population in the B-L-M complex is potentially exposed to artificial industrial lighting?

3.1.3 Chapter outline

The literature on species identification from track characteristics, and their use in nesting population surveys, is reviewed along with the characteristics of nesting beaches identified for the three species of sea turtles currently using the B-L-M complex nesting beaches. The methods used to select and characterise the survey beaches within the study area are outlined. Basic information on track size and characteristics of the local sea turtle nesting populations was gathered so that track counts could be done in the absence of adult animals. The two types of track counts that were used to conduct nesting beach track counts are outlined. Counts of the regional distribution of nesting turtle tracks within the B-L-M complex were documented and used as an indicator of nesting effort.

The results are presented in Section 3.4. The survey beach physical characteristics (beach types and foreshore) and beach light exposure are outlined. Track characteristics and the measurements used to identify individual species are analysed as a species identification tool. The length and peak of the nesting season for the three species found in the study area and the beach characteristics favoured by the three species is established. The density of tracks both between and within the three island groups (Barrow, Lowendal and Montebello islands) is compared. Track count data was used to estimates the size of the nesting population for each species and to put the nesting populations in the area into a national perspective. Selected beach track count data is used to provide a detailed indication of nesting effort on representative high density nesting beaches on individual beaches of Barrow Island and islands of the Lowendal group. These results are finally used to estimate the proportion of nesting beaches that are potentially exposed to light pollution within the study area.

3.2 Literature Review

3.2.1 Species track identification

Sea turtle species can be identified from the characteristic patterns made by the tracks they leave on the beach during nesting and is recommended for all baseline studies of nesting beaches (Pritchard and Mortimer 1999). The primary diagnostic features of tracks used to identify species include track width and symmetry of the front flipper imprint. The depth of the nest body pit is also an indicator of species, *i.e.* deep vs. shallow (Ehrhart 1995; Miller 1996; Pritchard and Mortimer 1999).

Tracks may be described as symmetrical or asymmetrical. Green turtles weigh up to ~230 kg and produce symmetrical tracks as they simultaneously move both front and back flippers forward at the same time to move their bodies across the sand (Bustard 1972). This symmetrical locomotion may change to alternate when green turtles are moving up slope or when they are startled (Bustard 1972). Their tracks are typically 100 -130 cm wide, deeply cut with a straight central tail drag mark characterised by a solid or broken line (Pritchard and Mortimer 1999).

A Hawksbills gait is alternating, producing an asymmetrical track as diagonally opposite front and back flippers are moved simultaneously (Bustard 1972). Hawksbills average ~60 kg and produce a relatively deep impression in the sand from the movement of the front flippers. Only 2 flippers are moved at a time and the front flipper marks are offset. Hawksbill tracks are ~70-85 cm wide (Miller 1996; Pritchard and Mortimer 1999).

Flatback turtle tracks are generally symmetrical. However, like green turtles, they may change to alternating on a slope or when the animal is startled (Bustard 1972; Pritchard and Mortimer 1999). Flatback turtles weigh up to 90 kg and produce tracks that are ~90 cm wide and relatively light cut (Miller 1996; Pritchard and Mortimer 1999).

Body pits are also used as an indicator of species. Green turtles leave a conspicuously large and deep body pit while the flatback body pit is relatively large but shallow. Hawksbills leave a very shallow body pit (Bustard 1972; Ehrhart 1995).

The specific characteristics of tracks left by green, flatback and hawksbill turtles nesting in Western Australia have not been described in the literature and were included as a preliminary aspect of this study.

3.2.2 Nesting habitat requirements

An understanding of the physical characteristics of the beaches favoured by the different turtle species is useful when survey areas are too large or inaccessible for regular beach inspections. Beaches that clearly do not provide suitable nesting habitat can therefore be rapidly eliminated from ongoing monitoring programs and the available resources focussed on beaches that provide good nesting habitat.

The process by which turtles select nesting beaches and nesting sites on a beach have not been clarified (Miller 1996). However, the general requirements for nesting beaches identified by Mortimer (1979) include the following characteristics;

- the beach must have accessibility from the sea
- the beach must be high enough to prevent inundation of the eggs by tides of the underlying water table
- the substrate must facilitate gas diffusion, and
- the substrate must be moist and fine enough to prevent collapse of the egg chamber during construction

Nest depth is a function of sand moisture (depth required to find sand moist enough to prevent egg chamber collapse) and animal size (Mortimer 1979; Miller 1996). All species excavate a body pit that is deep enough to bring their body level with the surface of the beach. An egg chamber is excavated from the body pit to a depth equal to the length of the rear flipper (Bustard 1972). Green turtles have long hind flippers and dig an egg chamber 69.2± 12 cm deep (50-92 cm range, (Limpus, C. J. *et al.* 1984a). Hawksbills have relatively short hind flippers and consequently dig a shallow nest chamber (43.2± 4.7

cm, 35 – 59.5 cm range, (Miller 1996). Flatback turtle nest depth falls between these two species at 54± 5.8 cm, (Guinea 1994)

The three species studied have been shown to exhibit general differences in the preferred beach type (Mortimer 1979; Diez and Ottenwalder 1999; Pritchard and Mortimer 1999). Deep water and open offshore approach with foreshores free of rock clutter are favoured by green turtles at Ascension Island (Mortimer 1979). Beaches may range from long and open to small coves and are often on steeply profiled high energy beaches (Pritchard and Mortimer 1999).

Flatback turtles, unlike green and hawksbill turtles, have little keratin in their carapace covering and consequently are susceptible to mechanical injury (Parmenter 1994). They avoid reef habitat and are commonly found in turbid water over soft bottom areas. They favour large open beaches and avoid reef areas near nesting beaches (Pritchard and Mortimer 1999). The body pit is shallow and poorly developed (Bustard 1972). Nests are typically shallower than green turtles but deeper than hawksbills.

Hawksbills are typically associated with hard substrate communities where they forage for sponges. They often traverse shallow reef habitat to reach narrow, heavily vegetated low profile beaches (Pritchard and Mortimer 1999). Their nests sites are often separated spatially or temporally from that used by other sea turtle species and may include beaches that are marginal for other species (Mortimer 1979; Miller 1994). The small size of hawksbill turtles reduce the depth of sand they require for successful nesting (Mortimer 1979; Miller 1996).

3.2.3 Nesting population census techniques

In the absence of any information on the location, size and species makeup of sea turtle rookeries, nesting effort can be confirmed from the documentation to species, of tracks, nesting pits or egg shells on the beach (Diez and Ottenwalder 1999). One of the most widely employed methods is to count the tracks left by females on nesting beaches (Mortimer 1979; Meylan 1995b; Godley, B. J. *et al.* 2001). While nesting beach surveys are the most commonly used tool in population status monitoring programs there is very little information available in the literature on detailed methodologies and data analysis that can be used for these types of surveys (Schroeder, Barbara and Murphy 1999).

The two methods that are typically employed to enumerate nesting activity are to count;

1. the "fresh" overnight tracks only, or
2. all tracks without differentiating between "old" or "fresh" or nesting or non-nesting crawls.

The methodology used to count both track types depends on a number of factors including: availability of trained observers; species to be monitored; nesting density; beach type, wind, rainfall and human activity on the beach. Fresh tracks can be counted in two ways, either those crossing a line installed on the beach the previous day (x-line count) or only those tracks that extend below the high tide line (BHT). Both are acceptable methods for estimating nesting effort, however, Schroeder and Murphy (1999) acknowledge that the BHT count may be slightly less reliable than the x-line count since the count depends greatly on the tidal conditions. The BHT count may underestimate the number of overnight tracks if animals left the beach before the overnight high tide. The overnight counts can then be converted to a daily average to account for day to day and variability in nesting effort.

3.3 Methods

3.3.1 Track identification

During the first summer season tracks were studied for overall species specific crawl patterns and for characteristics suitable to measure. Track measurements were made of individual flipper widths, overall track width, central belly channel width and individual flipper imprint offset from each other. This was done randomly at three different locations on each track, up and down. A number of limitations associated with this method arose during the first summer; it was difficult to carry out such detailed track measurements during the limited time available to complete the track census surveys; it added considerably to the amount of gear that had to be carried on long beach hikes; and it was difficult to do this unless the track was long and straight and laid on flat clean sand.

Consequently a fast and simple method using a metre stick was developed and tested. The species making the track was identified and the presence or absence of the adult noted. Where possible the track was measured on the flat dry sand. The total track width was measured at its widest point (="width"), the belly drag/channel width was measured at its widest point (="belly") and then the rear flipper impressions made in a 1m length of track were counted (= "stroke/m").

Measurements were also taken from hatchling tracks to determine if species identification could be done using the track size. The total track width was measured from the outside edge of adjacent rear flipper imprints. Where possible, hatchling track measurements were done on dry sand and on the flat part of the beach.

3.3.2 Physical characteristics and light environment of beaches

Preliminary assessment of nesting habitats were carried out for all beaches following standardized methods (Diez and Ottenwalder 1999). Physical features such as beach accessibility, dimensions, wave energy conditions and foreshore topography were recorded.

Each beach was assessed for quality of nesting habitat. The amount of available habitat is represented by beach width and sand depth. Beach lengths and widths were measured from aerial photography of the islands using the Western Australian Department of Land Information group mosaics of the Barrow Island and Montebello Islands (flown Oct 2001, scale 1:40.000, accuracy ±5 m, datum GDA94 and MGA50 projection). The photos used to construct the mosaic were made during low spring tides and so the distance from the highest strand line (representing the high spring tide line) to the base of the dune line (line where the vegetation density increases significantly) is used to measure beach width.

The accessibility of each beach to nesting sea turtles was evaluated based on foreshore and beach characteristics (Figure 3.1). The foreshore zone, defined here as the zone between the low tide line and the berm crest (Kennett 1982) for each beach was coded as follows:

1 = >50% of foreshore is wide (>100m) flat rocky or soft sediment

2 = > 50% of foreshore open sand or narrow (0m to 100m) flat rocky intertidal platform

3 = > 50% of foreshore coral reef

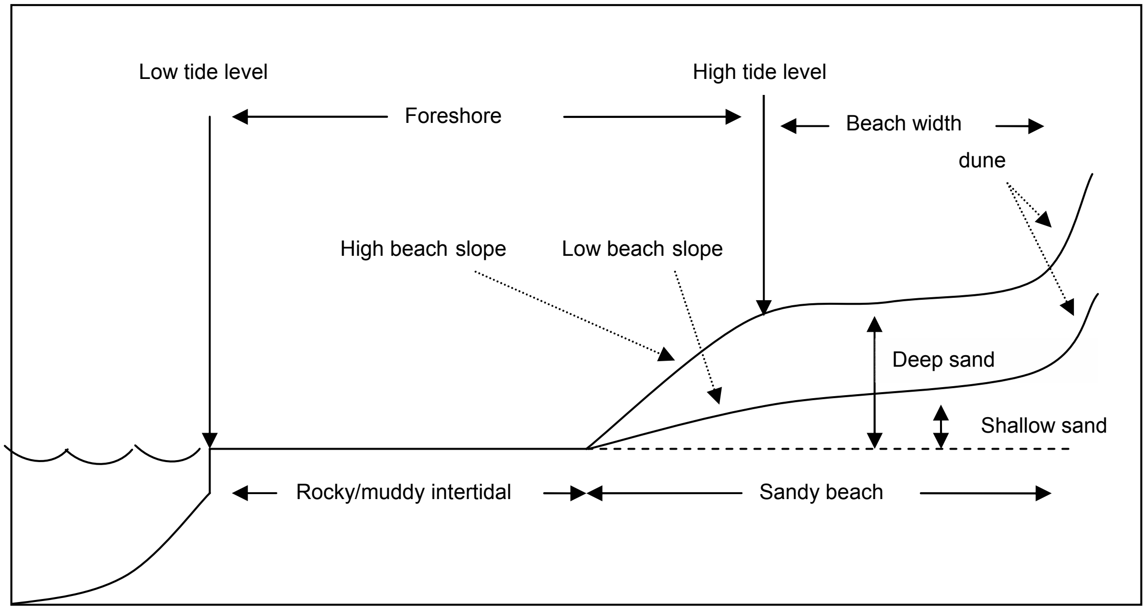


Figure 3.1: Foreshore and beach characteristics for high and low energy beaches.

Beach slope is a function of wave energy (Kennett 1982) and is related to sand depth. Sand depth was evaluated as deep (1) or shallow (2) based on presence of emergent beach rock, vegetation type (e.g. *Triodia angusta* requires red loam to grow (WAPET 1988), therefore its presence on or adjacent to the beach indicates shallow sand depth), and from digging nests. Offshore intertidal and subtidal habitat was documented from direct observation (low tide observations, snorkelling and aerial photography).

The exposure of each beach to light was determined by identifying the beaches that fell within a 1.5 km radius of known light sources. This distance was selected as this is the distance recommended by Limpus (2002) as the buffer zone necessary for the protection of sea turtle nesting beaches from light pollution on loggerhead nesting beaches on the east coast of Australia.

3.3.3 Track count survey beach selection, access and timing

The size and remoteness of the study area precluded detailed on ground track count surveys. Consequently a survey program was designed to provide a mix of aerial and ground truthing surveys. Regular on ground surveys were primarily employed on Barrow and the Lowendal Islands (OG), while aerial surveys (A) were the primary method used for the more remote island group of the Montebello group in conjunction with limited ground truthing transects (T).

Logistical support for access to the islands was provided by Apache Energy (dingy and helicopter) for islands of the Montebello and Lowendal Island groups, and by WAPET / ChevronTexaco (vehicle) for Barrow Island. The survey schedule was constrained by company operational and project activities, company safety requirements, cyclone evacuations and sea state (dinghy use), as well as the availability of Perth to Barrow charter flight seats, accommodation, vehicles, field assistants and helicopter time. The requirement to census all beaches within a 2 week period in order to get a regional perspective within a similar time frame further limited the time available in which to conduct an entire regional survey.

The survey schedule is listed in Table 3.1. Preliminary surveys were carried out over the 1998/1999 nesting season at all locations. Surveys were timed to coincide with the predicted peak of nesting for the three species (Hawksbill, Flatback and Green turtle), *i.e.* one in early summer (November or December) and the second in mid summer (January). Where possible selected beaches on Barrow, Lowendal and Montebello islands were surveyed over three consecutive days (a) while all beaches were inspected at least once a season (b) to document evidence of current and past nesting as determined by tracks (current season) and nest craters (current and past seasons). With limited resources this was the best that could be achieved. Opportunistic surveys of various beaches were also conducted outside of the regular monitoring schedule where other project work allowed.

Table 3.1: Beach usage field survey dates

Date	Lowendal Islands	Montebello Islands	Barrow Island
20 Nov – 3 Dec 1998	OG	T	
16 -22 Dec 1998	OG		OG
1 – 8 Jan 1999	OG	T	
15 -22 Jan 1999			OG
15 – 26 Nov 1999	OG	A, T	
10 – 14 Dec 1999	OG		
10 – 26 Jan 2000	OG	A, T	OG
29 Sep – 10 Oct 2000	OG	A,T	OG
2 – 14 Nov 2000	OG	A,T	
12 – 22 Dec 2000	OG		OG
5 – 15 Jan 2001			OG
15 – 23 Jan 2001	OG	A,T	
5,7,18,21 Oct 2001		A	
16 – 29 Nov 2001	OG	A,T	OG
14 – 21 Dec 2001	OG	T	
4 – 22 Jan 2002	OG	A,T	OG
13 – 30 Nov 2002	OG	A,T	OG
13 – 20 Dec 2002	OG		
3 – 10 Jan 2003			OG
10 – 23 Jan 2003	OG	A,T	
7 – 14 Nov 2003			OG
7-13 Dec 2003			OG
7-13 Jan 2004			OG
12-17 Nov 2004			OG
10-16 Dec 2004			OG
11-17 Jan 2005			OG
11-17 Feb 2005			OG

OG = regular on ground surveys, conducted over 3 days each survey month
A = aerial survey
T = One off inspection either by overnight camping or whole island hike, ground truth aerial survey findings.

Barrow Island beaches were surveyed on foot over 3 to 7 days in November/December and January each summer. During the first three seasons this included overnight monitoring of beaches (c) to confirm species by witnessing animals crawling onto the beach and to gain experience with species track identification. Lowendal Island beaches were generally surveyed on foot. The islands immediately adjacent to Varanus Island (i.e.

Abutilon Island, Bridled Island and Beacon Island) were accessed by a small dingy. The small size of Varanus Island allowed for all the beaches to be visited daily over a 3-5 day period while the adjacent islands were visited over 3 consecutive days unless strong winds prevented use of the dingy. Occasionally, when time permitted and weather prevented launching the dingy, the islands of the Lowendal group were also flown over by helicopter on the return from the Montebello group.

Access to the Montebello Islands was limited by their inaccessibility and lack of infrastructure. During the first three years on ground surveys were carried out on Beach #9 (Trimouille Island), Beach #3 (North West Island), Wilsons Beach (Hermite Island) and Beach #2 (Ah Chong Island) in order to confirm nesting species from overnight observations. Each survey season every beach on the main islands (Trimouille, North West, Ah Chong and Wilson’s Beach on Hermite) was surveyed with one day spent on each island. Aerial surveys of the Montebello group were carried out in a small, Bell 206 Longranger helicopter (Bristow’s Helicopters Ltd). Beaches were flown at an average height of 150m and at a speed of 20-30 knots. The helicopter flight height and speed was increased on very hot days (in January) to prevent the aircraft’s oil temperature increasing.

Preliminary surveys over the 1998/1999 summer indicated limited (< 1 track per beach per survey) sea turtle activity on the inside beaches of Hermite Island. Consequently, subsequent flight paths did not routinely include these beaches. Each routine survey was limited to an hour to minimise helicopter time and costs. A typical flight path is shown in Figure 3.2.

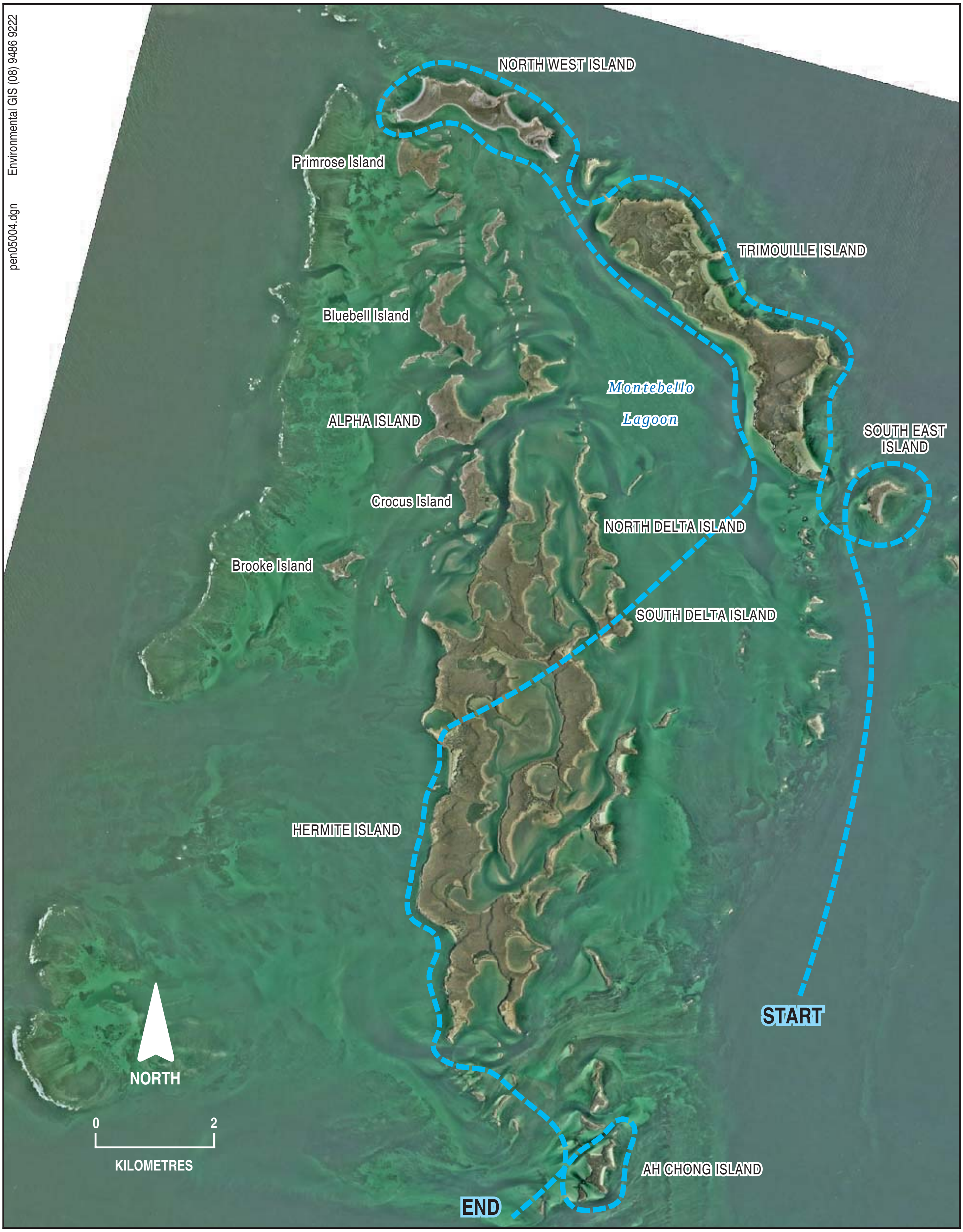


Figure 3.2: Helicopter flight path for the Montebello Island aerial track count surveys

Where possible all ground and aerial surveys were scheduled to coincide with morning low tides so that a count of tracks below the night time high tide (BLHT) could be made. Overnight (x-line) crawls were identified from tracks crossing the line previously installed in the sand above the level of the high tide. Fresh tracks crossing this line were quickly and easily identified, both on foot and from the air. Poorly placed lines, very strong winds or wind enhanced waves occasionally erased the line, reducing the utility of overnight track counts.

3.3.4 Track counts

The methods employed to carry out the Barrow, Lowendal. Montebello island complex nesting beach aerial and ground track surveys were based on the recommendations made by Schroeder and Murphy (1999).

Attempts were made to assign an age to tracks, however this was abandoned since environmental factors made it difficult to accurately date individual tracks. Factors that influenced the persistence of tracks and therefore confounded estimates of age included wind and rain weathering, beach sediment grain size, beach orientation with respect to the prevailing winds and animal size (heavier green turtles leave deeper track impressions than the lighter hawksbills).

Two different overnight track counts were made. These were fresh below high tide (BHT) counts and fresh overnight line cross (x-line) counts.

BHT counts

These counts are used for nesting beach physical characteristics (3.4.3), between island group comparisons (3.4.6).

Fresh tracks below last high tide (BHT) counts were made of down tracks traversing the beach after the previous night's high tide. These counts did not include animals nesting prior to the high tide (generally underestimates the number of animals visiting the beach over night). This count was used on beaches that could not be visited over three consecutive days and for aerial counts. As a minimum these counts were carried out on all beaches surveyed (including census beaches) within the B-L-M complex between 1998 and 2003.

All beaches surveyed aerially for BHT counts were also ground truthed at least once per season to confirm species identifications. Each beach visited on foot was surveyed for the presence of crawls and nesting pits. All aerial counts, and most on foot counts, were done by the same observer with the exception of ~2 weeks of counts conducted by tagging personnel for the Lowendal Island group.

x-line counts

These counts are used for monthly distribution of nesting crawl track counts (3.4.4), track to nest ratios (3.4.5), beach usage by each species (3.4.7), estimation of the number of nesting animals (3.5.3), estimation of number of nesting animals exposed to light (3.5.4).

During the first summer of preliminary regional track count surveys a number of beaches that were identified as having high-density nesting were selected as representative ‘census’ beaches for ongoing surveys investigating the impacts of light on sea turtle adults and hatchlings. The number of overnight turtle nesting attempts was enumerated using the x-line track census method over a minimum of three consecutive days. The results provide an indication of the number of animals using individual beaches. This data was then used to quantify the proportion of the nesting population potentially exposed to light.

Cross line (x line) counts were made of tracks crossing a line installed along the beach above the high tide line. These counts include all animals nesting during the previous night. This census count was used on beaches that could be visited over three consecutive days and was used on Barrow Island and the Lowendal Islands between 1998 and 2003 and then on Barrow Island only between 2003 and 2005. The x-line data were used for analysis of monthly nesting effort (Table 3.2 and 3.3), quantifying beach usage at the peak of the nesting season and for estimating the proportion of the nesting population exposed to light.

The application of each of these different count types is presented below.

3.3.4.1 Beach preferences

The BHT data were used for identification of nesting beach physical characteristics and between and within island group comparisons of attempted nesting crawls. Assessment of beach preferences was determined by coding each survey beach for foreshore type, beach slope and sand depth above the supratidal line. The combinations of these characteristics were then related to BHT track density to establish a beach type favoured by each species. The total number of beaches and beach survey days are shown in Table 3.2.

Table 3.2: Total number of beaches surveyed and the number of survey days for the B-L-M complex

Group	Total number of beaches surveyed	Total number of beach survey days
Lowendal	14	429
Barrow	62	424
Montebello	24	719

The distribution of species attempting nesting crawls on each of the island groups was also calculated using BHT data from the peak of the nesting season for each species. The total number of tracks counted on each island group was divided by the number of survey days for the same time period to give a mean number of crawl tracks per day. The details on the number of beaches surveyed, number of beach survey days as well as the month the data was collected and the species for which the data applies is given in Table 3.3.

Table 3.3: Between island group comparisons by species, survey effort.

Island group	Number of beaches surveyed	Total number of beach survey days	Month	Species
Barrow	28	94	January	green, flatback
		29	October	hawksbill
Lowendal	19	113	January	green, flatback
		143	November	hawksbill
Montebello	32	329	January	green, flatback
		139	October	hawksbill

3.3.4.2 Length and peak of nesting season

Cross line track counts from census beaches were used to determine the length of the nesting season for the three species using the B-L-M complex. The number of beaches and locations of beaches surveyed for each species are shown in Tables 3.4 and 3.5.

Table 3.4: Monthly x-line track distribution green and flatback turtles. Number of survey beaches, survey days and the range of the number of survey days per beach for each species.

Survey month	Barrow Island east coast flatback 2003 to 2005			Barrow Island west coast green turtle 2003 to 2005		
	total # census beaches	total # survey days	range (# of days/beach)	total # beaches	total # survey days	range (# of days/beach)
Oct	NR	NR	NR	NR	NR	NR
Nov	4	21	2-5	8	41	4-10
Dec	6	85	6-26	8	49	3-8
Jan	7	57	3-13	8	57	2-11
Feb	6	30	5	7	35	5

NR = Not Recorded

Table 3.5: Monthly x-line track distribution hawksbill turtles. Number of survey beaches, survey days and the range of the number of survey days per beach for each species.

Survey month	Lowendal Island and Montebello Island hawksbills 1998 to 2003		
	total # census beaches	total # survey days	range (# of days/beach)
Oct	17	224	6-44
Nov	25	417	2-69
Dec	18	445	11-53
Jan	27	495	6-62
Feb	NR	NR	NR

NR=Not Recorded

Tracks that did not extend above the high tide line (*i.e.* “aborted crawls”) were not included in the total count. It was not possible to confirm nests at the end of each track within the logistical constraints on field time. The total number of down tracks for a beach, therefore, represents the number of turtle visits on that beach and does not equate to the total number of animals actually nesting on the beach.

3.3.4.3 Track to nest ratio

Some preliminary studies were carried out on the ratio of tracks to nests so that estimates of the size of the flatback and green turtle nesting populations using Barrow Island could be derived. Between December 2 - 12, 2004 and January 12 – 17, 2005 data was collected on the number of overnight tracks that resulted in a successful nesting. During the daily track counts on east (6 beaches) and west (7 beaches) coast census beaches, every track was checked for a successful nest. Logistically it was not possible to dig every nest to search for eggs. Instead biologists with experience in sea turtle beach surveys scored a nest if it met some or all of the following criteria.

- Presence and shape of the backfill trench (typically 1-5m long and frequently curved),
- Shape of the body exit hole (shallow and flat bottomed)
- Change in the compaction of the sand in the backfill trench (less compact)
- Variation in the sand composition around the nest site (sediment from deeper, egg chamber, depths are frequently a different grain size and colour to the overlying sand),
- Length of the overnight up and down tracks associated with the nest (a large difference indicates the animal has been on the beach for a long time and if she has not left a series of abandoned egg chambers and has left a backfill trench there is a high likelihood she has nested)

Using the above criteria experienced sea turtle biologists are able to assess the presence of a nest with a high degree of confidence (Bjorndal *et al.* 1999; Godley, B. J. *et al.* 2001). To maintain consistency the nest success counts were all carried out by the author (KP) or an assistant (AV).

The combined total nest count data for December 2004 and January 2005 was divided by the number of tracks counted on the same beaches over the same survey period and a ratio derived for the number of tracks relative to the number of nests. The resulting ratio is used to estimate the size of the adult female nesting population of green and flatback turtles at Barrow Island.

3.3.4.4 Distribution of track crawls between and within island groups

In order to quantify the number of nesting females and hatchlings potentially exposed to the misorientation effects of industrial lighting it was necessary to establish where the three species of sea turtles nested within the B-L-M complex. The BHT track data collected at the peak of each species' nesting season were used to compare island usage by adult turtles on each of the Barrow Island, Lowendal Island and Montebello Island groups, and on individual islands within each group. This (BHT) data were used so that comparisons could be made with the Montebello results since the Montebello track counts were primarily BHT. For each of the 125 beaches surveyed over the 1998 – 2005 period the track data were analysed to establish which of the islands the three species favoured for nesting as a proportion of the total number of tracks counted.

The within island distribution for each species was calculated as a proportion of the total number of turtle tracks counted for each island. The total number of tracks used to calculate the within island group percentages for each species is shown in Table 3.6. The proportion of each species within the entire region was calculated as a percentage of the total number of flatback (1560), green turtle (1945) and hawksbill (418) tracks counted at the peak of the nesting season (shown in Table 3.6) within the entire B-L-M complex over the survey period

Table 3.6: Total number of tracks used to calculate the within group percentages. BHT 1998 - 2005 data taken from peak nesting period.

Island group and survey month	species	total tracks
Barrow		
January	flatback	941
January	green turtle	974
November	hawksbill	43
Total tracks		1958
Lowendal		
January	flatback	245
January	green turtle	4
November	hawksbill	156
Total tracks		405
Montebello		
January	flatback	374
January	green turtle	967
November	hawksbill	219
Total tracks		1560

3.3.4.5 Beach usage, Barrow Island and Lowendal Islands

The Lowendal Island group provided the largest and most consistent x-line track count dataset collected during the 1998 – 2003 surveys. Beaches on four main islands were surveyed over a minimum of three days during the peak hawksbill (November) and flatback (January) nesting periods between November 1998 and January 2003. These data include only the flatback and hawksbill counts as the green turtle track counts were extremely low.

East and west coast census beach x-line track data was used to demonstrate beach usage on Barrow Island. This data provided both a mean number of tracks per day per beach and a track density value when the daily average was divided by the length of each beach. Track data from the January peak of the east coast flatback and west coast green turtle nesting season were used to calculate daily mean tracks per day and densities. The number of x-line counts for hawksbills were excluded since the numbers were so low as to be meaningless.

The west coast beaches selected as census beaches were both accessible and representative of the beach types typically found on this coast (*i.e.* deep and shallow sandy beaches, open foreshore approach). They were all from the North West region of Barrow Island and included; Ti Tree (Beach #16), V Beach (Beach #17), Perched Beach (Beach #18), Tortuga Beach (Beach #19), North Whites Beach (Beach #23), Whites Beach (Beach #24), Flacourt Beach (Beach #29) and Petal Beach (Beach #30).

East coast census beaches were selected from each of the three coastal regions (North East, South East and Mid Central). Beach #2 in the North East was selected as an indicator beach for this region of the east coast. Within the Mid Central region five beaches were selected based on the consistently high track densities, relative to the rest of the Mid Central coast beaches, documented during the 1998 – 2003 beach surveys. These were YC S (Beach #66), YC N (Beach #67), Bivalve (Beach #69), Terminal (Beach #70) and Mushroom (Beach #71).

3.4 Results

3.4.1 Track identification

Characteristics of adult tracks

Before any track data could be collected the types of tracks left by turtles attempting nesting crawls on B-L-M complex beaches had to be characterised. No information on

Western Australian turtle track characteristics was available in the literature. The characteristics of B-L-M complex turtle tracks compiled during the course of this study are listed below and shown in Plates 3.1 – 3.3.

Green turtle

- Front flipper mark significantly overlaps the back flipper mark
- Front flipper marks paired with each other, symmetrical gait
- Short steps, short distance between flipper marks
- Generally deep cut track, related to weight of the animal
- Often a straight channel down the centre, belly drag section of the track, caused by the fleshy section of the tail
- Often a line of equally spaced dots from the tip of the tail digging into the sand on each forward stroke
- Often a row of lines across the central tail drag channel, running perpendicular to the direction of travel, caused by the rear edge of the carapace digging into the sand on each forward step

Flatback turtle

- Front flipper slightly overlap the back, less overlap than green turtle
- Equal or alternating gait, depends on speed and slope. Animals travelling up or down a steep slope, or one moving quickly, may have an alternate gait.
- Straight unbroken or dotted line from tail tip
- Broad central belly mark

Hawksbill turtle

- Front flipper equal to or slightly wider than back flipper mark
- Alternating gait, produces zig-zag pattern in rear flipper marks
- Rear flipper marks widely spaced, distinctly curled pattern
- Belly drag zig-zag pattern
- Tail tip zig-zag line down centre of central belly mark

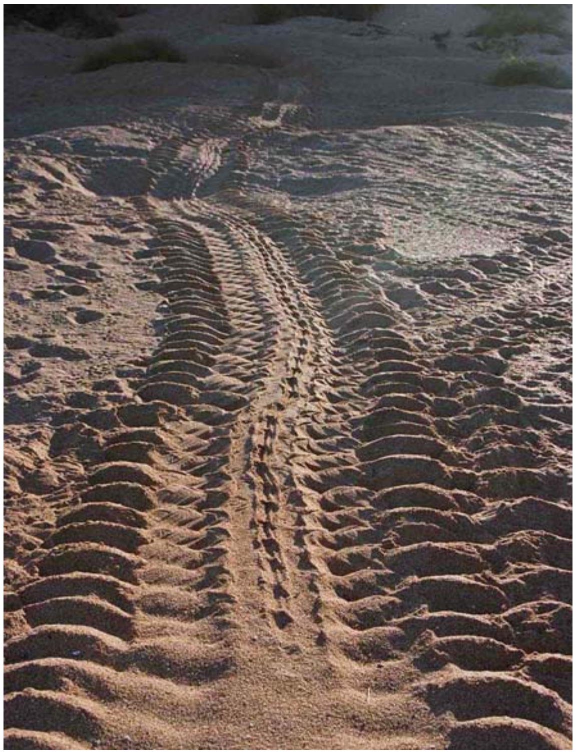


Plate 3.1: Green turtle track

Plate 3.2: Flatback turtle track

Plate 3.3: Hawksbill track

Size of adult tracks

Assignment of species from the tracks alone was not attempted during the first two seasons until the observer had become confident in identification of tracks. With the exception of hawksbill stroke/m measurement, there was no significant difference between characteristics of tracks (track width, belly width and stroke/m) when turtles had been identified compared to when turtle species had been assigned (Table 3.7) Thus, identification of species from characteristics of the tracks alone was deemed reliable and data was pooled for further analysis. The mean and standard deviation for the track measurements are shown in Table 3.8 for green, hawksbill and flatback turtle and includes analyses for tracks arising from animals that were observed and for tracks where no animals were observed and an assignment made (by an experienced observer) of the species based on the characteristics of the track.

Green turtle tracks were, on average, wider than flatback tracks (107.61 cm vs. 102.72 cm) while hawksbill tracks were the narrowest at 79.45 cm. The track sizes for green and hawksbill turtles visiting beaches in the B-L-M complex fell within the ranges reported elsewhere (Miller 1996; Pritchard and Mortimer 1999). However, the mean size of flatback tracks was larger than the ~90 cm reported by these authors.

Table 3.7: Student t test results of comparisons between track metrics for tracks of turtles where the species had been identified versus tracks for species that had been assigned.

Track metric	n observed	n assigned	t statistic	df	p value
HB width	82	164	0.5017	171	0.6165
HB belly	53	4	0.0502	3	0.9631
HB stroke/m	40	67	2.1965	82	0.0308*
FB width	72	223	-1.0136	153	0.3124
FB belly	41	122	-1.5625	88	0.1217
FB stroke/m	30	141	-1.1181	65	0.9064
G width	39	167	0.2569	82	0.7979
G belly	3	87	1.5132	61	0.1354
G stroke/m	23	120	1.7787	41	0.0827

Table 3.8: Measurements for pooled (observed and assigned) green, hawksbill and flatback adult turtle track metrics.

Species	statistics	B-L-M Island species			(Pritchard and Mortimer 1999)
		width (cm)	belly (cm)	stroke/m	width (cm)
Green n=90	mean	107.61	14.79	6.43	100-130
	stdev	9.64	3.26	1.18	
	se	0.95	0.32	0.12	
	range	86 -135	6 - 24	3 - 10	
Flatback n=173	mean	102.72	18.27	4.26	~90
	stdev	8.90	3.60	0.73	
	se	0.68	0.27	0.06	
	range	78-125	11-30	3-7	
Hawksbill n=57	mean	79.45	15.65	3.65	70-85
	stdev	7.01	3.81	0.73	
	se	0.92	0.50	0.10	
	range	60-94	8-24	2-5	

* Explanation of track width, belly width and stroke/m are given in section 3.3.1

The value of the three track measures as an indicator of species was tested using a discriminant analysis. The results are shown in Figure 3.3 and Tables 3.9 and 3.10. The results show a clear separation of the hawksbill group centroids from green turtle and flatback centroids and a slight overlap between the latter two species. Ninety percent of the multivariate variance of the discriminant analysis was associated with the first eigenvalue, *i.e.* the discriminant axis Function 1. These results indicate that the measured track characteristics are valid criteria for identifying the tracks of the three species.

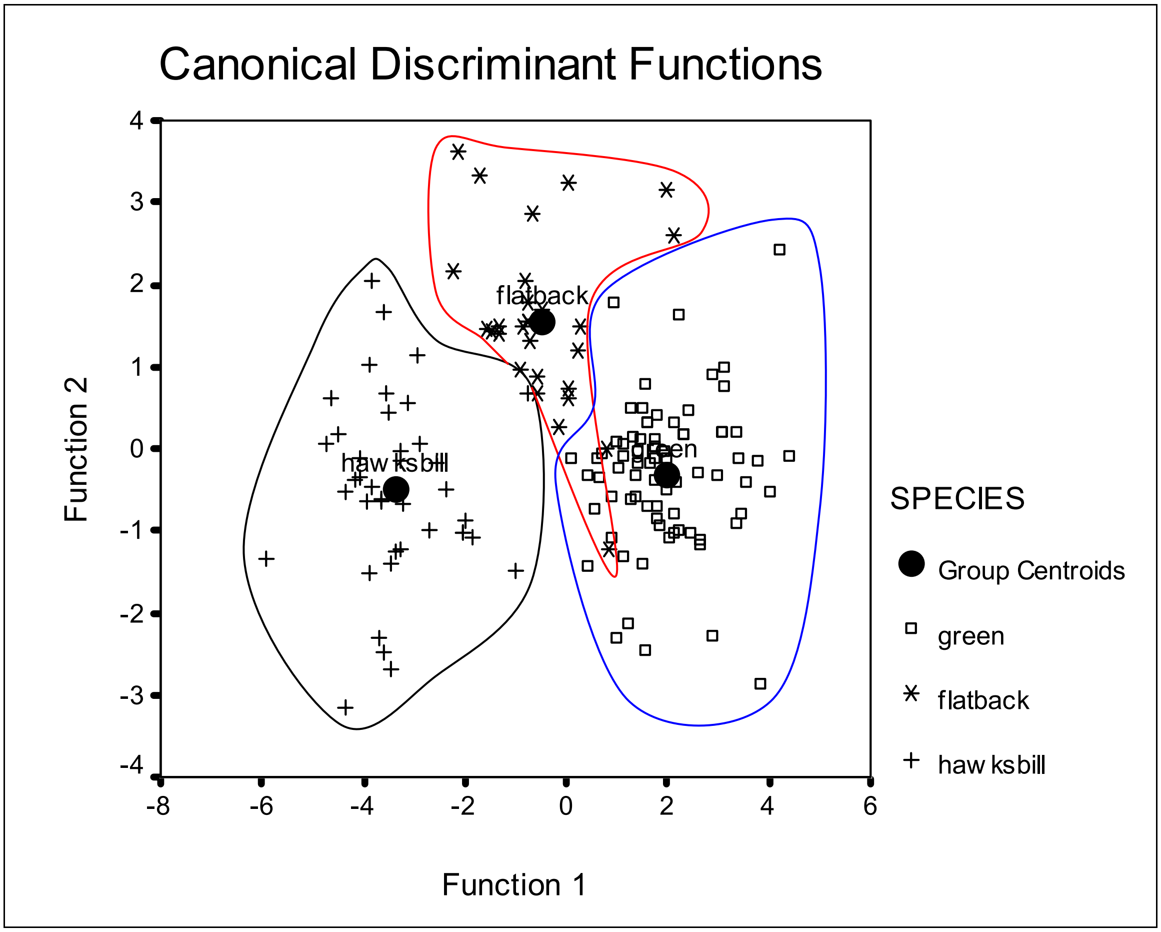


Figure 3.3: Discriminant analysis results for green turtle, flatback and hawksbill tracks based on the characteristics of widths, belly width and stroke/m measurements.

Table 3.9: The percentage of tracks correctly allocated by the discriminant analysis.

	Predicted Group Membership			n
SPECIES %	hawksbill	flatback	green turtle	
hawksbill	97.5	2.5	0	40
flatback	0	92.9	7.1	28
green turtle	0	2.7	97.3	75

96.5% of original grouped cases correctly classified.

Table 3.10: Standardized Canonical Discriminant Function Coefficients

	Discriminant function coefficients	
	Function1	Function 2
WIDTH	0.823	0.435
BELLY	-0.065	0.820
stroke/m	0.814	-0.303

Hatchling tracks

Hatchling tracks are highly variable and difficult to identify to species. Track patterns are affected by the animals speed, beach slope, the presence of protruding egg yolk sac and sand moisture. The data used to analyse mean track width for hatchling tracks includes only the results of measurements made when the species was confirmed by the presence of hatchlings.

Flatback turtles are the largest of the three species of hatchlings and their tracks were correspondingly wide (10.6 ± 0.9 cm, range 8 – 14 cm, n=214). Green turtle hatchlings are smaller than flatback hatchlings and their tracks correspondingly narrower (6.5 ± 0.99 cm, range 5 – 8 cm, n=23). Hawksbill hatchlings are the smallest of the three species however their tracks were a similar size to the green turtles (6.6 ± 0.7 cm, range 5 – 8 cm, n=254).

A one way analysis of variance of the data shows the tracks widths of the three species are significantly different ($F_{2,\ 488}$= 531.3, $p < 0.001$). The Tukeys HSD test shows a significant difference between flatback and hawksbill track sizes and between flatback and green turtle track sizes ($p < 0.01$) however green turtle and hawksbill track size was not significantly different.

3.4.2 Survey of beach physical characteristics and light environment

The dimensions of each island surveyed during this study are shown in Table 3.11 and includes the proportion of sandy shoreline as a percentage of the total coastline. The percentages have been calculated from aerial photograph measurements.

Sandy beaches comprise 38 km (45%) of the Barrow coastline, 15.8 km (17%) of the Montebello islands coastlines and 2.75 km (18%) of the Lowendal islands coastlines.

Table 3.11: Barrow, Lowendal, Montebello island dimensions

	Island length (km)	Island width (km)	Coast-line length	Sandy nesting beach (km)	% sandy beach
Barrow Island	26	11	85	38	45
Montebello Group					
Trimouille Island	9.2	1.5	19	5.7	30.0
North West Island	3	0.5	7.4	5.4	73.0
South East Island	0.7	0.2	2.5	0.8	32.0
Hermite Island	10	1	60	2.3	3.8
Ah Chong Island	0.8	0.45	4	0.9	22.5
South East Island	0.68	0.26	2.03	0.71	35.0
Lowendal Group					
Parakeelya Island	0.8	0.3	1.9	0.25	13.2
Bridled Island	0.8	0.2	3.7	0.8	21.6
Beacon Island	0.2	0.14	0.9	0.2	22.2
Varanus Island	2.9	0.8	7.8	1.2	15.4
Abutilon Island	3.7	0.3	1.2	0.3	25.0

Individual beach dimensions, physical characteristics and proximity to anthropogenic lighting (as at 2003) of the sandy beaches on Barrow Island, the Montebello Islands and the Lowendal Islands are listed in Appendix 1. The beach names and code numbers are shown in Figure 3.4 (Barrow Island) Figure 3.5 (Lowendal Islands) and Figure 3.6 (Montebello Islands). The west coast of Barrow is a high wave energy region with wide deep sandy beaches (75% of North West and 95% of South West beaches) and all have a narrow (rocky or open sand) foreshore approach to the beaches. The east coast of Barrow Island is a low wave energy coastline that is characterised by long narrow shallow sandy shorelines. The sandy shorelines of the North East and mid East coast regions are primarily deep sandy beaches (70% and 75% of sandy shoreline) while the South East coast shorelines are dominated by thin strips of shallow sand (80% of the sandy shorelines). A broad (up to 1 km wide), flat intertidal platform dominates the mid and South East coastal regions and is reduced in width in the north east. The north coast is

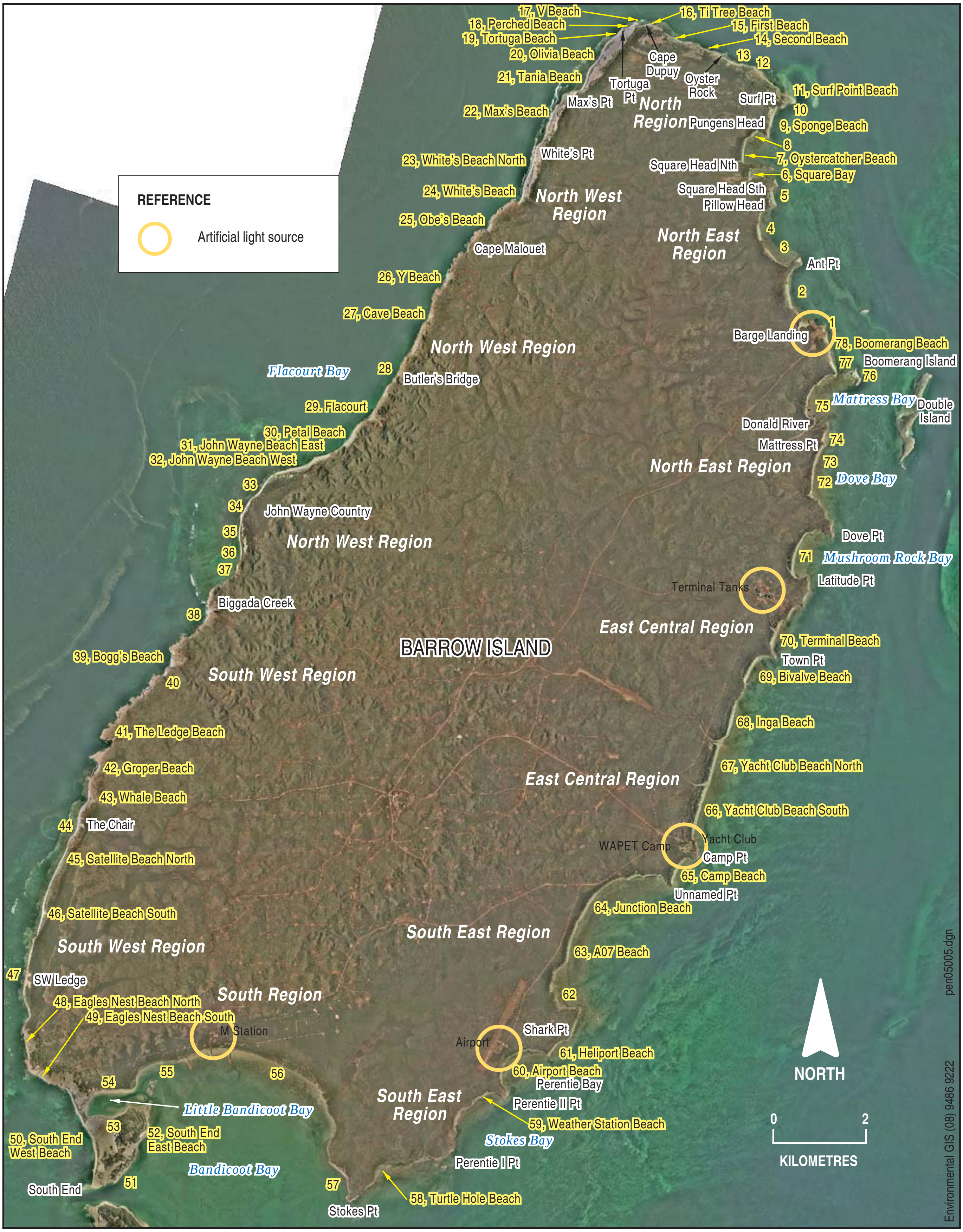
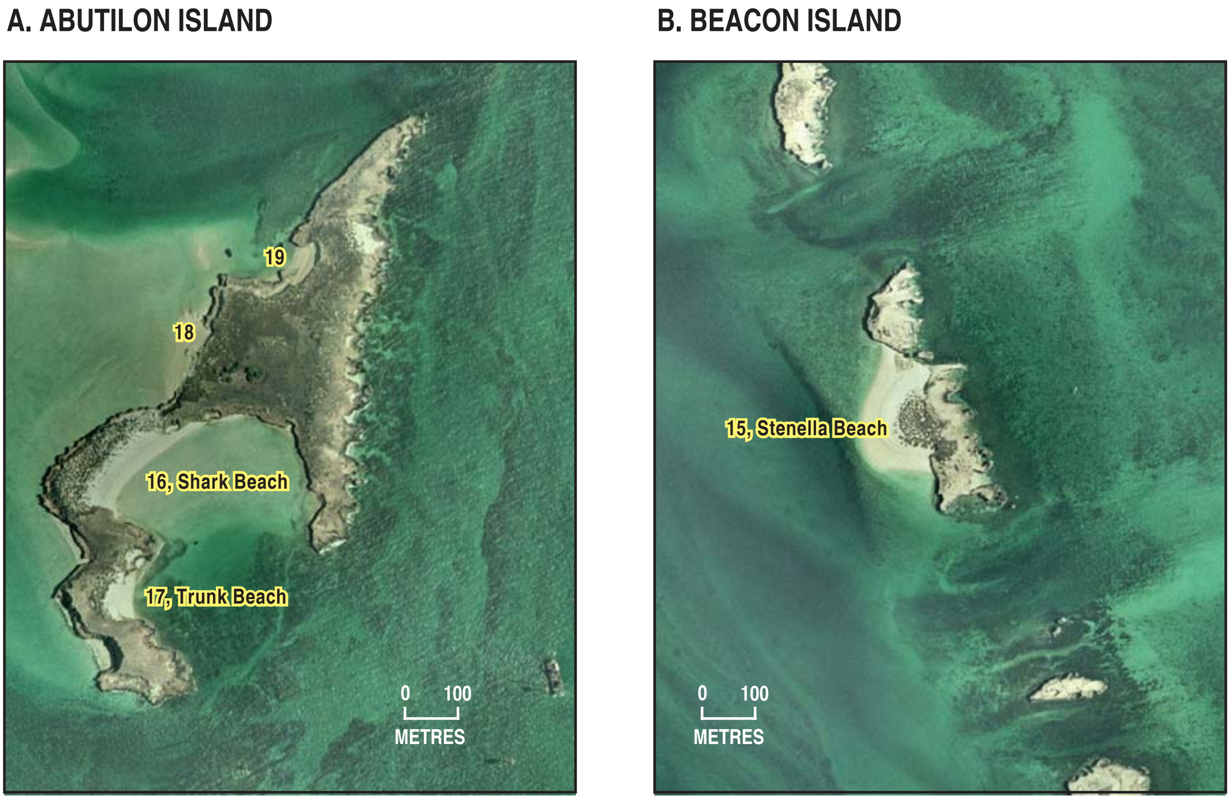


Figure 3.4: Barrow Island track count survey regions, beach locations and location of artificial light sources



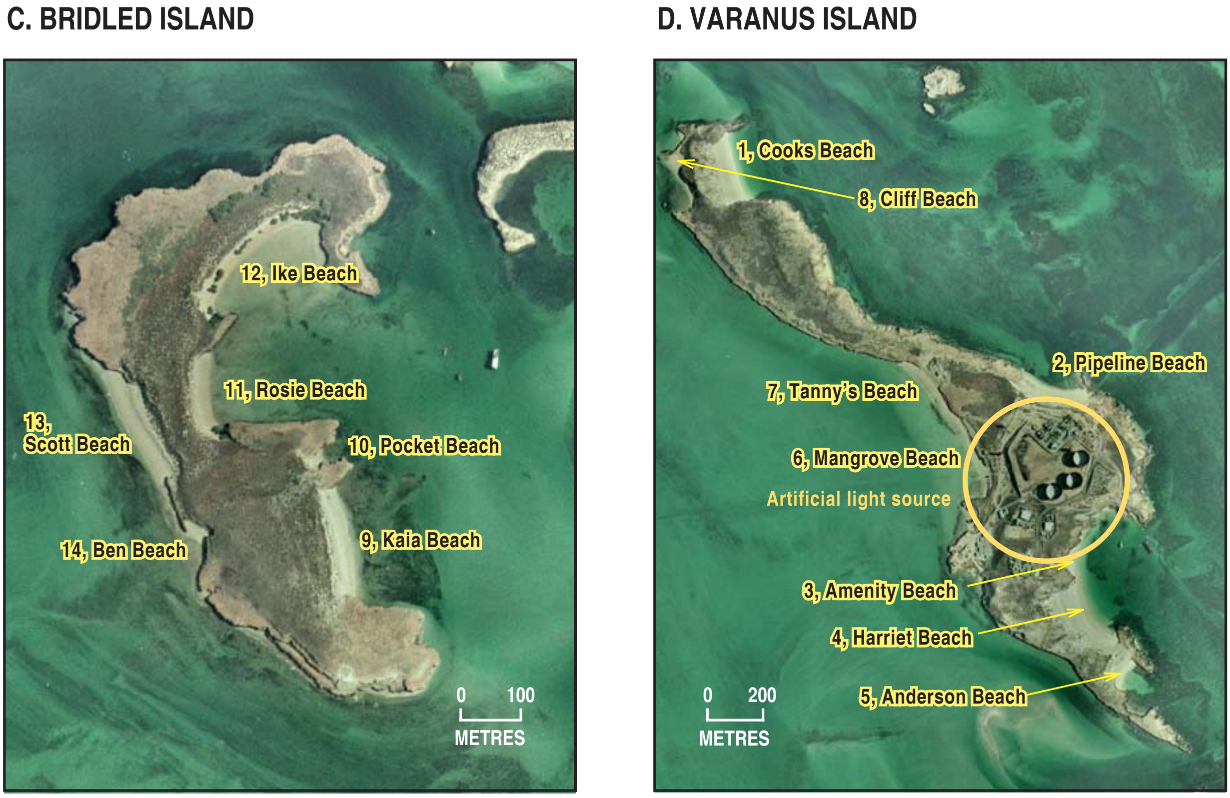


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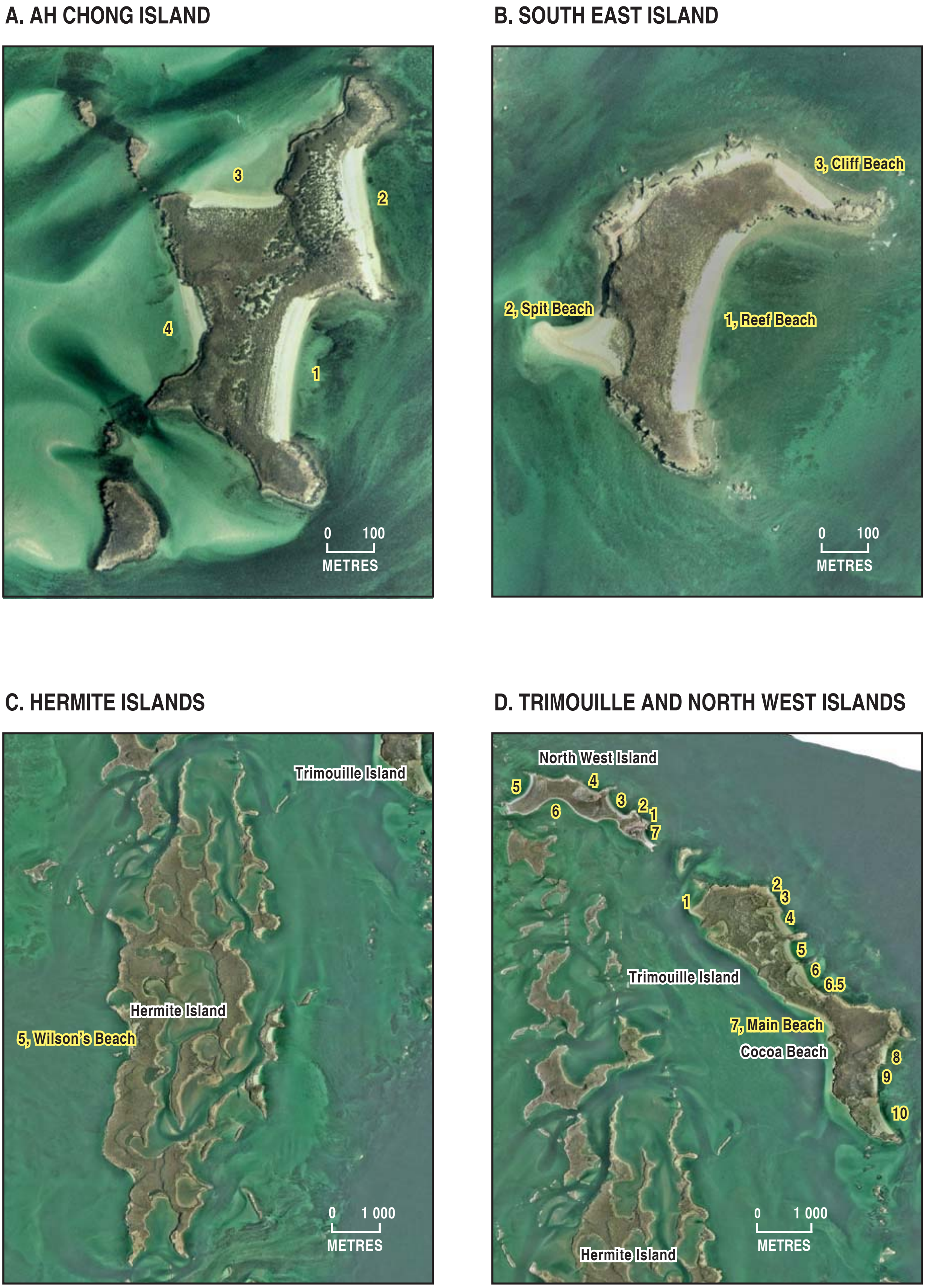
Figure 3.5: Lowendal Island track count survey beach locations and location of artificial light sources


A. AH CHONG ISLAND

B. SOUTH EAST ISLAND

C. HERMITE ISLANDS

D. TRIMOUILLE AND NORTH WEST ISLANDS

Figure 3.6: Montebello Island track count survey beach locations

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similar to the west coast, *i.e.* high energy wave regime, deep sand (79% of beaches) and a narrow rocky foreshore approach. The South coast resembles the east coast *i.e.* low energy wave regime and 81% of beaches are narrow strips of shallow sand. The foreshore environment differs from the east coast in that it is dominated by a wide shallow sand/silt seabed in the intertidal zone.

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Barrow Island beaches that fell within the 1.5 km buffer zone proposed by Limpus (2002) for the protection of nesting adults and hatchlings are shown, as at 2000-2005, on Figure 3.4. None of the north or west coast beaches was exposed to light. A small section of the shoreline on the south coast was exposed to light from an oil and gas installation. Three sources of light occur on the east coast: the airport on the south eastern coastline, the WAPET camp (living quarters) and the Terminal storage tank facility on the mid eastern coastline.

Five of the islands within the Lowendal Island group support sandy nesting beaches. Beacon and Parakeelya Islands each have a single sandy beach, comprising deep sand and a coral foreshore (Beacon Island) or a narrow rocky foreshore (Parakeelya Island). The shorelines of Bridled Island, Abutilon Island and Varanus Island comprise 64%, 83% and 76% deep and sandy beaches respectively. The foreshore approach at Bridled and Abutilon Islands is over a wide sandy intertidal zone, while the foreshore approach at Varanus Island is narrow due to the shallow sandy shore approach to all the island beaches.

Within the Lowendal Island group the primary permanent light source between 2000 and 2003 was the oil and gas processing facility on Varanus Island. The light sources consisted of a processing plant illuminated 24 hours a day, with up to three gas flares. While these light sources were visible from most of the islands within the Lowendal group the beaches that fell within a 1.5 km radius of the light were all on Varanus Island.

The beaches of the Montebello Islands show variability in character and wave energy. Ah Chong is situated within a low wave energy environment; 36% of the shoreline is deep sandy beach and the foreshore approach to the beach is unobstructed around the entire island. The single beach monitored at Hermite Island is a low to moderate energy beach, with deep sand and an open sandy foreshore approach. The three beaches on South East Island differed only in their foreshore approach. They are all deep sandy beaches set in a low wave energy environment. However, the foreshores of these beaches included a narrow rocky intertidal zone (Beach #3), a coral reef intertidal zone (Beach #1) and an open sandy approach (Beach #2).

The two largest islands of the Montebello group, North West and Trimouille Islands, can be divided into regions like Barrow Island. The outer, sea facing beaches are higher energy environments than the low energy, inner lagoon facing beaches. Ninety seven percent of the sandy shoreline on North West Island is deep sand with a narrow rocky or open sandy foreshore approach, including the lagoonal low energy beach on the southern coast of the island. Of the 12 beaches identified on Trimouille Island, 76% of the sandy shoreline provides deep sandy nesting habitat. The foreshore approach is primarily over open sandy seafloor or narrow rocky foreshore (91%) and coral reef (9%).

None of the Montebello Island beaches were within a 1.5 km radius of light.

3.4.3 Beach preferences

The distribution of green, flatback and hawksbill turtle between Barrow, Lowendal and Montebello nesting beaches was investigated based on beach characteristics. Track density data were sorted into groups based on foreshore type, beach slope and sand depth above the supratidal line. These results (Figure 3.7) show a clear preference by green turtles for deep, steeply sloped, sandy beaches with an unobstructed foreshore approach (e.g. the west coast of Barrow Island). Flatback turtles also favour beaches with deep sand, however, beach slope is typically low and the foreshore characterised by wide shallow intertidal zones (e.g. east coast of Barrow Island). Hawksbill nesting was most closely associated with beaches that had coral habitat in the foreshore zone (e.g. Beacon Island, Lowendal group).

These results were used in conjunction with the beach track survey results to classify the sandy shorelines of the B-L-M complex as high or low quality nesting habitat. Nesting effort on beaches not subject to routine surveys could be predicted based on the quality of the nesting habitat.

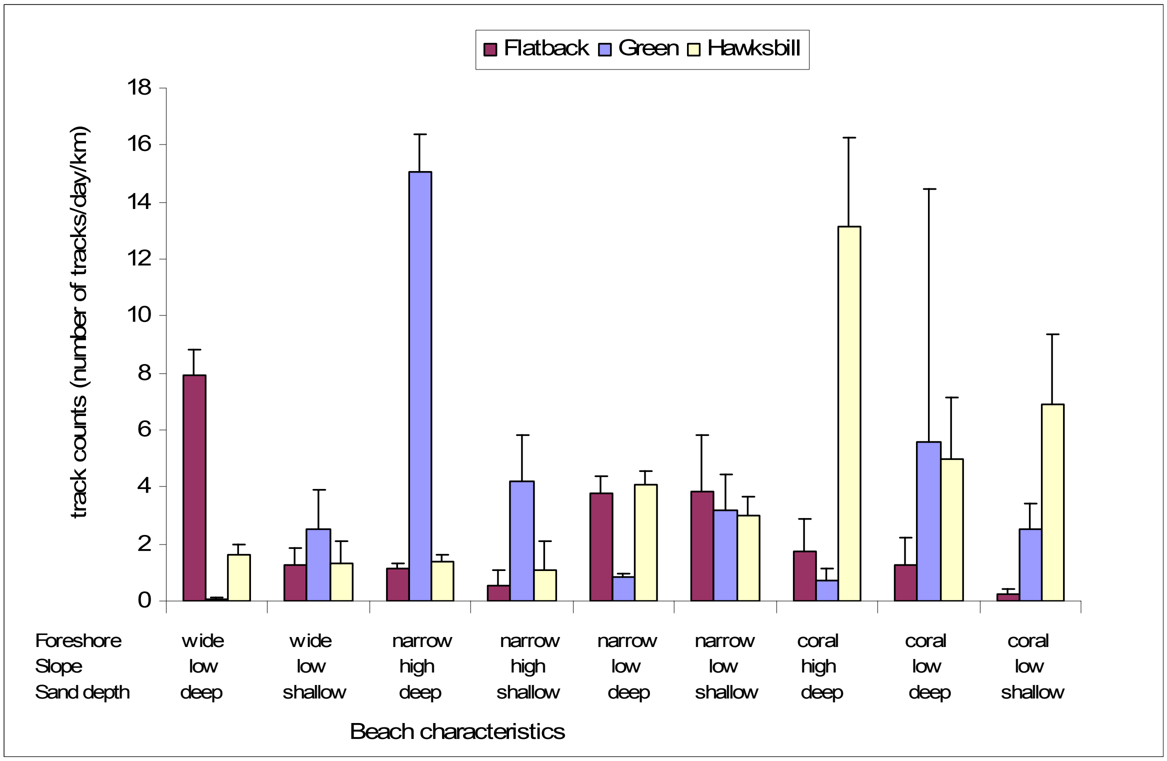


Figure 3.7: Mean (+se) track number per km (BHT) sorted by beach characteristics. n=1573 beach survey days per species.

3.4.4 Length and peak of nesting season

The peak nesting periods for each species was determined by averaging the track counts for each month over the number of nesting days for the 2003 – 2005 census beach results for flatback and green turtle tracks on Barrow Island and the 1998 – 2003 survey results for hawksbill tracks on the Montebello and Lowendal Islands. The track data were converted to average number of tracks per day to account for variability in the day to day totals and in survey effort.

The results (Figure 3.8) suggest a difference in the start and finish of the nesting season for the three species nesting in the B-L-M complex. Hawksbills commence nesting in October, a month earlier than the green and flatback turtles. Green turtle nesting commences early in summer and continues through to February. Limited beach inspections over 2 days in March 2001 on Barrow Island suggested nesting effort fell off in March however this requires additional surveys to confirm. Maximum nesting density occurs in January and February. Flatback turtles appear to display the narrowest nesting season, commencing with very low numbers in November, peaking in December and January and ending in February. Nesting at Mundabullangana Station on the mainland Western Australian coast commences in October, however, no season end is available due to lack of presence on the beach after January each year (pers com RIT Prince 2004).

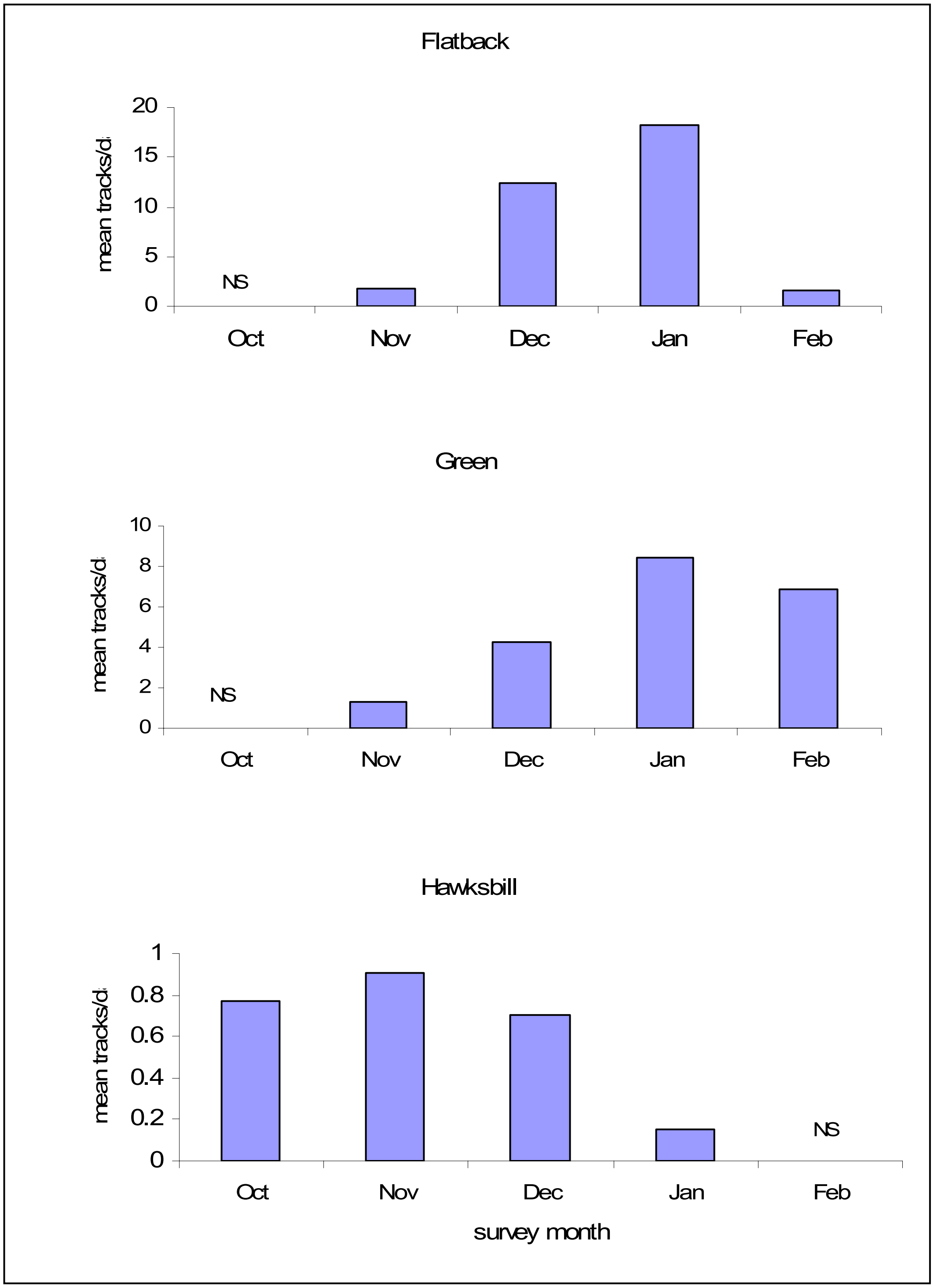


Figure 3.8: Monthly distribution of green turtle, flatback and hawksbill tracks. All data from mean number of x-line counts only. Flatback turtle data Barrow Island east coast 2003 - 2005 surveys (n=21-85 beach survey days/month). Green turtle data Barrow Island west coast 2003 - 2005 surveys (n=35-57 beach survey days/month). Hawksbill data Lowendal and Montebello 1998 - 2003 surveys (n=6-661 beach survey days/month). NS = Not Surveyed

3.4.5 Track to nest ratio

The ratio of successful nests to total track counts on census beaches was calculated from the December 2004 and January 2005 census beach results. The nest to track ratio for green turtles was 0.49 (n=168 nets and 340 tracks) and for flatback turtles it was 0.52 (n=480 nests and 926 tracks).

3.4.6 Distribution of track counts between and within the B-L-M island groups

This analysis of the BHT track data was used to show how the three species of turtles were distributed within each island group and how the distribution of each species compared between the three island groups.

The results (Table 3.12) show that the largest proportion of flatback nesting attempts were found on Barrow Island (60%), followed by the Montebello group (24%). Green turtle tracks were divided equally between Barrow Island (50%) and the Montebello Islands (50%). The largest proportion of hawksbill tracks were found within the Montebello group (53%) with fewer in the Lowendal (37%)and Barrow groups (10%).

The proportional distribution of species tracks within each of the three island groups was estimated using the same BHT track data from the peak of the nesting season (Table 3.7). Most green turtle and flatback nesting attempts were on Barrow Island (48% and 50% of all Barrow Island tracks). Nesting attempts within the Lowendal group was confined to flatback and hawksbill turtles (60% and 40% of all Lowendal tracks). All three species used the Montebello Island beaches, with green turtle tracks the most common (62% of all Montebello tracks) followed by flatback turtles (24%) and hawksbill turtles (14%).

Table 3.12: Proportion of tracks for each species documented over the entire B-L-M complex. BHT track data, 1998-2005, taken from the peak of the nesting season for each species.

Island group	species	total tracks	mean	stdev	n	se	% of individual island count	% of total island complex count
Barrow								
Jan	F	941	3.75	6.74	250	0.43	48%	60%
Jan	G	974	3.88	10.5	260	0.65	50%	50%
Nov	H	43	0.07	0.67	589	0.03	2%	10%
Lowendal								
Jan	F	245	2.15	3.63	110	0.35	60%	16%
Jan	G	4	0.04	0.3	111	0.03	1%	0%
Nov	H	156	1.42	2.01	111	0.19	39%	37%
Montebello								
Jan	F	374	1.14	3.69	328	0.20	24%	24%
Jan	G	967	3.04	5.81	317	0.33	62%	50%
Nov	H	219	0.81	2.04	270	0.12	14%	52%

Having established which islands were used by each species, the track data from each island were then standardised for effort (mean number of tracks /day) and compared to density (mean number of tracks/day/km) to demonstrate the relative importance of each of the three island groups to nesting sea turtles.

The mean daily track counts and density were plotted (figure 3.9) for each island group. The figures show that while a large number of green and flatback turtles visit Barrow Island (Figure 3.9 (a)) when converted to densities based on the availability of potential nesting habitat (38 km) these figures translated into relatively low overall island densities (Figure 3.9 (b)). Similarly the number of green turtle tracks found on the 11.8 km of potentially available nesting habitat within the Montebello Island group converted to a moderately low overall density.

The available nesting habitat on the Lowendal Islands is the lowest of three groups at 2.33 km and while the average number of tracks recorded per day was also low the density of both hawksbill and flatback was higher than all three species on Barrow and the Montebello islands combined.

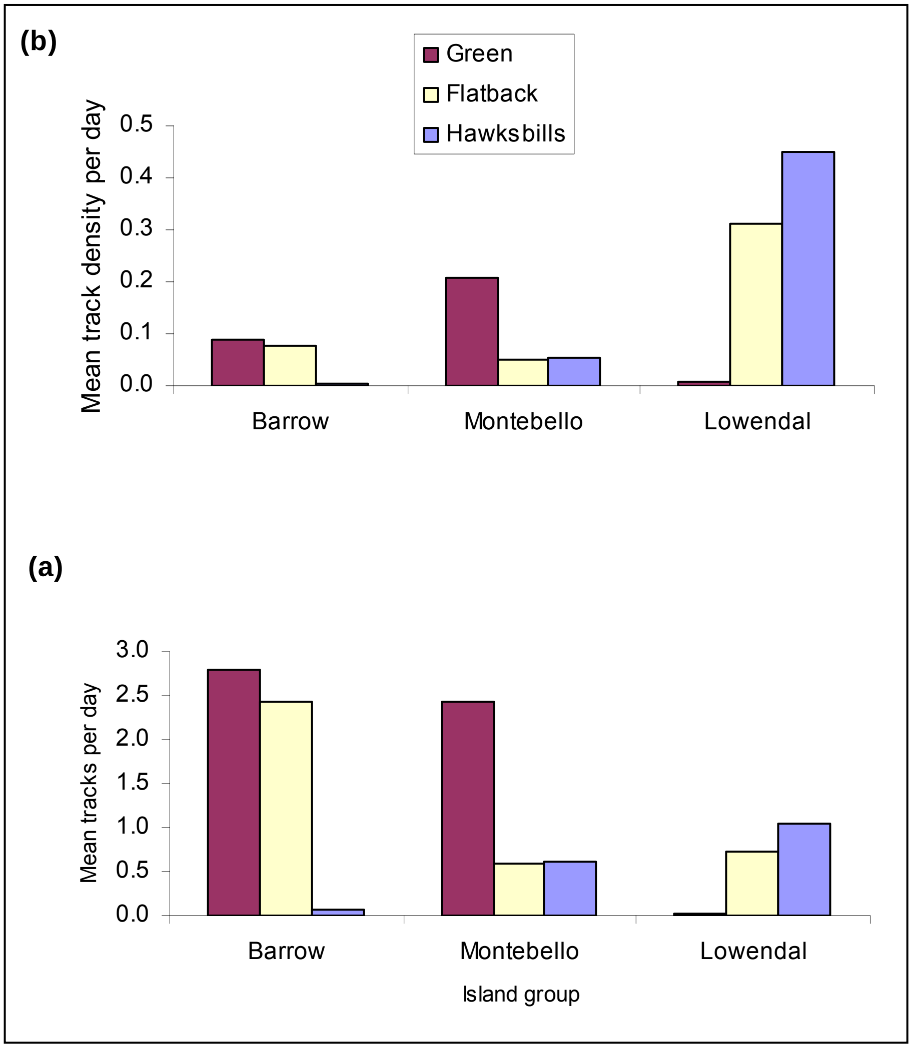


Figure 3.9: BHT track counts. (a) Mean (number of tracks/d) and (b) density (number of tracks/d/km) for peak nesting periods of each species (January for green turtle and flatback, November or October for hawksbills).

The preceding results established the location of nesting species within the B-L-M complex and the relative densities of each species within each island group. However the field surveys clearly showed that the nesting sea turtles were not spread out evenly around the coast of Barrow Island or the Montebello Islands and in fact the tracks were concentrated on beaches displaying the characteristics presented in Section 3.4.3. The next step was to further refine the locations of the favoured nesting sites so that the proportion of the population potentially exposed to the point sources of industrial lighting could be estimated.

The locations of the onshore light sources mapped on Figures 3.4 (Barrow Island) and Figure 3.5 (Lowendal Islands) indicated that the sea turtle beaches within the B-L-M complex potentially exposed to industrial light sources were: the flatback populations on the east coast of Barrow Island, and the flatback and hawksbill populations on all of the Varanus Island beaches. The relative densities of nesting species on these islands are presented in the next section.

3.4.7 Beach usage, Barrow Island and Lowendal Islands

The x-line data for Barrow Island (2003 – 2005) and the Lowendal Island group (1998 – 2003) is presented below. The beach and foreshore characteristics of the census beaches were all representative of the types shown to be favoured by the individual species in Section 3.4.3 (Species beach characteristic preferences).

Barrow Island

East and west coast census beach x-line track data was used to demonstrate beach usage on Barrow Island. This data provided absolute track numbers and density (Figure 3.10) of flatback tracks on east coast Barrow Island census beaches during the January peak of the flatback nesting. While the absolute number and density (Figure 3.11) of x-line green turtle track counts on Barrow Island west coast census beaches was obtained from the January peak of the green turtle nesting. The number of x-line counts for hawksbills were excluded since the numbers were so low as to be meaningless.

The North East and the South East census beaches had fewer flatback tracks than the Mid East coast beaches. The two South East coast nesting beaches surveyed during the census program (Beach #62 and Beach #63) displayed low density flatback nesting, ranging form 4 – 4.5 tracks per day. The North East coast indicator beach (Beach #2) had the lowest track count of all the census beaches at 0.83 tracks per day. Within the Mid East region four of the five census beaches (Beaches #66, #67, #69 and #71) displayed similar daily mean track counts ranging from 22.13 to 23.5 tracks/day while the fifth, #70 had a lower average at 12.23 tracks/day. Track densities displayed similar trends with the North East and South East beaches supporting lower track density than the Mid East coast beaches.

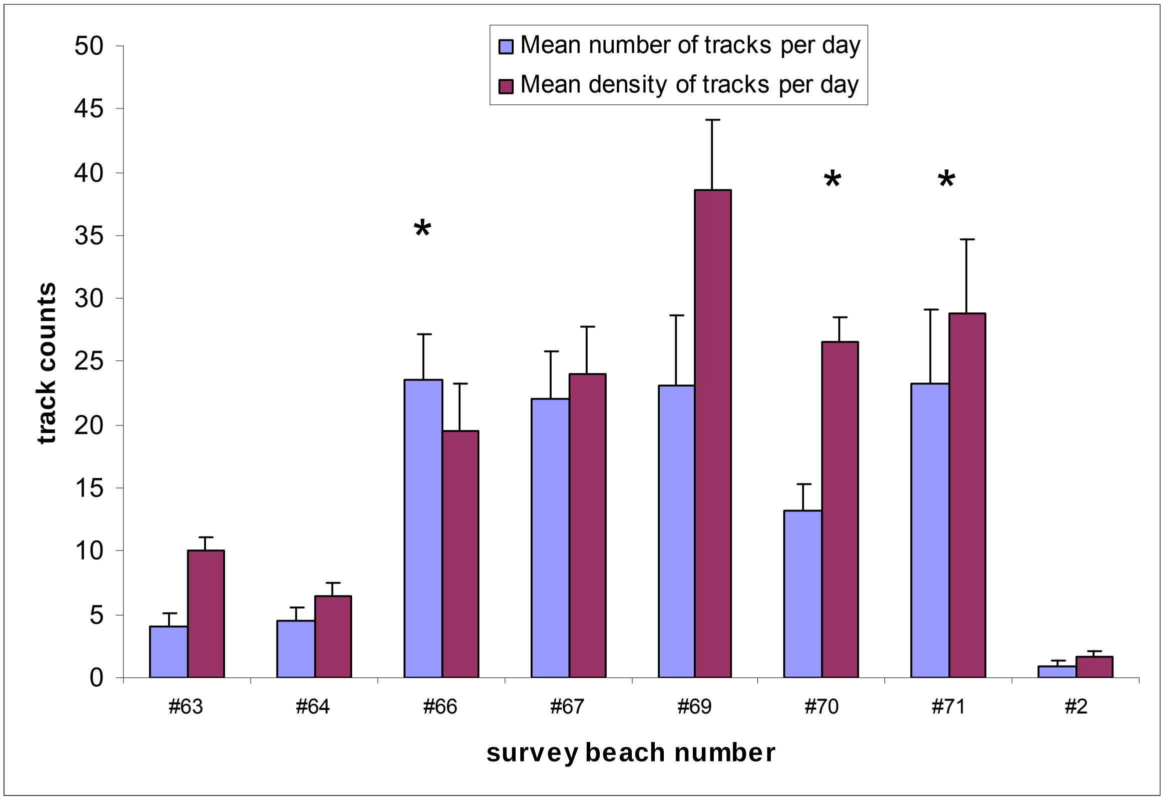


Figure 3.10: The number and density of x-line track counts for flatback turtles on Barrow Island east coast beaches during the peak nesting period. Data derived from census beach surveys during January (2003, 2004, 2005). * Denotes beaches that are located within 1.5 km of oil and gas facility light sources

The west coast green mean daily track count was highest on Beach #19 followed by Beach #24, Beach #29 and Beach #30 and lowest on Beach #23 and Beach #18. The track counts on west coast beaches ranged from 1.2 tracks/day on Beach #23 (where sand depth is limited by a shallow limestone platform) to 21.67 tracks per day on the deep sand of Beach #19. Track densities on these beaches show similar trends in nesting effort and highlight the importance of small deep sandy beaches such as Beach #17.

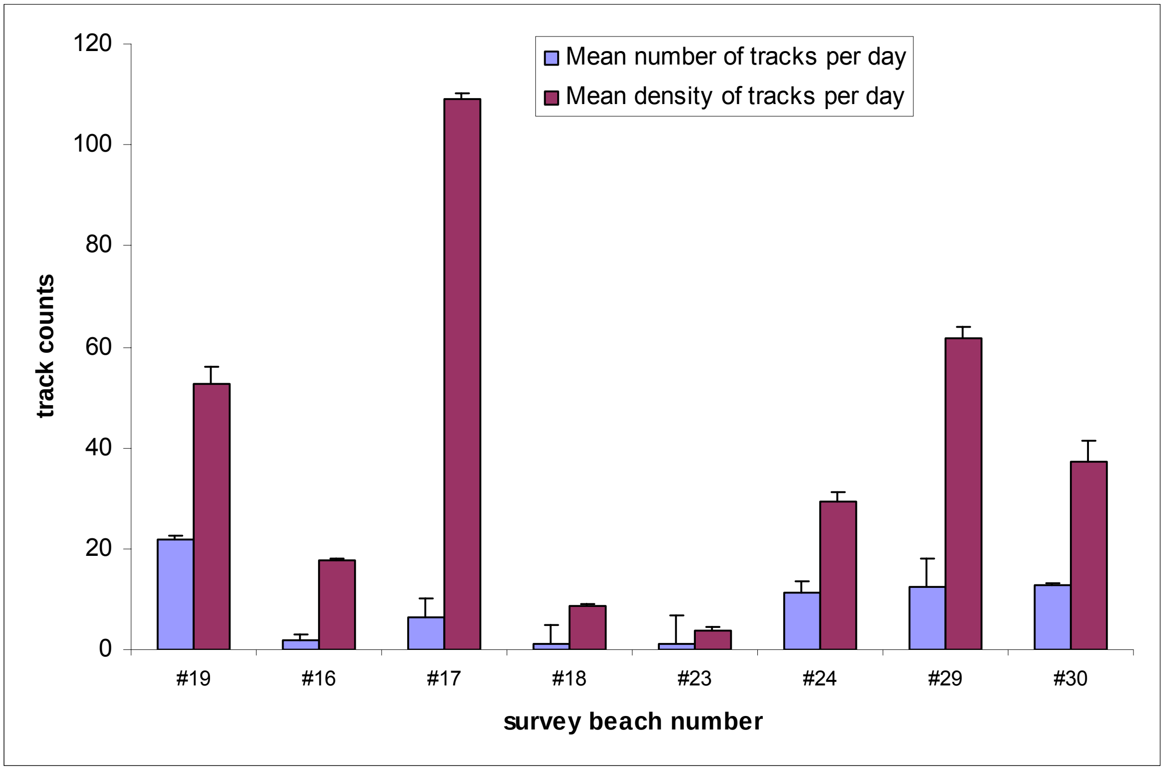


Figure 3.11: The number and density of x-line counts for green turtles on Barrow Island west coast beaches during the peak nesting period. Data derived from census beach surveys during January (2003, 2004, 2005).

Lowendal Islands

There was more track activity by hawksbill than flatback turtles on the Lowendal Islands (Figure 3.12 and Figure – 3.13). The number of hawksbill tracks ranged from a minimum of 0.13 tracks/day on Beach #6 to a maximum of 2.67 tracks/day on Beach #15. High hawksbill track counts were also found on Beach #2 and Beach #9. Track densities indicated similar effort in nesting effort on Lowendal Island beaches.

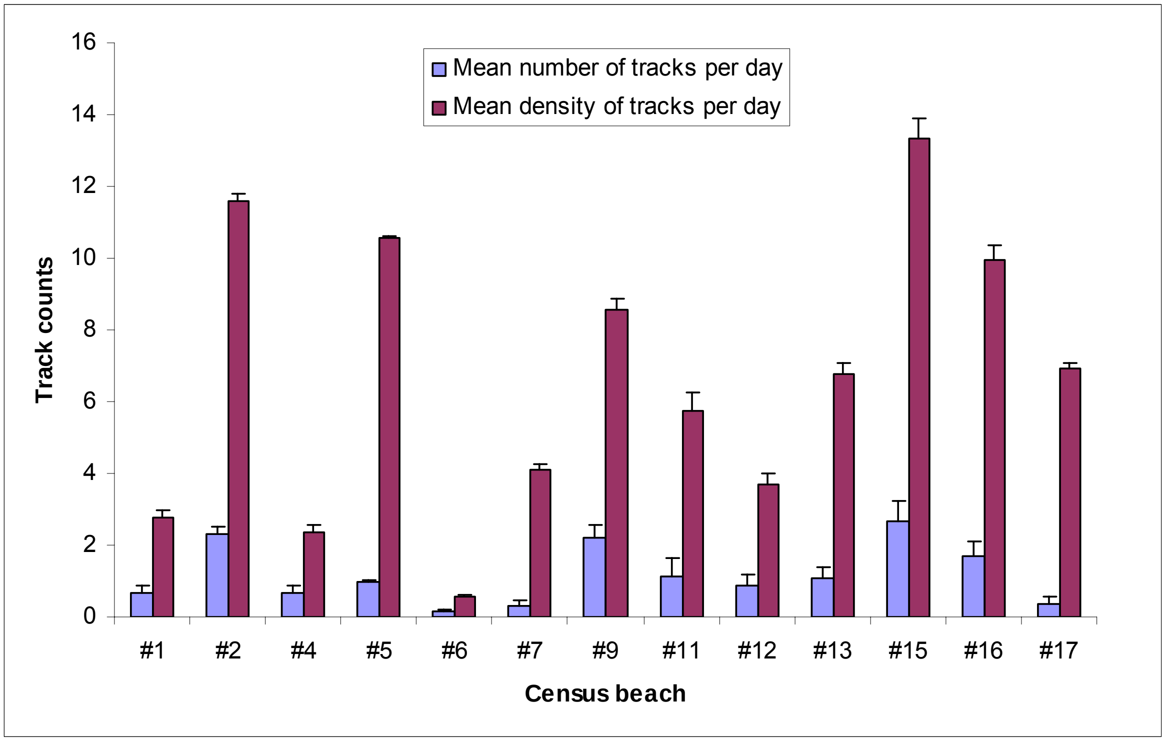


Figure 3.12: The number and density of x-line counts for hawksbill turtles on Lowendal Island beaches during the peak nesting period. Data derived from census beach surveys during November (1998 – 2003). For beach codes see Appendix 1.

Flatback track counts were highest on Beach #13 (6.46 tracks/day), Beach #16 (2.92 tracks/day) and Beach #9 (1.58 tracks/day), and lower at Beach #1 (1.06 tracks/day) and Beach #7 (0.72 tracks/day). The density calculations reflected the daily mean track count.

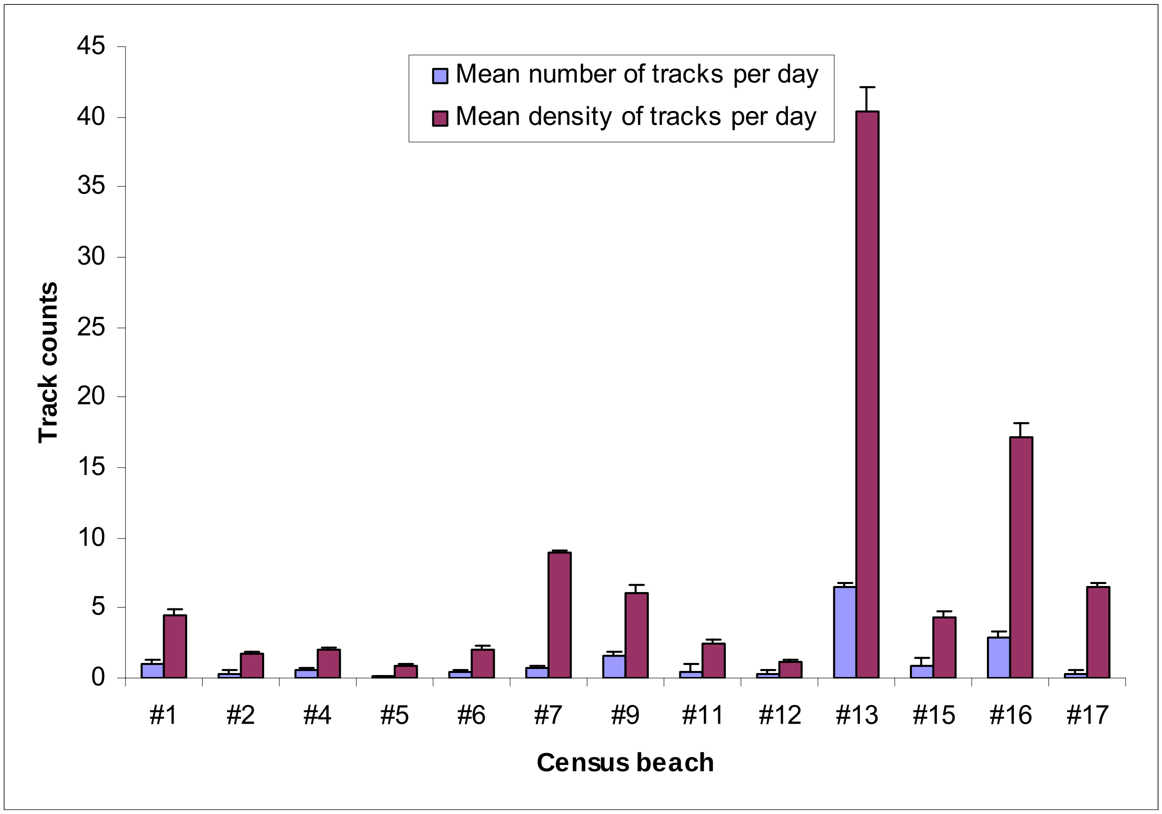


Figure 3.13: The number and density of x-line counts for flatback turtles on Lowendal Island beaches during the peak nesting period. Data derived from census beach surveys during November (1998 – 2003). For beach codes see Appendix 1.

3.5 Discussion

The beach survey results presented here provide the first demographic details on the species that routinely nest within the B-L-M island complex. The species using the beaches are identified along with nesting population sizes, nesting season length, nesting season peak and favoured nesting locations. The characteristics of the local populations are discussed below.

3.5.1 Track identification

The track characteristics presented here are the first systematic descriptions to be made of the B-L-M Island group sea turtles. These track characteristics were not substantially different from those described in the literature from other regions. Flatback tracks were the most difficult to distinguish from green turtle or hawksbill tracks due to their ability to switch between even or alternating gaits, depending on the slope of the beach and speed of the animal. Typically, flatback turtles moving over a slope or moving quickly will use an alternating gait, leaving a track that resembles those left by hawksbill turtles. Alternatively, large, heavy and slow moving flatback turtles may leave a track with an even gait and short steps much like a green turtle. Where there is confusion in the identification of a track, size may be used to distinguish between the species.

There are no published data on track belly widths or stroke/m measurements. Nor is there any information on discriminant analysis of track characteristics. The results from this study suggest that the track width and stroke/m values are valid indicators of species and can be used to help identify unknown tracks in conjunction with an assessment of track characteristics.

Literature sources for hatchling track size data are similarly lacking. The results presented here indicate a clear difference in size between flatback hatchlings and the smaller green turtle and hawksbill hatchlings. It was not possible to distinguish between the green turtle and hawksbill hatchling track sizes from the available data.

3.5.2 Beach/foreshore characteristics favoured by each species

The process by which sea turtles of any species select their nesting beach has not been defined and is highly variable world wide (Miller 1996). The results of this research suggest that turtles within the B-L-M complex will nest on any stretch of sandy beaches within the region. However there is variability in nesting density that can be related to beach and foreshore characteristics which does suggest some degree of preference.

Green turtles are limited by the depth of sand they require to successfully nest in (average 69 cm, Limpus 2006a) and consequently the most dense nesting was found on high energy beaches with deep sand (e.g. west coast of Barrow Island, east coast of Trimouille Island and north coast of North West Island). The foreshore approach to these beaches was over an open sandy bottom or a narrow rocky intertidal zone. Beaches favoured by green turtles within the B-L-M complex are also characterised by strong near shore tidal current flows (e.g. west coast of Barrow Island).

Flatback turtles, by contrast, favour low energy beaches presumably since they are more susceptible to mechanical damage due to a lack of keratin in their carapace. They are able to nest in shallower sand (average 55 cm, Limpus 2006c) than green turtles. The densest nesting populations of flatback turtles were found on deep sandy and low energy beaches on the east coast of Barrow, west coast of Varanus Island and Bridled Island, and on the west coast of Hermite Island. The foreshore approach to these beaches was over broad shallow intertidal platforms or sand/silt bottom. On Barrow Island the highest concentrations of flatback tracks was on beaches that lay adjacent to a tidal node off the east coast of the island. This area experiences little or no tidal movement .

Hawksbill tracks were found in low to very low densities on most of the beaches surveyed. Higher density concentrations were most evident on small shallow sand beaches (unsuitable for green and flatback turtles due to the shallow sand depths), that were typically characterised by coarse grained sand or coral grit interspersed with rocks and beach wrack. The largest density concentrations were found on beaches adjacent to near shore coral reef such as Beacon Island in the Lowendal group (Figure 3.5), Beaches #6a and #8 on Trimouille Island, and Reef Beach on South East Island in the Montebello group (Figure 3.6). Relatively strong tidal flow occurs ff the beaches favoured by hawksbill nesting .

3.5.3 Nesting season length, peak and population size

Green turtles

The October to March green turtle nesting season identified for the B-L-M complex is similar in time and length to the season identified for the Eastern Australian and Torres Strait nesting populations (Limpus, Colin J. and Nicholls 1988; Limpus, C. J. *et al.* 2001). Nesting of green turtles in both the Eastern Australian Great Barrier Reef and Bramble Cay, rookeries is almost entirely confined to summer with a peak in nesting effort in December and January (Bustard 1972; Limpus, C. J. *et al.* 2001; Limpus, C. J. 2006a in prep). An analysis of thirteen years of tagging data from Varanus Island also indicated green turtles nested between October and February and peaked in December and January (n=66 observations, (Pendoley 1999).

The results of the B-L-M surveys confirm the relative abundance and approximate order of magnitude of population estimates made by (Prince 1994) for green turtles (1,000 – 10,000s) and flatback turtles (100s – 1000s). However, these results suggest larger hawksbill numbers than those estimated by Prince (1994) at 10s – 100s. Nesting population estimates were made from the track count data collected during the 1998 – 2004 surveys and assumed one track = one nesting animal. This assumption will over estimate the number of nesting animals since not all beach crawls result in a nest and a single animal may make multiple nesting attempts before she is successful. The track and nest counts made during the 2004/2005 season on Barrow Island returned a ratio of 0.52 nests for each flatback track (n = 480 nests and 926 tracks) and a ratio of 0.49 for green turtle nest and track counts (n= 168 nests and 340 tracks). In the absence of any long term nesting data for the B-L-M complex, the track data were used to provide a preliminary estimate of population size for each species.

Based on the green turtle track counts from the current study, individual beaches on the west coast of Barrow Island may be considered minor rookeries for green turtles. For example, the mean number of tracks at the peak of the green turtle nesting season on Tortuga Beach was 21.67± 9.07 (range 6-34, n=9 nights) while Brambles Cay, identified as a minor green turtle rookery in the Torres Strait by (Limpus, C. J. *et al.* 2001), hosts 42.6 ± 16.8 tracks per night (range 19-101, n=31 nights). However, Tortuga Beach represents only a small proportion of the good quality nesting habitat on the west coast of Barrow Island (~ 8%) and if the average nightly track count is extrapolated to the rest of the west coast beaches displaying the characteristics favoured by green turtles (*i.e.* deep sand, open water approach) this represents ~270 green turtles attempting to nest per night. If this number represents 80% of the available nesting females for the season ((Limpus, C. J. 2006a in prep) and assuming a 12 day renesting interval (Limpus, C. J. *et al.* 2001), approximately 4,000 nesting females were using the west coast nesting beaches over each of the 2003/2004, 2004/2005 seasons. If they are returning on a 5 year remigration interval it represents a total nesting population of 20,000 females.

However the size of the green turtle nesting population may be subject to wide interannular fluctuations (Limpus, Colin J. *et al.* 1993) and the number of nesting animals in the 2003/2004 and 2004/2005 nesting seasons were not as large as have been seen in previous years. The assessment of relative size of the nesting season is based on limited field observations and baseline surveys (Table 3.13). This estimate of 20,000 females using the west coast of Barrow Island for nesting is therefore likely to be an underestimate.

Table 3.13 : Track observations of Below high tide and Above high tide track counts at Tortuga Beach during January field surveys in 1999, 2000, 2001, 2003, 2004 and 2005.

survey year	survey days (n)	BHT tracks	Above high tide line track counts
1999	1	5	sparse single tracks
2000	1	105	100's of tracks
2001	2	0	sparse single tracks
2003	1	43	10's of tracks
2004	4	13.5	10's of tracks
2005	6	13.3	10's of tracks

There is insufficient x-line census data from this survey to estimate nesting population sizes in the Montebello island group. However the number of BHT tracks observed on Hermite Island, NW Island and Trimouille Island, compared to the west coast of Barrow Island suggest the Barrow Island populations (based on mean daily track counts of estimated at 3.88 tracks/day) are approximately equal to all of the Montebello Islands combined (3.04 tracks/day, Table 3.12, Figure 3.9 section 3.4.6).

The largest green turtle rookery identified to date in Western Australia is the Lacepede Island rookery adjacent to the Kimberley coast. This rookery hosts 60 – 100 nesting animals per night in poor years and up to 1600 per night in good years (Prince pers com 2004). Based on the track census data collected during this survey the individual B-L-M Island rookeries do not appear to support the same level of nesting as the Lacepede Islands.

Flatback turtles

The flatback turtle nesting season in the B-L-M complex is very short, confined almost exclusively to December and January with substantially fewer animals beaching in November and February. The Varanus Island 1986-1999 tagging results showed the same short nesting period over December and January (n=184 observations; (Pendoley 1999) . Short nesting seasons for flatback turtles have also been reported in central and south Queensland; they extend from mid-October to late January (Limpus, Colin J. *et al.* 1984b). The B-L-M nesting season appears to be even more restricted than the Queensland season.

The five east coast Barrow Island flatback nesting beaches surveyed over the 2003 to 2005 nesting seasons had the highest flatback track density documented during the five previous years of east coast surveys. The nightly averages for these five beaches (YC S, YC N, Bivalve, Terminal and Mushroom) during the January 2004 and 2005 nesting season peak ranged from 12 – 23 tracks per night. This compares well with the Peak Island rookery in Queensland where the average was 26 tracks per day (n=17 nights, range 3 – 55 tracks per day). The Peak Island flatback rookery is ranked as significant (Limpus, Colin J. *et al.* 1981), with an estimated 500 females nesting during the 1980 - 81 season. In comparison if the average number of flatback tracks per night on the 5 east coast Barrow Island survey beaches is summed (103 per night) and assuming a 14 day renesting period which and, in the absence of a better estimator for the percentage of the population present, we assume 80% of the population is present at the peak of the nesting season, this equates to 1,802 nesting females during the nesting season (Limpus, C. J. 2006a in prep). Assuming a 2.17 year remigration interval and a two week internesting period (Pendoley 1999) 3,900 flatback females may use these five beaches on the east coast of Barrow Island. The Barrow Island flatback population is of the same order of magnitude as the Crab Island rookery in the north eastern Gulf of Carpentaria, the largest flatback rookery identified to date, with several thousand flatback turtles breeding annually (Limpus, Colin J. *et al.* 1981).

Flatback nesting in the Lowendal group is most similar to the Queensland Peak Island rookery (mean of 26 tracks per day), with a mean of 18 tracks per night for the entire island group at the peak of the nesting season.

Hawksbill turtles

Hawksbill nesting commences earlier in the summer than green and flatback nesting. Hawksbill nesting in the B-L-M complex peaked over October, November and December. A similar October to December peak has been recorded on Rosemary Island in the Dampier Archipelago where up to 45 hawksbills per night have been recorded (Vitenbergs, pers. com. 2004). Hawksbill nesting in Eastern Australia and the Torres Strait peaks between January and April, several months later than in Western Australia (Miller 1994).

Hawksbill nesting within the B-L-M complex is concentrated within the Lowendal and Montebello island groups. November track census data were used to estimate nesting population size. A total nightly average of 15.39 hawksbill tracks was recorded for November surveys between 1998 and 2005. Using a 14.28 day renesting interval (Limpus, C. J. 2004b in prep) and assuming the peak of the nesting period capture 80% of the nesting females then an average of 274 females were nesting during the survey period. Assuming a 3.73 year remigration interval (Pendoley 1999) the estimated total number of nesting female hawkbills using the Lowendal Islands is over 1000 animals.

Based on the BHT track ratios (section 3.4.5) for the Lowendal and Montebello islands, the animal numbers using the Montebello Island beaches may be ~1/3 greater than the Lowendal group nesting population (e.g. ~ 1,300 animals). Approximately 10% of the hawksbill turtles nesting in the region were recorded on Barrow Island (~ 100 animals). This gives a estimated total of 2,400 hawksbills using the B-L-M complex nesting beaches. Similar calculations for Rosemary Island (using 40 animals per night, 14 day internesting interval and 3.73 remigration interval) suggest that Rosemary Island (recognised as a globally significant hawksbill rookery) supports an estimated 2,600 animals, of equal magnitude to the combined Barrow, Lowendal and Montebello group nesting population estimates.

These population figures are estimates only and long term routine tagging and beach track census surveys are required to better enumerate the population sizes.

3.5.4 Nesting beaches exposed to industrial light in the B-L-M island complex

The results of the analyses of track counts versus beach characteristics in the previous section shows that the three species may show preferences for particular beach types that are related to beach geomorphologic characteristics. This results in a clustering of nesting activity on certain types of beaches. This variability in productivity has implications when assessing the impacts of human activity. If this clustering occurs close to light pollution sources there is an increase in the potential risk of disruption of nesting adult females and to the successful orientation of hatchlings to the sea. The influence of light on nesting females may also cause them to nest elsewhere.

The light exposure codes assigned to Barrow Island, Lowendal Islands and Montebello Islands beaches (Appendix 1) suggest that 14% of Barrow, 0% of Montebello and 35% of Lowendal island beaches fall within the 1.5 km radius recommended by (Limpus, C.J. 2002) as a buffer zone for the protection of sea turtle nesting beaches from the impact of artificial light. This buffer zone size will vary depending on the type and intensity of light and the species of turtle exposed to the light. It has been used here as a starting point for estimating beach exposure to light. Measurements of light intensity and spectral composition for industrial lighting within the B-L-M complex (Chapter 5), as well as light perception of sea turtle using the nesting beaches within the complex (Chapters 4 and 6) are presented in the following chapters.

On Barrow Island, ten beaches were exposed to oil and gas facility lights. One of these was on the south coast adjacent to Bandicoot Bay and three adjacent to the Barrow Island airport. No turtle nesting was recorded on these beaches and so they are not addressed further. The remaining six beaches were located on the south east and mid east coast. These beaches were in the vicinity of the artificial light emissions at the WAPET camp (Junction #64, Camp #65 and YC S #66) and the oil terminal storage tanks (Terminal #70, Tank #71 and Mushroom #72). Relatively low density flatback nesting was documented on Junction Beach and Camp Beach, while some of the highest density flatback nesting on the east coast was recorded on YC S Beach, Terminal Beach and Mushroom Beach.

Within the Lowendal group 6 of 20 beaches are fall within the 1.5 km radius. These beaches included Cooks (#1), Pipeline (#2), Harriet (#4), Anderson (#5), Mangrove (#6) and Tannys (#7) on Varanus Island. These beaches support predominantly hawksbill nesting (52% of all Barrow, Lowendal and Montebello complex hawksbill tracks were found in the Lowendal Island group).

Based on the maximum x-line track counts for these beaches and the proportion of flatback turtles estimated to use the Barrow Island beaches, approximately 42% of flatback nesting in the B-L-M complex were potentially exposed to in industrial lighting (comprises 39% of Barrow Island and 3% of Lowendal Island turtles). Similar calculations for hawksbill suggest 12% of hawksbill turtles within the B-L-M complex were exposed to industrial lighting at Varanus Island.

Track census surveys show that the presence of light does not completely dissuade adult turtle from using light affected beaches. However, the major impact of light on nesting beaches is in misorientation of hatchlings which may lead to mortality. The results of these track count studies were therefore used to help focus the subsequent experimental and field studies on the beaches with the highest density of turtle nesting combined with the greatest potential for exposure to industrial lighting. Consequently, the results of investigations into the effects of industrial lighting on flatback hatchlings were carried out on the east coast of Barrow Island and hawksbill studies were focussed on Varanus Island.

The types of industrial lights present within a representative oil and gas processing facility on Varanus Island and the effects of these light types on hatchlings both under controlled laboratory conditions and under natural field conditions are addressed further in Chapters 4, 5 and 6.

The comparison of mean daily track counts versus daily track density suggests that while the overall number of animals using the Lowendal beaches is low relative to other beaches in the B-L-M complex, the activity is highly concentrated. Consequently this small concentrated population is potentially at risk from the influence of light from the oil and gas processing facility.

Chapter 4 Hatchling wavelength preference experiments

4.1 Introduction

4.1.1 Background

Light has been recognized as affecting the orientation of hatchling sea turtle since 1911, when Hooker reported a negative reaction to green turtle and red light and a positive reaction to blue light (Hooker 1911). Since that time numerous international studies have shown that the orientation of sea turtle hatchlings is strongly influenced by light wavelength and intensity (Daniel and Smith 1947; Carr and Ogren 1960; Mrosovsky and Carr 1967; Lohmann, Kenneth J. *et al.* 1997).

The effect of light pollution on the orientation of sea turtle hatchlings has been recognised by Australian State and Commonwealth environmental agencies as an issue requiring management and mitigation when assessing and reviewing development proposals in the vicinity of mainland and offshore island sea turtle rookeries (WAPET 1987; EA 1998). These regulatory requirements have, however, been based on the findings of the international studies described in section 4.2. Importantly, these studies exclude flatback turtles since this species is endemic to Australia. Consequently, there are no published studies on the behaviour of flatback hatchlings under the influence of artificial light.

A single experimental study on the effects of light on Australian sea turtle populations has been published (Pendoley 2000). This study identified the misorienting effects of flare light and some industrial light sources on green sea turtle hatchlings. With the increase in industrial and urban development in coastal areas Australia-wide, the lack of knowledge on the impact of light on Australian sea turtle populations has become evident and places constraints on the accuracy and effectiveness of environmental risk assessments for these developments.

Therefore, this component of the research aimed to identify the light wavelengths visible to West Australian flatback, green turtle and hawksbill hatchlings and to assess the preferences of these species to short or long light wavelengths. While logistical constraints and lack of animals placed limitations on the experiments, the results provide a preliminary indication of the response of West Australian sea turtle hatchlings to various wavelengths of light and, in conjunction with the light emission analyses in Chapter 5, are used to identify the lights that are potentially the most disruptive to hatchlings on Barrow, Lowendal, Montebello (B-L-M) complex nesting beaches.

4.1.2 Research questions

1. Do green turtle, hawksbill and flatback hatchlings always select a short wavelength of light over a long wavelength?
2. How do West Australian hatchlings respond to light relative to species tested elsewhere against standard light wavelengths?
3. How does the response of flatback hatchlings compare to green turtle and hawksbill hatchlings?

4.1.3 Chapter outline

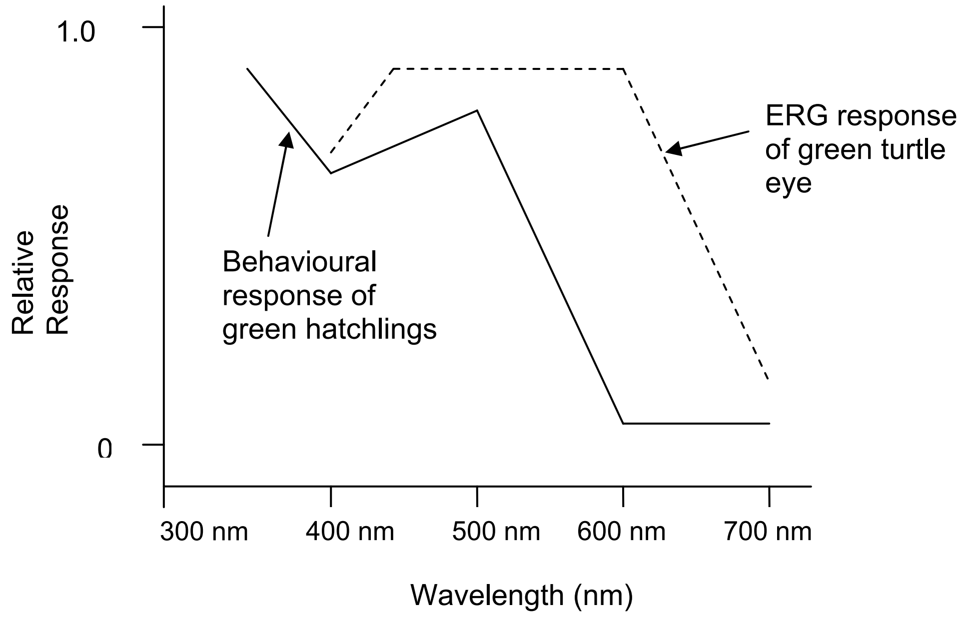
In this chapter the literature on the orientation of hatchlings in response to light is reviewed in section 4.2 and the methods used to select, find and collect test hatchlings from the

Barrow Island and Lowendal Islands nesting beaches are detailed in section 4.3. This section also describes the design of an experimental raceway apparatus and the operational criteria for the light measurement equipment. Results of two colour choice experiments are presented in section 4.4. These results are discussed in the context of results from similar experiments conducted overseas in section 4.5.

4.2 Literature Review

Light has many properties that may influence orientation in hatchlings, e.g. intensity, wavelength, directivity and polarisation (Lohmann, Kenneth J. and Lohmann 1996a). Studies suggest hatchlings have a strong tendency to orient towards the brightest direction, with brightness being a function of light intensity, wavelength and hatchling spectral sensitivity (Witherington 1992). The brightest direction on natural beaches is typically towards the ocean where the horizon is open and unhindered by dune or vegetation shadows.

The brightness of a light to a turtle hatchling is also a function of the spectral characteristics of the light. A light will not be detected if its wavelength is outside the spectrum of light that is visible to the animal. Eelectroretinography (ERG) studies have shown that green hatchling turtles can see blue (450 nm 0 500 nm), green turtle (500 nm to 570 nm), yellow (570 nm to 590 nm) and orange (590 nm to 610 nm) light well (Figure 4.1) (Granda and Dvorak 1977). However experiments with hatchlings have shown that both green and hawksbill turtles are notably more responsive to shorter wavelengths (*i.e.* near ultraviolet violet to yellow, < 400 nm to 590 nm) than to longer wavelengths of light (*i.e.* orange to red light, 590 nm to >700 nm), even at heightened intensities (Mrosovsky and Shettleworth 1968; Witherington and Bjorndal 1991a; Witherington 1992a). Red light must be almost 600 times more intense than blue light before green turtle hatchlings show an equal preference for the two colours (Mrosovsky 1972).



Source: Adapted from Witherington and Bjorndal 1991

Figure 4.1: Results of electroretinography and behavioural studies on green turtle hatchlings. Relative response in hatchling behaviour shows the number of hatchlings selecting the wavelengths shown on the x axis over a fixed 520nm light. The ERG curve shows the response of green turtle eyes to stimulus at the wavelengths shown on the x axis.

The importance of light wavelength has been identified during experiments with different intensity lights (Witherington 1992a). At high light intensities green turtles detect light using colour sensitive cone receptor (photopic vision). However, at low light intensities at night, rod receptors, insensitive to wavelength, are used (scotopic vision) (Granda and Dvorak 1977). Studies of dark-adapted green turtles indicate that they are more sensitive to blue and green wavelengths than light adapted turtles. Therefore at very low light levels hatchlings may not be able to discriminate between colours and respond only to the light-dark sensitivity of their scotopic rod vision.

(Loew and Lythgoe 1985) suggest that green turtles have heightened sensitivity to shorter wavelengths of light as an adaptation to living in seawater in which longer wavelengths are quickly attenuated within the top 1m leaving green and blue light to penetrate the depths. These conclusions are supported by ERG studies (Granda and O'Shea, 1972) which have shown green turtles are uniformly sensitive to light between 400 nm (blue) and 550 nm (green).

4.3 Methods

4.3.1 Test species

The three species tested for light preference were *Nattator depressus* (flatback), *Chelonia mydas* (green turtle) and *Eretmochelys imbricata* (hawksbill). Experiments were run from oil field facilities based on Barrow Island and Varanus Island. These islands are over 2000 km north of Perth, Western Australia and are operated by ChevronTexaco and Apache Energy. The sites are accessed via charter aircraft from Perth to Barrow Island and then helicopter from Barrow Island to Varanus Island. Access to the islands was provided by ChevronTexaco and Apache Energy and was limited in the number of trips and duration on site. These logistical constraints meant that the time available to find and test hatchlings was limited and that equipment failure in the field could not be easily rectified.

The three species do not all nest in high numbers on the same islands (see Chapter 3). Consequently green turtle and flatback hatchlings were tested on Barrow Island and hawksbill hatchlings on Varanus Island in the Lowendal Group.

The number of animals used in tests varied depending on the availability of test animals. Experiments were conducted across three summer seasons between January 2000 and January 2002. The numbers of green turtles nesting over these seasons were low relative to previous years and consequently a limited number of hatchlings were available for testing. Hatchlings were used once only and released to the ocean following each set of experiments.

4.3.2 Animal collection and treatment

Sea turtle research activity on both islands is limited to tagging by volunteers 2-6 weeks per year. Accommodation restrictions precluded the use of large numbers of volunteers during this research program and consequently sourcing hatchlings had to be done by a field team of two people.

The timing for the light experiments was determined by assessing nesting activity over each of the three summers 2000, 2001 and 2002. Where possible, trips to the islands were then scheduled 6-8 weeks after the peak of the nesting effort for each species each summer. Hatchlings were found by a combination of searching the beaches for emerging or partially emerged nests and monitoring terrestrial predator behaviour. For example nests being dug by the perentie lizard (*Varanid giganteus)* frequently contained live hatchlings. Seagull behaviour indicated nest locations in several ways. Gulls standing in a circle around an area might pin point a nest about to emerge or the location of a perentie excavating a nest. Gulls screeching and wheeling overhead or diving for the beach and flying away generally indicated a nest location. Gulls were observed hunting and predating nests both at night and during the day. The golden bandicoot (*Isoodon auratus* *barrowensis*) was only observed at night digging up nests and flipping hatchlings onto their backs so the abdominal egg yolk could be eaten. The location of digging animals was an indicator for nest locations with live hatchlings.

Beaches were usually patrolled first thing in the morning and late afternoon. Nests identified either from predator activity or from the tracks left by emerged nests were excavated and any hatchlings collected were placed directly in to heavy black fabric bags. Hatchlings were only collected for use in experiments if they were fully uncurled. Some hatchlings were taken from the bottom of nests and while uncurled, it is possible they may not have been ready to emerge at that particular time. Hatchlings were transported to the lab and held in the dark until used. Green turtle and hawksbill hatchlings not used within 6-8 hours of collection were not tested since they tended to lose energy and fall into a torpor. They were difficult to rouse for testing and if placed into the test apparatus either did not respond or would take over to 2 minutes to make a choice. Conversely the flatback turtles would quickly quieten down, becoming inactive when left in a dark place after collection. They were easily roused for testing.

Hatchlings were held in the dark until required for testing. Each animal was used only once. For each trial a single animal was placed on the hatchling start point shown in Figures 4.2 and 4.3 and allowed 2 minutes to crawl towards the preferred light source visible along either arm of the raceway apparatus. Hatchlings were scored as having made a choice once they had passed completely into one of the arms of the raceway.

4.3.3 Test equipment

Raceway apparatus

Experiments measuring light response in hatchlings had to be performed in field locations shortly after collecting the hatchlings. Consequently the experimental setup was not like that which could have been constructed within an institutional laboratory environment, nor could the use of the same items of equipment be generated. Equipment variability was encoded, where appropriate, as a factor in the statistical analysis.

The raceway was constructed out of lightweight black foam board that could be collapsed for transport by helicopter. The open top of the raceway was covered with dark material or black plastic and taped to exclude extraneous light.

Hatchlings were tested against two colour choices in the raceway test apparatus shown in Figures 4.2 and 4.3. In 2000 and 2001 the light was delivered to the test animals directly (Figure 4.2). In 2002 the apparatus was adjusted to deliver the light as a reflection off the (white) back wall of each raceway arm (Figure 4.3).

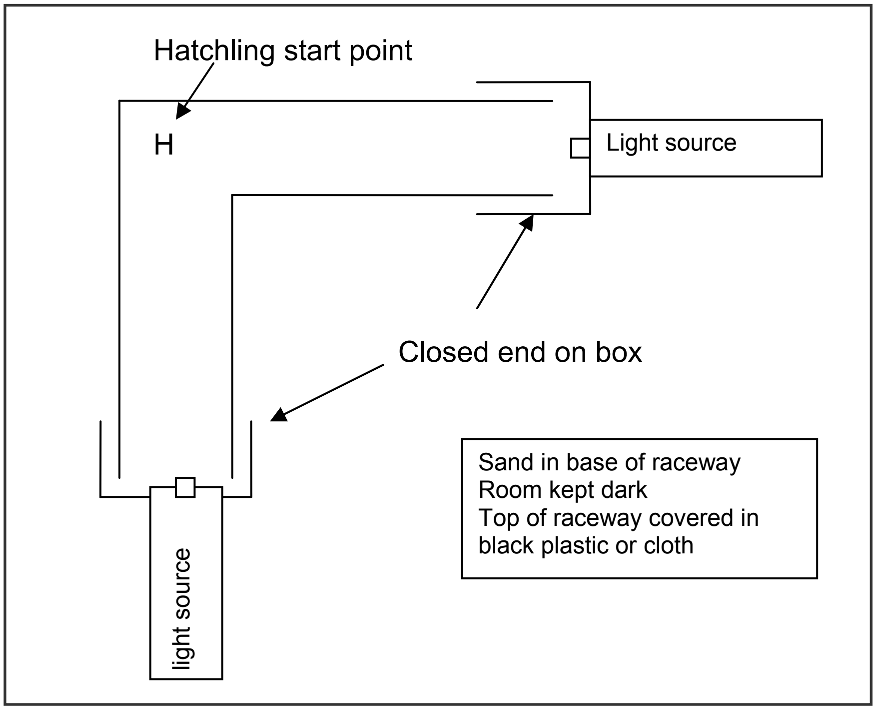


Figure 4.2: Direct light raceway setup

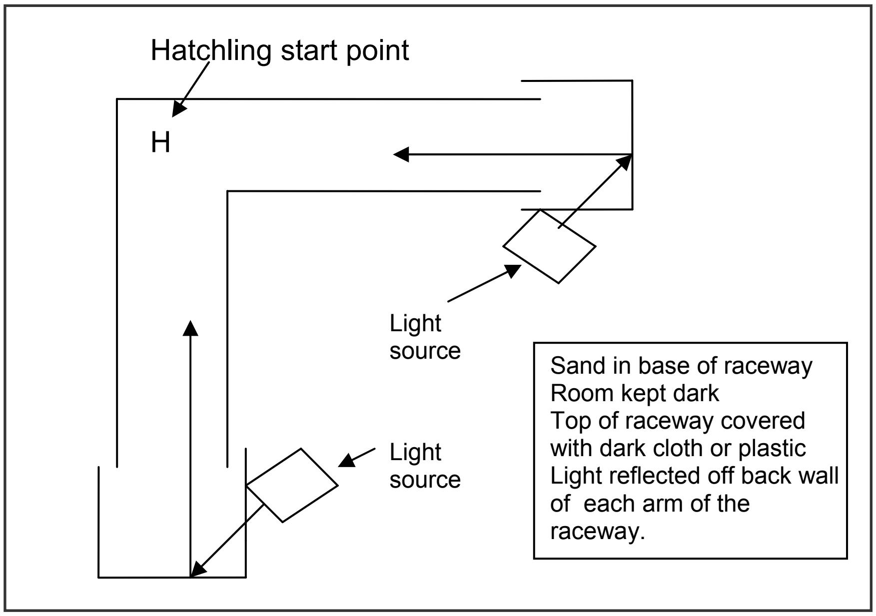


Figure 4.3: Reflected light raceway setup

Light sources

Standard slide projectors were used to provide a light source. Projectors were selected because they were readily available light sources that could provide a support base for the different coloured filters. An old style Noris projector was used in combination with a more modern Elmo projector for the first 2 years of experiments. Sourcing bulbs for the different projectors proved difficult, consequently two types were used; 250 Volt/250 Watts in the Noris and 250 Volt/300 Watt in the Elmo. The light produced was manipulated using diffusing filters and different sized delivery holes so that equivalent pre-filtered light intensity was delivered to the animals from each projector. The pre-filtered light emission intensity was checked using an OceanOptics Miniature Spectroradiometer (see Chapter 5 for operating conditions). The consequence of this is that the modifications of the wavelength by the filters may have modified the intensity of the light also. A the time these experiments were carried out no equipment was available that could directly measure light intensity.

In late 2001 a Kodak projector that was a similar model to the Elmo was found and used for the following 2002 experimental season. The same 250V/250V bulbs could then be used in both projectors producing the same light intensity and diffusion. This equipment performed well until the Kodak projector exploded during experimental runs on Barrow Island in February 2002. Logistical constraints precluded leaving or rescheduling the field trip and consequently light sources had to be found on Barrow Island. Two lamps (100 Watt bulbs) were rigged up to provide light that was directed through the Elmo and Kodak optics to the raceway set-up. Experiments were completed using this equipment at lower light intensities.

Filter holders were made up from standard reticulation equipment. These could be attached to the front of the Noris projector or slotted into a cavity in the Elmo and Kodak projectors.

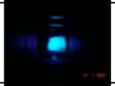
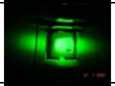
Filters

Ten filters were used in combination to test for a two colour choice response in hatchlings. The filters used were all research grade single bandwidth filters (supplied through the CSIRO Department of Exploration and Mining) and are listed in Table 4.1. Each filter was tested against all or some of the other filters. The variable filters were changed for each group of animals while the fixed filter was held constant throughout each trial. For example 450 nm was tested against 450, 480, 500, 550, etc for each species. The second trial then tested 480 nm against 450, 500, 550 etc, the third tested 500 against 450, 480, 550 and so on.

The light offered to each hatchling using the reflected raceway set up is shown in Table 4.1. A photograph of the reflected light provides an indication of the colours visible to the hatchlings.

Where possible a minimum of 6 hatchlings were used for each filter combination treatment. This was not always possible and the range for animal numbers tested in all three species was from 2 – 26.

Table 4.1: Filter wavelength and colour.

Wavelength (nm)	Colour	Photo of reflected light
450	Blue/violet	
480	Bright blue	
500	Blue green	
550	Bright green	
570	Dark green	
600	Yellow	
630	Yellow orange	
650	Orange	
670	Red	
700	Dark red	

Spectroradiometer

Spectral characteristics of anthropogenic and natural light sources were made using an OCEAN OPTICS miniature fibre-optic spectroradiometer supplied by LasTek, Thebarton, South Australia (www.lastek.com.au). Further details of the operating specifications of this unit are given in Chapter 5.

4.3.4 Statistical treatment

The logistic regression and hierarchical log linear modelling module of the SPSS statistical package were used to fit a range of models, including wavelength difference, light source type and where appropriate individual animal preferences. Choice of light source by a hatchling was trialled as binomial (true/false) variable. The choice was scored on whether the hatchling selected the shorter wavelength over the longer. Whilst it was possible to analyse each wavelength combination independently testing the expectations of a 1:1 ratio (no choice) this was deemed to be an unsatisfactory approach. In the first instance sample sizes for each combination were low and consequently independent tests of random assortment (which is the null hypothesis) would have very low power. In the second instance such an approach would mean repeat testing and the use of some correction process, such as a sequential Bonferroni correction, to ascertain the appropriate significance levels that should be used. Consequently a better approach would be to analyse data through a general linear model which tested different experimental combination as factor levels. The appropriate linear model in this case would be a logistic regression since this assumes a binomial response variable. On the basis of findings by light studies conducted elsewhere ((Witherington 1992a)), across the range of wavelengths included in this experiment we would expect the animals to select the shorter wavelengths in each choice. Consequently the binomial variable was defined as whether the animal moved to the shorter wavelength or not.

The logistic regression also tested for the effect of the scale of the wavelength difference between the two wavelengths being compared. For example it looked at the effect of wavelengths separated by 50 nm compared to a separation of 100 nm. It should be borne in mind however it is unclear that these represent wavelength difference or intensity differences. The analysis also tested for the effects of light delivery methods (direct or reflected) and projector/bulb types.

4.4 Results

The results of the green turtle (Figure 4.4), hawksbill (Figure 4.5) and flatback (Figure 4.6) hatchling trials show the proportion of hatchlings selecting the variable wavelength (shown on the x axis) over the fixed test wavelengths along the y axis. Standard error bars are shown for trials where the choice was less than 100%. The number of animals tested for each combination is shown above each data point. Lines are provided to more easily indicate where ratios have changed and do not imply interpolation across the combinations.

The results (Table 4.2) showed that, for all three species, when selecting the filter setup delivering a shorter wavelength over the filer setup delivering a longer wavelength, it did not matter what the actual value of the shorter wavelength was. The regressions returned a result of no significant difference when testing the hypothesis that when offered a choice hatchlings would always select a shorter wavelength (LOWWL, $p > 0.05$). It was the difference in the wavelengths that were a significant factor in the choices being made (WLINDIFF, $p < 0.05$). The analysis also showed a minor effect on green turtle hatchlings contributed by the different projector light sources ($p < 0.05$) but this was not significant for the flatback trials ($p > 0.05$).

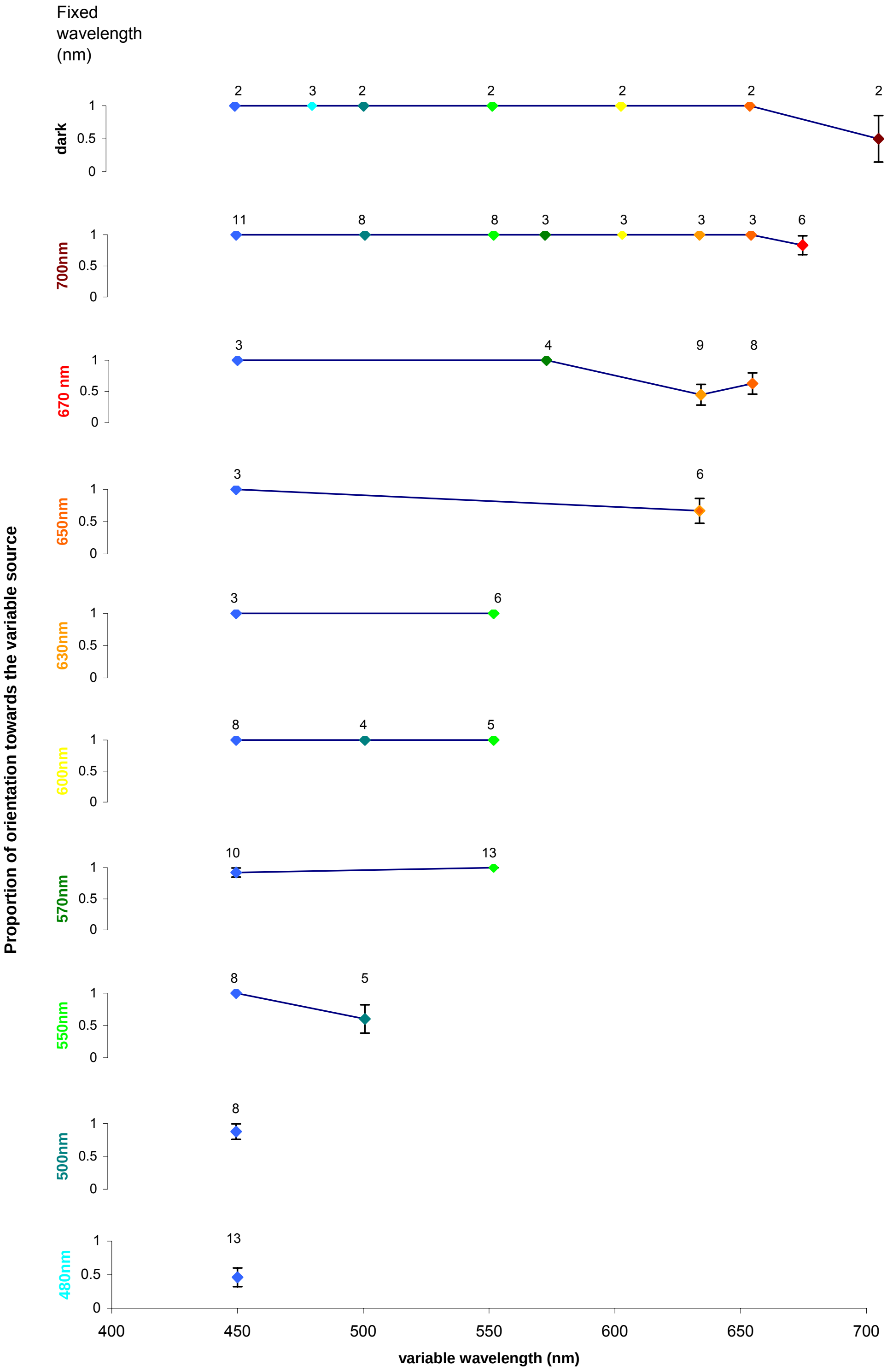


Figure 4.4: Barrow Island green turtle hatchling wavelength choice results. Proportion of green turtle hatchlings selecting the variable wavelength over the fixed wavelength. Standard error bars are provided (where n=2 the bars indicate the range).

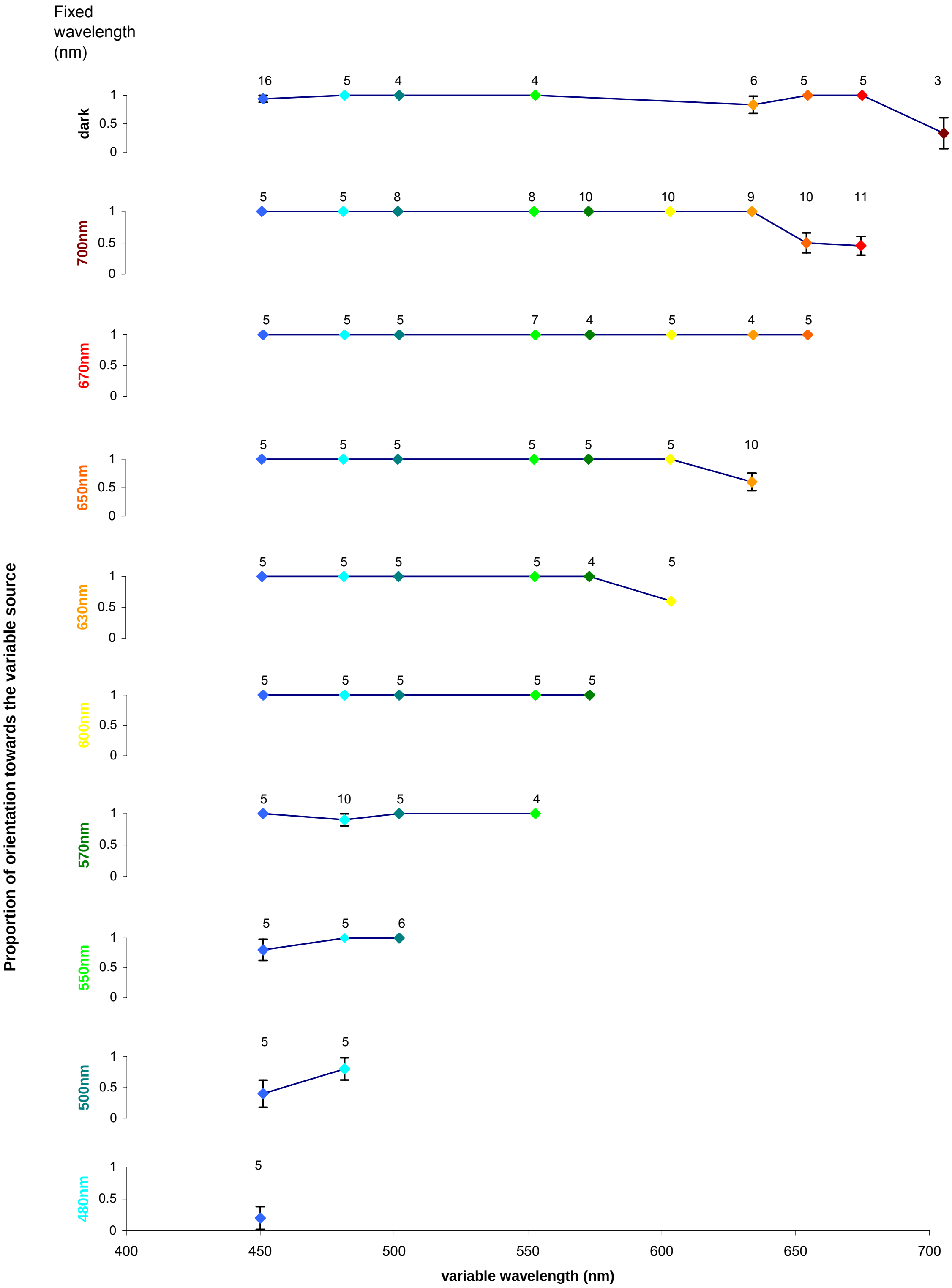


Figure 4.5: Varanus Island hawksbill hatchling wavelength choice results. Proportion of hawksbill hatchlings selecting the variable wavelength over the fixed wavelength. Standard error bars are provided (where n=2 the bars indicate the range).

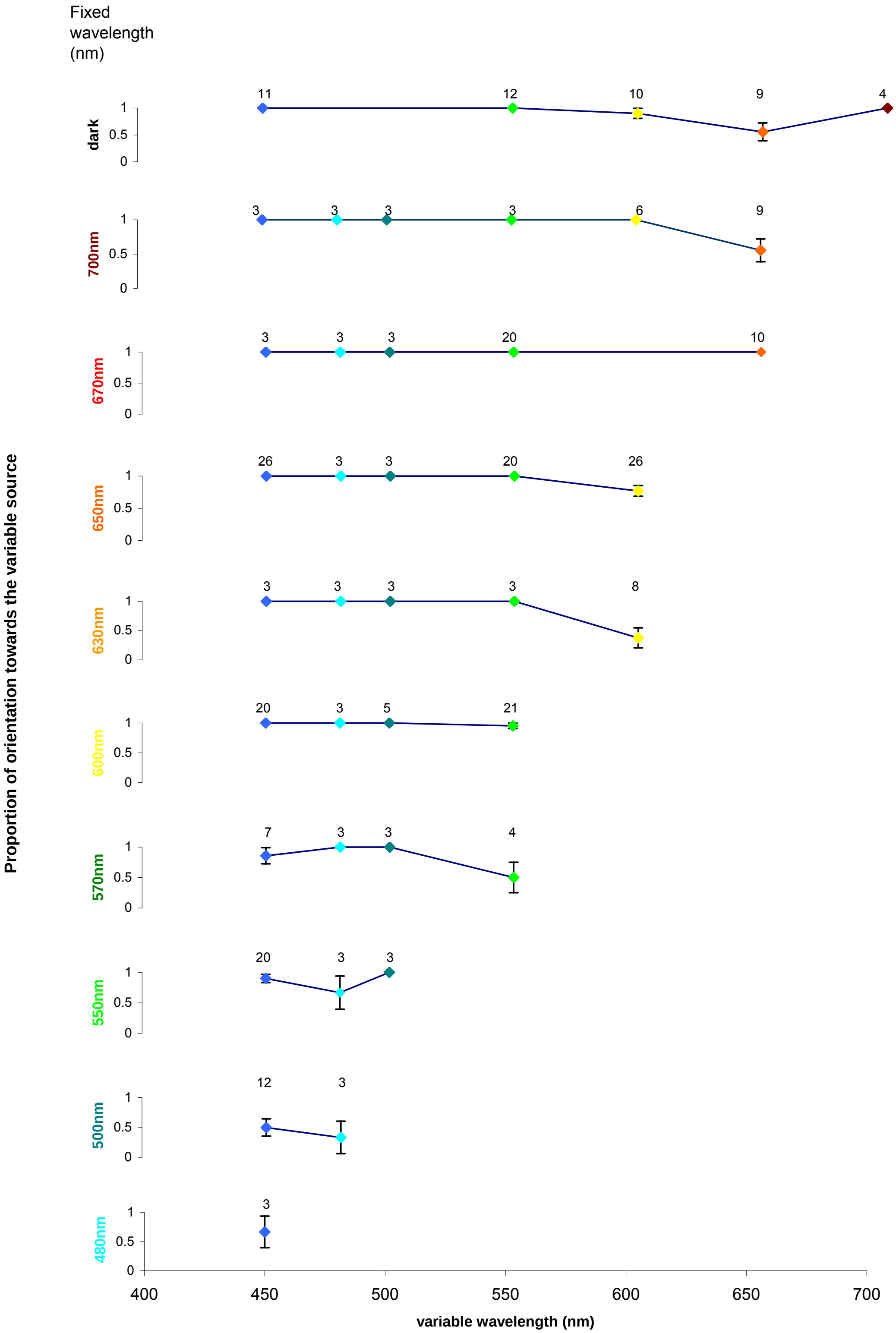


Figure 4.6: Barrow Island flatback hatchling wavelength choice results. Proportion of flatback hatchlings selecting the variable wavelength over the fixed wavelength. Standard error bars are provided (where n=2 the bars indicate the range).

Table 4.2 Logistic regression equations and significance of regression terms for the proportion of animals selecting the shorter wavelength option.

species	variable	B (Coefficient)	Exp(B)	S.E.	Wald χ^2	df	P	
Green turtle	SHORTWL	-0.031	0.970	0.076	0.16	1	0.687	n.s
	WLINDIFF	0.451	1.570	0.174	6.76	1	0.009	**
	SOURCE (FACTOR)				6.13	1	0.013	*
	Constant	2.275	9.731	0.868	6.86	1	0.009	**
Hawksbills	SHORTWL	-0.069	0.934	0.058	1.43	1	0.232	n.s
	WLINDIFF	0.432	1.540	0.107	16.15	1	0.000	***
	Constant	1.218	3.380	0.433	7.93	1	0.005	**
Flatback	SHORTWL	-0.033	0.967	0.053	0.39	1	0.530	n.s
	WLINDIFF	0.315	1.370	0.095	11.06	1	0.001	**
	SOURCE (FACTOR)				7.12	3	0.068	n.s
	Constant	20.47036	8.E+08	15176.36	1.82E-06	1	0.999	n.s

The variable SHORTWL refers to the index value of the shorter wavelength of the two choices; WLINDIFF is the difference in the index values of the two wavelengths; and SOURCE is a factor referring to the alternative light source configurations used in the experiments. The form of the logistic regression equation for each species is:

$$\frac{p}{1-p} = Exp^{[\,Constant + LOWWL \times B_1 + WLINDIFF \times B_2 + SOURCE(i)\,]}$$

Where *p* is the estimated probability of animals selecting the shorter wavelength option, and the term SOURCE(i) is omitted for hawksbills where only a single source configuration was used.

4.5 Discussion

This study is most similar to a set of experiments conducted by Witherington (1992) who tested loggerhead, green turtle, hawksbill and olive ridley hatchlings against variable wavelengths while holding the fixed light source at either 520 nm or a darkened window. He used the 520 nm (green) wavelength as the fixed light source in his experiments as it had been identified by electroretinography studies as the most visible to green turtles (Figure 4.1). The closest wave length available for the study described here was 500 nm (blue/green). The results for trials comparing 500 nm with the variable wave lengths were plotted against Witherington's results and are shown in Figure 4.7 (green turtle hatchlings) and Figure 4.8 (hawksbill hatchlings).

The preferences of the Barrow Island green turtle hatchlings were similar to those shown by green turtle hatchlings in Witherington's experiment at all variable wavelengths when tested against the fixed 500 nm wavelength suggesting that Barrow Island green turtle hatchlings respond to light the same way as green turtle hatchlings elsewhere. That is, they favour shorter wavelength light over longer wavelength light within the 450 nm – 700 nm spectral range.

The comparison between the hawksbill results was less clear cut (Figure 4.8). Unlike the hawksbills hatchlings in Witherington's experiments the Varanus Island hawksbills selected the shorter wavelength (450 nm) less frequently than 500 nm while the variable 480 nm wavelength was selected more often than 500 nm. From 550 nm onwards the Varanus hawksbills exhibited choices of shorter wavelength over longer wavelengths similar to the hawksbill hatchlings in Witherington's experiment. The smaller sample sizes in the experimental setup for hawksbill hatchlings from Varanus Island may have influenced the robustness of these results.

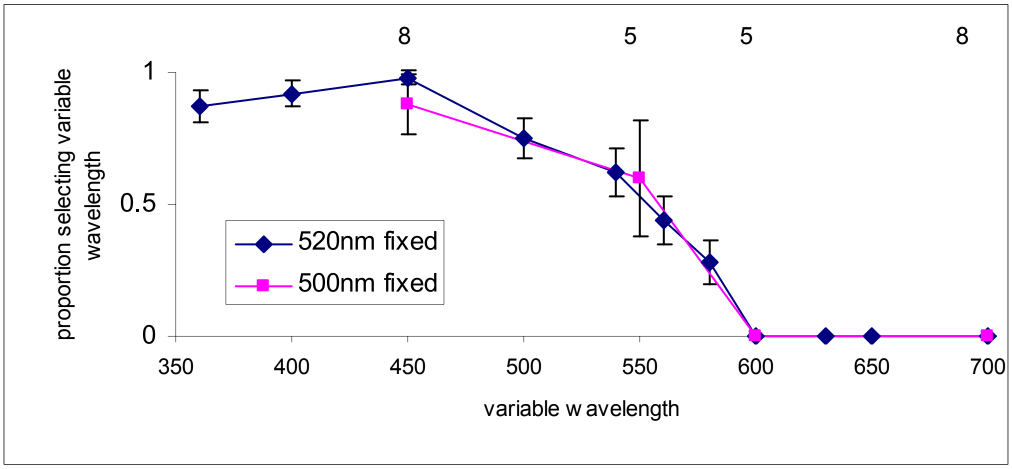


Figure 4.7: Green turtle hatchlings. Comparison of Witherington's results using 520 nm as the fixed wavelength (n = 30 per trial) with test results from this study using 500 nm as the fixed wavelength. The number of Barrow Island flatback hatchlings used per trial is shown above the appropriate data point on the plot. Standard error bars are included where the proportions are not 0 or 1

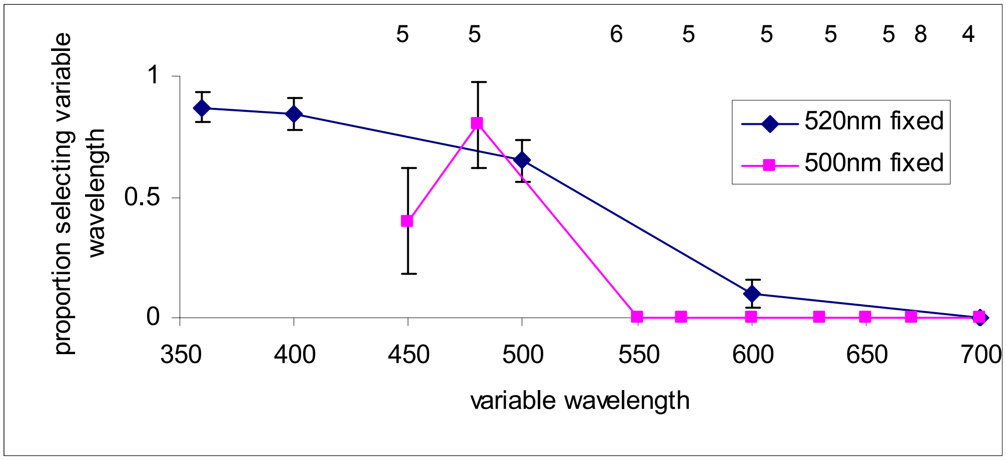


Figure 4.8: Hawksbill hatchlings. Comparison of Witherington's results using 520 nm as the fixed wavelength (n = 30 per trial) with test results from this study using 500 nm as the fixed wavelength. The number of Barrow Island hawksbill hatchlings used per trial is shown above the appropriate data point on the plot. Standard error bars are included where the proportions are not 0 or 1

Aside from the anomaly in the hawksbill experiment, the results indicate that the Barrow Island green turtle and Varanus Island hawksbill hatchlings response to light is not substantially different to hatchlings tested overseas. Since flatback turtles are not found overseas and have never been tested for light prior to this study the results of the Barrow Island flatback trials (fixed = 500 nm, n=3-12 animals per trial) have been compared with

Witherington's green turtle and hawksbill results (n=30 animals per trial fixed = 520 nm) in Figure 4.9.

The flatback results suggest that the hatchlings did not respond to shorter wavelength light in the same way as the green turtle and hawksbill hatchlings. The flatback hatchlings did not select the shorter wavelength over the longer wavelength more frequently for variable wavelengths between 450 nm and 500 nm (50% of the time for 450 nm and 33% of the time for 480 nm). These results suggest the blue (450 – 480 nm) light was no more attractive than the green (500 nm) light. However for combinations of a fixed 500 nm (green) versus variable, 550 nm – 700 nm (bright green through to red) wavelengths the 500 nm was selected 100% of the time.

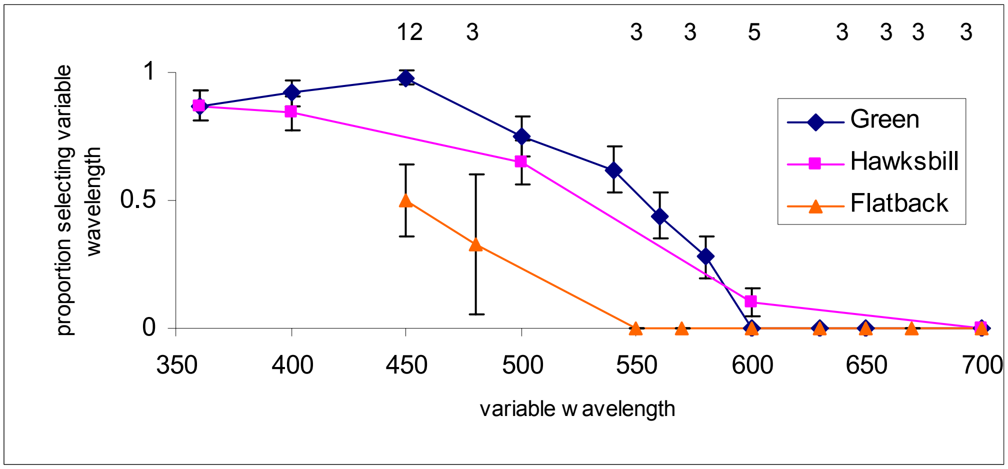


Figure 4.9: Comparison of Witherington's results for hawksbill and green turtle hatchlings using 520 nm as the fixed wavelength (n = 30 per trial) with Barrow Island flatback hatchling response using 500 nm as the fixed wavelength. The number of Barrow Island flatback hatchlings used per trial is shown above the appropriate data point on the plot. Standard error bars are included where the proportions are not 0 or 1

A comparison between Witherington's results for green turtle and hawksbills selecting between variable wavelengths and a fixed dark choice is shown in Figure 4.10 along with the Barrow Island flatback results. The response of flatback hatchlings to the variable light sources is very similar to Witherington's green turtle and hawksbill results. Flatback hatchlings selected the variable wavelength over the dark option for wavelengths up to 550 nm. At 600 nm and 650 nm they began to choose the dark option more frequently before selecting 700 nm over dark every time. Although this could be an intensity response rather than a sensitivity to wavelength alone, these results suggest that flatback hatchlings do not display the same type of aversion to yellow light as has been documented by Witherington (1992) in loggerheads. It also suggests that as the variable wavelength increases from yellow to orange light the attractiveness of these wavelengths over dark decreases.

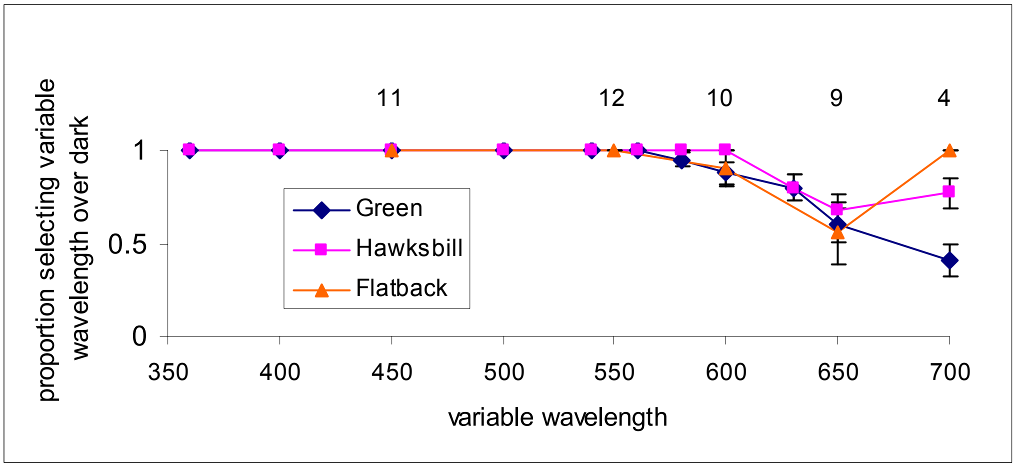


Figure 4.10 Comparison of the proportion of green turtle, hawksbill and flatback hatchlings selecting the variable wavelength over the fixed (dark) wavelength. Witherington results green turtle and hawksbill hatchlings (n = 30), Barrow Island flatback turtles, (n shown above appropriate data points). Standard error bars are included where the proportions are not 0 or 1

This lack of attractiveness to blue light may be a result of the differences in flatback reproductive potential and ecological strategies relative to green turtle and hawksbill turtles. Of the three species studied the flatback turtle lays fewer but larger eggs than greens and hawksbill turtles (Miller 1996). The increase in the size of flatback eggs and hatchings has been achieved by reducing the number of eggs in the clutch as opposed to increasing the size of the adult (Limpus, Colin J. *et al.* 1984b). The large size of the flatback hatchlings reduces the predation rates by crabs, birds and some marine predators relative to the smaller green turtle and hawksbill hatchlings (Limpus, Colin J. *et al.* 1984b).

With the exception of flatback hatchlings, most neonate sea turtles are thought to disperse to (low turbidity) open ocean nursery habitats (Walker and Parmenter 1990). Flatbacks lack a pelagic stage in their life cycle and instead remain in turbid near shore waters (Walker 1991; Musick and Limpus 1996). The large size of the flatback hatchling combined with a rapid growth rate is thought to improve the survivorship of this species in their neritic nursery habitat. Additionally the high turbidity of the 5-20 m depth range that most flatback juveniles are found reduces the visibility of these small sized turtles to predators (Walker 1991).

The turbidity, and related light penetration, of the flatback habitat may also influence the way this species responds to the different light wavelengths. Light attenuation with depth is shown in Figure 4.11 below. In the near shore turbid waters favoured by flatback turtles the high levels of dissolved organic matter (humics) strongly inhibit the transmission of the light in the blue and violet (300 nm – 450 nm) range in addition to the longer wavelength (600 nm – 700 nm) orange and red light (Gross 1982). Approximately 90% of the light is attenuated within the top few meters of the water column in turbid water while ~ 50% of light can penetrate to the same depth in clear ocean waters.

Given the differences in the light penetration experienced by pelagic (hawksbill and green turtle) and neritic (flatback) hatchlings it is possible that the response of the flatback eye to light is adapted to shorter light intensities and narrower wavelength range (yellow/orange light) found in turbid water.

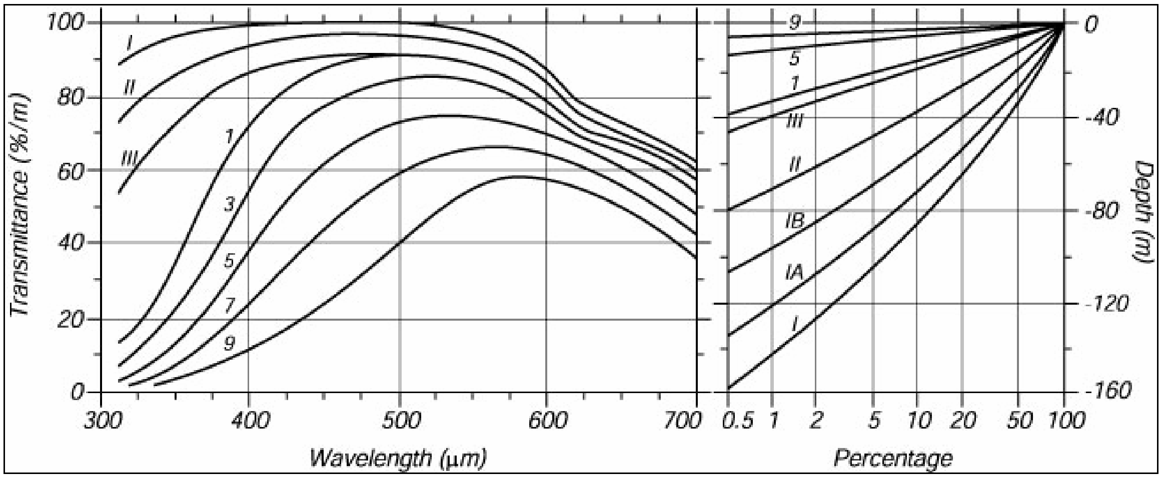


Figure 4.11: Left - Attenuation of daylight in the ocean. I is extremely pure sea water, II is turbid tropical-subtropical water, III mid latitude water and 1-9 coastal waters of increasing turbidity. Right – Percentage of 465 nm light reaching indicated depths for the same types of water (Source: (Stewart 2004).

Observations made during the experiments also showed a clear difference in hatchling behaviour (and consequent energy expenditure) following collection for the three species. Green turtle and hawksbill hatchlings continued to actively crawl within the dark holding box for up to ~8 hours, after which they would quieten down and appeared to rest. Flatback turtles however would become torpid soon after being placed in a holding box and were not roused until exposed to the light of the raceway apparatus. This difference in activity may be related to the differences in the location of the nursery habitat for this species. Unlike species with offshore open ocean nursery habitats flatback turtles do not need to spend the first 24-48 hours after emerging from the nest escaping from the near shore waters.

These results provide an indication of the response of green turtle and flatback hatchlings from Barrow Island and hawksbill hatchlings from Varanus Island to different light wavelengths and suggest that all three species favour shorter wavelength light over longer wavelength light regardless of where the combination occurs in the spectrum. They are less able to discriminate between wavelengths lying close to each other in the spectrum (*i.e.* similar colour hues). Flatback hatchlings may be less sensitive to shorter wavelength light than hawksbill and green turtle hatchlings. The behaviour of the three species was examined in a field situation in an attempt to quantify these effects under the influence of actual industrial light sources. The light sources typically used in an industrial setting were measured and characterised (Chapter 5) and these results were then used in conjunction with field based arena experiments with hatchlings (Chapter 6) as a case study to examine hatchling behaviour under real conditions.

Chapter 5 Spectral measurements of natural and artificial light sources

5.1 Introduction

5.1.1 Background

Oil and gas processing facilities are typically operated 24 hours a day. Illumination is therefore required for night shift operators working in and around facilities. Historically the most common type of light used in industrial settings are unshielded high pressure sodium vapour, low pressure sodium vapour, halogen, mercury and fluorescent lights, all of which are generally unshielded and elevated high above the facilities.

Preliminary spectral measurements of some of the light types present within the study area were made by CSIRO during the mid 1990s (Hick 1995; Hick and Caccetta 1997). These studies were done in response to industry and government concerns over the effects of flares and artificial light on sea turtle hatchlings. These preliminary studies provided evidence, based on the overseas literature, to suggest that the light types on the two islands could potentially be visible to sea turtles.

The primary aim of this component of the research project was to systematically identify and measure the spectral signature of lights typically used in an industrial setting on the NW Shelf, using the Varanus Island facility as a case study. At this time there was little readily available information on the spectral characteristics of artificial lights or flares. Consequently it was necessary to gather this information from the study site. These results identified the lights that, based on the findings of the two choice wavelength experiments in Chapter 4, were likely to be most attractive to hatchlings emerging onto light exposed beaches at Barrow Island and Varanus Island.

5.1.2 Research questions

1. What natural and artificial light types were present on Varanus Island?
2. What was the most common light type used on the island?
3. Which light types emitted the most attractive light to hatchlings
4. How does yellow filtering a fluorescent light bulb affect the spectral output both in terms of wavelength and power?
5. How does shielding a fluorescent light bulb affect the luminous intensity and illuminance of the light on a nearby nesting beach?

5.1.3 Chapter outline

The theory on light spectral characterization and measurement is summarized in section 5.2. A justification for the study site selection is given in section 5.3 along with a summary of the location and number of all of the light types present at the oil and gas facility on Varanus Island. The technical specifications and data manipulation for the light measuring instrument, and the data output, are also detailed in section 5.3. Furthermore the operating conditions of the four flares in use during the light survey on Varanus Island in 2000 are outlined in this section. The spectra recorded for each light type was used in conjunction with the hatchling light experiment results from Chapter 4 to assess which lights interfere with hatchling sea finding (Discussion, section 5.5).

5.2 Literature Review

The study of electromagnetic radiation between 200 nm and 30,000 nm is termed radiometry. Visible light is in the small region of the electromagnetic spectrum between 400 nm and 700 nm. The study of this visible region of the spectrum, in units that are weighted to the sensitivity of the human eye, is called photometry. The artificial light sources used in the oil and gas facilities all emit in the visible range of the electromagnetic spectrum. White light consists of a mixture of the different wavelengths, and therefore colours, of light. The colour spectrum of visible light is shown below.

<400 ultra-violet	400-450 violet	450-500 blue	500-570 green	570-590 yellow	590-610 orange	610-700 red	>700 infra-red

As light radiates away from a point source it spreads out. The amount of illumination received by a sensor (or eye) therefore varies inversely with the square of the distance from the point source. So if the distance from a point source is doubled the intensity falls off by a factor of 4. Tripling the distance decreases the intensity by a factor of 9 and so on. As the distance from a point source increases the intensity of the light that can be detected decreases. In a field situation a light may therefore have a high radiance level, however the amount of light reaching the nesting beaches (irradiance) may be relatively small depending on the distance between the two.

The two main sources of artificial light at oil and gas facilities are incandescent and gas discharges. Incandescent sources can be anything that produces light when heated to 1000°K or more. A natural incandescent light source is the sun. Man made sources are tungsten filament light bulbs which produce light by passing a current through a tungsten filament which causes it to become hot and glow.

Gas discharge lamps operate by passing an electric charge through a gas to produce light. These lamps contain an easily ionized gas (typically Argon) that emits light and heat when an electric voltage is passed across electrodes. The heat produced by this arc of electricity then vaporizes the metal contained within the lamp. These metal vapours produce light as the pressure and temperature within the arc tube rises. The colour of the light is a function of the gas used. High pressure light sources will produce a more intense light relative to a low pressure sources (*i.e.* high pressure sodium vapour vs. low pressure sodium vapour).

Lights are generally described using a spectral power distribution plot of energy as a function of wavelength. This is a visual profile of the colour characteristics of a specific light source. A light type emits different amounts of energy at each wavelength across the visual spectrum. The graph of the power emitted across the spectrum is termed the Relative Power Distribution Curve, or more commonly the spectra, for that light source. A spectra was collected for each of the light types on Varanus Island.

5.3 Methods

5.3.1 Study site selection

Measurements of lights typically found in industrial situations were made at Varanus Island. This location was selected as the study site for this component of the research program because;

1. hatchling misorientation has been noted on the island beaches (see Chapter 6),
2. logistically it was the most efficient place to conduct this work , and

3. both gas flares and electric lights were present and visible at many of the nesting beaches (within the 1.5 km radius proposed by Limpus 2002, as a dark buffer zone around nesting beaches).

Two shielded gas flares are also present on Varanus Island, the Harriet and the East Spar Ground Flares. Under normal operating conditions these flares operate full time. Two unshielded, elevated, flares are also present: the East Spar Elevated Flare and the Harriet Elevated Flare. Gas production is automatically diverted to one or both of these flares when processing plant upsets cause non routine operating conditions.

Offshore facilities associated with the Varanus Island processing hub include the Harriet A platform and gas flare, and various smaller platforms that are illuminated at night for navigation purposes. Periodically, other offshore light sources may be present in the vicinity of Varanus. These include jackup drilling rigs, work boats, pipe lay construction barges, seismic vessels and pearl boats.

5.3.2 Light sources

Representative anthropogenic electric lights and gas flares (under routine and non routine operating conditions) that were present on Varanus Island between January 2000 and June 2000 were measured for their spectral characteristics. A summary of the type and power of the lights on Varanus Island is listed in Table 5.1 (light audit results, March 2000).

The locations of these lights are shown in Figure 5.1 and summarized below.

1. Incandescent
    - Flares. Harriet Elevated Flare and pilot light, East Spar Elevated Flare, East Spar Ground Flare and Harriet Ground Flare
    - Halogens; mounted on tall poles or structures on the East and West jetties, workshops, the helicopter hanger, the path to the bottom camp and the painters shed.
2. Gas discharge
    - Fluorescent lights; mounted on tall poles within the process plant area on the wind sock, power house and riggers shed.
    - Sodium vapour; used as street lights, as bollard lights on the east jetty and within the plant are.
    - Metal halide, on the tennis courts.
    - Mercury vapour; in the LTS plant, at the helipad, on the *Ensco 56* drilling rig and on supply barges and work boats.

Table 5.1: Light types, wattages and number of fixtures documented on Varanus Island during a light audit in March 2000.

Light type	Wattages	Number of fixtures on Varanus Island
Fluorescent	18W – 36W	300+
Halogen	500W, 1000W, 1500W	22
Sodium vapour	125W, 500W	10
Mercury vapour	125W, 150W, 250W	8
Metal halide	1000W	4
Shielded ground flare	-	2
Unshielded elevated flare	-	2

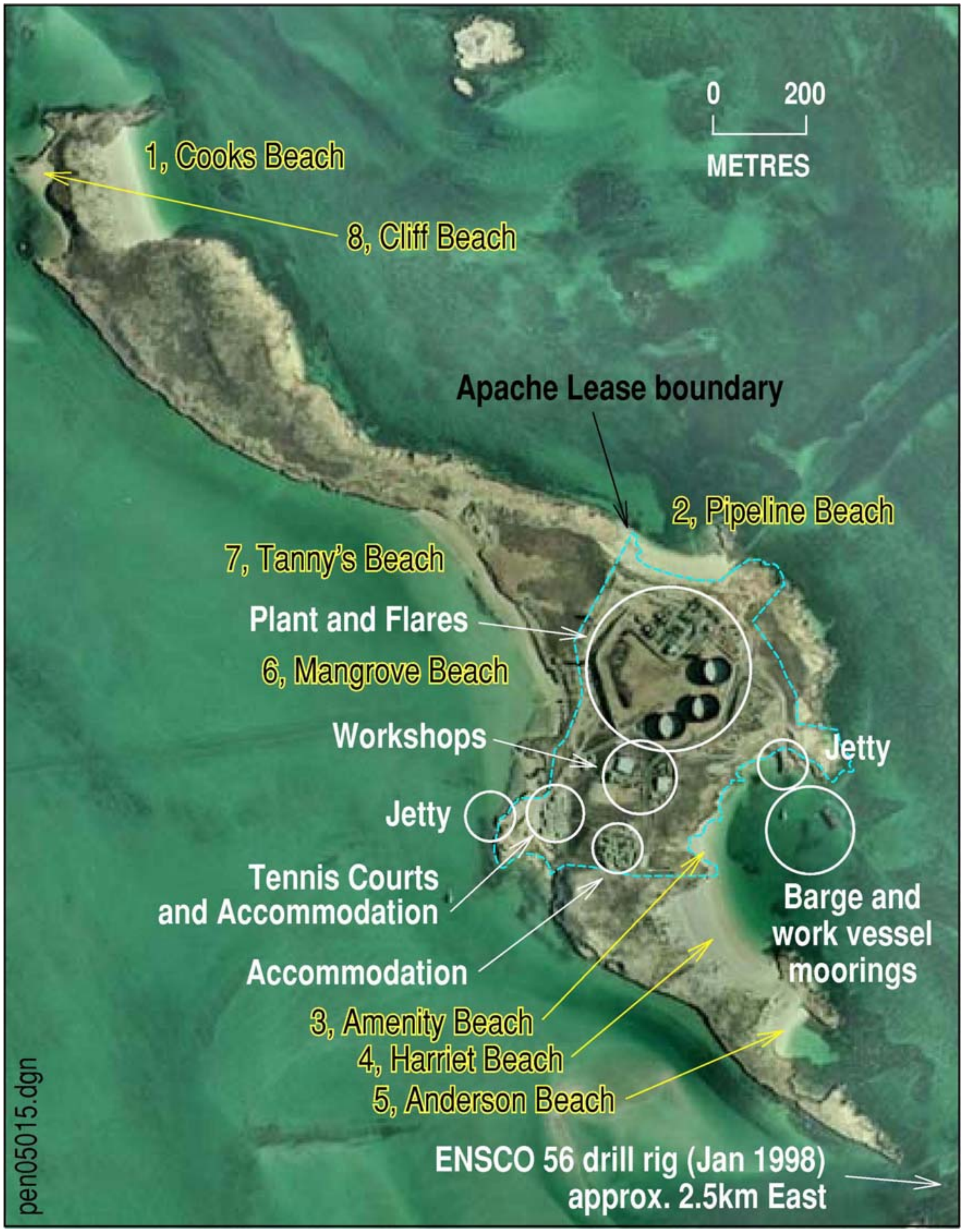


Figure 5.1: Location of artificial lights at Varanus Island (March 2000).

5.3.3 Equipment

Spectral characteristics of anthropogenic and natural light sources were collected using an Ocean Optics miniature fibre-optic spectrometer supplied by LasTek, Thebarton, South Australia (www.lastek.com.au). This unit measured spectral response using holographic diffraction gratings in the 350-850nm range. It was linked directly to a lap top computer running SpecSolv Jr.™ software that allowed for real time display and recording of spectra. The instrument was initially developed for laboratory applications by the Perth based CSIRO Remote Sensing of Mine Environment, Minesite Rehabilitation Research Program.

The unit was adapted to field application with the addition of a simple lens which focused light onto a 400 μm optical fibre. The lens had a <3° Field of View and better than 98% transmission over the full wavelength range. The output has a ±3 nm error in measured spectra (pers comm. C Ong). Several measurements of each source were made and only those spectra with maximum signal were retained.

Wavelength was calibrated against a standard Mercury Argon light source. All spectra are in units of voltage (i.e. millivolts). The spectra provided information on the specific wavelengths of each light source, relative heights and positions of peaks within each spectra, the decay of the peaks with distance from the sources and the effects of filtering and shielding materials on different light sources.

SpecSolv Jnr software was developed by LasTek Pty Ltd for use with the Ocean Optics miniature spectrometer. It displays the data graphically in real time and saves the results to disk. It allows the user to set integration time, number of scans in an integration cycle and to calibrate the spectrometer. The data files were all converted into excel files for further processing and graphing. The operating system for the spectrometer was limited in its ability to quantify the light spectra. The spectral signal strength was measured in millivolts and while it cannot be converted into a standard light unit (*i.e.* Lux or uW/cm^2/nm) the scale does allow for relative comparison of light emission spectra.

5.3.4 Data manipulation

Standards were run at the commencement of each batch of light measurements. A standard Mercury/Argon light source was used and all the field wavelength measurements were calibrated against this source. Spectra were collected from the dark night sky to check that no other source of light was interfering with the spectral measurements of the artificial light sources. These control spectra were indistinguishable from the spectrometer detector noise.

5.3.5 Flare operating conditions

Flares are a critical component of the oil and gas processing system, providing a way to safely vent the gas responsible for high pressure levels in the plant equipment, pipe work or vessels. Flares are also used to prevent the explosion hazards associated with air ingress in to the gas system. Three flares were operating on Varanus Island during this study. The East Spar Ground Flare, the East Spar Elevated Flare and the Harriet Elevated Flare. At the time of this study none of the flares were fitted with flow meters, consequently the flow rates quoted are estimates made by the Field Engineer on site in January 2000.

Under routine operating conditions during 2000 the bulk of gas production at Varanus Island (~99.75%) was sent to the mainland via two 16” Sales Gas pipelines. In 2000 this equalled approximately 39 million std cubic foot per day. The balance of the gas was burnt in the shielded Ground Flare. Under non routine operations, which typically arise from processing plant upsets, all or part of the Sales Gas volume was diverted to the East Spar Elevated flare and/or the Harriet Elevated Flare. These flares were not shielded and were elevated approximately 35 m above the ground. They both had small pilot lights that allowed immediate ignition of the gas under increased flow rates.

The Elevated flares were also used in non emergency situations. During periods when project work was occurring on or near Varanus Island (*i.e.* new oil or gas fields or process equipment was being installed, commissioned and integrated into the existing process system) the number of plant shut downs (planned and unplanned) typically increased and the diversion of sales gas to the elevated flares occurred for periods of hours on a daily basis to 24 hour flaring. For example for at least four months between March and June 2000 the elevated flares were used to burn the purge gas (normally sent to the Ground Flare) whilst the East Spar Ground Flare underwent maintenance (Plate 5.1). A slightly greater gas flow rate (~0.35% per flare) was used to ensure the flame was maintained on both flares for this period.

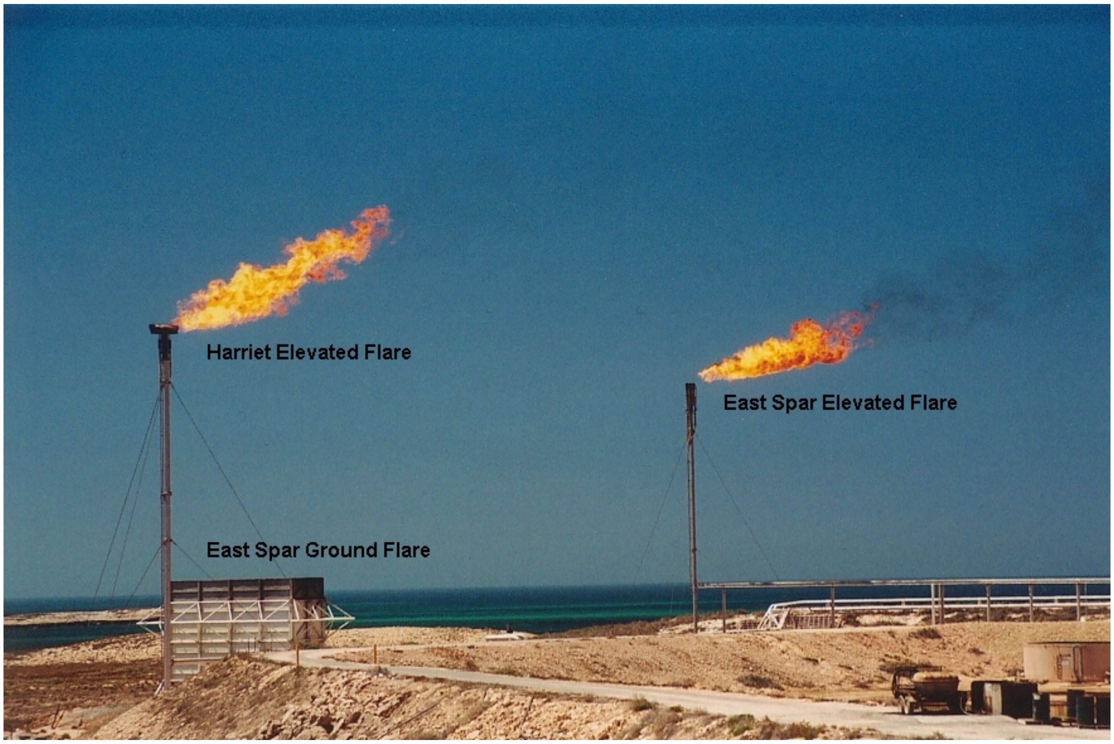


Plate 5.1: Flares operating under non-emergency shutdown conditions on Varanus Island 2000

5.4 Results

5.4.1 Natural sources

Measurements of the background deep sky radiance were taken in March 2000. Deep sky radiance was not detectable over baseline noise.

Spectral measurements of a rising full moon (~10° above the ocean) and a risen full moon (~80° above the ocean) are shown in Figure 5.2. The rising moon data is presented here for two different detector settings. The spectrum for a gain of 8 is used to show the detailed characteristics for the rising moon for comparison with a risen moon. However for comparison of the spectral characteristics of the rising and the risen full moon the spectra, at gain=1, is also presented for a rising moon.

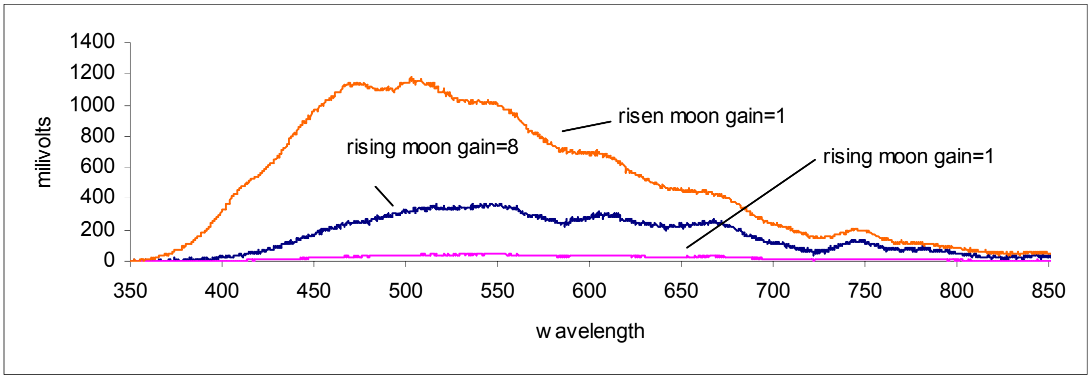


Figure 5.2: Rising full moon (gain = 8 and 1) and risen moon (gain = 1)

The rising full moon light spectra ranges from ~370 nm to >850 nm. There is a fairly equal distribution of light intensities across the range with the largest peak occurring at 550 nm. The rising moon is deficient in the blue components that are present in the risen full moon, as a result of scattering of the light through the atmosphere as the moon rises above the horizon. The peak intensity light from the risen full moon was shifted slightly to the shorter wavelengths, occurring at 506 nm.

A risen full moon can produce light that swamps the visibility of all other artificial light sources (Hick 1995). Unlike a flare or an electric light, moonlight lights up the entire sky and diminishes the relative brightness of these other point light sources to the viewer. Throughout a single lunar cycle the relative brightness of the artificial lights will therefore fluctuate as a function of the moon phase.

The spectral fingerprint for day light measured by pointing the spectrophotometer collector directly overhead at 1100 hrs on a cloudless sunny day is shown in Figure 5.3. This light is concentrated in the short wavelength 350 nm to 500 nm (violet, blue, green range) with minimal contribution from wavelengths greater than 600 nm (yellow, orange and red light).

The peak intensity occurs at 450 nm. Relative to all other natural or artificial lights measured, daylight has the greatest weighting towards the uv, violet and blue end of the spectrum.

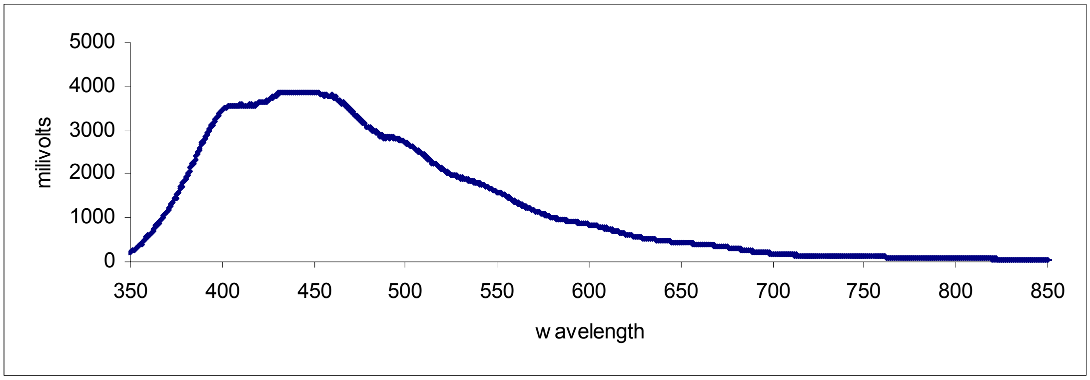


Figure 5.3: Daylight, 1100 hrs

5.4.2 Flares

The light spectrum produced by the Harriet Elevated Flare pilot light is shown in Figure 5.4. The pilot light consisted of a very low flow rate of flare gas, enough to keep a flame lit. The spectra is a continuum between 370 nm and >850 nm, centred on 650 nm with secondary peaks at 600 nm and 720 nm. When the flow rate to the elevated flare was increased to 0.35% of total plant production in January 2000, the spectra (tagged operating flare in Figure 5.4) shifts slightly to the right relative to the pilot light flame. The intensity of the operating flare light was increased by an order of magnitude over the pilot flame and the spectra centred on 750 nm, with a secondary peak at 620 nm (Figure 5.4).

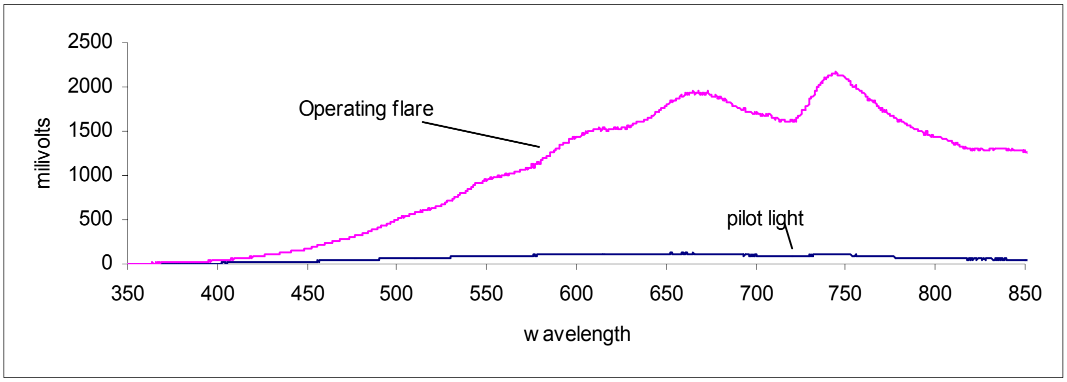


Figure 5.4: Harriet Elevated Flare pilot light and operating flare, measured at 200m distance.

Night time observations from Varanus Island beaches in early 2000 indicated that the pilot flame was barely visible from adjacent beaches. However, when all or part of the sales gas flow was diverted to one or both of the elevated flares (Harriet or East Spar), either the flame or the glow from these flares can be seen from all of the Varanus Island beaches. Visibility was a function of beach location and/or gas flow rates. This is demonstrated in Plate 5.2 which shows the light spill onto Tannys Beach during the operation of the Harriet Elevated Flare in March 2000. The gas flow at that time was slightly greater than the volume that normally is burnt in the Ground Flare (0.35% of total production). However, it was not representative of the much greater flow rates that were burnt through the flare under emergency shut down conditions.

The height, intensity and areal extent of the both of the elevated flares was significantly increased under emergency shut down flaring conditions. The flame produced under these conditions illuminated a larger proportion of the Varanus Island beaches and was also visible from adjacent islands of the Lowendal Group.

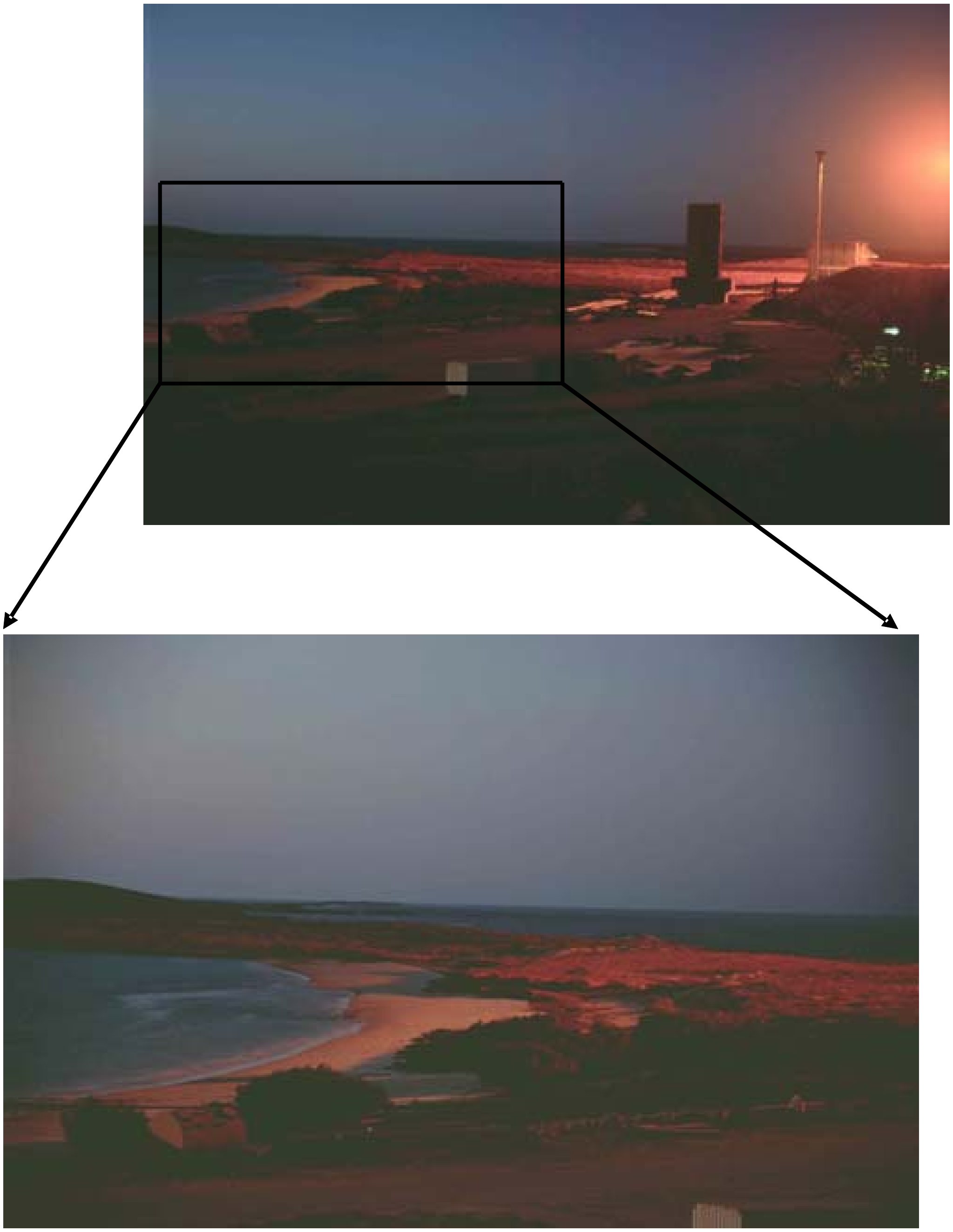


Plate 5.2: Light from the Harriet Elevated flare (right of photo in top plate) falling on Tannys and Mangrove Beaches, March 2000.

An attempt was made to measure the glow over the top of the shielded East Spare Ground Flare. This measurement was made on a cloudless calm night. The spectral response was indistinguishable from the detector noise.

Similar studies on the spectral characteristics of oilfield gas flares were carried out at Thevenard Island in 1995 (Hick 1995). The spectral characteristics of the Thevenard flare were similar to the flares measured as part of this study.

5.4.3 Electric lights

Four types of light are typically used on Varanus Island; halogens, mercury vapour, metal halide and fluorescent. At the inception of this project the information on light spectra was not readily available. Hence the need to generate spectra for the industrial light sources studied here. The spectra for each of these light types are shown below.

Halogens

Halogens (500 W – 1000 W) were located on 6m tall poles on both jetties and on the painters shed adjacent to the western jetty. Halogens are commonly used both within the onshore plant area and as deck lighting on workboats, barges and pearling vessels They are high intensity lights that produce a broad light field for large work areas. An example of the halogen light spectra is shown in Figure 5.5. Emissions are continuous across the spectrum peaking at 515 nm.

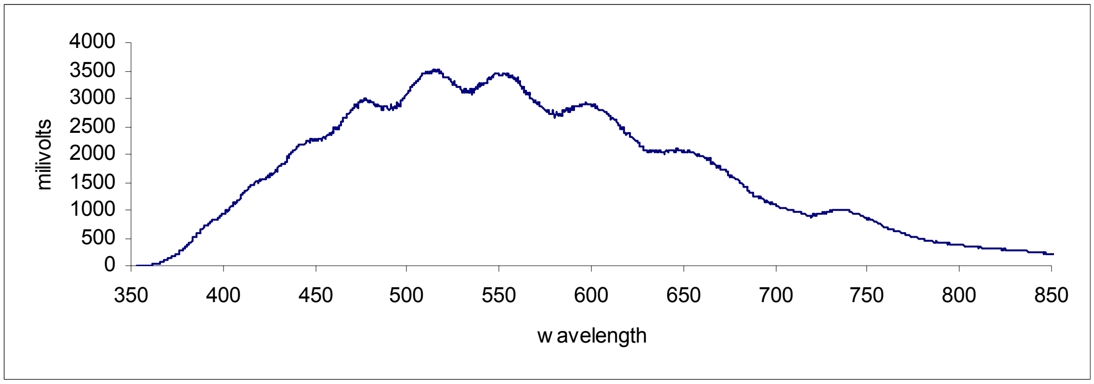


Figure 5.5: Halogen light on the jetty, measured at 30 m.

Mercury vapour – Metal halide

These very bright white lights are used to illuminate the main deck of the *Ensco 56* offshore drilling rig (Plate 5.3), the work deck of the supply barge, the walkway within the LTS plant and the tennis courts.

Mercury vapour and metal halide (mercury vapour lamp with metal halides added to the tube) lights are high intensity lights that have no emissions in the red region of the spectrum (>610 nm). One of the four 1000 W metal halide lights over the tennis court (Figure 5.6) was measured from 50 m away. These lights emitted sharp peaks at 410, 433, 475, 510, 547 and 590 nm, encompassing the entire ultra-violet, blue green, yellow and orange light within the 377-610 nm spectral range.

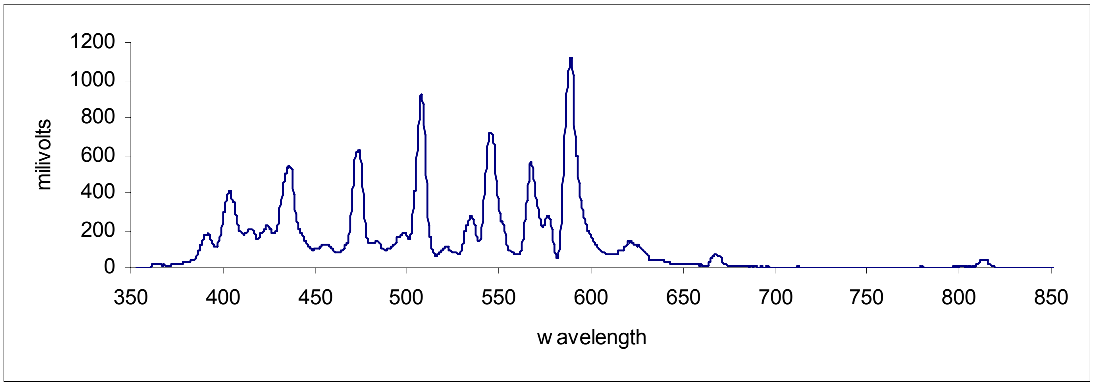


Figure 5.6: Metal halide on Tennis courts from 50m.

The barge lights were measured whilst the vessel was moored in Harriet Bay, approx 350 m from the measuring location at Harriet Beach (Figure 5.7). These large flood lights were used to illuminate the back work deck of the vessel (125 – 250 W). The spectral peaks are less distinct than the tennis court lights with only two distinct peaks (at 420 nm and 536 nm) discernible within the broad emission envelope. This spectrum does not extend beyond 550 nm, being wholly confined within the violet, blue and green region.

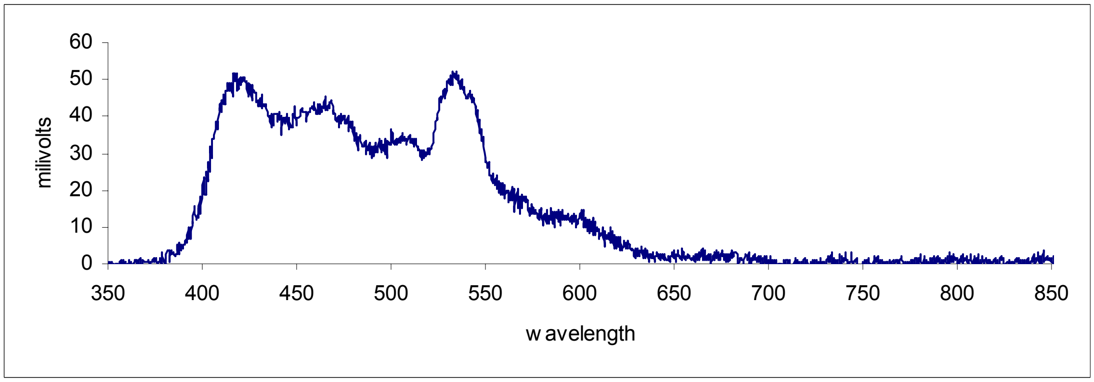


Figure 5.7: Mercury vapour floodlights on barge, measured from 350 m at Harriet Beach

The 125W mercury vapour lamp in the LTS plant (Figure 5.8) is typical of the older style (green tinted) mercury vapour lamps used in industrial work sites. The emission spectrum is distinct in its total lack of blue light between 450 and 530 nm. The light is characterized by dual peaks at 405 nm/433 nm and at 543 nm/575 nm.

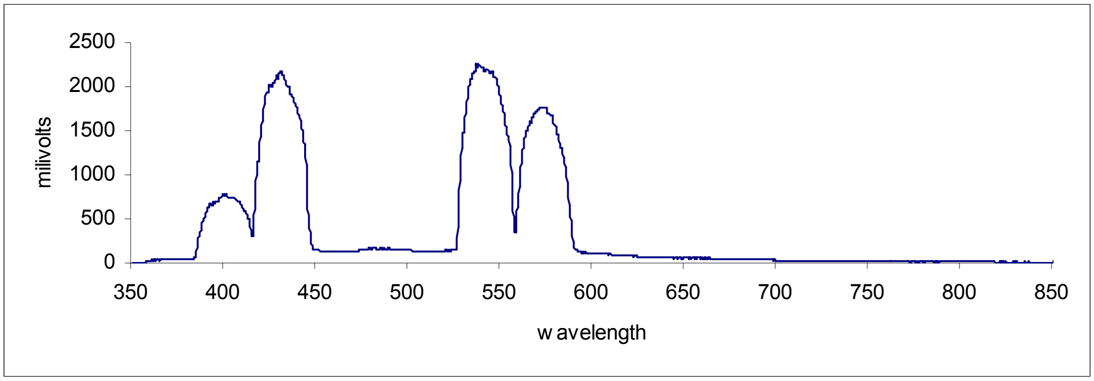


Figure 5.8: Mercury fluorescent, LTS plant, from 50m.

The light emitted from the *Ensco 56* (Figure 5.9) was measured across a distance of ~1.5 km. At that distance it was not possible to target a single light source on the rig and so the spectrum is representative of the light field for the whole rig (Plate 5.3). The spectrum shows a distinct mercury vapour fingerprint with sharp peaks at 405 nm, 435 nm, 541 nm and 577 nm.

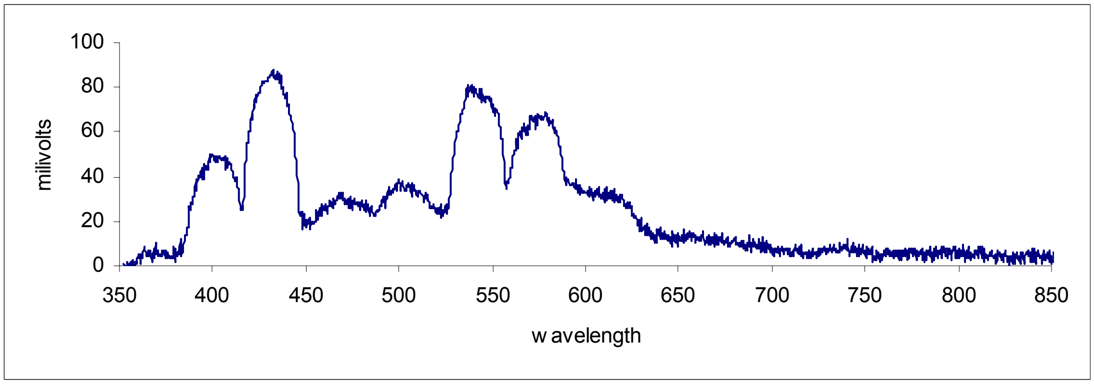


Figure 5.9: *Ensco 56* light field, measured from Varanus Island over 2 km distance

Plate 5.3:The drilling rig *Ensco 56* light field photographed from 1.5 km, 70-200 mm zoom lens

High pressure sodium vapour

These lights are almost pure yellow/orange light. Three sodium vapour lights were measured on Varanus. These were; road light (Figure 5.10), jetty bollard lights (Figure 5.11) and on the pig launcher behind Pipeline Beach (bare vs. shielded, Figure 5.12).

The main emission peaks for all of these lights were centred on the 570-600 nm region. Small peaks also occurred at 466 nm and 500 nm. The purest yellow light was produced by the jetty bollard lights with two sharp peaks at 567 nm and 590 nm. Slightly more orange was present in the road light with the dominant peaks occurring between 569 and 596 nm. Both these lights also had a secondary blue peak at 500 nm. Both lights were measured from a distance of ~100m.

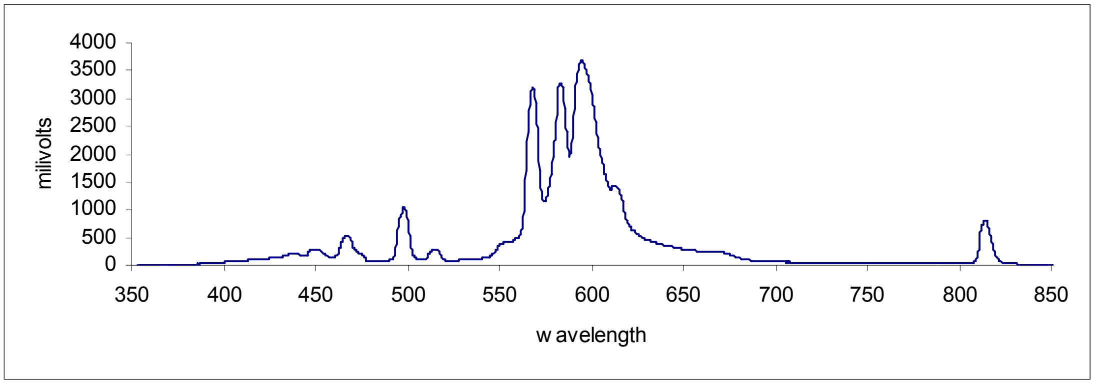


Figure 5.10: Sodium vapour, road lights

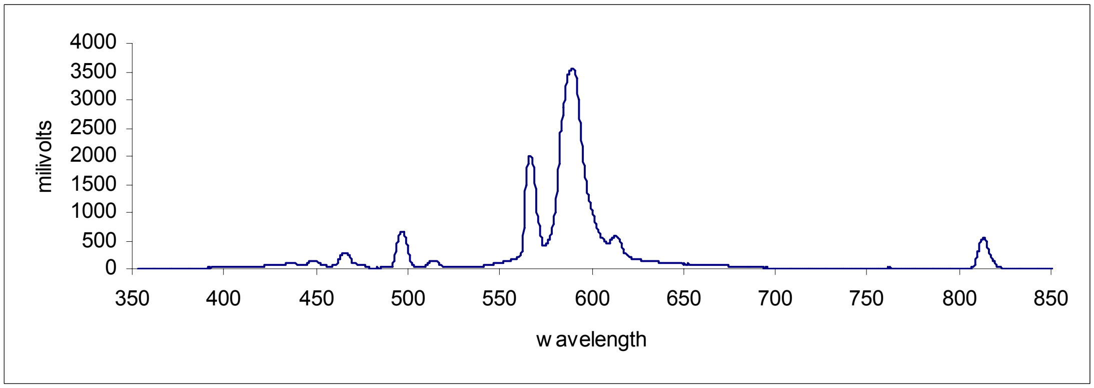


Figure 5.11: Sodium vapour, orange bollard lights on jetty

The sodium vapour lights measured in the plant were on the 16" pig launcher behind Pipeline Beach. One of these lights was physically shielded from the beach (facing away from it) the other was not shielded and was directed towards the beach. The results are shown in Figure 5.12. The relative light signal from detectable at 100 m from a shielded sodium vapour light (as measured in millivolts) was approximately 85% less intense than the bare light. This result displays the benefits of shielding these lights.

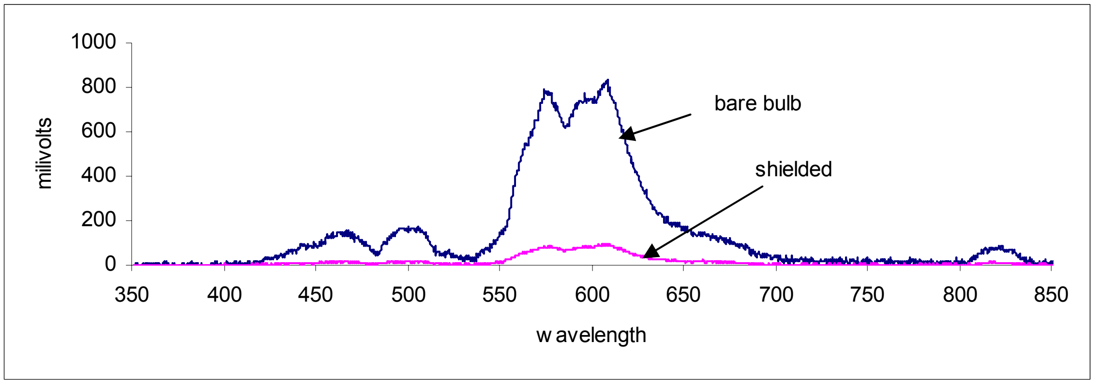


Figure 5.12: Sodium vapour lights on pig launcher, shielded and non shielded, from 100m on Pipeline Beach

Fluorescent light

The fluorescent lights on Varanus Island make up the more than 85% of the lighting sources on the island. Twin tube 18W and 36W fixtures are located atop high poles over all vessels and equipment within the plant area. The total number is estimated at well over 200 fixtures.

The majority of the light emissions that illuminated Pipeline Beach were fluorescent lights. This is shown in Plate 5.4.

Plate 5.4: Light field behind Pipeline Beach

The fluorescence light sources visible from Pipeline Beach were measured both from within the plant (10-20 m distance) and from Pipeline Beach (100-150 m away). The results are shown in Figures 5.13 to 5.15.

The spectra show a consistent spectral fingerprint for every source. They all are characterized by a sharp peak at 440 nm and a second around 500-555 nm. Both of these peaks sit on a broad continuum of light between 390 nm and 715 nm. They contain very little red light and emit a bright white light into the atmosphere.

Figure 5.13 shows a fluorescent light measured directly from Pipeline Beach. This spectrum is compared with the light reflected from the side of a white painted vessel within the plant. The light produced by reflection from this solid surface is measurable and comparable in intensity to the light produced by a rising moon or the pilot flame on the elevated flare.

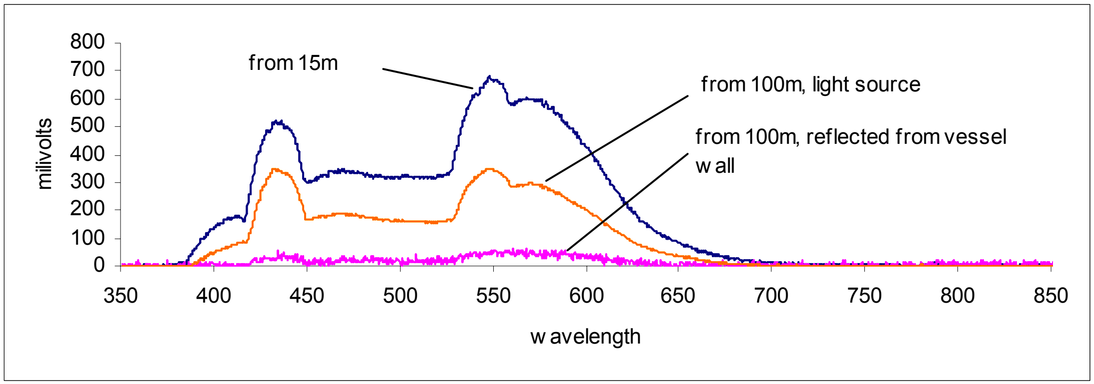


Figure 5.13: Fluorescent light on Rossette separator

Figure 5.14 shows the effects of wrapping yellow coloured filter paper around a fluorescent bulb within the plant area. This was done in an attempt to find a simple and economical method for reducing the short wavelength emissions from facility lighting. The filter removed approximately 60% of the short wavelength blue light at 440 nm falling to 10% at

600 nm. It is clear that the filter successfully reduced the intensity of light in the violet blue and green region. The filtered fluorescent light was also measured from two different distances (within the plant and Pipeline Beach) (Figure 14). The effects of filtering and distance on the light source produce a reduced intensity light that is almost completely depleted in the violet and blue light and diminished in the green region.

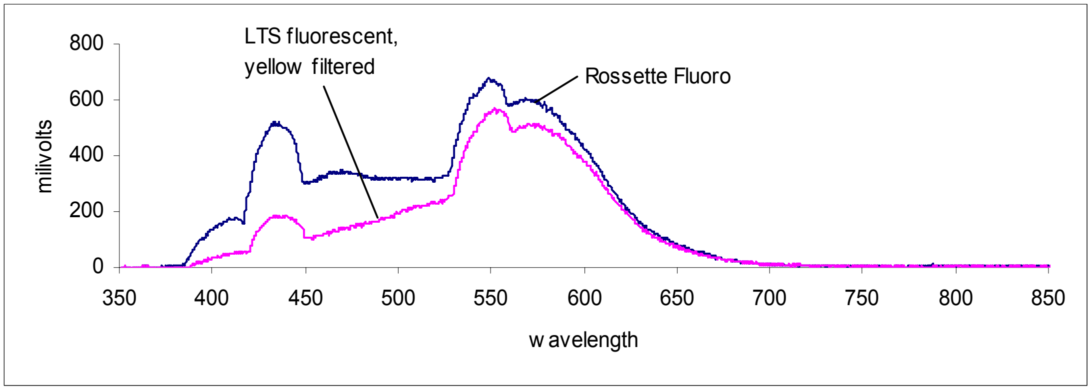


Figure 5.14: Fluorescent light with and without yellow filter, both from 100 m

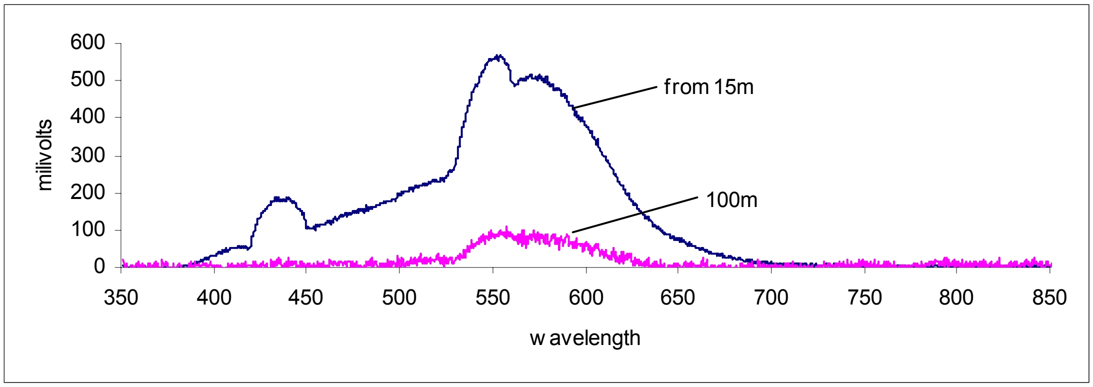


Figure 5.15: Fluorescent light with and without yellow filter from 15 m and 100 m

Qualitative observations

All the measurements made during this study were of point sources of lights. The spectrometer was not able to detect the very low light levels in the glow above the lights or in the light reflected from rocky surfaces. In the absence of quantitative measures for these low light sources, some qualitative observations were recorded and these are presented below.

On nights with cloud cover the entire light field over the island changed. Any light from the camp or processing facilities was reflected from the clouds. This resulted in a significant brightening of the sky over the plant and a relative darkening of the sky over the ocean. A similar effect is created from cloud cover above both the shielded Ground Flares and the elevated flares. On nights when there was no moon present and the lights immediately behind Pipeline Beach were switched off the lights from the eastern end of the plant were visibly reflected off the light coloured limestone rock face at the eastern end of the beach.

Depending on the viewing location, point sources of light were sometimes obscured behind physical barriers such as dunes or headlands. The effect is similar to that of the solar corona during an eclipse. While an unshielded light source is visible as a bright spot of light that blinds the eye to any other low light emissions the shielding of the central light source increases the visibility of the light glow caused by scattering in the atmosphere. The glow appears to brighten a broader area of sky than the point source.

Offshore drilling rigs or workboats located close to the island are often visible as bright halos of light behind dark headlands. The size of the light field varies in intensity depending on the distance from the source and the size of the light bulbs used. These halo glows are most highly visible on nights around the new moon.

Other indirect sources of light on the nesting beaches are reflected lights. Light reflected from the shiny white vessels in the plant were measured (Figure 5.13) however a second source of reflected light on Pipeline Beach that was visible but not measurable (below the detection limits of the spectroradiometer) was light reflected of the light coloured limestone rock at the east end of the beach. It is possible that this reflected light was a source of attraction for hatchlings on Pipeline Beach (see Chapter 6).

Numerous remote point sources of light are visible from Varanus Island. These primarily comprise the navigation lights on the offshore oilfield production structures located 5.5 to 7.5 km offshore or lights located on Barrow Island 10 km to the east. While the artificial point sources of light are slightly larger than stars on the horizon, they are of equal low intensity and insignificant relative to nearby lights or the moon.

5.5 Discussion

While sea turtle hatchlings see both ultra-violet and visible light, when given a choice they will select a lower wavelength light statistically more often that a higher wavelength (Witherington and Bjorndal 1991a, Chapter 5). The results form the experimental studies presented in Chapter 4 was used to identify the lights that have the biggest chance of misorienting hatchlings at Varanus Island. Hatchlings on Varanus Island beaches were primarily exposed to six light types; halogen, fluorescent, mercury vapour, metal halide, sodium vapour and flare light.

Halogen light spectral characteristics were weighted towards the short wavelength blue-green end of the spectrum. The results of the wavelength experimental trials (Chapter 4) showed that these lights contained the wavelengths that were most visible to sea turtles. An example of misorientation by vessel light was documented in November 2000. That night hatchlings emerging from a nest on the northern end of the Beacon Island were tracked as they crawled 200m along the beach towards the lights on a pearling vessel moored ~400m off the southern end of Beacon Island. These hatchlings ignored the ocean located 5 m and 90° from their line of travel.

The mercury vapour and metal halide lights were heavily concentrated in the short wavelength range relative to halogens and sodium vapour and had a similar emission range as fluorescent lights. These emissions are strongly attractive to all species of sea turtle hatchlings and can be considered extremely disruptive to hatchlings (Chapter 4). Mercury vapour lights (used to illuminate the back deck of some work boats and barges) were documented misorienting hatchling emergences on Harriet and Anderson's Beaches. The reflection of these lights off the white sand dunes backing Harriet Beach may also have been responsible for the misorientation documented on this beach.

The fluorescent lights on Varanus Island collectively produced the largest amount of light and glow in the sky over the island. The fluorescent lights were used almost exclusively within the process areas and were typically mounted on tall poles high above the equipment. None of them were shielded or directed onto specific work areas. Fluorescent light emit across the visible spectrum and strongly in the short wavelength region most attractive to sea turtles. Encasing the fluorescent bulb in yellow filter material reduced the short wavelength emissions reaching Pipeline Beach. Increasing the distance between the light source and the beach reduced the illuminance of the light at Pipeline Beach.

Low pressure sodium vapour lights were only used on the roadways and had limited visibility from the beaches. Of all the light types measured on Varanus Island these contained the least amount of disruptive short wavelength light with the major peaks occurring in the yellow and orange regions of the visible spectrum. These lights were classified as moderately disruptive by Witherington and Martin (1996) due to their widespread usage (primarily as road lights) and the associated documented misorientation of hatchlings.

Under normal, pilot light conditions, the light from the flares are unlikely to impact on hatchling orientation. However under non standard operating conditions the flare(s) were highly visible and while their emissions were weighted towards the least attractive (to hatchlings) long wavelength end of the visible spectrum they have been shown to be attractive to green turtle hatchlings on nights with no moon visible (Pendoley 2000). In the presence of moonlight, however, hatchlings will selectively crawl towards the ocean as opposed to nearby gas flares. Witherington (1992) classified open fires as moderately to highly disruptive depending on the size and temperature of the flame. The spectral power curves suggest the flare light does not contain a high proportion of the light wavelengths that have been shown to be disruptive to hatchlings. Consequently flares are not likely to be as disruptive to hatchlings as fluorescent, metal halide, mercury or halogen sources. However, at increased flow rates and in the absence of the moon this light will be visible and potentially disruptive to hatchlings (Chapter 4, Results)

Of the various light management methods available for minimizing light emissions, *i.e.* replace light types, physically shield source, relocate, redirect, filter etc., two were tested as part of this study. The two tested, filtering and shielding the light source, showed a decrease in the light visible on the nearby nesting beach. For example filtering the fluorescent lights with yellow film removed approximately 60% of the light emitting around 440 nm and approximately 15% of the light at 550 nm. When measured from 15 m distance, the same filtered fluorescent light measured from Pipeline Beach had an 80% decrease in intensity across the 150m distance.

Chapter 6 Field surveys - Hatchling orientation

6.1 Introduction

6.1.1 Background

Evidence for misorientation of hatchlings by road lights, stadium lights and city lights is strong (McFarlane 1963; Philibosian 1976; Peters and Verhoeven 1994; Witherington and Martin 1996; Hughes *et al.* 2002; Rusenko *et al.* 2002). The evidence from the wavelength preference presented in Chapter 4 further suggest that the light emissions from the oil and gas facilities identified in Chapter 5 would also misorient sea turtle hatchlings. The effects of these industrial light sources on hatchling orientation was therefore tested in the field under experimental conditions to determine if the light preferences found in the laboratory were influencing behaviour of hatchlings on nesting beaches or not. The findings from these experiments are the focus of this chapter.

During the course of these field based orientation experiments it became clear that there was a need to monitor the behaviour of hatchlings on many beaches. Performing orientation experiments on every beach that was exposed to industrial light was logistically difficult, given the remoteness of the study site and the resources (both personnel and equipment) required, and were impractical on an ongoing basis. A simpler method to efficiently monitor the behaviour of hatchlings *in situ* was required. A method to map nest emergence fans was therefore developed as part of this research program. Mapping tracks not only removed the need to carry out large scale experimental programs but also the need to be physically present when hatchlings are emerging, an important consideration when resources are limited.

6.1.2 Research question

The objectives of this chapter were to document and quantify the impact of oil and gas facilities on sea turtle hatchlings and to develop hatchling emergence fan mapping methods that could be simply incorporated into company environmental monitoring programs. The specific research questions explored were:

1. Can light effects be demonstrated under controlled conditions of light type, wattage and distance?
2. Can the effects of light be demonstrated under real world conditions on beaches in the vicinity of oil and gas processing facilities?
3. Can measurement of hatchling fan criteria retrospectively on beaches provide information on light impacts as a monitoring tool?

6.1.3 Chapter outline

The research was broken into three components. The methods and results for each of these components are presented separately. The effects of three of the most common light types identified in Chapter 5 were individually tested under controlled conditions to see if light in a field situation would cause misorientation of hatchlings. The intensity at which each light type might reduce the ability for hatchlings to find the ocean was also tested. The spectral characteristics of each light type were measured and the intensity of the light at different distances and power (Wattage) recorded. The effects of existing oil and gas facility light conditions on hatchling orientation was then tested using arena experiments on nesting beaches exposed to an oil and gas processing facility. The hatchlings were tested in the presence of different beach topographic features (eg did the effect of a shadowed headland affect hatchling orientation) and under moon and no moon conditions to assess the impact of natural conditions on hatchling behaviour. The final component of this work used a hatchling emergence fan mapping method to determine if it could be used to monitor misorientation of hatchlings *in situ*. The success of this method as a monitoring tool was explored. The results were then used to quantify the proportion of hatchlings potentially at risk from misorientation by industrial lighting.

6.2 Literature Review

6.2.1 Effects of photopollution on sea turtle hatchlings

(Verheijen 1985) defines photopollution as “the degradation of the photic habitat by artificial light”. A large body of literature is available that shows sea turtle hatchlings can be misoriented by artificial lights immediately after emerging from the nest (McFarlane 1963; Verheijen and Wildschut 1973; Mortimer 1979; Witherington and Bjorndal 1991a; Peters and Verhoeven 1994). This misorientation can be fatal for the hatchlings.

Mortalities by desiccation, road kills or increased predation may result from misorientation (hatchlings are diverted away from their course to the ocean), or disorientation (hatchlings circle aimlessly with no set direction). Loggerhead, hawksbill and green turtle hatchlings are all reported to have suffered mortalities due to beach lighting (Witherington and Bjorndal 1991a). Two examples of hatchling misorientation as a result of photopollution are documented by McFarlane (1963) and Mortimer (1979). McFarlane (1963) reports the death of 109 (of 115) loggerhead hatchlings in Florida that had emerged from a nest 10.7 m from the high tide line. In addition, ninety hatchlings were crushed by motor vehicles on a highway 30.5 m from the loggerhead nest. McFarlane (1963) concluded that the hatchlings were orientated the wrong way as a result of the illuminated sky above the city and a mercury vapour street light 45.7 m away from the nest. A similar incident was reported from Ascension Island where Mortimer (1979) found the bodies of 500 charred green turtle hatchlings that had wandered into a beach bonfire.

Hatchlings use multiple cues to find the ocean. These are presented in the following sections.

6.2.2 Light direction

Early studies on the response of green turtle hatchlings to light described their behaviour as “positive phototrophotaxis” (Mrosovsky and Carr 1967; Mrosovsky and Shettleworth 1968). In this response the hatchlings turn as they balance brightness inputs between two eyes, and react positively to light by moving towards the direction of their open eye when unilaterally blindfolded (Mrosovsky & Shettleworth, 1968).

The positive response of green turtles to light can explain the hatchlings orientation towards the illuminated seaward horizon in their natural environment. However, the mechanism by which a green turtle orients itself towards the illuminated horizon is still not clear. One issue of debate has been whether the hatchlings are attracted to a point source of light (*i.e.* the brightest sector on the horizon) or whether they integrate visual cues from a wide field of view. Mrosovosky (1972) observed that hatchings did not always take the shortest route to the (moonlit) sea and concluded that they were not taking their cues directly from the nearest, usually brightest, expanse of water, but from a distribution of brightness over a wide area.

The area over which hatchlings are thought to integrate light cues is known as a cone of acceptance. A narrow vertical component of between a 'few degrees' and ± 30° has been proposed for green turtles (Verheijen and Wildschut 1973; Witherington 1992a) while the horizontal component is broad (180°). Hatchlings integrating light across a broad area will be influenced by the irradiance of a light (the amount of light per unit area reaching the hatchling) more than the radiance of the same light (intensity of light per unit area at the source). A low intensity light close to a hatchling can therefore cause the same degree of misorientation as a more distant, but brighter, light source. Lohmann *et al.* (1996) suggested that the integration of light over a broad range may also be important for mitigating the effects of the sun and the moon on orientation direction. A broad acceptance cone gives hatchlings a larger 'sample' and diminishes the influence of any single point source of light.

6.2.3 Shape and form vision

Limpus (1971) proposed that most hatchlings oriented away from dark silhouettes as opposed to towards the region of maximum irradiance. Van Rhijn (1979) supported this idea and further suggested that turtles could recognise the form of silhouettes on the horizon (*i.e.* tree-line) and could use this as a basis for orientation. At this time turtles were thought to be seriously myopic, so without evidence to the contrary these hypotheses were not favoured. However, ongoing work by Northmore and Granada (1982) indicated that sea turtle hatchlings were not excessively short-sighted while Green *et al.* (1980) described the hatchling eye as having "considerable depth of focus".

Several researchers have investigated the significance of shape and form vision in sea finding hatchlings (eg (Limpus, Colin J. 1971; Mrosovsky and Kingsmill 1985; Witherington and Bjorndal 1991a, 1991b). Limpus (1971) found that shape and form vision are a primary function in sea finding for many sea turtles. Hatchlings orient away from the dark elevated horizon and towards the lower illuminated horizon. Limpus (1971) concluded that given a choice between brightness at two elevations the hatchlings will always select the lowest of the horizons and if the elevations are similar they will select the brighter of the two.

Silhouettes may be used as a primary sea finding mechanism in preference to just photic cues because of their “reliability” (Salmon et al. 1992). Evidence has been building that suggest horizon elevation and shape is the dominant orientation cue where dunes of vegetation profiles are high or distinctly shaped. Of lesser importance is the light intensity gradient (Salmon, M. *et al.* 1992; Witherington 1992a; Salmon, M and Wyneken 1994; Salmon, M. and Witherington 1995). Silhouettes towards the land are constantly dark and elevated; in contrast, the lower illuminated horizon may vary in light intensities as a result of lunar and weather influences (Salmon et al. 1992). However, green turtles often inhabit fairly flat islands and the lack of elevated silhouettes on these islands may mean that photic cues are more important for sea finding orientation in these environments. Therefore the orientation cues hatchlings may use is influenced by the physical structure of their habitat (*i.e.* absence or presence of dunes, vegetation etc.).

Witherington’s studies (1992) generally supported the work by Limpus (1971) concluding that hatchlings were able to prioritise the brightness and shape cues they were receiving with form vision taking precedence over brightness direction. However, hatchlings are still able to orient towards the brightest direction if form vision was disrupted. This is significant when considering natural lighting on beaches; on moonless nights the ocean is usually the brightest horizon, however, on moonlit nights the rising and setting moon (low on the horizon) are not always in a seaward direction and yet, in spite of this, hatchlings orient seaward.

6.2.4 Influence of lunar cycles

Until recently there has been a common misconception that hatchlings only emerge on nights of the full moon. This is probably due to the fact that it is easier to see hatchlings by moon light. Moonlight does affect the ease with which hatchlings find the ocean, with greatest disruption from artificial light occurring on nights on, or near, the new moon (Salmon, M. and Witherington 1995).

The illumination of the moon appears to reduce the anisotropy (directivity) of the artificial light source (Verheijen and Wildschut 1973; Salmon, M. and Witherington 1995). The entire sky is brighter under moon light and the relative importance of individual point sources of light, including artificial lights and the moon, are smoothed out. Salmon & Witherington (1995) found misorientation of loggerhead hatchlings exposed to artificial light decreased as the moon illumination increased suggesting that it is the background illumination and not the moon itself that reduces the effect of artificial light. These findings are strengthened with results from studies which found that visible sun or moon failed to attract green (Van Rhijn 1979) or loggerhead (Witherington 1992) turtles.

This information on the lunar cycle must therefore be taken into account when studying the influence of artificial light on hatchling orientation. Salmon & Witherington (1995) suggest these studies should be undertaken on dark nights when artificial lights will have the most influence on turtle orientation.

6.2.5 Orientation cues – non visual

The use of beach slope (geotaxis) as an orientation cue for sea turtle hatchlings is considered secondary to optic cues (Salmon, M. *et al.* 1992). Loggerhead and green turtle hatchlings descend inclines in the absence of visible light (Van Rhijn 1979; Salmon, M. *et al.* 1992). Salmon *et al.* (1992) concluded that visual cues "supersede" slope cues in loggerhead hatchlings, and although visual cues are also of primary importance to green turtle hatchlings, slope cues may contribute weakly to their orientation during sea finding. Ecological surroundings may be of some significance in weighting the importance of geotaxis in orientation. For example, hawksbill hatchlings often emerge in heavy vegetation where visual cues are not prominent. With a lack of visual cues available geotaxis may become more important as an orientation cue (Salmon, M. *et al.* 1992).

6.2.7 Illuminance measurements

Photometry is the term used for the study of visible light in units that are weighted to the human eye (Ryer 1998). Humans use two forms of vision; photopic for light adapted conditions (*i.e.* daylight) and scotopic for dark adapted conditions (*i.e.* night). Freshwater turtles also show a shift in sensitivity between light and dark adapted (Granda and Dvorak 1977). Photopic vision in both human and sea turtles eyes uses cones to see the different colours of light, while the dark adapted eye uses rods to see light in shades of grey at night. The rods do not sense colour and the scotopic eye is most responsive to light in the blue region of the spectrum (at 507 nm).

The amount of photopic light falling on a unit of area over a given distance is termed illuminance and is measured in lumens/m^2 or Lux. Lux is a measure of the power of visible light and depends on the sensitivity of the human eye. It is based on the CIE Luminous

Efficacy Curve for photopic (light adapted) or scotopic (dark adapted) conditions (Figure 6.1). The photopic CIE curve weights the light at the ends of the spectrum (400-500 nm and 625-700 nm) at zero and has a peak response at 555 nm. Hence, commercial photometers that quantify illuminance in Lux include little of the total radiant flux between 400-500 nm and 625-700 nm. The scotopic curve included in Figure 6.1 shows the weighting of the light most visible to a human eye under dark adapted conditions. The light emissions under the scotopic curve that fall outside of the photopic curve are not included in the photometric measurements.

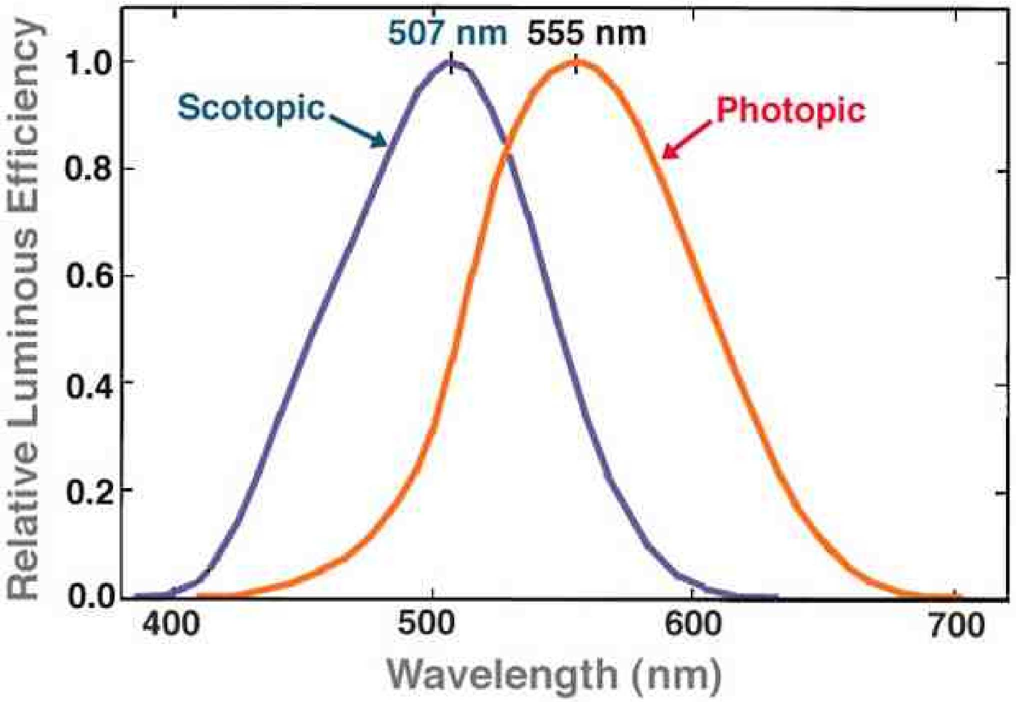


Figure 6.1: CIE photopic and scotopic relative spectral luminance efficiency curves. Source (Taylor 2000)

Some typical illuminance values are:

Bright sunlight	100,000 lux
Cloudy day	10,000 lux
Night sports field	200 – 1,000 lux
Residential street	1 – 10 lux
Full moon	1 lux
Cloudy moon	0.25 lux

(Sources www.schorsch.com and www.pc.ibm.com)

6.3 *Methods*

6.3.1 Arena experiments

Hatchling orientation in the presence of both controlled light sources (specific methods described 6.3.2) and uncontrolled (specific methods described section 6.3.3) were tested using a circular pitfall arena design. This design has been used successfully in the past (Mrosovsky and Carr 1967; Witherington 1992a; Pendoley 2000). Arenas were used to test the effects of uncontrolled light on misorientation of hawksbill and flatback hatchlings on Varanus Island in 1998 and of controlled light on misorientation of flatback and green turtle hatchlings on Barrow Island in 2004 and 2005.

Arenas were positioned between the high tide line and the dune vegetation line. They ranged from 4-8 metres in diameter depending on the amount of beach available between the vegetation and high tide line. A circular trench approximately 30 cm deep and 30 cm wide was dug around the circumference of the arenas (Plate 6.1). During the 2005 trials walls of the trench were lined with fine mesh material that stabilised the walls. The trench was subdivided into 12 segments of approximately 30° each. The segments were divided by rigid boards. Segments 1 and 12 were positioned most seaward (Figure 6.2). The segments (1-12) proceeded in numerical order clockwise around the arena. Prominent rocks or debris were removed from within the arena.

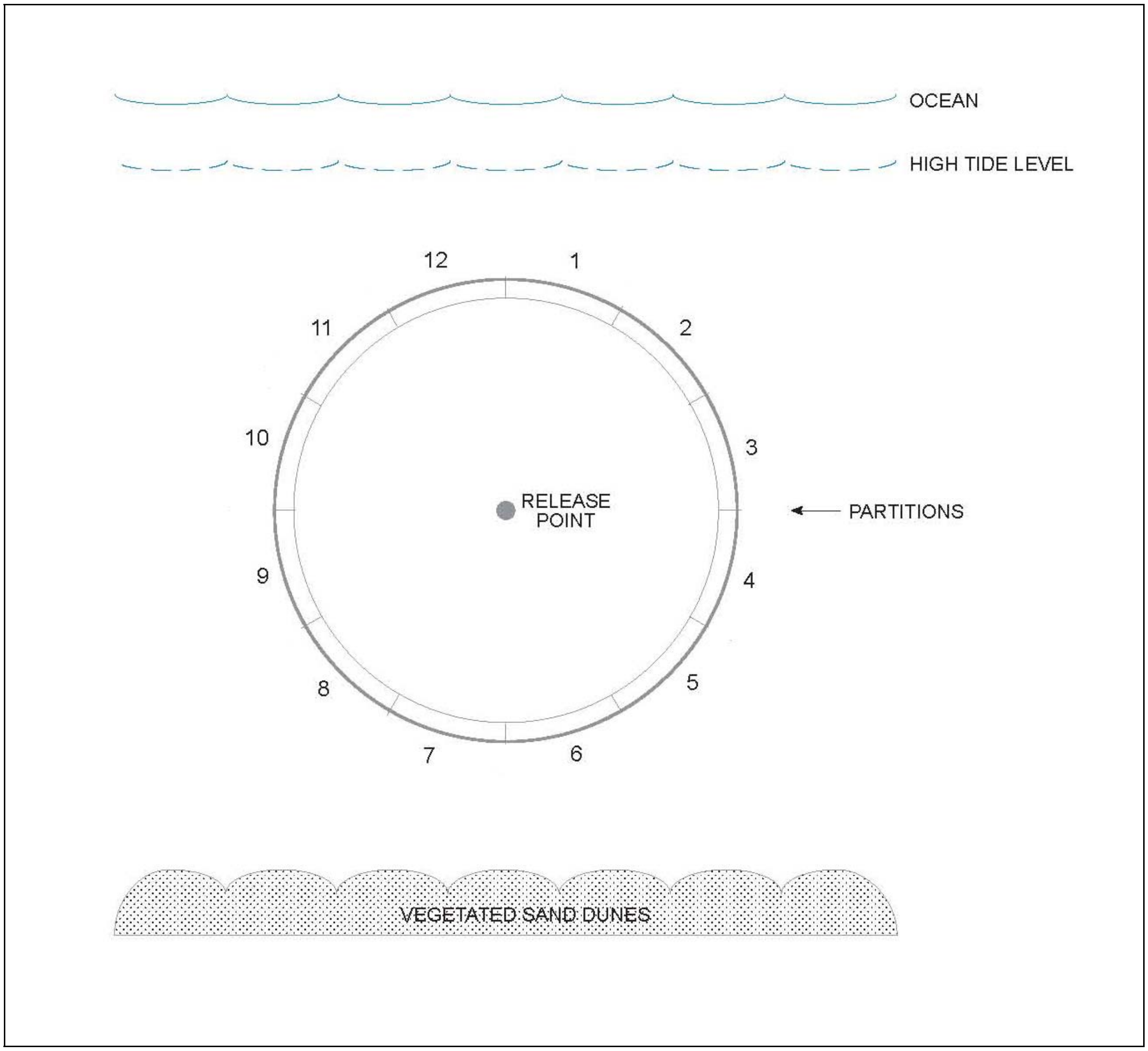


Figure 6.2: Arena layout design

Turtle hatchlings were collected and held in the dark in a darkened container until testing. The hatchlings, in groups of 30, were released at the center of each arena by upending them from a cloth bag attached to a line that was run to the outside edge of the arena. The hatchlings were given 3 minutes to reach the trench at the edge of the arena. Hatchlings were then collected and the number in each segment, as well as those remaining in the center, was scored for the 30° intervals.

Plate 6.1: Arena design, Barrow Island February 2005

6.3.2 Controlled light sources - arena studies

These arena experiments were carried out on Barrow Island between 16 - 22 April 2004, and 1-5 February 2005, on nights of the new moon, using green turtle (2004) and flatback (2005) hatchlings. The arenas were installed at 100 m, 200 m, 500 m and 800 m from a controlled light source on North Yacht Club Beach. The 2005 layout of the light array and arenas is shown in Plate 6.2. In 2004 the location of the light array and arenas was 100m further south, located at the mouth of the creek bed (shown in Plate 6.2). This location exposed the hatchlings tested within the 100m arena to an inland facility light glow along the low profiled creek bed. This difference in light exposure and topography was evident in the results and hence the entire array was shifted 100m to the north away from the inland facility light flow for the 2005 experimental trials.

Prior to performing arena experiments to test the response of hatchlings to different artificial light sources a set of experiments was run to assess the impact of retesting hatchlings in different light trials. Retesting of hatchlings was necessary since the total number of animals needed for each of the three experimental trials was very high (~500 animals on each night of the study), and it was not possible to find and collect 500 animals in one night. The retesting trials were carried out at the 200 m arena using 250 W light intensity (on Barrow Island in 2005). One hundred and twenty hatchlings were divided into four bags. The order of testing against the three light regimes is listed below.

Bag 1	Bag 2	Bag 3	Bag 4
Control	Sodium vapour	Metal halide	Fluorescent
Sodium vapour	Metal halide	Fluorescent	Control
Metal halide	Fluorescent	Control	Sodium vapour
Fluorescent	Control	Sodium vapour	Metal halide

The first light treatment each bag of animals was exposed to was their first exposure to the arena and light. The hatchlings were then retested under the different light conditions in sequence to determine if previous exposure to light sources had any impact on their behaviour. For example the hatchlings in Bag 1 were tested in the arena under no light (control) conditions and then retested with a sodium vapour light trial, then the metal halide trial and finally a fluorescent trial. Hatchlings in Bag 2 were tested against sodium vapour light as their first exposure to control/light conditions, followed by metal halide, fluorescent and control in sequence, Bag 3 hatchlings were tested against metal halide as the first exposure to light/control conditions followed by fluorescent, control and sodium vapour light sequences and finally Bag 4 hatchlings were tested against fluorescent light as their first exposure to test light conditions and then control, sodium vapour and metal halide in sequence. Hatchlings were allowed 2 minutes to reach the edge of the arena during test and then allowed 3 minutes between each test to become dark adapted once again.

All hatchlings were collected from Barrow Island beaches the same day (green turtle hatchlings) or the same evening (flatback hatchlings) as each trial was run. Hatchlings were held in the dark until use. Each group was held at the same arena for the duration of the trials. The acceptability of reusing individual hatchlings was tested in 2005 (see methods in section 6.3.4).

Plate 6.2: 2005 arena locations on Yacht Club Beach

The hatchlings were tested against three different controlled light sources which consisted of 2 x 250W high pressure sodium vapour (sodium vapour), 2 x 250W metal halide and 14 x 36W fluorescent fixtures mounted on a 3m tall stand (Plate 6.3). This light array was assembled on location and powered by a 5 KVa ‘silent’ running diesel generator positioned approximately 25m from the array. In 2005 the generator was placed on a rubber base to prevent the motor vibrations travelling along the beach and potentially influencing hatchling response during the arena trials.

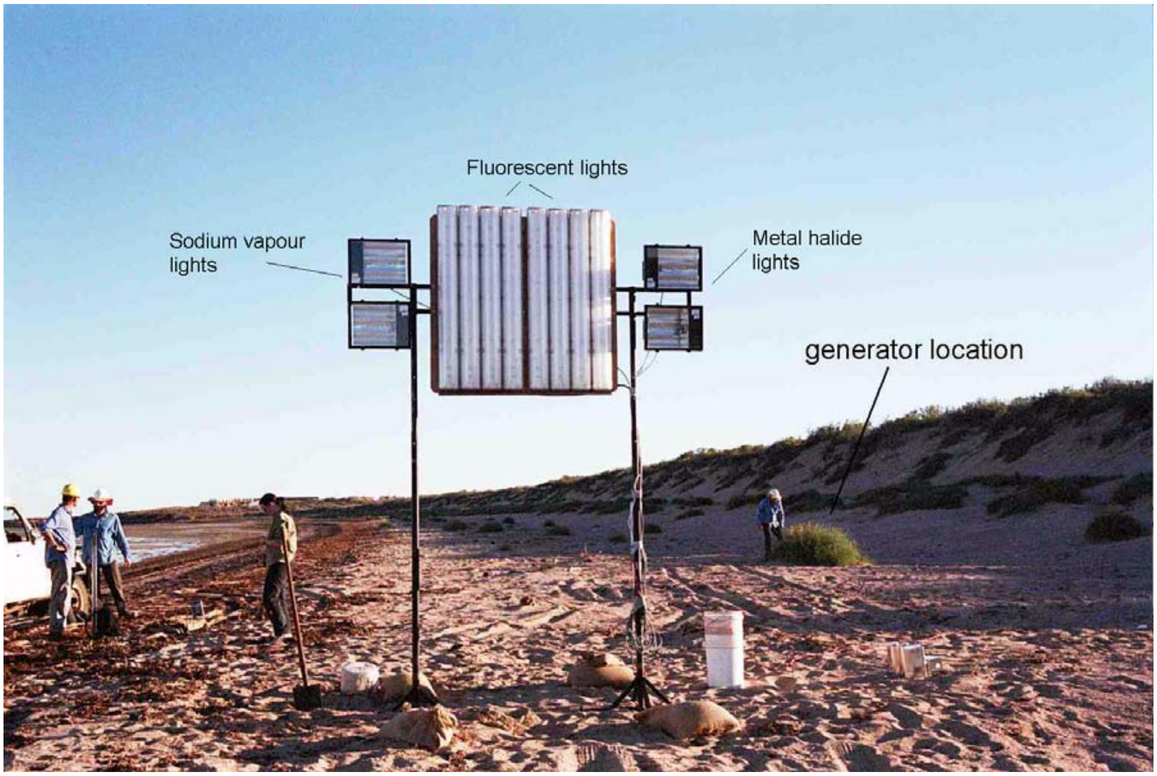


Plate 6.3: Light array set up for light trials

Equipment to measure light emissions was unavailable during the 1998 arena trials on Varanus Island. However by 2004 an updated model of the spectroradiometer used in the light characterisation studies described in Chapter 5 had become available. Unlike the old model, the new model and the revised operating software was capable of quantifying the spectral emissions. Therefore light measurements were made using a miniature Ocean Optics USB2000 spectroradiometer which provided a characteristic spectral chart for each light source and included the energy emissions in uW/nm/cm^2 at each wavelength. The spectroradiometer also provides a photometric measure of emissions in Lux. Commercial light meters such as those typically used in industrial settings, measure in units of Lux and include only the light emissions most visible to the human eye (*i.e.* in the 500 nm to 650 nm range). The Lux values presented include only the spectral emissions between 500 nm and 650 nm and ignore the spectral peaks above and below this range.

This value was recorded for each bioassay since it is the unit of light most commonly used in industrial lighting design.

6.3.3 Uncontrolled light sources – arena studies

The experiments were carried out on Varanus Island over the nights of January 12, 13, 14, 15 and 17, 1998 using hawksbill and flatback hatchlings. The programs were timed to coincide with predicted moon rise times that would allow for the testing of both moon phase variables over the 4 night period. Arena test sites were selected and installed on five beaches on Varanus Island (Figure 6.3) and were chosen to test the *in situ* light fields associated with the onshore and offshore facilities as described in Table 6.1.

On all but one occasion hatchlings were dug up from nests that had emerged the previous evening (as identified from hatchling tracks). The hatchling tracks were followed back to the source and the remaining live in nest young were collected for subsequent tests. While it is preferable to collect hatchlings that are from the first group to emerge it was not possible given the logistical limitations of the study site. Hatchlings were held for up to 6 hours prior to testing. All were released immediately following the completion of the tests. Between 10 and 90 turtles were used for each arena trial. The minimum number of 10 is the same group size used by Salmon and Witherington (1995) to assess the influence of lunar modulation on hatchling response to artificial lights. Difficulties in obtaining hatchlings (and restrictions on rescheduling field time) meant that it was necessary to retest the hatchlings for repeat treatments in all test arenas the same night. This was deemed acceptable since Mrosovsky and Shettleworth (1968) have suggested that repeated testing does not affect the sea finding ability of hatchlings.

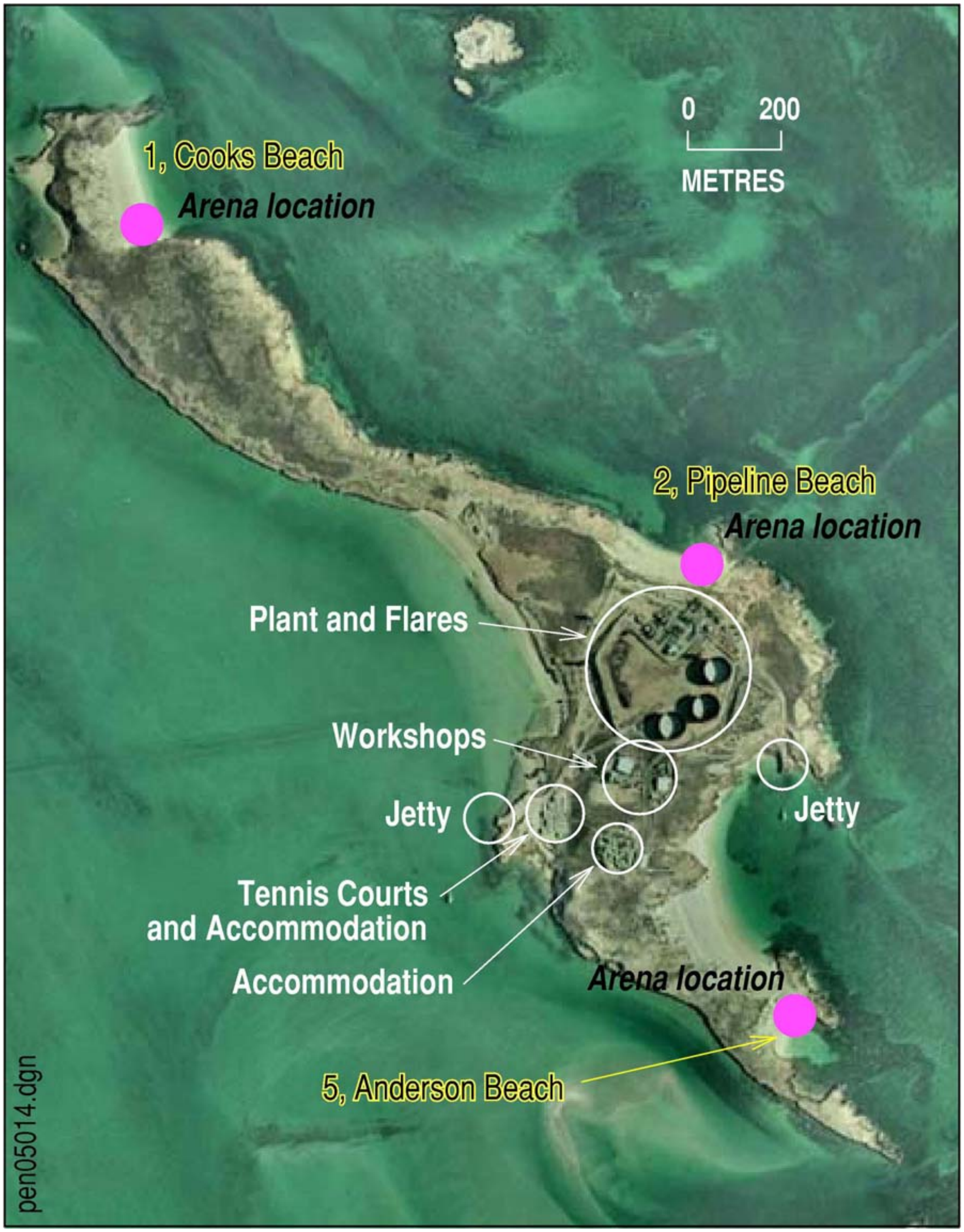


Figure 6.3 Varanus Island arena locations

Table 6.1: Location of artificial lights present during arena experiments on Varanus Island

Site Location	Light source	Distance	Direction
Cooks Beach	HA flare		
Pipeline Beach, eastern end	Harriet/East Spar facility lights HA flare (glow) Offshore drilling rig on Koombana location (glow) Moon rising during tests.	100m 6 km 3.3 km	SW NE SE
Andersons Beach, north east end	Offshore drilling rig on Koombana location (glow). . Moon rising during tests	2.5 km	E

6.3.5 Fan mapping

Three hundred and eighty four nests were mapped on Lowendal, Montebello and Barrow Islands between 1998 and 2003.

The fan mapping methods developed for this study are similar to those described by Salmon and Witherington (1995). The basic criteria measured for each nest are shown in Figure 6.4 and include; fan spread (angle between the fan arms, A – B) and offset (angle between the fan angle midpoint and the most direct line to the ocean, C – X). A compass bearing was taken from the nest down the outside arms of the fan encompassing the tracks (A and B). Occasionally fans were characterised by stray tracks, where hatchlings had travelled in a direction different to the bulk of the nest. The bearings of these strays (n ≤ 5 tracks) were recorded separately and were not included in the fan angle or offset measurements. A bearing was also taken on the most direct line to the ocean from the nest (X) in addition to angles of visible light sources within 3 km of the nesting beach. These data were then used to calculate the offset angle between the ocean bearing (X) and the midpoint of the fan spread (C). All nearby onshore and offshore light sources were recorded and coded for each nest record.

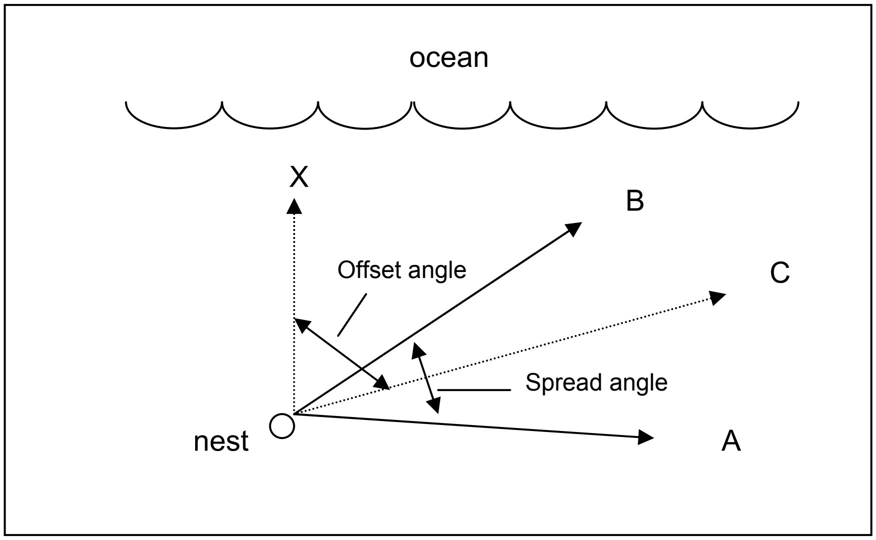


Figure 6.4: Fan mapping criteria. X = bearing on the most direct line to the ocean. A and B = bearing along the outer edge of the most dense part of the fan, C = the modal bearing for the fan.

Nests and fan orientation were noted on maps of each beach and where possible the nests were dug to confirm hatchling species. Each nest was coded for moon phase. Logistical and resource constraints prevented documentation of nest emergence times more accurately than to the night of emergence. Nests were therefore coded for the moon phase at 2300 hours on the night the nest emerged. It is not possible to determine if the nests emerged before or after moonrise. Moon phase predictions were made using QuickPhase Pro version 2 (http://www.bluemarmot.com/).

6.4 Results

6.4.1 Controlled light source experiments - Arena studies Barrow Island

6.4.1.1 Test light spectra

The light spectra for each light type are shown in Figure 6.5 for each arena location. These figures show the spectral distribution curve for each light type, in units of uW/nm/cm^2.

6.4.1.2 Experiments on the effects of retesting hatchlings

The trials to test the impact that retesting hatchlings may have had on their behaviour were run during the February 2005 experiments on Barrow Island. Trials were conducted using the three light types at 250W and a dark control. A chi-square analysis was run to test the effect of reusing hatchlings. The results found no significant difference in the orientation of hatchlings with no previous light exposure compared to retested animals ($X^2_{18} = 26.599$, n.s.), *i.e.* hatchlings oriented in the same way under a given light regime regardless of their exposure history. If the sequence of light exposure had a major effect then a significant bag effect should have been detected. For example hatchlings exposed to the three different light types in sequence oriented in the same direction as hatchlings tested against these light types without any previous light exposure. This result suggests hatchlings are responding to the different lights as if it was their first exposure and are not exhibiting learned behaviour.

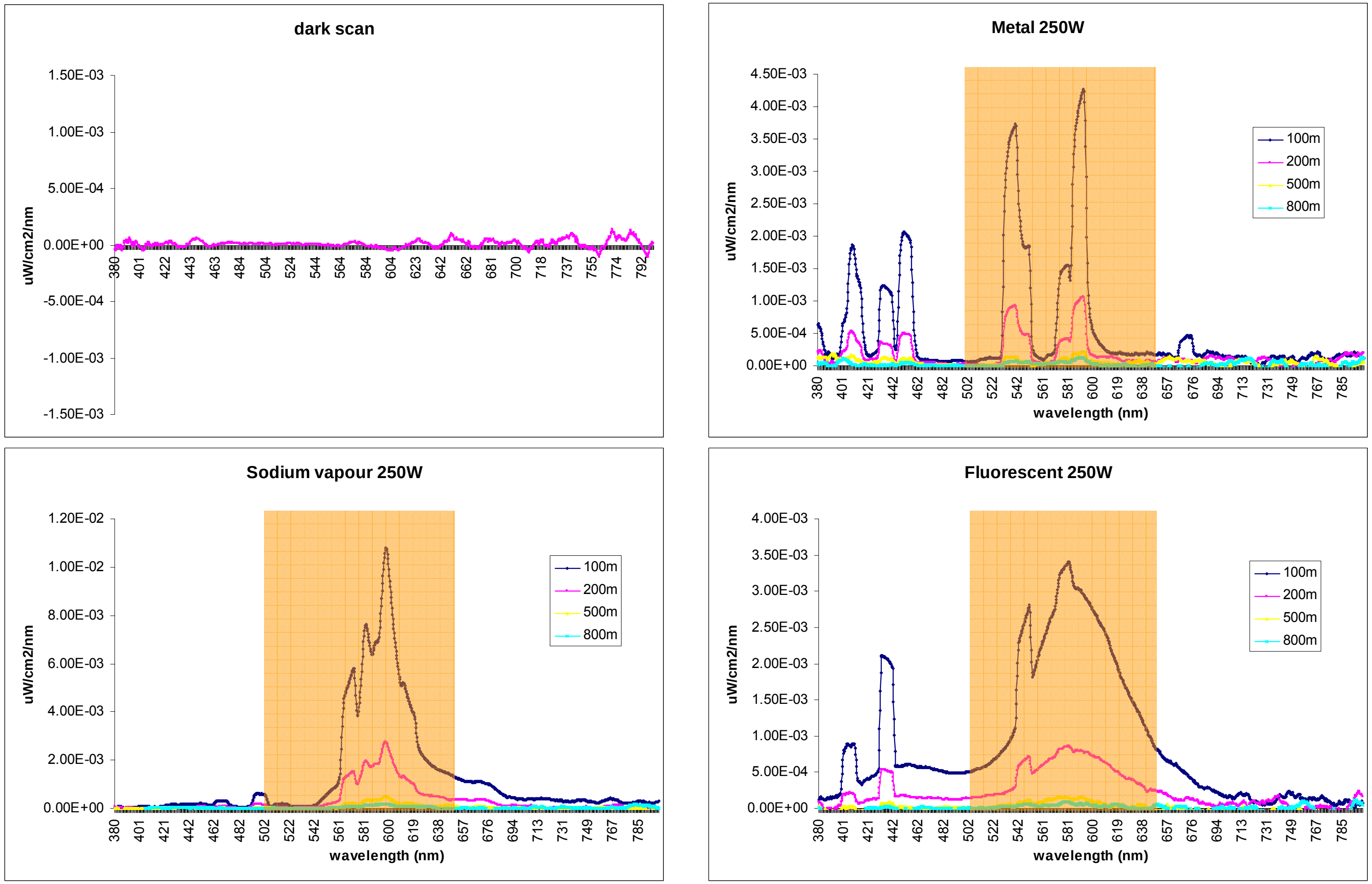


Figure 6.5: Dark scan, 250W sodium vapour, 250W metal halide and 250W fluorescent light sources measured from 100m, 200m, 500m and 800m arenas. Orange shading covers region of the spectrum that is included in the photometric Lux measurements. The dark scan is an example of the background night sky radiation and is indistinguishable from detector noise.

6.4.1.3 Flatback – 250 W and 500 W light trials

The light types (*i.e.* sodium, metal and fluorescent) used in these experiments were selected to be representative of the lighting typically used in industrial settings. The light intensities (250 W and 500 W) were selected based on previous studies, to provide a range of light most likely to elicit a detectable response in the hatchlings. The experimental trials were split into 250 W and 500 W trials and run over separate nights. The 250W and 500W trials were analysed separately.

The 250W and 500W results were analysed separately using multinomial logistic regression with light treatment as a factor (*i.e.* no light versus light) and distance as a covariate, and the set of direction intervals representing the multinomial dependent variable (*i.e.* light versus no light). There was a statistically significant difference in the response of hatchlings under control (no light) conditions and light treatment conditions (X^2_7 = 362.369 $p < 0.05$). The light treatment clearly had an impact on hatchling orientation. The analysis also found that the hatchling behaviour differed significantly with distance (and consequently light intensity) from the light source (X^2_7 = 328.226, $p < 0.05$).

The effect of distance was tested by splitting both the 250 W and 500 W light trial data (excluding 'no light' treatments) into two groups; near (representing the 100 m and 200 m arena results) and far (representing the 500 m and 800 m results). For the 500W treatments hatchling behaviour in the two near arenas was not significantly different (among different light types, X^2_{10} = 11.818 $p > 0.05$), nor was it significantly different in the two far arenas (X^2_{14} = 12.066 $p > 0.05$). For the 250 W treatments, however, there was a significant difference in hatchling behaviour under different light types in the near arena group (100 m and 200 m, $X^2_{16} = 55.542$ $p < 0.05$) while no significant difference was evident in the 500 m and 800 m arenas ($X^2_{12} = 18.436$ $p > 0.05$).

In order to look at fine scale trends, the data from each individual arena location was then analysed by comparing hatchling orientation under control vs light treatment conditions. A binary logistic regression analysis performed on the complete set of controls (run at the start and end of each group of light treatments) and including distance as a covariate, found no significant difference in hatchling orientation permitting the control data to be pooled for subsequent statistical analyses. The binary regression assumed animals either oriented towards the ocean (segments 12 and 1) or they did not (all other directions). A series of 2 x 2 contingency chi-square tests were performed for the proportion of animals oriented to the ocean versus the number that did not, in the presence of a particular light type versus the absence of light. The results of these tests are shown in Table 6.2. Since twelve separate contingency tests were performed for each of the 250 W and 500 W trials the results were subject to a sequential Bonferroni correction in order to account for repeat testing. The results showed that all three light treatments (sodium, metal and fluorescent), at both 250 W and 500 W light intensities, had a significant impact on hatchling orientation, relative to the controls, at 100 m and 200 m.

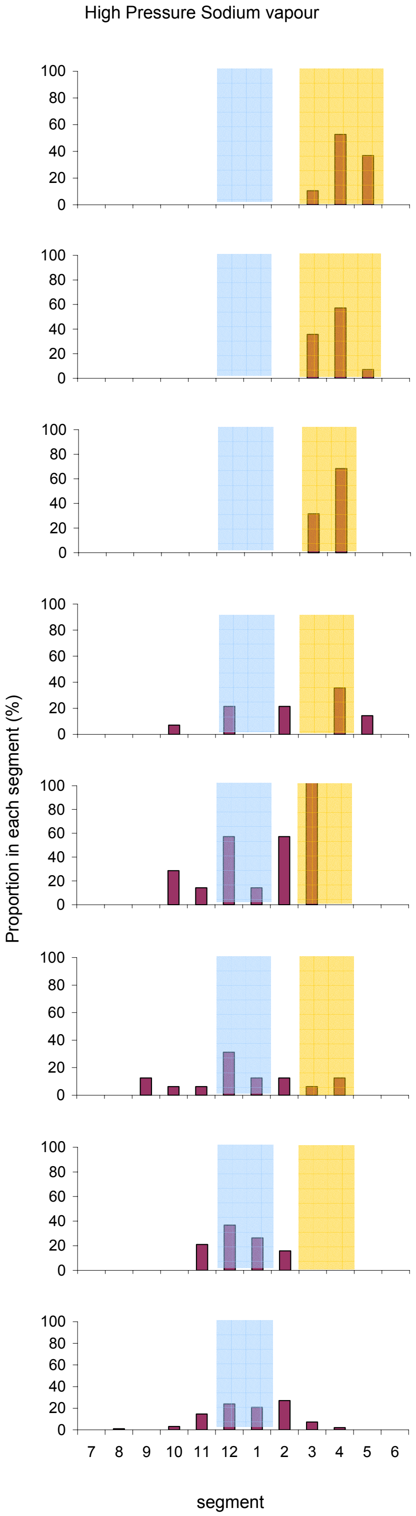
At 500 m and under 500 W light intensity for all three light types, hatchlings also showed a significant response to the light relative to the controls. However, at 800 m the 500 W fluorescent light was the only emission source to elicit a significant orientation toward the light array relative to the controls. In contrast the 250 W trials found no significant effect from the three light types at 500 m or 800 m with the single exception of the metal halide at 500 m.

These results are shown graphically in Figure 6.6 (sodium vapour), Figure 6.7 (metal halide) and Figure 6.8 (fluorescent). The figures include the results of both the 250 W and 500 W light intensity trials, sorted by the measured Lux value. If Lux values are considered, then for sodium vapour light any treatment (distance and wattage) that measured > 0.19 Lux showed a significant difference in the proportion of turtle hatchlings in selecting non ocean facing arena segments compared to pooled controls. This equated to a distance of 500m and an intensity of 500W (Figure 6.6). The effect of metal halide light was detectable at lower light intensities than the sodium light, with a significant proportion of hatchlings selecting the non ocean facing segments at estimated light intensities of ≥ 0.05 Lux, (Figure 6.6) which also equated to a distance of 500 m and an intensity of 500 W of light. For the fluorescent light treatments a combination of 500 m distance and 500 W light produced a measured intensity of 0.14 Lux showed a significant difference in the proportion of hatchlings selecting non ocean facing segments compared to pooled controls. However at a distance of 500m and an intensity of 250 W the estimated 0.06 Lux fluorescent light did produce a significant difference in the proportion of hatchlings orienting seaward compared to pooled controls, while the 500 W fluorescent light tested at 800m (estimated intensity of 0.05 Lux) did show a weakly significant response (Figure 6.8).

Table 6.2: Flatback hatchlings Chi^2 analysis results (corrected for repeat testing using the sequential Bonferroni correction) for 500 W and 250 W light treatment trials. *p ≤ 0.05, ** p ≤ 0.01, *** p ≤ 0.001, n.s. = not significant

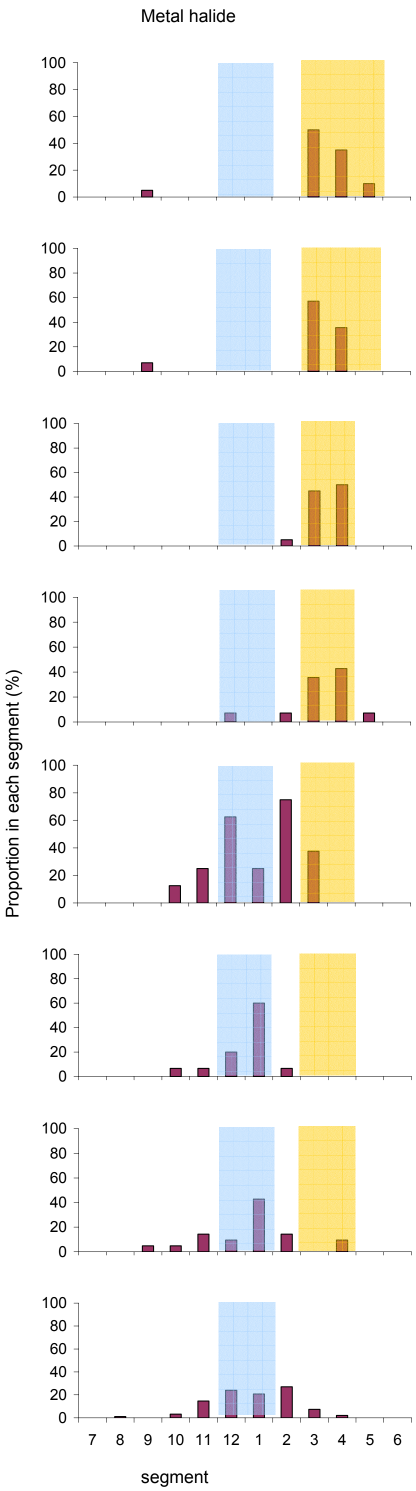
Light wattage	Distance (m)	treatment	# orienting seaward	# orienting other direction	X^2	p	Sig.
500 W	100	sodium	16	14	48.515	0.000	***
	100	metal	8	22	51.232	0.000	***
	100	fluorescent	6	24	50.333	0.000	***
	200	sodium	21	29	21.546	0.000	***
	200	metal	25	25	27.221	0.000	***
	200	fluorescent	20	30	21.165	0.000	***
	500	sodium	27	23	8.422	0.004	*
	500	metal	29	21	7.159	0.007	*
	500	fluorescent	32	18	7.009	0.008	*
	800	sodium	25	25	0.084	0.772	n.s.
	800	metal	22	27	0.001	0.981	n.s.
	800	fluorescent	27	22	5.857	0.015	*
250 W	100	sodium	1	28	53.429	0.000	***
	100	metal	0	30	58.784	0.000	***
	100	fluorescent	2	28	46.735	0.000	***
	200	sodium	6	23	47.709	0.000	***
	200	metal	0	30	72.121	0.000	***
	200	fluorescent	2	28	62.656	0.000	***
	500	sodium	16	14	1.386	0.239	n.s.
	500	metal	8	22	9.943	0.002	**
	500	fluorescent	13	17	4.344	0.037	n.s.
	800	sodium	15	15	0.606	0.436	n.s.
	800	metal	15	15	0.41	0.522	n.s.
	800	fluorescent	15	15	0.41	0.522	n.s.

Sig. = Significance using sequential Bonferroni correction



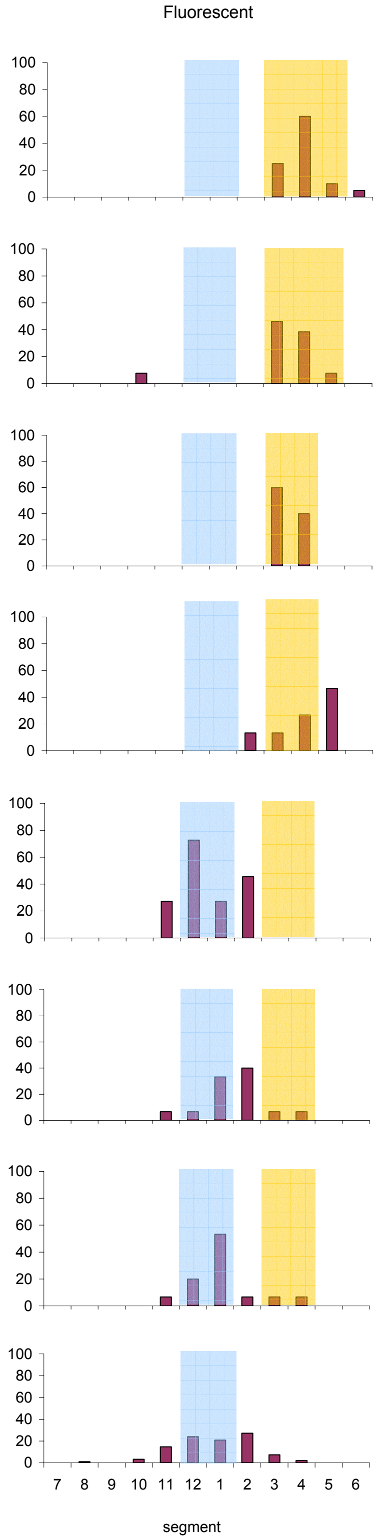
Arena location	WATTAGE	Lux	p value	significance of difference relative to controls (Bonferroni correction)
100m	500W	6.71	-	-
100m	250W		-	-
200m	500W	1.38	0.0165	ns
200m	250W		0.128	ns
500m	500W	0.16	0.8434	ns
500m	250W		0.8794	ns
800m	500W	0.07	0.6499	ns
pooled controls 200m-800m	0	0		

Figure 6.6: The proportion of flatback hatchings in each segment for each arena under 2 different light intensities (250 W and 500 W) for the sodium vapour light treatments. Date sorted by Lux value. Blue wash represent the arena segments oriented towards the ocean, yellow wash represents the arena segments oriented towards the light array. n = 30 (500W) and n = 50 (250W) animals per trial



Arena location	WATTAGE	Lux	p value	significance of difference relative to controls (Bonferroni correction)
100m	500W	3.38	-	-
100m	250W		-	-
200m	500W	0.55	0.0137	ns
200m	250W		0.0122	*
500m	500W	0.1	0.1502	ns
500m	250W		0.0341	ns
800m	500W	0.05	1	ns
pooled controls 200m-800m	0	0		

Figure 6.7: The proportion of flatback hatchings in each segment for each arena under 2 different light intensities (250 W and 500 W) for the metal halide light treatments. Date sorted by Lux value. Blue wash represent the arena segments oriented towards the ocean, yellow wash represents the arena segments oriented towards the light array. n = 30 (500W) and n = 50 (250W) animals per trial.



Arena location	WATTAGE	Lux	p value	significance of difference relative to controls (Bonferroni correction)
100m	500W	4.52	-	-
100m	250W		-	-
200m	500W	0.82	0.0137	ns
200m	250W		0.0018	*
500m	500W	0.1	0.5808	ns
500m	250W		0.7024	ns
800m	500W	0.05	0.1952	ns
pooled controls 200m-800m	0	0		

Figure 6.8: The proportion of flatback hatchings in each segment for each arena under 2 different light intensities (250 W and 500 W) for the fluorescent light treatments. Date sorted by Lux value. Blue wash represent the arena segments oriented most closely to the ocean, yellow wash represents the arena segments oriented towards the light array. n = 30 (500W) and n = 50 (250W) animals per trial.

6.4.1.4 Green – 250 W and 500 W light trials

The same industrial light types (*i.e.* sodium, metal and fluorescent) that were used for the flatback trials were used for the green turtle trials. The experimental trials were split into 250 W and 500 W trials and run over separate nights. The data were analysed statistically in the same manner, *i.e.* 250 W results as a dataset separate from the 500 W results. The major difference between the green turtle and the flatback arena experiments was the back beach topography and inland light exposure experience by hatchlings in the 100 m arena. The positioning of this arena near the mouth of the creek bed meant hatchlings were exposed to glow from an inland source (visible in segment 5) along a low profile creek bed instead of the tall dark dunes backing the beach at the 200 m, 500 m and 800 m arena locations. Therefore results from this arena were not included in the statistical analyses. The results also do not include data for the 800 m arena under 250 W lights since the limitations on hatchling availability meant a choice was made in favour of increasing the sample size in the 100 m – 500 m arenas over running the 800 m arena.

The analyses (Table 6.3) and data (Figures 6.9 – 6.11) for the arena experiments using green turtle hatchlings were handled in a similar way as for the flatback hatchlings. A multinomial logistic regression analysis was also performed on the green turtle hatchling results using light treatments as a factor, distance as a covariate and direction as the multinomial dependent variable (including all control and light treatment data amalgamated, *i.e.* light versus no light). Both of the 250 W and 500 W results showed a statistically significant difference in the response of hatchlings under control conditions and light treatment conditions (250W $X^2_9 = 36.428$, $p < 0.001$; 500W $X^2_7 = 113.237$, $p < 0.001$). The light treatments clearly had an impact on hatchling orientation. The analysis also found that the hatchling behaviour differed significantly with distance (and consequently light intensity) from the light source (250W $X^2_9 = 40.294$, $p < 0.001$; 500W $X^2_7 = 183.024$, $p < 0.001$).

Tests on the within group response of hatchlings in near and far arenas could not be carried out due to insufficient data. Specifically, the confounding influence of the inland light glow reduced the confidence in the hatchling orientation results at the 100m arena while the 800m arena could not be used due to the lack of sufficient test animals

The data from each individual arena location was used to compare hatchling orientation under control vs. light treatment conditions. A binary logistic regression analysis performed on the complete set of controls (run at the start and end of each group of light treatments) and including distance as a covariate, found no significant difference in hatchling orientation ($p=0.167$ at 250W and $p=0.24$ at 500W) permitting the control data to be pooled for subsequent statistical analyses. The binary regression assumed animals either oriented towards the ocean (within segments 12 or 1) or they did not (all other segments). A series of 2 x 2 contingency chi-square tests were performed for the proportion of animals oriented to the ocean versus the number not, in the presence of a particular light type versus the absence of light. The results of these tests are shown in Table 6.3. Since twelve separate contingency tests were performed for each of the 250W and 500W trials the results were subject to a sequential Bonferroni correction in order to account for repeat testing. In addition a similar series of 2x2 contingency tests were performed, for each wattage and distance, using conglomerated light data (Table 6.4) since, using binary logistic regression, no significant difference had been found between the individual light types at either wattage.

The corrected logistic regression results suggest that sodium vapour, metal halide and fluorescent light treatments (sodium, metal and fluorescent) had a significant impact on hatchling orientation (relative to the controls) at 200 m and 500 W and only fluorescent and metal halide light produced a weakly significant response at 250W and 200 m.

These results are shown graphically in Figures 6.9 (sodium), 6.10 (metal) and 6.11 (fluorescent). The Figures include the results of both the 250W and 500W light intensity trials, sorted by the measured Lux value.

Table 6.3: Green turtle hatchlings Chi^2 analysis results (corrected for repeat testing using the sequential Bonferroni correction) for 500 W and 250 W light treatment trials. * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$, n.s. = not significant

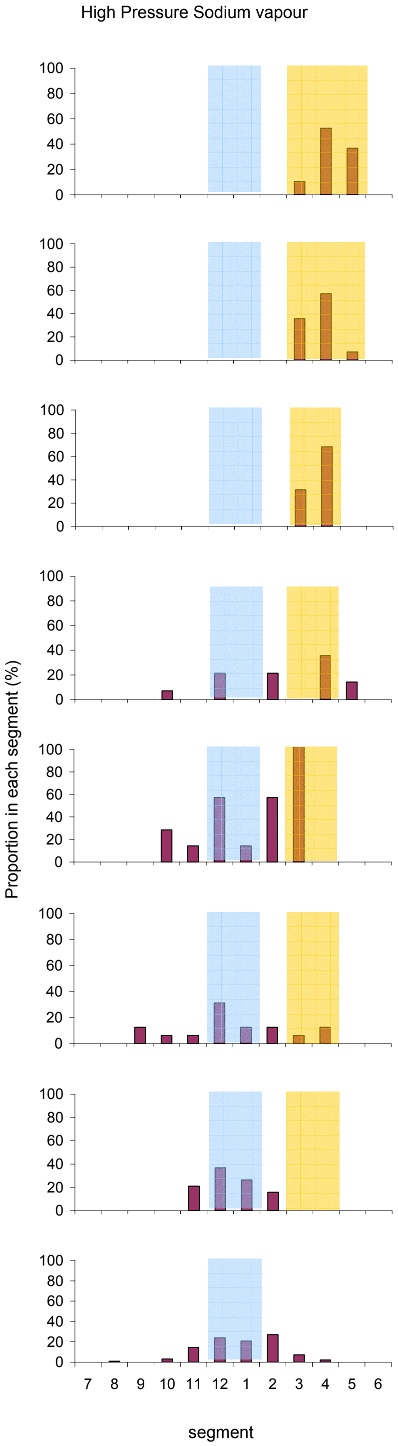
Light wattage	Distance (m)	treatment	# orienting seaward	# orienting other direction	X^2	p	Sig.
500 W	200	sodium	0	20	5.742	0.016	n.s.
	200	metal	0	20	6.076	0.014	n.s.
	200	fluorescent	0	20	6.076	0.014	n.s.
	500	sodium	05	15	0.039	0.843	n.s.
	500	metal	7	13	2.07	0.150	n.s.
	500	fluorescent	11	9	0.305	0.581	n.s.
	800	sodium	12	8	0.206	0.650	n.s.
	800	metal	11	8	0.000	1	n.s.
	800	fluorescent	13	7	1.678	0.195	n.s.
250 W	200	sodium	3	12	2.311	0.128	n.s.
	200	metal	1	14	6.273	0.012	*
	200	fluorescent	0	15	9.738	0.002	*
	500	sodium	7	9	0.023	0.879	n.s.
	500	metal	12	3	4.49	0.034	n.s.
	500	fluorescent	6	9	0.146	0.702	n.s.

Sig. = Significance using sequential Bonferroni correction

Table 6.4: Green turtle hatchlings Chi^2 analysis results (corrected for repeat testing using the sequential Bonferroni correction) for 500 W and 250 W light versus control trials. * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, n.s. = not significant

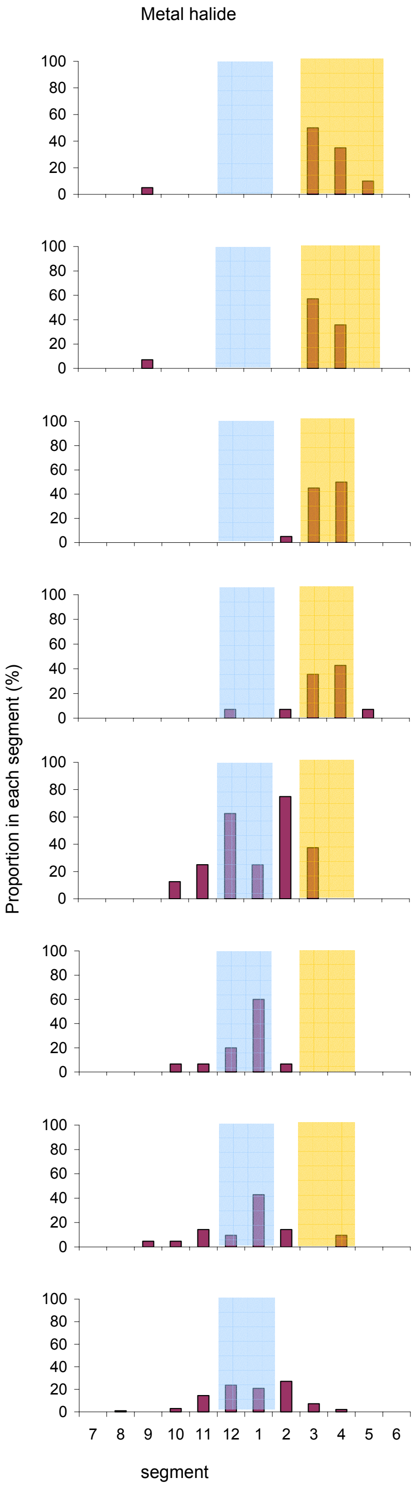
Light wattage	distance	X^2	p	Sig
500 W	200	7.833	0.005	*
	500	0.305	0.581	ns
	800	1.678	0.195	ns
250 W	200	9.738	0.002	**
	500	0.146	0.702	ns

Significance using sequential Bonferroni correction



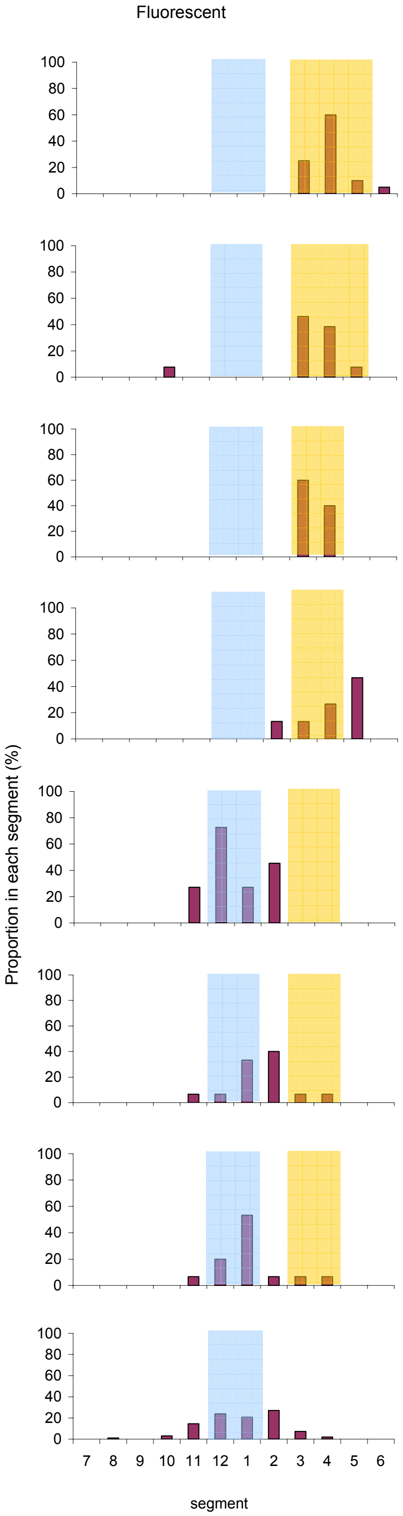
Arena location	WATTAGE	Lux	p value	Sig.
100m	500W	6.71	-	-
100m	250W		-	-
200m	500W	1.38	0.0165	ns
200m	250W		0.128	ns
500m	500W	0.16	0.8434	ns
500m	250W		0.8794	ns
800m	500W	0.07	0.6499	ns
pooled controls 200m-800m	0	0		

Figure 6.9: The proportion of green hatchings in each segment for each arena under 2 different light intensities (250 W and 500 W) for the sodium vapour light treatments. Data sorted by Lux value. Blue wash represent the arena segments oriented most closely to the ocean, yellow wash represents the arena segments oriented towards the light array. Note: ‘ - ‘ signifies no p value code for the 100m arena due to the confounding influence of inland light glow visible from this arena. Sig = Significance of difference relative to controls (Bonferroni correction)



Arena location	WATTAGE	Lux	p value	Sig.
100m	500W	3.38	-	-
100m	250W		-	-
200m	500W	0.55	0.0137	ns
200m	250W		0.0122	*
500m	500W	0.1	0.1502	ns
500m	250W		0.0341	ns
800m	500W	0.05	1	ns
pooled controls 200m-800m	0	0		

Figure 6.10: The proportion of green hatchings in each segment for each arena under 2 different light intensities (250 W and 500 W) for the metal halide light treatments. Data sorted by Lux value. Blue wash represent the arena segments oriented most closely to the ocean, yellow wash represents the arena segments oriented towards the light array. Note: ‘ - ‘ signifies no p value code for the 100m arena due to the confounding influence of inland light glow visible from this arena. Sig = Significance of difference relative to controls (Bonferroni correction)



Arena location	WATTAGE	Lux	p value	Sig.
100m	500W	4.52	-	-
100m	250W		-	-
200m	500W	0.82	0.0137	ns
200m	250W		0.0018	*
500m	500W	0.1	0.5808	ns
500m	250W		0.7024	ns
800m	500W	0.05	0.1952	ns
pooled controls 200m-800m	0	0		

Figure 6.11: The proportion of green hatchings in each segment for each arena under 2 different light intensities (250 W and 500 W) for the fluorescent light treatments. Data sorted by Lux value. Blue wash represent the arena segments oriented most closely to the ocean, yellow wash represents the arena segments oriented towards the light array. Note: ‘ - ‘ signifies no p value code for the 100m arena due to the confounding influence of inland light glow visible from this arena. Sig = Significance of difference relative to controls (Bonferroni correction)

6.4.2 Uncontrolled light source experiments

The results for the hawksbill arena trials at each beach are shown in Figures 6.12 – 6.16. The arena data are presented by beach location, for moon and no moon trials. Logistical constraints prevented trials on both moon and no moon nights for all arena locations.

Hawksbills

Cooks Beach was initially selected as a control location since it was located the greatest distance from the illuminated facilities on Varanus Island (Figure 6.3). However, it was only run once as it was difficult to reach at night by dinghy. The Harriet A flare, 6 km offshore, was also visible at this location. The hatchlings tested here all oriented parallel to the water and directly away from a tall dark headland adjacent to the arena. There was no artificial light visible from the direction of travel of the hatchlings (Figure 6.12). The Harriet A flare was located on a 355° bearing (segment 12) and did not appear to have influenced the hatchling orientation. This arena was tested under full moon light conditions visible in segments 12 and 1. The arena was in the moon shadow of the headland (in segments 3 and 4, Figure 6.12) which appears to have triggered an avoidance response in the hatchlings (Lohmann, Kenneth J. *et al.* 1997; Tuxbury and Salmon 2005) since they did not crawl towards the brightest horizon visible in segments 12 and 1 over the ocean.

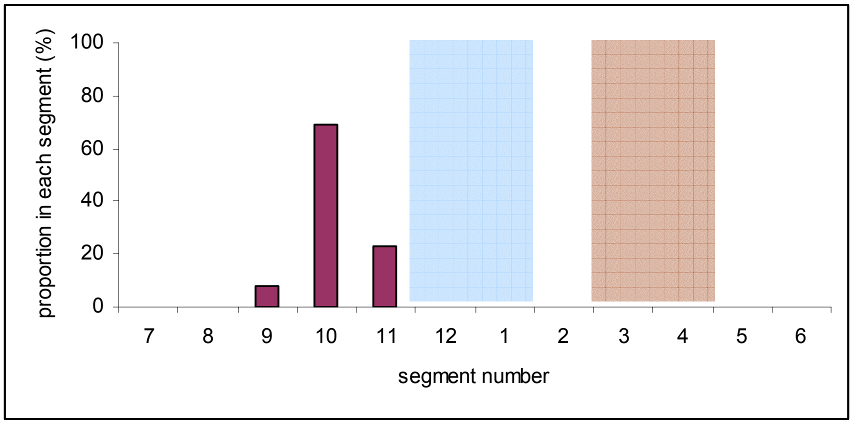


Figure 6.12: .The proportion of hawksbill hatchlings found in each arena segment at Cooks Beach, Varanus Island. Blue wash = ocean facing segments, brown wash = headland shadow facing segments, n=13. Full moon rising over the ocean.

Pipeline Beach was the most brightly illuminated of all test beaches. The plant was not strongly visible from the arena on full moon nights but was highly visible on dark nights. The glow from the *Ensco 56* drilling rig on the Koombana location (~3.3 km south east) was visible behind the low limestone headland 100m south of this beach both on full moon and dark nights. The experimental trial performed on a full moon night (Figure 6.13) saw hatchlings scattered widely and orienting away from the ocean in the direction of the *Ensco 56* glow over the rocks at the east end of the beach. On a dark, new moon, night (Figure 6.13) the hatchlings continued to scatter widely. However, their mean direction shifted around ~100° towards the plant (segments 3 - 10).

The proportion of hatchlings orienting towards or away from the ocean on full moon versus dark night was significant ($t_{50} = -4.0742$, $p = 0.0002$). This response was quantified by calculating the percentage of hatchlings that did not crawl towards the ocean, assuming orientation in the 4 most seaward quadrants (excluding segment 3 which was exposed to both the ocean direction and light) is normal. On moonlit nights 35% of the hatchlings oriented exclusively towards the ocean segments, while on new moon nights only 3% successfully oriented in an exclusively seaward direction.

These results clearly demonstrate the influence of the artificial lights on hatchling orientation both with and without the influence of moon light.

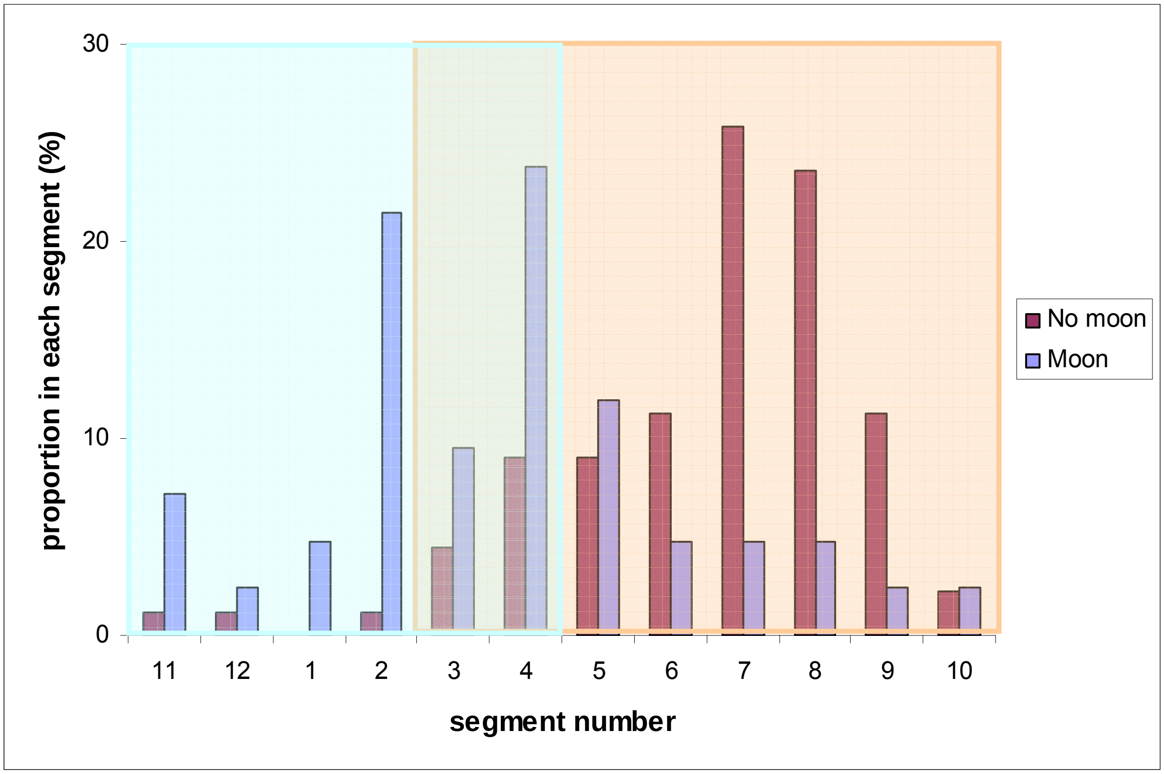


Figure 6.13: The proportion of hawksbill hatchlings found in each arena segment at Pipeline Beach, Varanus Island. Full moon, n=89, No moon n = 42.. Yellow wash signifies segments exposed to artificial plant light (segments 7 - 10) and to the *Ensco 56* offshore drilling rig glow (segments 3 – 6), while the blue wash denotes segments adjacent to the ocean.

Andersons beach is a semi-enclosed south east facing shoreline located at the southern end of Varanus Island. The arena was installed on the eastern end of the beach in front of a low neck of sand that separates Andersons beach from Harriet Beach. The glow from the camp and the jetty are visible at this location and hatchling tracks had frequently been observed orienting across the sand strip towards Harriet Beach. However on the nights that hatchling orientation was tested at Anderson Beach the glow from the *Ensco 56,* located 2.5 km to the east, dominated the horizon over the low profile rocks at the eastern end of the beach and rendered the camp and jetty lights invisible by comparison.

Figure 6.14 shows the influence of the glow from the *Ensco 56* on the nights when no moon was present. During the experimental trial the hatchlings spread out and crawled in the direction of the drilling rig (segments 10 and 11). During the trial under the influence of the moon (Figure 6.14) hatchlings continued to scatter broadly but in a more seaward direction. The difference in orientation direction under moon and no moon conditions was significantly different ($t_{39} = -5.4507$, $p < 0.05$).

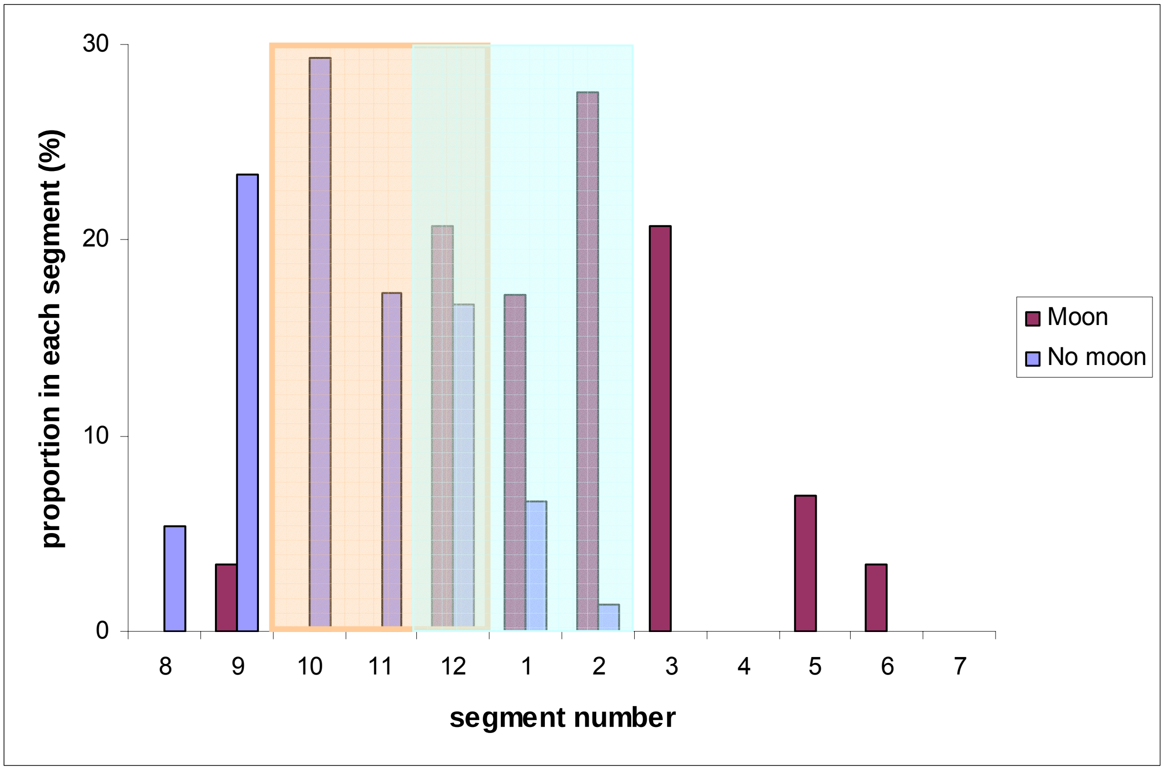


Figure 6.14: The proportion of hawksbill hatchlings found in each arena segment at Anderson Beach, Varanus Island. No moon, n = 75, Moon n = 29. Yellow wash signifies segments exposed to the offshore drilling rig, *Ensco 56*, light glow, while the blue wash denotes segments adjacent to the ocean.

The percentage of hatchlings in the three most seaward segments was greatest when the moon was risen (45%) compared to no moon when only 8% of the hatchlings oriented towards the sea. Hatchlings crawling to the east on Andersons Beach towards the Ensco

56 glow typically become trapped in the highly weathered karst limestone ridge that separates the beach from the ocean.

The presence of artificial lights both on shore and offshore clearly impacted the orientation of hawksbill hatchlings on the light exposed beaches that were tested (Pipeline and Anderson Beach) and the influence of the lunar modulation described by (Salmon, M. and Witherington 1995) was also evident.

6.4.3 Fan mapping

Effects of onshore and offshore light regimes

A total of 384 sea turtle nests were mapped on beaches of the B-L-M group between 1998 and 2003. These included 213 hawksbill (55%), 96 flatback (25%), 27 green turtle (7%) and 48 (13%) unidentified nests. The nests were coded for the four possible combinations of light regimes, *i.e.* onshore light (artificial light from the plant), onshore dark, offshore light (artificial light from drilling rigs, boats or pipe lay barges) and offshore dark. The mean A-B spread and offset angles (see Figure 6.4) are shown in Table 6.5 and Figure 6.15. A multivariate analysis of the combined fan angle and offset data is given in Table 6.6. Individual ANOVA analyses of fan spread and offset are given are Table 6.7.

The greatest scattering of hatchlings occurs when hatchlings emerge onto beaches with light exposure from both onshore and offshore locations (mean spread angle of 65°), while the mean offset of the fan, relative to a direct line to the ocean (at 0°), was 52° (Table 6.5). Beaches with onshore light and no light offshore had slightly smaller fan spread and offset angles (60° fan angle, 30° offset), followed by beaches with dark onshore and light offshore light fields (41° fan spread, 24° offset). The smallest fan spread and offset were seen on completely dark beaches (onshore and offshore) with a mean fan spread of 39° and offset of 15°.

Multivariate analysis of variance was performed on the with log transformed fan angle and offset angle as dependant variables and moon phase, presence or absence of onshore lights and presence or absence of offshore lights and facilities. Beach use treatment is a factor within offshore and onshore lighting combinations. The multivariate analysis showed this influence of onshore light was significant ($p < 0.05$) while the effect of offshore light and moon phase was not ($p > 0.05$, Table 6.6). The interaction between the fan spread and offset, for the combination of onshore light and offshore light, was also not significant ($p > 0.05$). However, the interaction between the individual beaches and the onshore/offshore light regime was highly significant ($p < 0.001$). Individual ANOVA analysis of fan spread and offset for the factors of moon phase, onshore light, offshore light and individual beach effects, showed the presence of onshore light was a highly significant factor influencing fan spread angle and offset angle ($p < 0.001$, Table 6.7).

The results indicate that onshore light influences hatchling orientation more than offshore light. This is demonstrated in Figure 6.15 which shows the greatest fan angles and offsets for nests exposed to onshore light and the least in nests exposed to no onshore light, regardless of whether offshore light were present or not. This is not unexpected since an offshore light will assist in attracting hatchlings the direction of the ocean whilst they are traversing the beach. The attraction of hatchlings to offshore lights does not reduce the threat to hatchling survival since they may then become exposed to higher predation rates relative to animals that continue to swim offshore.

Onshore lights, on the other hand, are typically behind or at the ends of the beach and appear to draw hatchlings away form the most direct line to the ocean. This is reflected in the results of the multivariate analysis (Table 6.5) which showed an interaction between the two different light regimes and individual beaches.

Table 6.5: Analysis of combined fan spread angle and fan offset angle (mean ± se)

Onshore	Offshore	Mean A B spread angle (degrees)	Mean fan offset from X (degrees)	n
Light	Light	65.19 ± 8.05	52.54 ± 7.40	101
	Dark	60.14 ± 4.81	30.24 ± 4.14	103
Dark	Light	41.04 ± 3.19	25.00 ± 3.14	47
	Dark	39.19 ± 1.69	15.54 ± 2.30	133

Table 6.6: Multivariate analysis of variance of the dependant variables, fan spread angle and fan offset angle (Wilks' Lambda)

Effect	F	Hypothesis df	Error df	Sig.
Onshore light	4.545	2	338	0.0113
Moon phase	0.205	2	338	0.8157
Offshore light	1.588	2	338	0.2058
Onshore light and Offshore light	0.050	2	338	0.9511
Beach number and light sources (onshore and offshore)	1.784	80	676	8.08E-05

Table 6.7: Individual ANOVA analysis of fan angle and offset. Test subjects; moon phase, onshore light, offshore light and individual beach effects.

Source	Dependent Variable	df	Mean Square	F	Sig.
Moon phase	AB angle	1	0.0328	0.3996	0.5277
	Offset angle	1	0.0196	0.0733	0.7869
Onshore light	AB angle	1	0.5948	7.2451	0.0076
	Offset angle	1	1.1027	4.1239	0.0431
Offshore light	AB angle	1	0.0303	0.3695	0.5437
	Offset angle	1	0.8465	3.1657	0.0761
Onshore light x Offshore light	AB angle	1	0.0082	0.1001	0.7518
	Offset angle	1	0.0028	0.0103	0.9190
Beach number x onshore light x offshore light	AB angle	40	0.0774	0.9423	0.5739
	Offset angle	40	0.6936	2.5940	0.0000
Error	AB angle	339	0.0821		
	Offset angle	339	0.2674		

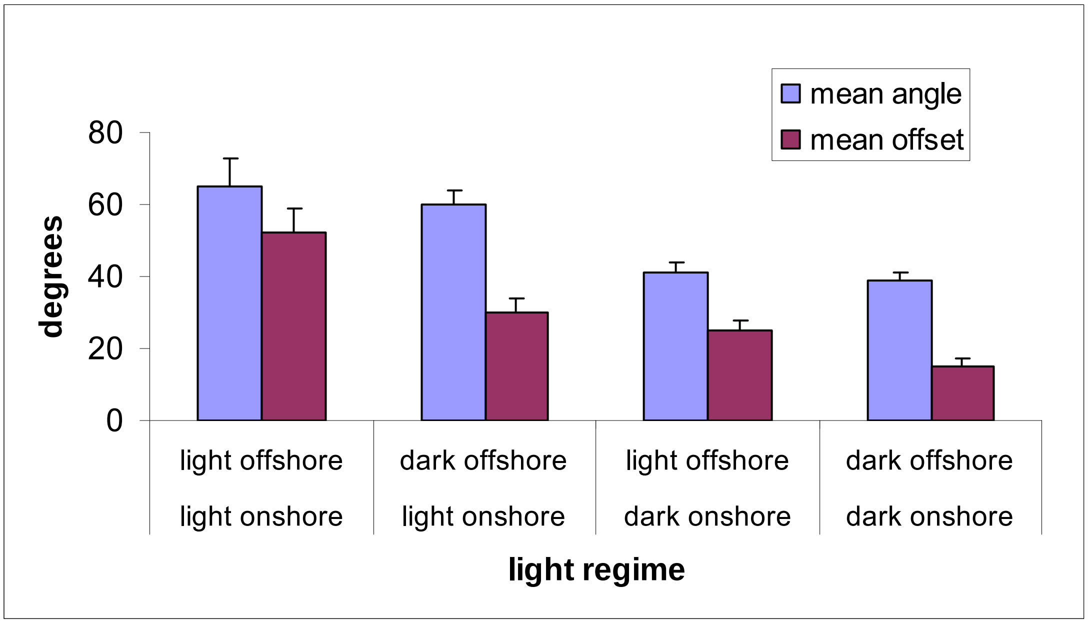


Figure 6.15: Mean fan spread and offset angles for nests exposed to a combination of light or dark horizons located onshore or offshore relative to nesting beaches.

Effects of headlands

The effect of headlands was tested by extracting the data for the naturally dark beaches and sorting them for the presence or absence of headlands. There is no difference in fan spread angle for beaches with (40.97° ± 21.03°, n = 90) and without (40.33° ± 21.01°, n =

67) headlands (t_{142}=0.1882, p = n.s.), however there was a significant difference in offset angle (t_{119}=3.5381, $p < 0.001$). The fan offset angle for nests on beaches with headlands (20.16°± 30.41°, n = 90) was significantly different to the offset angle on beaches with no rocky headland (7.83° ± 11.17°, n = 67).

Comparisons of fan spread and offset angles recorded on Florida beaches with that from B-L-M beaches indicate there is a difference in fan characteristics between the two locations. Examples of mean fan spread angle and mean offset angle from loggerhead nests orienting in arenas under naturally dark conditions are shown in Table 6.7 along with the results for nests on dark beaches within the B-L-M Island complex. The mean spread and offset angles for the latter beaches fall within the range defined by Salmon and Witherington (1995) for naturally dark beaches, i.e. fan spread angle < 90° and offset angle < 30°. Both the Florida and B-L-M nests demonstrated greater offset mean spread angles than mean offset angles. However, both the magnitude and the range of both spread and offset angles were substantially greater for the Western Australian nests than the Florida nests. The reasons for this difference in fan angle and offset may be may be related to beach geomorphology.

Table 6.7: Comparisons between fan spread and offset angles from naturally dark Florida and the B-L-M complex.

Fan metric	Salmon and Witherington (1995)		This study	
	Mean ± SD	range	Mean ± SD	range
Fan spread angle	34° ± 10°	20° - 30°	41° ± 21°	10° – 110°
Fan offset angle	3° ± 4°	0° - 10°	15° ± 26°	5° - 205°

6.4.4 Industrial Case Study results

The two locations within the study area that were exposed to anthropogenic lighting were Varanus Island and the east coast of Barrow Island, discussed separately below

Pipeline Beach, Varanus Island

Pipeline Beach was exposed to the highest levels of artificial light on Varanus Island. It was also the densest Hawksbill rookery on the island (mean 11.6 tracks/day/km, Table 3.9 Chapter 3). Of the 108 nests mapped on this beach, 87% were hawksbill nests, with flatback nests making up the balance. Pipeline Beach was exposed to artificial light at all times and included illumination from unshielded and shielded fluorescent lights, mercury vapour light and flare light from the onshore oil and gas processing plant situated within 100m of the beach. The offshore light exposure at Pipeline Beach varied over time depending on offshore construction and drilling activities. Onshore light regimes varied depending on flare operations and the success of the plant operators in regularly extinguishing the plant lights adjacent to Pipeline Beach.

The 6+ m dunes behind Pipeline Beach shield the hatchlings from light when emerging from nests in the central and western portions of the beach. However, the light from the eastern end of the plant was not shielded by tall dunes and was visible as a reflection off the rocks at that end of Pipeline Beach. It was not unusual to find hatchlings crawling eastward along the entire length of the beach (100m+), under or over the partially buried sales gas pipeline bisecting the eastern end of the beach and across the rocky area bounding the east end of the beach (Figure 6.16). Nor was it unusual to find hatchlings crawling out of the water and back up the beach at the eastern end of Pipeline Beach.

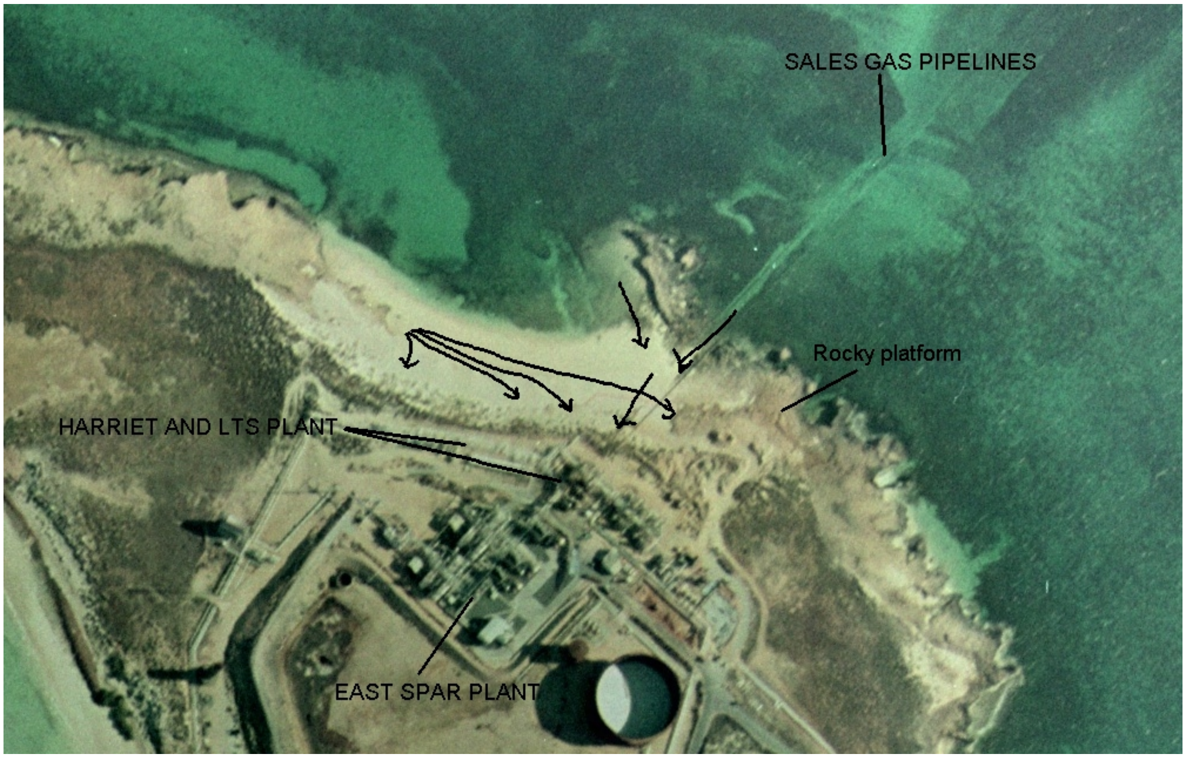


Figure 6.16: Common hatchling track orientation directions on Pipeline Beach when plant lights adjacent to the beach were illuminated.

Hatchlings that reached the rocky area at the eastern end of Pipeline Beach became trapped in the rocks or were predated by seagulls (*Larus novaehollandiae*), terns (*Sterna caspia*) or the ubiquitous green rock crab (*Leptograpsus variegatus,* personal observation Jan 1998).

Evidence to show the benefits of turning off lights close to nesting beaches can be found in the Pipeline Beach results. Since the multivariate analysis of the fan data showed the influence of onshore light was more significant than the influence of offshore light on fan offset and spread, the Pipeline data were analysed by pooling the data for all fans coded with onshore light on and compared to fan data for fans coded onshore dark (ignoring the offshore light regime). Fans were mapped when both the Harriet/LTS and East Spar lights were on and then when the Harriet/LTS lights only were extinguished. The mean fan spread angle when the lights were on (72°± 88°, n = 90) was significantly different (t_{106}= 4.3178, $p < 0.001$) to the spread angle when the lights were off (27°± 19°, n = 20). A significant reduction in offset angles was also evident when the lights were extinguished behind Pipeline Beach (64°± 82° lights on, 20°± 27° lights off) (Figure 6.17).

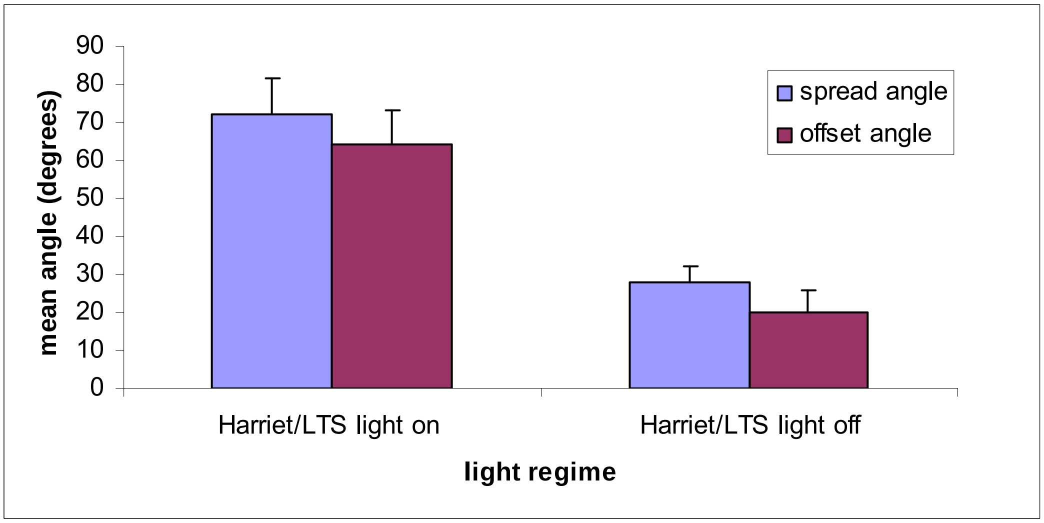


Figure 6.17: Comparison of mean fan spread angle and offset angle for nests emerging on Pipeline Beach with the Harriet/LTS plant lights turned on and turned off. Standard error bars

Evidence of this change in orientation related to the artificial light regime was clearly seen in December 2001 when a split emergence occurred from a single nest over two nights of a waxing moon with and without the plant lights on. The night the plant lights were on the hatchlings oriented towards along the beach as shown in Plate 6.4 (left photograph), two nights later when the plant lights were turned off the hatchlings oriented in the opposite direction towards the ocean (Plate 6.4 right photograph).

Plate 6.4: Hawksbill split nest emergence, mapped on 17 December 2001 (left) with plant lights on and on 19 December 2002 (right) with plant lights off. Arrows denote direction of the bulk of the hatchling tracks. Waxing new moon (3.8% and 14.8% respectively)

Yacht Club and Terminal Tank beaches – Barrow Island

Fan data from flatback nests emerging on the east coast of Barrow Island were split into those exposed to light within a 500 m radius and those with light sources ≥ 500 m from the beach. The light sources consisted primarily of high pressure sodium fixtures. The total number of nests mapped within 500m of the light sources was 23, while 54 nests were mapped at locations more than 500m from the light sources. None of the mapped nests were adjacent to tall headlands since these topographic features appeared to influence the offset angle of the hatchling fan in the absence of artificial light.

The mean fan spread angle for nests within 500m of light sources was 64.5°± 28.6°, n = 23 and significantly greater than those beyond 500m, which were 37.7°± 19.2°, n = 54 (t_{33} = 4.0479, $p < 0.001$). The offset angles displayed similar differences (Figure 6.18). Nests within 500 m of light sources had mean offset angles of 21.4°± 29.8° whereas those on dark beaches had a mean offset angle of 7.5°± 11.7° (t_{26} = 2.2532, $p < 0.05$). These results demonstrate the value of using fan mapping as a monitoring tool when used in the absence of the confounding influence of headlands on hatchling orientation.

These results also suggest that the influence of the light sources on Barrow Island was restricted to within 500m, markedly less than the 1.5 km buffer zone proposed by Limpus (2002) for the protection of Australian rookeries. However the existing light usage on Barrow Island is not only small scale relative to the typically larger and unrestrained urban light usage, it is also dominated almost exclusively by sodium vapour light types which have been shown to be less disruptive of flatback hatchlings than the more visible white metal halide and fluorescent light sources that are commonly found in urban setting (see Figures 6.6, 6.7 and 6.8).

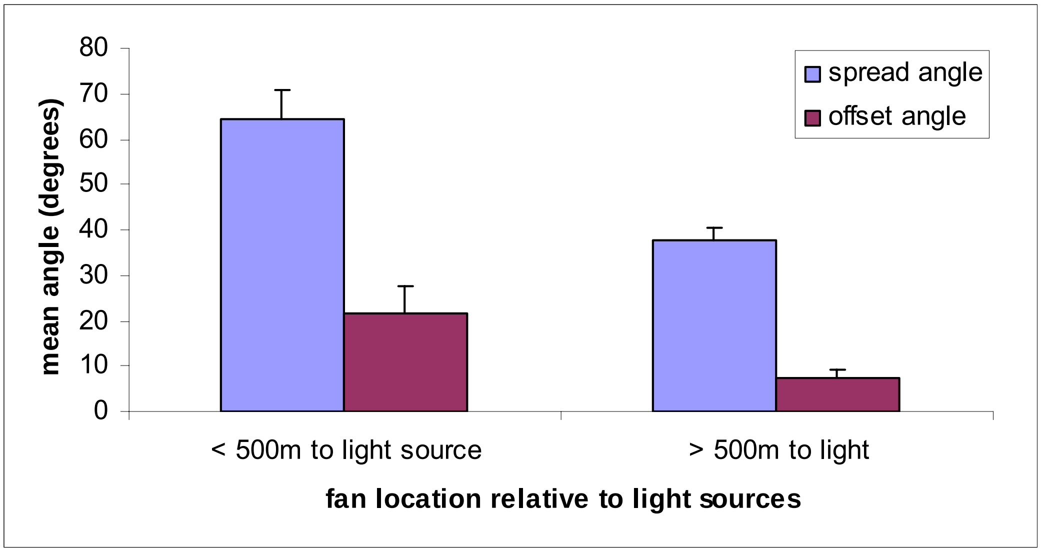


Figure 6.18: Mean fan angle and offset for nests on east coast Barrow Island beaches, within 500m of light sources and > 500m from light sources. Standard error bars.

6.5 Discussion

6.5.1 Effects of artificial illumination on hatchling seafinding

The results of the arena experiments with controlled light sources show that green turtle and flatback hatchlings exposed to artificial light orient significantly different from hatchlings not exposed to artificial light (Tables 6.2 and 6.3, Figures 6.6 – 6.8 and Figures 6.9 – 6.11). Both light type and intensity (as a function of distance) were significant factors in hatchling response. Generally, under the different light types, hatchlings oriented towards the lights in the two near arenas (100m and 200m) and to the ocean in the two far arenas (500m and 800m). Under the higher intensity 500W light the hatchlings orientation in the two near arenas was similar, as was the orientation in the two far arenas. Reducing the light intensity to 250W was sufficient to cause a significant difference in hatchling response in the two near arenas but not in the two far arenas. These results suggest that hatching response is closely linked to light intensity and that hatchlings are able to discriminate between small increments in intensity.

Chi square tests using ocean direction versus all other directions as a binary choice showed all three light types significantly influenced flatback orientation at the higher light intensity levels (100 m and 200 m arenas, Table 6.2). As the light intensity decreased hatchling response to sodium vapour light was no longer detectable at 500 m and 250 W. At lower light levels both fluorescent (500 W at 800 m) and metal halide (250 W at 500 m) caused a weakly significant attraction to the light. For sodium vapour light, relative to the other light types, the intensity levels required to elicit a misorientation response is higher and therefore sodium vapour lights are the preferred light option for use in industrial facilities near sea turtle rookeries.

While the statistical analyses showed that green turtle hatchlings were significantly affected by the three light types and light intensities the results of the sequential Bonferroni correction on the Chi square results, used to investigate the significance of the individual light sources, showed there was no significant difference between the controls and the hatchlings behaviour under the individual light sources (Table 6.3). Corrected logistic regression results suggest that the three light types tested (sodium vapour, metal halide and fluorescent) had a significant impact on hatchling orientation (relative to the controls) at 200 m and 500 W. At lower light intensity (250W and 200m) only fluorescent and metal halide light produced a weakly significant response while sodium vapour did not have a significant impact.

Arena experiments on beaches exposed to artificial industrial lighting associated with an actual oil and gas installation also demonstrated the effects that these lights have on hatchlings emerging from nearby nesting beaches. The presence of an illuminated industrial facility within 100m of a nesting beach and a well lit offshore drilling rig based light source, 3.3 km away, had a significant impact on hatchling orientation. The study also provided evidence to support Salmon and Witherington (1995) who proposed moonlight countered the misorientation effects of artificial lights. On one beach at Varanus Island, in the absence of moonlight and under the influence of artificial light, 3% of hawksbill hatchlings oriented in a seaward direction. Orientation under the same artificial light conditions and a full moon increased the seaward orientation by hawksbill hatchlings to 35%.

On another beach on Varanus Island exposed to only brightly lit offshore artificial light source (2.5 km away) and in the absence of moonlight, 8% of hawksbill hatchlings crawled toward the ocean whilst under the moderating influence of a full moon this proportion to increased to 45%.

6.5.2 Fan mapping as a monitoring tool and beach topography effects

The beaches in Florida are contiguous over 10's of kilometres and not characterised by the same tall headland and extensive dune development found in the B-L-M group. Headlands confine nesting to relatively short (10's – 100's of meters) stretches of sand and are present on 53% of Barrow beaches, 81% of Montebello beaches and 80% of Lowendal beaches. Much of the primary dune system has been lost behind Florida beaches and they are often backed by stands of *Casuarina* or tall condominium structures (personal observation 1979-1984). The beaches of the B-L-M complex are typically backed by sand dunes (with or without large blow-out areas separating the primary and secondary dune line), cliffs or hills and low *Spinifex longifolius* vegetation.

The B-L-M results showed a significant effect on the fan spread and offset angle within the different light regimes from individual beaches. The beach effect detected by these results support the hypothesis that hatchlings locate the ocean by 'discriminating between high and spatially variable silhouette of the dune and the lower and less spatially variable ('flatter") view toward the sea' (Limpus, Colin J. 1971; Salmon, M. *et al.* 1992; Salmon, M. and Witherington 1995). Salmon and Witherington (1995) further proposed that these geomorphologic beach characteristics were a primary cue in sea finding and of over riding influence relative to light intensity.

Observations made during the collection of hatchling fan and adult track data (Chapter 3) suggested the presence of headlands had a strong influence on fan offset on naturally dark beaches. Nests emerging close to, or within, the night time shadow of headland inevitably oriented either at, or close to, a line which took them along the beach away from the headland on a heading that bisected the angle between the headland and the ocean. Most of these hatchlings eventually reached the ocean as the tracks curved around onto an oceanic heading as the animals moved away from the headland. Rarely did the tracks take the shorter and more direct line to the ocean by traversing the sand along the base of the rock face. Similar patterns were noted in adult tracks. Animals crawling up the beach along the base of a rocky headland generally returned to the ocean at an angle to the headland and not back on the approach direction. Evidence of this aversion response to a tall dark silhouette over riding the attraction to a lower lighter horizon was seen in the results of the arena experiments at Cooks beach. The arena was located at the base of a very tall (~15m) rocky headland and the trial run under moonlight conditions (throwing the headland in to deep shadow). The hatchlings tested oriented at 180° to the headland, directly along the beach, and ignored the ocean 90° and ~ 5m to their right (Section 6.4.2).

Fan measurement data has also been used to assess the degree of disruption to emerging loggerhead hatchlings caused by artificial lighting on Florida beaches. The degree of disruption, termed the “Hatchling Orientation Index” was defined as ‘moderate’ for nest emergence fans that had offset angles of 30° – 90° and fan spread angles of 90° – 180° and ‘severe’ for fans that displayed a fan offset angles of ≥ 90° and spread angles of ≥

180° (Salmon, M. and Witherington 1995; Witherington *et al.* 1995). Application of this index to Barrow Island and Lowendal Island light impacted fan data suggests that nests exposed to onshore light were moderately disrupted based on the mean offset result however the mean spread angle suggests nests were not affected by light. The spread angles for Barrow and Lowendal Island hatchling fans influenced by both onshore and offshore light ranged from 5° to 360° suggests that some of the nests were severely affected by the light as defined by the above “Hatchling Orientation Index”.

Chapter 7 Satellite telemetry

7.1 Introduction

7.1.1 Background

Understanding the post-nesting movements of sea turtles is vital to the protection of individual animals and critical developmental habitats. While we have some knowledge on the location of Western Australia's Pilbara sea turtle nesting beaches (Prince 1994a) and on the offshore Pilbara Islands (Chapter 3, this thesis) the location of foraging areas and migratory corridors between the nesting and feeding grounds have not been confirmed. An understanding of the above is required to protect these habitats, and the sea turtle life stages present, from human impacts.

Very little published information is available on the dispersal of green turtles from their Pilbara nesting locations to remote foraging grounds. Of the 6,300 Pilbara green turtles flipper tagged between 1985 and 1996, (Prince 1997) a single tag was returned from Indonesian waters east of Timor and 17 from locations between Shark Bay and the North West Kimberley region. Two Barrow Island green turtles were found at 'west Kimberley coast' locations (Prince 1994a).

Even less is known about hawksbill dispersal patterns or feeding grounds. While a total of 1,050 Hawksbill turtles have been flipper tagged at Rosemary Island (1990 – 1996) and 304 Varanus Island (1986 – 1996), there have been no reports on the dispersal pathways of any of these turtles (Prince 1997). Their foraging grounds are unknown.

This component of the research sought to identify some of the habitats used by Western Australian sea turtles after they had left their nesting grounds at Barrow Island, Varanus Island, Rosemary Island and Sandy Island. Specific threats to these migrating and foraging animals could then be identified so that the potential impact of industrial activities at their nesting grounds could be put into perspective.

7.1.2 Research questions

Sea turtles in Western Australia had never been tracked, either by radio of satellite transmitter devices, prior to this study. The three primary research objectives of this study were therefore to address the following questions:

1. Where do nesting green turtle and hawksbill turtles internest at Barrow Island, Varanus Island and Sandy Island (Scott Reef)?
2. What are the migration routes of sea turtles between their nesting and foraging grounds?
3. Where are the foraging grounds for these turtles?

7.1.3 Chapter outline

Satellite tracking data from twelve green turtle and nine hawksbill turtle are used to identify the internesting grounds at Barrow Island (green turtles), Varanus Island (hawksbill turtles), Rosemary Island (hawksbill turtles) and Sandy Island, Scott Reef (green turtles). The migratory pathways used by these animals returning to their foraging ground are individually reconstructed and analysed. Swimming speeds are calculated during open ocean and near shore segments of selected migratory tracks. The location of foraging ground for the animals is proposed based on the duration of satellite signals from migratory path endpoints. These results are then used to identify threats to internesting, migrating and foraging green turtle and hawksbill turtles. Conservation measures are proposed for the protection of these critical habitats.

7.2 Literature Review

Genetic studies on Australian green and hawksbill turtles have shown that the Western Australian (WA) and Queensland (Qld) populations are genetically distinct (Broderick *et al.* 1994; Norman *et al.* 1994). There is no interbreeding between the two populations. Within WA there are no significant genetic differences between rookeries, suggesting that the interbreeding unit for WA green and hawksbill turtles is likely to be spread over the state. The genetic studies have provided additional support for the hypothesis that hawksbills undertake long distance migrations in the same manner as green turtles (Broderick *et al.* 1994; Fitzsimmons *et al.* 1996).

Sea turtles undertaking breeding migrations between their feeding and nesting habitats appear to show preferences for particular pathways (Morreale *et al.* 1996; Balazs and Ellis 1998; Luschi *et al.* 1998). Sea turtles are able to accurately target a location across large distances with apparent purpose in their approach path. The information used to return to a targeted location (nesting or feeding ground) may be linked to currents (Papi *et al.* 2000), chemical cues, (Luschi *et al.* 1998) memorized paths (Luschi *et al.* 2003), bathymetric contours (Morreale *et al.* 1993), time-compensated sun-compass (Luschi *et al.* 1998), and/or geomagnetic inclination and intensity (Lohmann, Catherine M. Fittinghoff and Lohmann 1992).

Published information on the internesting zones, migration pathways and mating aggregation zones for Western Australian sea turtles is limited and confined to grey literature (unpublished reports to government or industry) and personal observations. The available information for the B-L-M complex is shown in Figure 7.1 and is summarized below.

Barrow Island

Adult and juvenile green turtles are regularly found feeding year round on turfing algae along the entire west coast of Barrow Island, indicating that this in an important feeding ground for resident green turtles (Pendoley 1998-2004). A subtidal (6-10 m) survey of the west and north coast of Barrow Island commissioned by WAPET in October 1996 (Pendoley 1998-2004) surveyed thirty five spot locations between the South End and Surf Point. At each location, bottom topography, coral and algae cover, and sea turtle presence/absence and activity was described. The results indicated that sea turtles were most commonly found between the South End and Biggada Reef associated with highly variable bottom topography, variously described as “rough topography” and “good turtle country”. Large coral bomboras were common and pavements were covered with *Sargassum* and *Halimeda* algae. Sea turtle sightings were notably reduced in areas north of Biggada Reef where the sea floor bathymetry was characterized by low relief limestone pavement with sand veneer and patches of *Sargassum sp.*

Aggregations of green turtles during the summer nesting season were also recorded within Little Bandicoot Bay and off two east coast beaches (#5 and #9) in November 2003. Mating aggregations of green turtles are commonly sighted within 100-200m of the west coast beaches of Barrow Island prior to and early in the summer nesting season.

Montebello Islands

West Montebello Reef Complex

A large reef complex lies to the west of the Montebello group of islands and is denoted the West Montebello Barrier Reef (Figure 7.1). Adult sea turtles were frequently observed along the entire length of this system during aerial surveys of the Montebello complex over the summer months between 1998 and 2003. The use of this area as a foraging ground was suggested by Prince (Prince *et al.* 2001) following a winter season aerial survey of the region in April 2000.

In March 2001 an aerial survey (helicopter) of the complex was carried out following discussions with Apache Energy field staff at Varanus Island who, in mid January 2001, had seen “thousands” of turtles in the waters west of the reef complex.. During this survey 100’s of sea turtles were observed spread along an algal line oriented with the tidal flow that ran parallel to the reef complex. An estimated 1000+ were visible and they appeared to be moving along the tidal flow line in a south east direction. They appeared to be mostly male (long tails visible) green turtles.

Some animals (~20) were also visible on the western side of the nearby reef break. The colour and shape of the shells suggested these were flatback turtles. However, this high energy environment is not thought to be favoured by this species. Smaller dark coloured hawksbill turtles were also noted. Additional aerial and in-water surveys are necessary to identify these species and to further quantify the size of the aggregations.

Trimouille and North West Islands

Mating aggregations of 100-200+ green turtles were also documented in the shallow water off the western ocean facing beaches of Trimouille Island in November 2002. The aggregation of green turtles in shallow protected waters south of North West Island was first documented in November 1999, and again in November 2002, when the numbers were estimated by the three observers at up to 1000 animals.

Lowendal Islands

There are no records of mating aggregations, feeding or internesting areas for the Lowendal area.

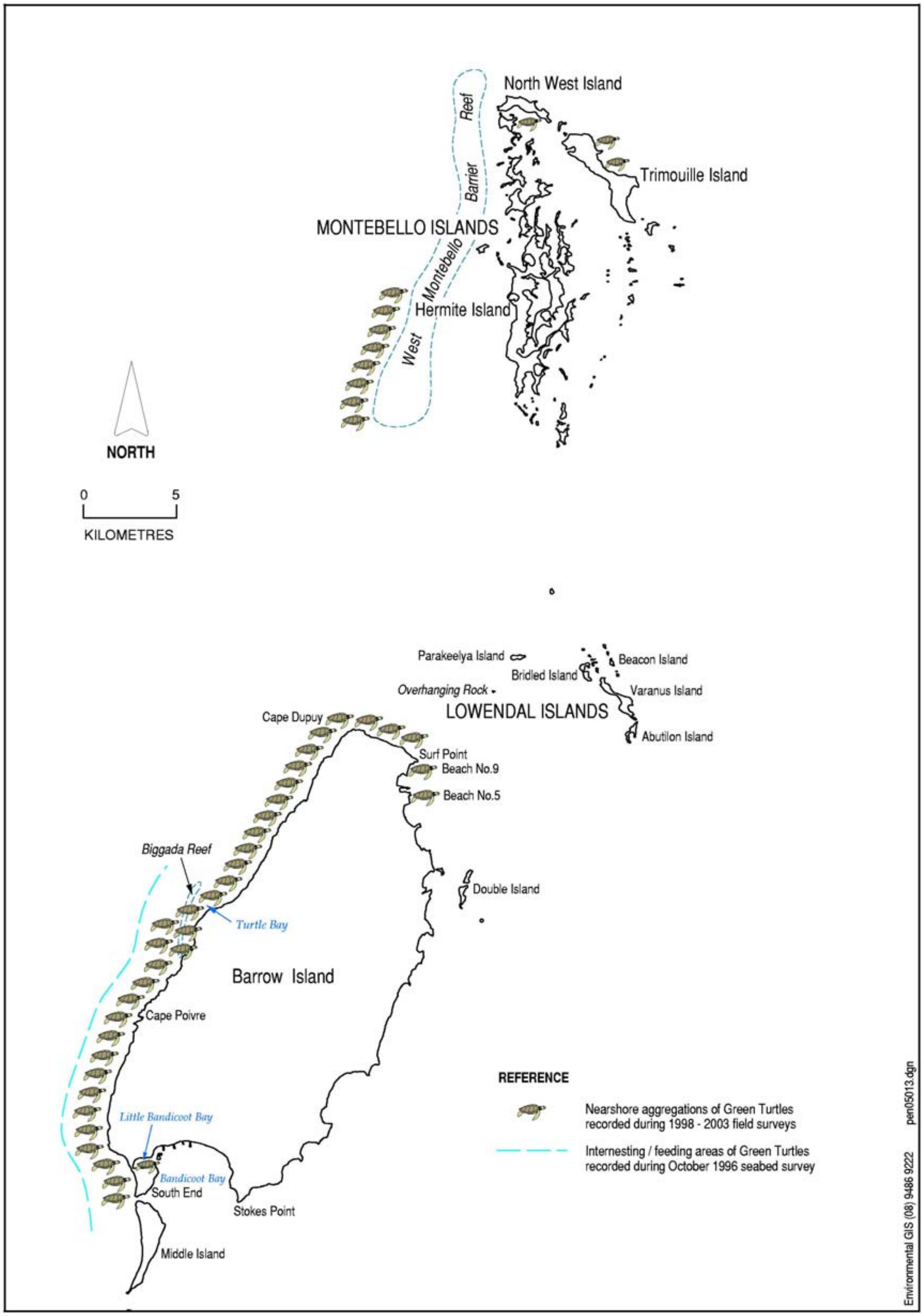


Figure 7.1: Location of turtle aggregations documented during the 1998-2005 field surveys.

7.3 *Methods*

7.3.1 Ptt deployment

Twenty one Kiwisat 101 platform terminal transmitters (ptts) were attached to sea turtles between December 2000 and January 2004 as follows:

- Eight units, female green turtles at Barrow Island in January 2001, 2002 and 2003 (Figure 7.2).
- Four units, female green turtles at Sandy Island, Scott Reef in October 2002, September 2003 and January 2004 (Figure 7.3). Located ~ 1100 km north east of the Barrow,Lowendal, Montebello Island complex
- Six units, female hawksbills at Varanus island in December 2000 and November 2002 (Figure 7.2).
- Three units, female hawksbills at Rosemary Island in November 2002 (Figure 7.2).

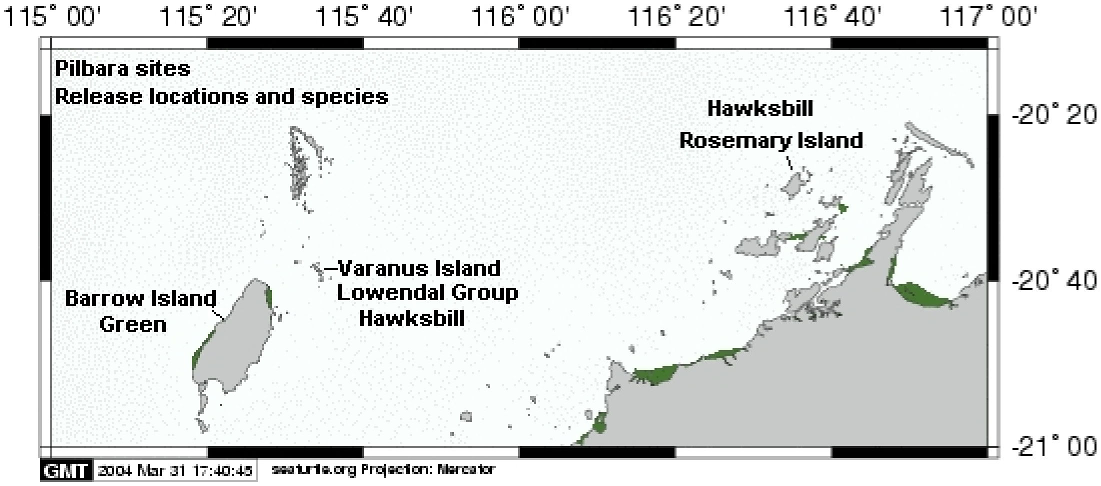


Figure 7.2: Pilbara Islands – Barrow Island, Varanus Island, Rosemary Island satellite tracked turtle release locations

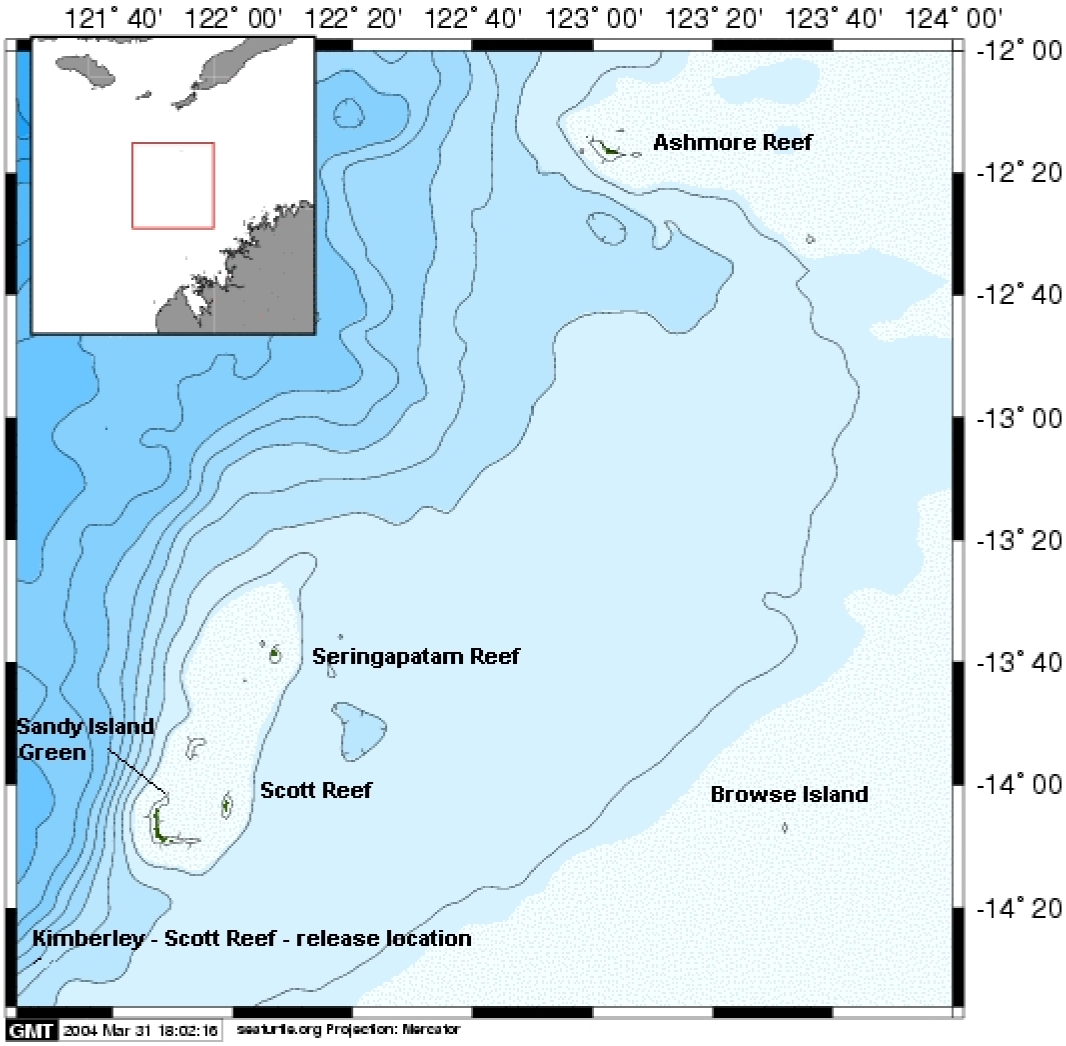


Figure 7.3: Offshore Kimberley Island – Sandy Island, Scott Reef satellite tracked turtle release location

Each turtle was captured as she came ashore to nest. Each was held in a wooden pen until the ptt attachment was complete and then released. Nineteen of the ptts were attached using fibreglass tape and resin (Balazs *et al.* 1995; Schroeder, Barabara *et al.* 1998). The ptt was placed on the first full vertebral scute behind the head. This procedure was long (average 3 hours per animal) and required the animals be held overnight so fibreglassing could be done in day light. The last two transmitters (Scott Reef turtles Eden and Manari) were attached using Foil-Fast™ (also known as Power-Fast™), a 2 part epoxy adhesive. Compared to the fibre glassing attachment method, the epoxy gel can be used in high humidity, on shell that is not perfectly dry or sanded and sets within 1 hour (it reaches full curing strength within 48 hours). The attachment could be done at night and took ~ 1.5 hours. The turtles were released immediately, significantly reducing the time the animals were held on the beach.

With the exception of the Scott Reef turtles, the ptts were attached during the peak of the nesting season for each species. Logistical constraints on accessing Scott Reef meant that these turtles were captured early in the summer nesting season.

The ptts were built and supplied by Sirtrack, New Zealand. The technical specifications and programming for each ptt is shown in Table 7.1. Feedback from this tracking program was used by Sirtrack to help improve the transmitter programming, electronic and packaging design.

Table 7.1: ptt technical specifications and programming

Ptt number	8 ptts (30325-30332) (2000/2001)	4 ptts 30333, 30334, 11275, 11276 (2001/2002)	6 ptts 37626 - 37632 (2002/2003)	2 ptts 11276(a), 30333(a) (2003/2004)
Output power	1 Watt	0.5 Watt 1 Watt	0.5 Watt	0.5 Watt
Package type	Box	½ tear drop	½ tear drop	Narrow waist ½ tear drop
Power source	4x Li C cells	2 x Li D cells	2 x Li D cells	2 x Li D cells
Repetition rate	45 sec	30 sec	30 sec	30 sec
Duty cycle	9 hr on / 3 hr off for 10 weeks 9 hr on / 51 hr off for 4 weeks 9 hr on / 99 hr off for 20 weeks	6 weeks on 1 week on / 3 weeks off for 46 weeks	60 days on 7 days on / 21 days off for 11 months	90 days on 1 day on / 5 days off for 12 months

7.3.2 LC filtering and data mapping

Over the past 20 years advances in satellite telemetry technology have made it possible to track sea turtles using platform terminal transmitters (ptt) which upload radio signals to 3-5 ARGOS polar orbiting satellites. Positions are calculated using the Doppler shift. The locations provided by the satellites can be classified into 7 location classes (LC) of increasing accuracy; LC B, A, 0,1, 2, 3. The accuracies for these LC positions is quoted by ARGOS (1996) as LC 3 < 150 m, LC2 150 m to 350 m, LC1 350 m to 1000 m, LC0 >1000 m. These locations are determined from at least 4 messages received during the satellite pass. LCA and LCB have no estimate of location accuracy and locations are determined from 3 message uplinks for LCA and 2 messages uplinks for LCB. Recent studies on the accuracy of the ARGOS location classes suggest LCA data has similar accuracy to LC1, both are better than LC0 while LCB has the greatest error (Vincent et al 2002; Hays et al 2001). The error in the locations is greater in longitude (east west) than latitude (north south, (Vincent *et al.* 2002).

Several researchers have noted the inaccuracies in LC data, where a position may be reasonable and acceptable in one transmission and clearly inaccurate for the same location class at a different time (Balazs *et al.* 1998; Ellis *et al.* 1998; Vincent *et al.* 2002). This error is frequently associated with the spatial behaviour of the turtle, for example (Vincent *et al.* 2002) and (Hays *et al.* 2001) note that while LC A and B locations have poorer accuracy on stationary (internesting and feeding) animals they still remain acceptable when the range of movement of the animal is large, as occurs during migration. This is thought to be due to differences in diving behaviour (on feeding grounds vs when migrating) which influences time separation between uplinks and in turn affects location accuracy (Hays *et al.* 2001)

The data from the original 4 green (Barrow Island) and 4 hawksbill (Varanus Island) turtles were mapped by hand and filtered manually. Maps were then generated using ARCVIEW/petrosys (provided by Apache Energy) and then Maptool when it became available (www.seaturtle.org). This was an extremely time consuming process given that the entire sample (21 animals) returned over 7,000 transmission records. In 2004 the Sea Turtle Analysis Tool was developed to filter and map the data automatically, based on user defined criteria (Coyne 2004). The data from all 21 turtles was subsequently filtered and mapped this way. Where possible, data analysis for identification of internesting, migration and feeding ground locations was based on LC 3,2,1 fixes. However selected LC 0, A and B fixes were sometimes used after evaluation of the signal location (stationary vs travelling), quality and plausibility. Positions were disregarded if they showed an unreasonable swimming speed between fixes (>6km/hr), locations with a swim direction > 90° from the locations recorded in the 3 days before and after a fix (during migration), or if the location was well inland (Luschi *et al.* 1998; Papi *et al.* 2000; Hays *et al.* 2001).

Since post nesting turtles are known to perform very long non stop journeys, it is reasonable to assume that the presence of an animals in a fixed area for periods ranging from weeks to months, after migrations of days to weeks, is indicative of a foraging ground (Papi *et al.* 1995). Feeding grounds are therefore identified by an extended stay within a restricted area at the end of a migration. After analysing the data from the Pilbara and Scott Reef turtles a minimum of 2 weeks was selected as a reasonable time frame to identify an extended stay at a feeding ground. Whether sea turtles have a permanent foraging ground or move between different grounds is not known.

These data were then used to determine;

- Internesting/nesting location and duration (using LC321 only),
- Dates the migration started and finished, and the pathway taken (using LC 3,2,1 for all animals and LC 0,A,B where data was limited),
- Feeding ground location (using LC 3,2,1 for all animals and LC 0,A,B where data was limited), and
- Estimated swimming speed during migration.

7.4 Results and Discussion

7.4.1 Location class

A breakdown of the LC classes received from the ARGOS system during this study is shown in Table 7.2. It is clear that the amount of good quality class fixes (LC 1,2 3) is generally limited (4% - 29% of all data, excluding Manari and Julie) while the bulk of the results are the lower quality LC 0, A and B fixes.

Table 7.2: Location class data distributions

Turtle name	total hits including LCZ with no location fix	total number of hits with location fixes	LCZ hits no location	% LC123	% LC 0	% LC A	% LC B	% LC Z	% hits no location fixes	Data classes used for filtering and mapping
Fran	71	28	43	25	4	29	36	7	61	3210AB
Vicky	231	172	59	11	20	23	36	10	26	321
Anna	175	93	82	19	6	22	49	3	47	3210AB
Sharon	175	102	73	8	21	16	48	8	42	3210
Julie	486	319	167	50	11	11	25	3	34	3210AB
Lyn	331	238	93	15	18	23	37	7	28	321A
Desiree	333	248	85	15	16	29	32	8	26	321
KellyB	878	613	265	29	14	21	32	4	30	3210AB
Trouble	410	280	130	23	16	21	36	4	32	3210AB
Manari	49	41	8	68	15	7	7	2	16	321
Eden	648	452	196	20	12	21	38	8	30	321
Emma	195	151	44	5	16	11	40	27	23	321
Erica	197	143	54	6	37	10	24	23	27	321
Marilyn	199	192	7	4	28	13	29	27	4	321
Marnie	67	21	46	5	29	14	43	10	69	321
Rachel	385	283	102	12	28	19	24	17	26	321
Eugenie	204	139	65	11	13	20	37	19	32	3210
Isobel	359	232	127	19	19	15	39	7	35	321
Sylvia	539	439	100	6	28	13	25	27	19	321
Rosie	604	415	189	18	18	23	32	9	31	321
Chloe	565	380	185	26	8	24	38	3	33	321

7.4.2 Tagging details

The ptt tag number for each turtle is presented in Table 7.3 (hawksbill turtles) and Table 7.4 (green turtles) along with the date and place of release and a summary of the tracking data. Tracking data included total days each animal spent internesting/nesting, migrating and on feeding grounds, estimated swimming speed on migration and the location of the migration endpoint.

7.4.3 Mapping

The detailed reconstructed migration pathways have been mapped for each turtle and are presented in Appendix 3. These include the approximate date each turtle left the nesting area, dates for selected locations along the migratory routes and the approximate date the turtle arrived at her endpoint (usually her feeding ground). Locations on internesting and foraging grounds are also mapped and identified by extended residency in a given area (denoted by clustering of LC positions). Summary migration pathway maps, grouped by ptt tagging location were compiled, using filtered data as described in Section 7.3.2 (LC filtering and mapping methods).

Nineteen turtles were tracked through all, or part, of their migration between their Pilbara and Scott Reef nesting grounds and remote feeding grounds. Transmissions from 2 turtles (Erica and Manari) ceased prior to their migration commencing. The migratory pathways for the 21 animals tracked are summarised in Figure 7.4 (Barrow Island green turtles), Figure 7.5 (Varanus Island hawksbill turtles), Figure 7.6 (Rosemary Island hawksbill turtles) and Figure 7.7 (Scott Reef green turtles).

In all cases the quality of transmissions for each turtle decreased over time. The reason for this is unknown but may be a function of animal behaviour (remaining under water for long periods while swimming or feeding) combined with transmitter programming (programmed on for 1 day out of 5 prevents transmission of sufficient data to get a good fix), battery performance and life or salt water switch fouling.

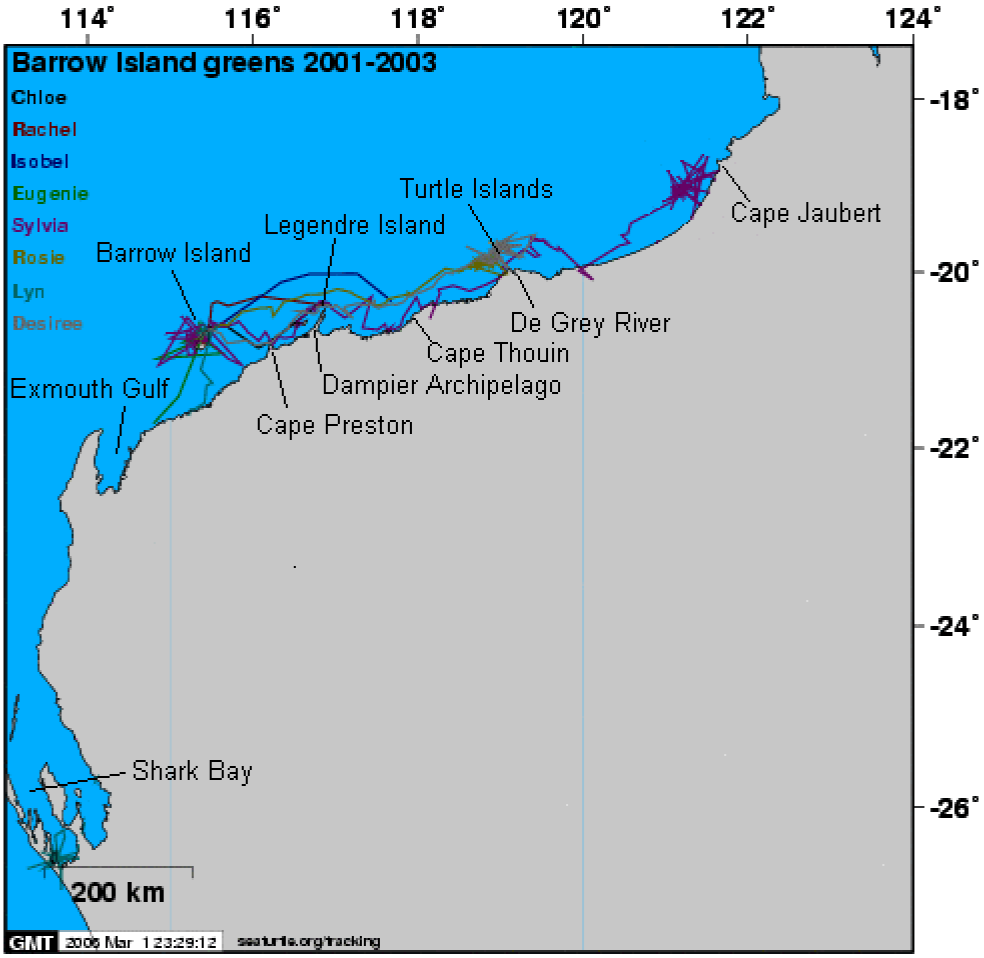


Figure 7.4: Green turtle project map showing migratory pathways between Barrow Island and the north eastern and southern foraging grounds. (Source: seaturtle.org STAT)

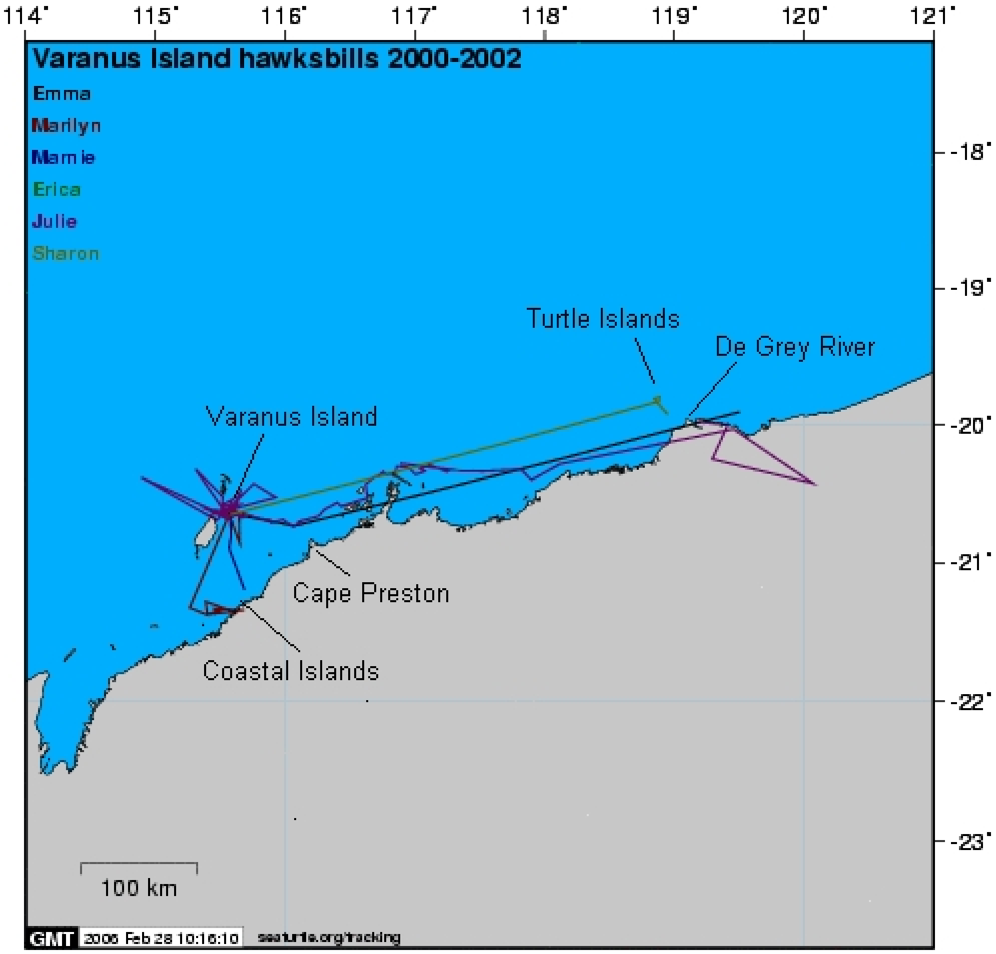


Figure 7.5: Hawksbill turtle project map showing migratory pathways between Varanus Island and the north eastern and southern foraging grounds

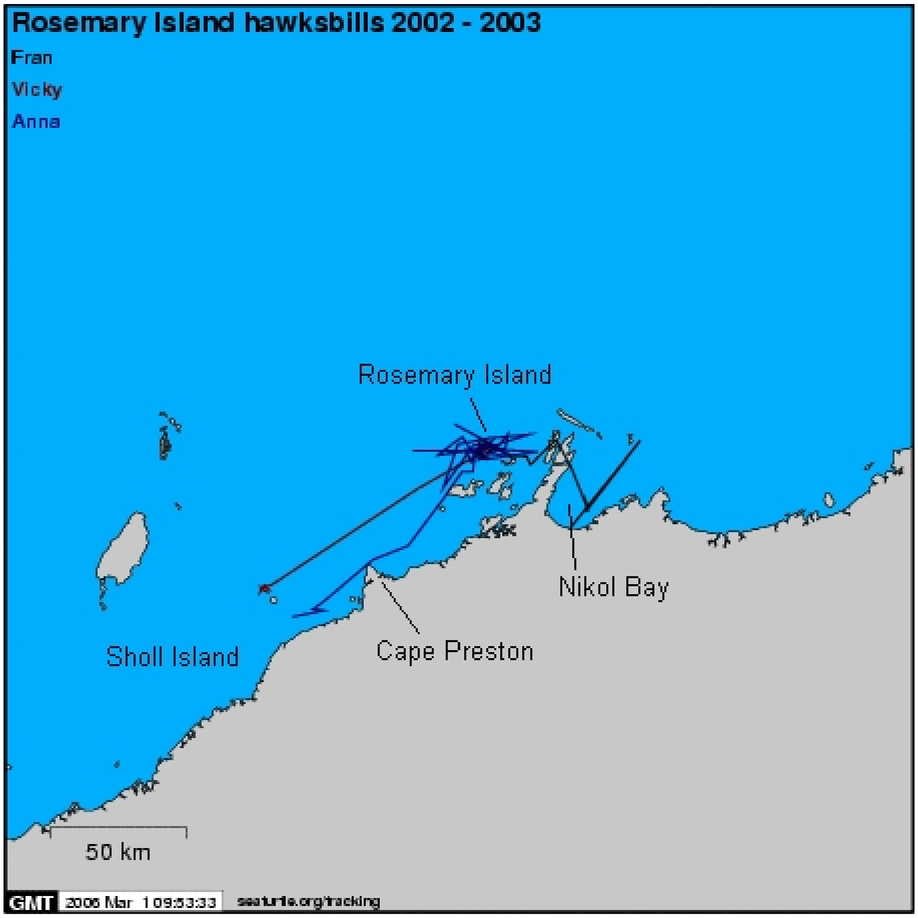


Figure 7.6: Hawksbill turtle project map showing migratory pathways between Rosemary Island and the south western and eastern foraging grounds

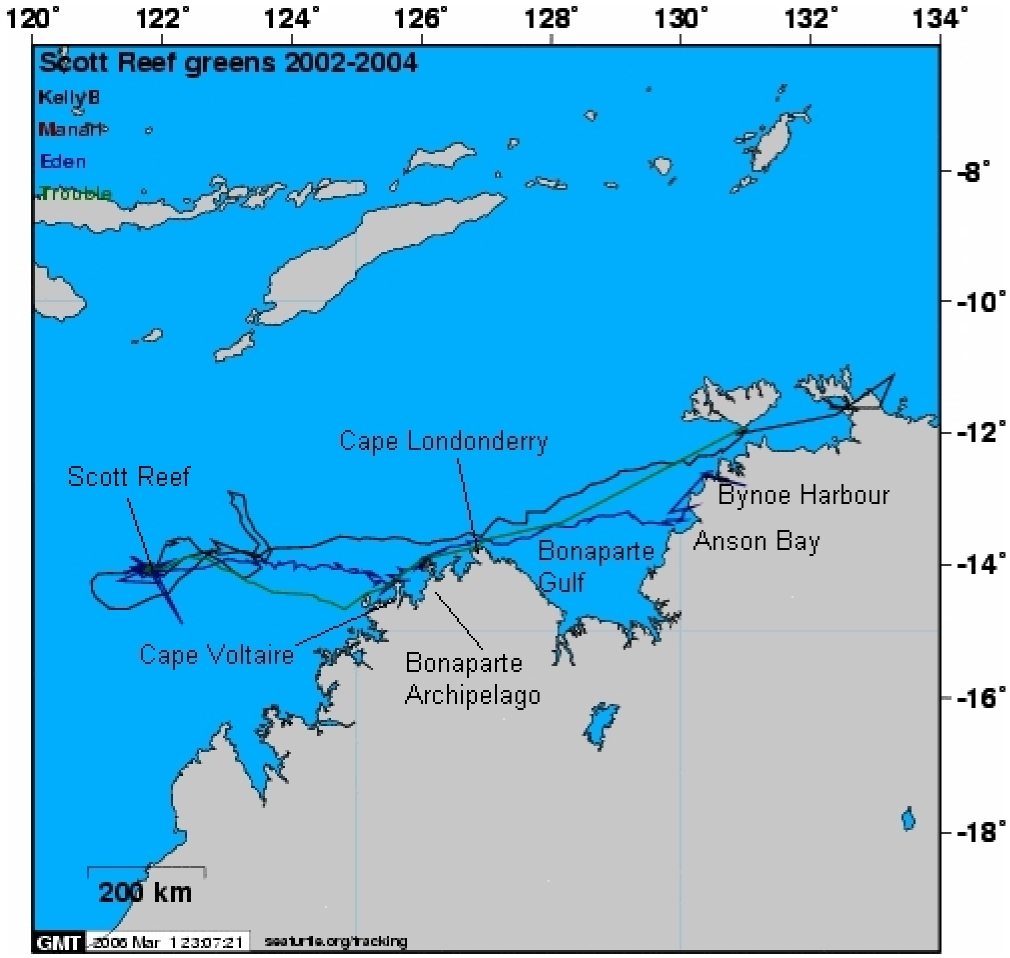


Figure 7.7: Green turtle project map showing migratory pathways between the Scott Reef rookery the Northern Territory foraging grounds

Table 7.3: Hawksbill tracking details – Varanus Island and Rosemary Island

ptt no.	NAME	place released	date ptt attached and turtle released	date left nesting region	date of last fix	Place of last fix	total days tracked	total days of migration	distance from nesting to feeding locations (km)	straight line speed (km/hr)	total days at end-point	End-point
30325	Emma	HB VI	16/12/2000	01/01/2001	16/03/2001	De Grey River, WA	90	21	450	0.8	56	F
30331	Erica	HB VI	18/12/2000	N/A	24/02/2001	East of Varanus, WA	68	N/A	N/A	N/A	N/A	
30330	Marnie	HB VI	20/12/2000	10/01/2001	27/02/2001	Sandy Island Group, WA	69	2	70	1.2	46	F
30327	Marilyn	HB VI	21/12/2000	10/01/2001	26/07/2001	Mary Anne Group, WA	188	N/A	85	N/A	217	F
37630	Fran	RI	06/11/2002	09/11/2002	28/12/2002	Nickol Bay, WA	52	5	50	0.4	45	F
37631	Vicky	RI	06/11/2002	08/11/2002	27/06/2003	Sholl Island, WA	233	7	100	0.6	224	F
37632	Anna	RI	07/11/2002	15/12/2002	03/06/2003	Fortescue and Mardie Island, WA	208	7	100	0.6	81	F
37629	Sharon	PB VI	26/11/2002	16/12/2002	25/04/2003	Turtle Islands, De Grey River, WA	152	15	369	0.9	115	F
30334	Julie	PB VI	27/11/2002	17/12/2002	02/03/2003	De Grey River, WA	96	47	450	0.4	28	F

HB VI = Harriet Beach, Varanus Island, RI = Rosemary Island, PB VI = Pipeline Beach, Varanus Island. Endpoint; location of animals at end of tracking program; I = internesting ground, M = migrating, F = feeding ground.

Table 7.4: Green tracking details – Barrow Island and Scott Reef

ptt no.	NAME	place released	date released	date left nesting region	date of last fix	Place of last fix	total days tracked	total days of migration	distance from nesting to feeding locations (km)	straight line speed (km/hr)	total days at endpoint	End-point
30326	Rachel	JWB BWI	08/01/2001	17/02/2001	07/03/2001	Turtle Islands, De Grey River, WA	58	18	420	0.8	2	M/F
30329	Eugenie	JWB BWI	09/01/2001	07/02/2001	11/02/2001	SW Ashburton River, WA	33	partial 5	150	1.25	M	M
30328	Isobel	JWB BWI	10/01/2001	04/03/2001	11/03/2001	Off Cape Thouin, WA	60	partial 8	250	1.3	M	M
30332	Sylvia	JWB BWI	12/01/2001	28/01/2001	28/03/2001	Cape Bossut, 80 mile Beach, WA	75	18	500	1.1	33	F
30333	Rosie	JWB BWI	06/01/2002	18/01/2002	14/07/2002	Turtle Islands, De Grey River, WA	188	10	360	1.5	178	F
11276	Chloe	JWB BWI	07/01/2002	09/02/2002	24/03/2002	Legendre Island, WA	76	6	200	1.4	57	F
37626	Lyn	JWB BWI	05/01/2003	02/02/2003	17/12/2003	Freycinet Estuary, Shark Bay,	343	61	1000	0.7	8 months	F
37627	Desiree	JWB BWI	05/01/2003	05/01/2003	12/03/2003	Turtle Islands, De Grey River, WA	66	11	360	1.4	55	F
11275	KellyB	SS	12/10/2002	12/10/02, 7/11/02	18/03/2003	east Van Diemen Gulf, NT	169	21	1000	4	80	F
37628	Trouble	SS	12/10/2002	25/11/2002	08/03/2003	Melville Island, NT	179	50	1000	0.8	56	F
11276	Manari	SS	22/09/2003	-	24/09/2003	Sandy Island	2	-	-	-	-	-
30333	Eden	SS	05/01/2004	15/02/2004	15/02/2004	Anson Bay, Daly River, NT	60	18	900	2.1		M/F

JWB = John Wayne Beach, Barrow Island, SS = Sandy Island, Scott Reef. Endpoint; location of animals at end of tracking program; I = internesting ground, M = migrating, F = feeding ground.

7.4.4 Internesting

The internesting locations for all turtles are mapped together for each of the three release locations (Varanus Island, Barrow Island, Rosemary Island and Sandy Island) and show the approximate location of nesting and internesting animals (Figures 7.8 – 7.11). These maps show a clustering of positions around the nesting sites suggesting the animals remain close to their nesting beaches and do not disperse to other regional locations (*i.e.* nearby islands) during internesting.

The LC 3,2,1 internesting data for Varanus Island hawksbills has been pooled and is shown in Figure 7.8. The map suggests that the turtles remain close to Varanus Island during internesting and do not travel to Barrow or the Montebello Island groups. Unlike the green turtles, hawksbills do not haul out on the beach or sleep on the water line and so onshore locations are likely to be nesting attempts. Plots of all internesting data (including LC A, B and 0) shows scattering of locations over a greater area but it is still centred on Varanus Island. Caution must be used when conducting fine scale interpretation of these results since the errors in the ARGOS locations, may be large (up to 1000m for LC1).

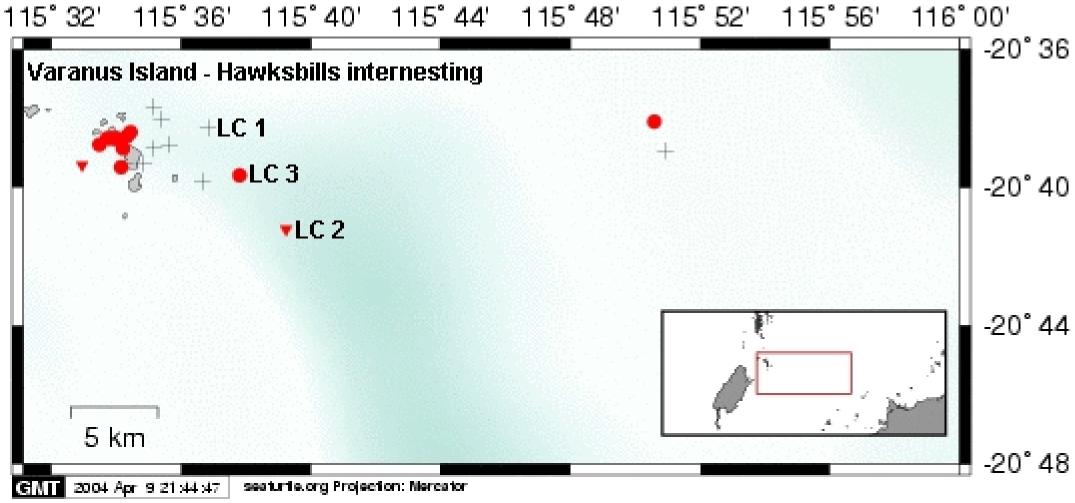


Figure 7.8: Combined Varanus Island hawksbill internesting positions, (LC 1 2 3 locations only)

Rosemary Island internesting locations are shown on Figure 7.9. The clustering on this data is on and around Rosemary Island for the entire nesting period of the turtles. This clustering at the nesting grounds Included Fran, whose feeding ground in Nickol Bay was no more than 20 km away from her nesting site.

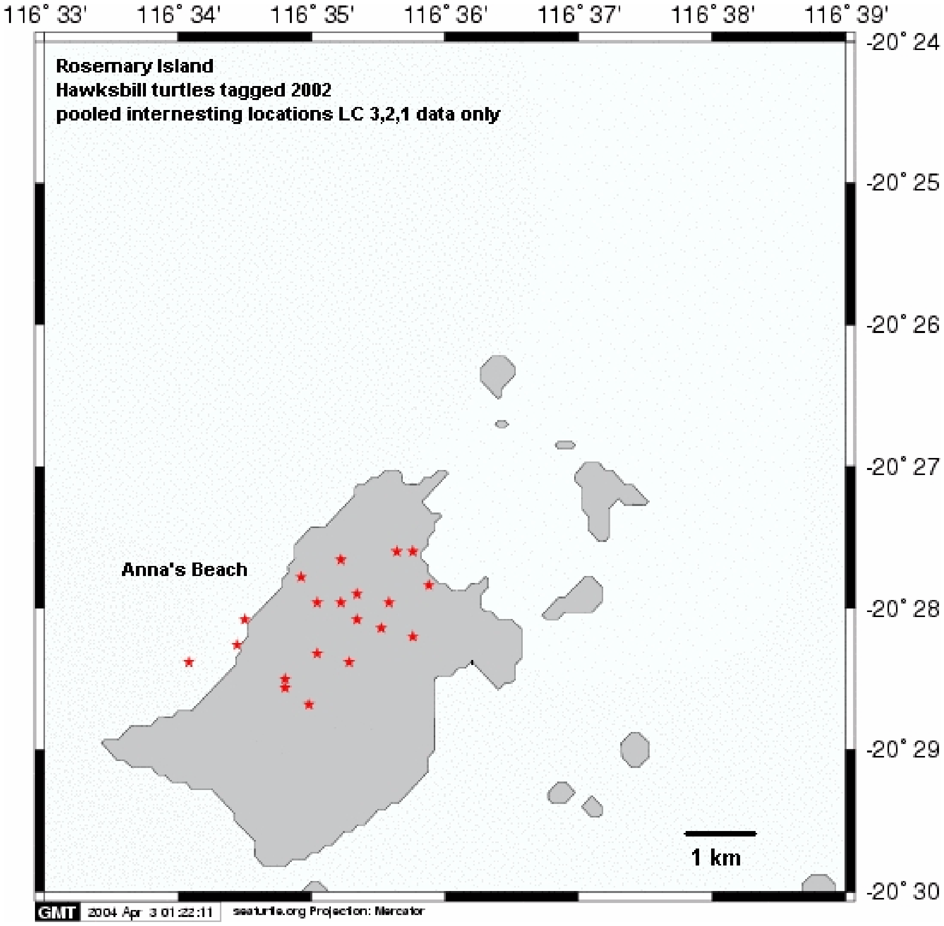


Figure 7.9: Combined Rosemary Island hawksbill internesting positions (LC 1 2 3 locations only).

The pooled internesting data for Barrow Island is shown in Figure 7.10. All locations are within 5 km of the island. The amount of internesting data for green turtles is greater than was received for hawksbills. This is likely to be due to the longer time green turtles spend on the beach while nesting (2-3 hours for green turtles versus 1 hour for hawksbills) and the fact that green turtles typically rest on intertidal zone of beaches and limestone platforms around these offshore islands whilst hawksbills do not (pers. obs. 1998 – 2004).

All of the green turtles were captured and released at John Wayne Beach however the concentration of internesting locations fixes are spread along the north western and northern coasts of Barrow, from Whites Beach to Cape Dupuy and extending to two beaches south of Surf Point. These data suggest that green turtles nesting at John Wayne may also nest or internest on beaches along the entire north western and northern coasts of Barrow. There is no evidence of clustering away from these Barrow Island sites when LC 0, A or B locations are plotted, suggesting that the turtles remain close to Barrow during the nesting season.

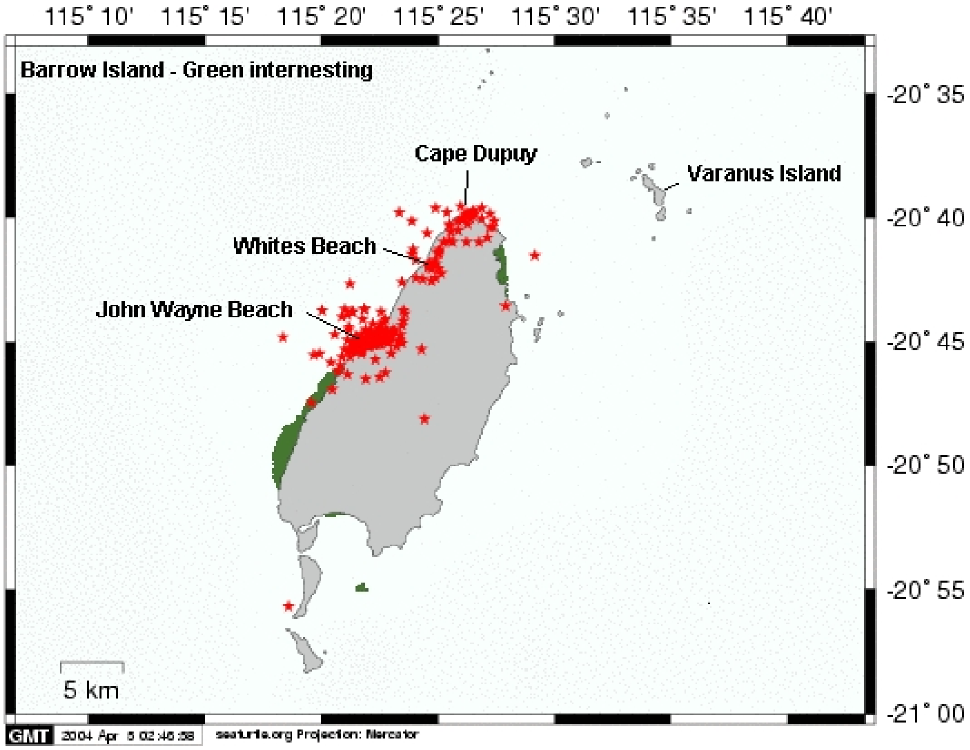


Figure 7.10: Combined Barrow Island green turtle internesting locations (LC 1 2 3 locations only).

Internesting results for Sandy Island, Scott Reef are shown in Figure 7.11. Scott Reef is a large horse shoe shaped coral reef system, 30 km across the widest part. The positions are clustered around a south east trending sand bar (not shown on this mapping software). All locations (including poor quality LC locations) fall within 5 km – 10 km of the island, with most on or near the island.

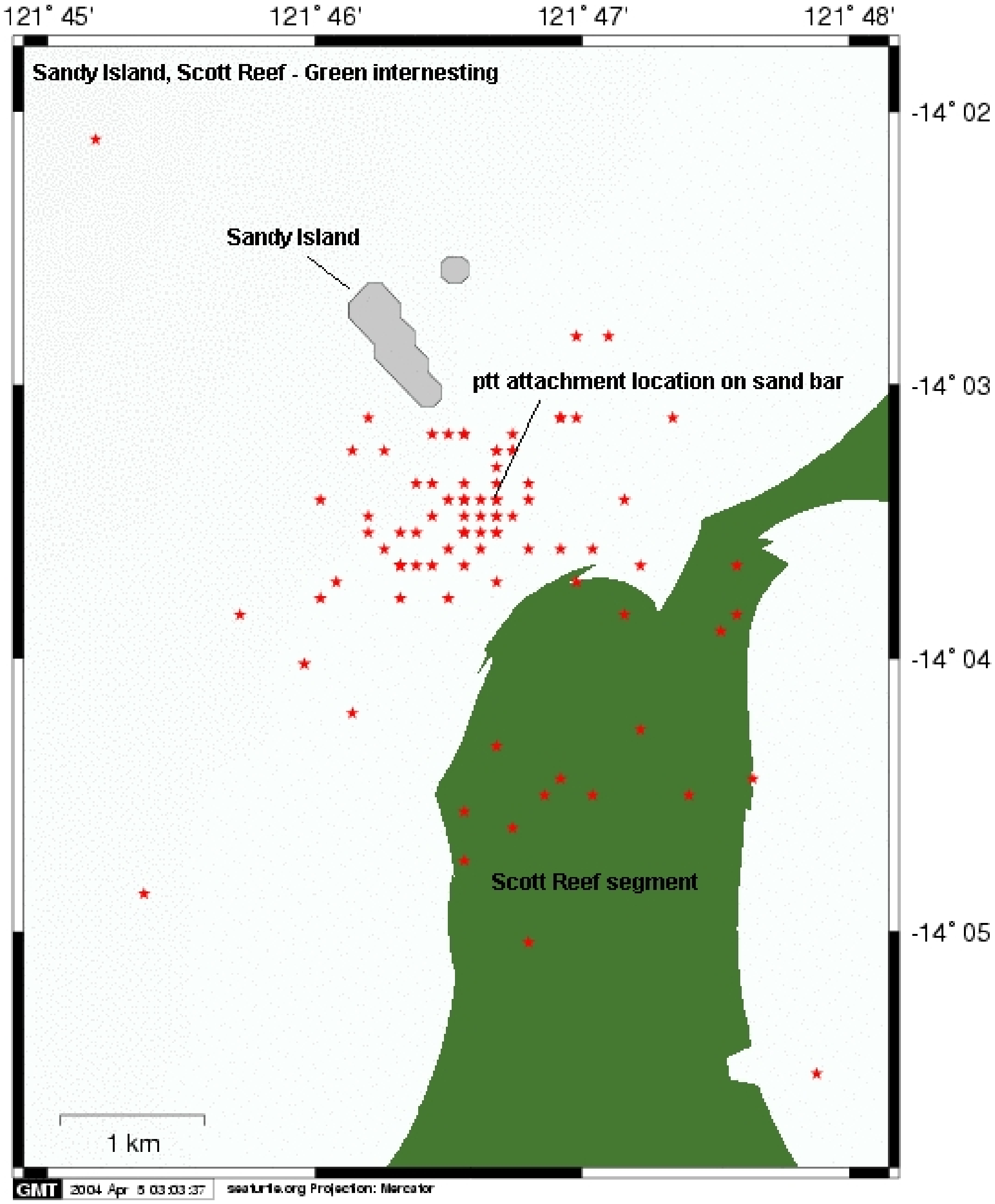


Figure 7.11: Combined Scott Reef green turtle internesting locations (LC 1 2 3 locations only).

7.4.5 Migratory pathways

The individual migratory pathway maps presented for each animal in Appendix 3 provides additional detail for this discussion. A total of six green and three hawksbill turtles, tagged over three successive summer nesting seasons, migrated in a northerly direction from the Barrow/Lowendal region. These migratory pathways were split into near shore and offshore tracks between the nesting islands and Cape Thouin east of Dampier Archipelago.

Three green turtles (Sylvia – January 2001, Chloe – January 2002 and Desiree – January 2003; Figure 7.4) and three hawksbills (Emma – December 2000, Sharon – November 2002 and Julie – November 2002; Figure 7.5) left the islands and travelled east tracking along the 20m contour that leads to McLennan Bank off Cape Preston, and then turning north and following the 20m contour that leads to Dampier Archipelago and Legendre Island at the outer edge of the Archipelago (Figure 7.4). This segment between the offshore islands and Cape Preston is the shortest line to the mainland coast east of Barrow Island.

The remaining three green turtles (Isobel – January 2001, Rachel – January 2001 and Rosie – January 2002,) left Barrow Island in a north and north east direction remaining further offshore than Sylvia, Chloe and Desiree. Rosie and Isobel remained well to the north of Dampier Archipelago but within the 50m isobath and did not turn towards the coast until they were well past the Archipelago (Figure 7.4). Isobel ceased transmitting part way through her northward migration (off Cape Thouin) while Rachel swam north from Barrow along the western edge of the Montebello Islands (the only turtle to take this route leaving Barrow) before turning east and tracking directly for Legendre Island in the

Dampier Archipelago. From there her signals ceased until she reappeared at North Turtle Island. Chloe alone remained at Legendre Island while the rest travelled north to the De Grey River region inshore of the 30m contour. Of these nine turtles one green turtle, Sylvia, continued on past the De Grey River region, and still within he 30m isobath, to an endpoint off Cape Jaubert at the north end of Eighty Mile Beach.

The only green turtles to migrate south away from Barrow were Eugenie (January 2001) and Lyn (January 2003). Both swan due south from Barrow taking the shortest path to the mainland and then turned south and tracked along the coast Figure 7.4). Eugenie ceased operating prematurely near Locker Island at the mouth of the Exmouth Gulf while Lyn's signals ceased temporarily at Coolgra Point (50 km east of Lyn's final transmission) until she reappeared in the bottom end of Shark Bay.

Two hawksbills (Julie and Sharon, Figure 7.5) were tagged at Varanus Island within 1 day of each other in late November 2002 and observed on the same beach within 10m of each other on the same night on the 14 December 2002. They left Varanus Island within a day of each other and travelled an almost identical pathway to the De Grey River area. They did not, however, have the same endpoints. Sharon's feeding ground was around North Turtle Island west of the De Grey River mouth (115 days of transmissions from this area) while Julie's was in near shore water east of the De Grey River mouth (28 days of transmission from this area). These hawksbills migrated a straight line distance of approximately 400 km.

The remaining 2 hawksbills, also tagged one day apart at Varanus Island (Marnie and Marilyn – December 2000), took a completely different migratory pathway (Figure 7.5).

Within 10 days of each other they headed directly south to the coastal island chains. The end points for both turtles were different with Marnie ending up near Great Sandy Island and Marilyn within the Mary Anne Group. These endpoints were only 65-85 km and 2 days swim away from the nesting ground. It is interesting to note the turtles did not appear to travel back to the feeding ground during nesting.

The migration pathways taken by the three hawksbills tagged at Rosemary Island in November 2002 (Fran, Vicky and Anna – November 2002; Figure 7.6) were similarly split, with Fran alone travelling east across Mermaid Sound and into Nickol Bay to the east. Anna and Vicky, on the other hand, travelled south west past Cape Preston to endpoints separated by ~20 km near Sholl Island. The reconstructed pathways suggest a direct route with Anna taking a slightly more inshore route to her (inshore) end point than Vicky. Anna's route follows the 10m depth contour while Vicky's appear to track the 15m contour.

The final three turtles that were successfully tracked during their migration (Figure 7.7) were green turtles (KellyB, Trouble and Eden) that were tagged at Sandy Island, Scott Reef in October 2002 (KellyB and Trouble) and January 2004 (Eden). Eden was tagged and tracked 12 months after KellyB and Trouble. Her track to the mainland was slightly south of KellyB and slightly north of Trouble. She arrived at the Kimberley coast at Cape Voltaire, 60 km north of Trouble's landing point. Eden then followed a track resembling that taken by Trouble along the outer edge of the Bonaparte Archipelago. She appears to depart from coast at the intersection between Vansittart Peninsula and Holothuria Banks and then follows KellyB's track as she skirted the outer edge of the Bonaparte Archipelago as far as Cape Londonderry. All three took a similar heading across the Joseph Bonaparte Gulf, however Eden's track curved slightly more eastward until she reached

Anson Bay on the Northern Territory coast. She then travelled in a northward direction until her transmissions ceased a month later in the vicinity of Bynoe Harbour. It is not clear if this is her feeding ground or if she also tracked northward along the coast to the Clarence Strait area.

The straight line ocean crossing segments displayed by these three turtles is similar to those found in green turtle migrations elsewhere (Luschi *et al.* 1998) and suggest the turtles know where they are going. This makes the break in the migration to track along the Kimberley coast all the more curious. The diversion of these tracks along the Kimberley coast and off a straight line course to the Northern Territory endpoints increases the time and effort required to make the whole journey. A hypothesis explaining the behaviour has been given by (Godley, B.J. *et al.* 2002) who suggested the turtles are exploiting feeding opportunities en route to their final home range foraging area. Because the turtles sometimes make open ocean crossings instead of continuing along a coastal area suggests they are making choices and may combine open ocean travel with coastal movements for energetic reasons rather than navigational necessity alone. These hypotheses are yet to be proven. The data for the near shore Kimberley coast segments of these Scott Reef turtles was not characterized by the degradation in signal and clustering of data that is characteristic of a stationary ptt suggesting that these animals were not pausing to feed along the way.

Green and hawksbill turtles migrating from the Pilbara island tagging locations all swam towards and then along the mainland coast to their feeding grounds. The shortest line from the offshore Pilbara islands (*i.e.* Barrow and Varanus Islands) to the De Grey River foraging area is 420 km. However, the actual tracks taken by the turtles along the coast were closer to 500 km in length. Since the swimming speeds of the turtles travelling from the Pilbara did not change as significantly as the Kimberley green turtles (see next section) it is possible they are using the coast to navigate to their home range using the protection of the shallow near shore waters.

7.4.6 Swimming speed and mid migration grazing

Of the 21 animals tracked only 8 provided sufficient data of high quality (LC 321 only) for calculating swimming speeds. These were the hawksbills, Marnie, Anna, Julie, and the green turtles, Desiree, Rosie, Eden, KellyB and Trouble. The data were analysed by segment to determine if the mid migration pauses noted by (Godley, B.J. *et al.* 2002) could be seen in the tracks.

The results for the turtles identified above are summarized in Table 7.5. Average speeds for green turtles in open water ranged from 1.8 – 2.8 km/hr. In shallow water the speeds dropped to 0.4 – 1.6 km/hr. Hawksbills in open water showed speeds of 0.9 – 1.6 km/hr, while in shallow water speeds were 0.4 – 1.2 km/hr.

A review of the available literature on swimming speeds reported estimated average speeds of 1.4 to 3.73 km/hr for mature green turtles (Papi *et al.* 1995; Wyneken 1996). Speeds calculated using satellite tracking methods similar to those used in this study reported average swimming speeds of 2.4 km/hr (Papi *et al.* 1995). Kimberley green turtles swimming speeds in open ocean waters were in a similar range, *i.e.* 2.21 – 2.67 km/hr. This speed was consistently maintained over the 8 -21 day segments of open ocean migrations. Pilbara green turtles (Des and Rosie) average speeds were similar at 1.6 – 2.24 km/hr in open water.

Table 7.5: Swimming speed for Western Australian green and hawksbill turtles during migration

Turtle	segment	Open water Shallow/Coastal water	Mean speed (km/hour)	Number of locations used to calculate speed (LC 1,2, 3 only)
green turtle				
KellyB	Loop	Open Ocean	2.26	83
	Sandy Island to feeding ground	Open Ocean	2.32	65
Trouble	Sandy Island to Kimberley coast	Open Ocean	2.21	17
	Kimberley coast segment	Shallow water	1.16	5
Eden	Sandy Island to Kimberley coast	Open Ocean	2.49	23
	Kimberley coast segment	Shallow water	1.88	12
	Kimberley coast to Northern Territory coast	Open Ocean	2.67	14
Rosie	Barrow Island to feeding ground	Open Ocean	2.24	14
Desiree	Barrow to feeding ground	Open Ocean	1.62	15
Hawksbill				
Marnie	Varanus Island to feeding ground	Open Ocean	1.6	3
Anna	Rosemary Island to feeding ground	Shallow water	0.4	8
Julie	Varanus to De Grey River foraging ground	Open Ocean	3.19	4

Wyneken further noted that little data are available on the swimming speed of hawksbill turtles, with one report of 0.7 km/hour, slower than reported for green turtles. Satellite tracking results from Hawaiian hawksbill turtles found faster speeds of 1.6 – 2 km/hour (Balazs 1994). Pilbara hawksbills Marnie and Anna swimming on a direct track to nearby feeding grounds, reached speeds of 0.4 – 1.6 km/hr, while the mean speed for Julie was 3.19 km/hr for a longer migration to more remote feeding ground (n = 4 position locations). The speeds for the hawksbill migrations are not substantially different from each other regardless of migratory path location (confined to shallow coastal water versus crossing open water) or length (65 – 450 km).

The swimming speed was calculated separately for turtles passing through shallow water areas mid migration. The mean speeds dropped for the two of the Scott Reef green turtles

(Trouble and Eden) suggesting that they may have paused, possibly to graze along the Kimberley coast, on the way to their Northern Territory feeding grounds. It is also possible that the increased time required to swim along the highly convoluted coastline of the Kimberley may account for the slower speeds. The lack of degeneration in LC signal quality or the clustering arising from accumulated satellite locations, that generally signifies a stationary transmitter, supports the convoluted path hypothesis.

The Pilbara green turtles and hawksbills did not appear to pause along the migration route and instead appeared to use the Dampier Archipelago as a navigation marker for their migration along the coast. The annual humpback whale migration along the Western Australian coast are thought to use the B-L-M group in a similar manner (Curt Jenner, pers. com. June 2005).

The 24 day long (917 km) loop KellyB swam before returning to Sandy Island to nest again was the only record of this behaviour documented during this program. It is possible she could have been aboard an Indonesian fishing boat as the Indonesian traditional fishers are known to hunt sea turtle for food at Scott Reef. However swimming speed data for the two segments of this track (loop and straight line, Table 7.5) indicates there was little difference in the speed of the animal suggesting that she was swimming the entire time.

This mid nesting season excursion displayed by KellyB is similar to a partial track reported by (Luschi *et al.* 1998) who found one of the 6 turtles they tracked form Ascension Island swam in a pair of loops to the east of Ascension rather than travelling in the straight line westerly direction taken by the other 5 animals tracked. They suggested she was exploring the waters around Ascension in search of feeding grounds. Her behaviour suggested she had the navigational skills to return to Ascension Island after each of these excursions, in much the same way as KellyB did prior to her final departure in a direct line for the Clarence Straits in the Northern Territory. She was also the only green turtle from Scott Reef that did not swim directly to, and along, the Kimberley coastline on her eastward migration.

7.4.7 Foraging grounds

The accumulation of satellite locations characteristic of a prolonged stay in a restricted area is typical of both internesting and feeding ground transmissions. An extended residency at an endpoint is generally accepted as a feeding ground (Balazs 1994; Cognetti 1996; Balazs *et al.* 1998). Hhowever, the reported length of time a turtle should be in an area before it can be termed a feeding ground is vague since it is not clear if sea turtles remain at the same feeding ground until the next nesting migration, or if they move from one area to another during that period. Most researchers report the number of days transmissions are received from an endpoint, and anything more than a few weeks appears to be accepted as a foraging area.

Analysis of the migratory pathway and swimming speed data from the current study indicated that the Pilbara green and hawksbill turtles swam directly from their nesting grounds to feeding grounds without breaking their trip to graze along the way. Tracks from the Kimberley turtles suggest that at least one, Trouble, may have paused to feed along the way. However the lack of accumulated positions in a restricted area along the Kimberley coastal segments, and the consistent eastward movement of the transmission locations from one day to the next, suggests that these animals did not stop on any particular feeding ground for more than a few hours. Furthermore the behaviour of the turtles at their endpoints (internesting and feeding) is characterized by an increase in the number of low quality LC locations, a decrease in the accuracy of all LC locations and an accumulation of these transmissions clustered around a central location that is presumably close to the actual location of the animal.

Using the above, 15 turtles were deemed to be on foraging grounds. The amount of time ranged from 28 – 218 days. Detailed maps of the feeding grounds, identified as the place of last fix in Tables 7.3 and 7.4, are shown in Appendix 3 and summarised in Figure 7.12. Feeding grounds identified included the De Grey River area (2 Barrow Island green turtles and 3 Varanus Island hawksbills), Shark Bay, Legendre Island and Cape Bossut north of Eighty Mile Beach (3 Barrow Island green turtles), Melville Island and Cobourg Peninsula (2 Scott Reef green turtles), Nickol Bay (one Rosemary Island hawksbill) and within the Pilbara coastal island chain due south of Barrow Island (4 hawksbills from Varanus Island and Rosemary Island).

Determining spatial ranges for the feeding ground locations is difficult due to the error inherent in the ARGOS data. Other authors have reported 30-100 square mile and the upper end of this range appears to be conservatively large based on the clustering of high quality LC data from the Western Australian results (see Appendix 3) (Renaud *et al.* 1996).

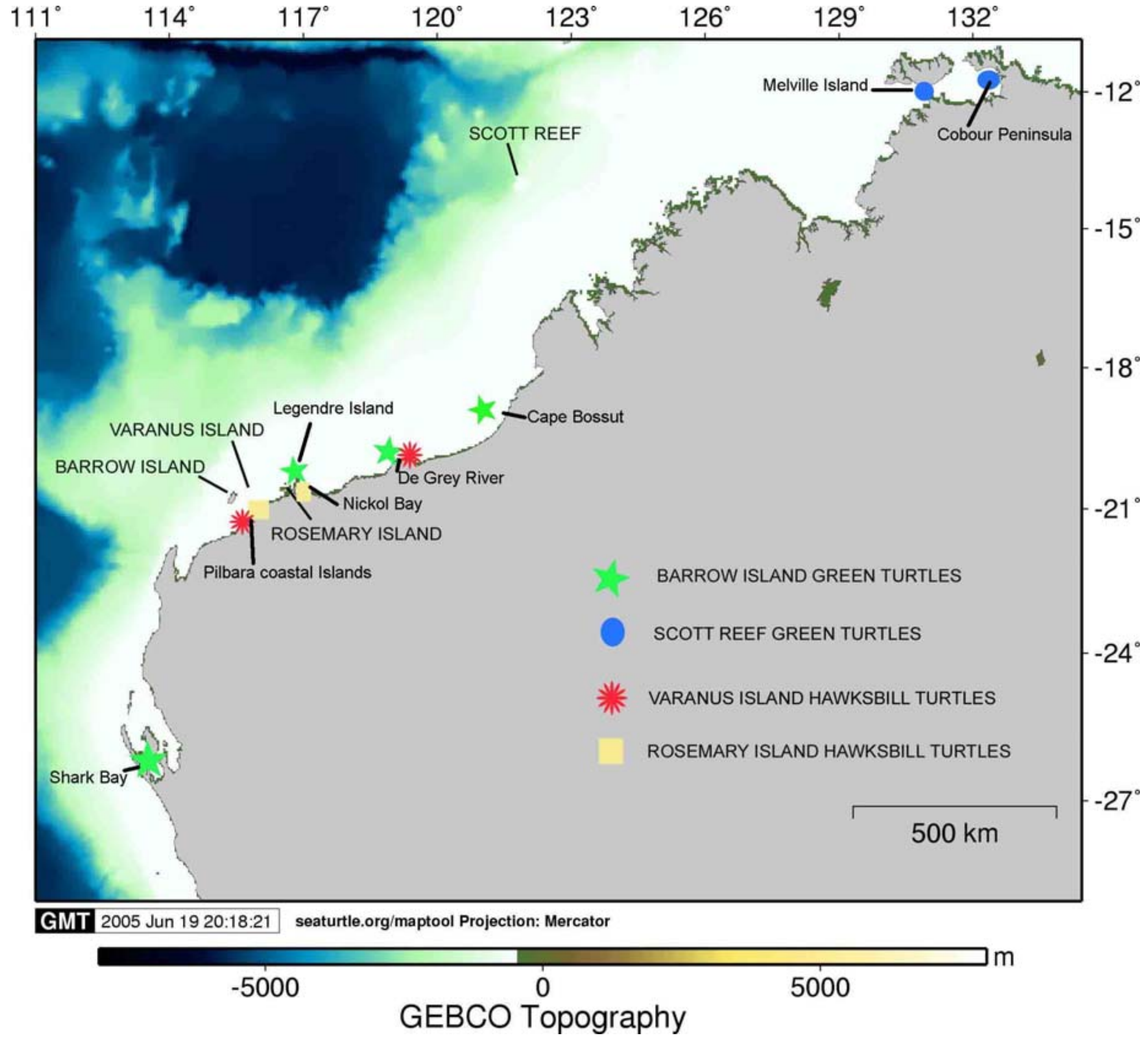


Figure 7.12: Foraging ground locations for Barrow Island, Varanus Island, Rosemary Island and Scott Reef green and hawksbill turtles

7.4.8 Threats and Conservation priorities

Three habitats critical to sea turtle conservation in WA have been identified that warrant protection. These are the internesting and feeding grounds and the migratory corridors between the two areas.

Internesting turtles concentrated in the shallow waters within 5-10 km of Barrow, Varanus, Rosemary and Sandy Islands are at risk during the sensitive breeding phase of their life cycle. Disturbances in these waters during the nesting season could potentially impact internesting turtles. Internesting zones near Barrow and Varanus Islands are contained within protected waters since the creation of the Barrow Montebello Islands Marine Conservation Reserves, established on 10 December 2004.

Planning is also underway for the Dampier Archipelago – Cape Preston Marine Conservation Reserve. This reserve will encompass the hawksbill internesting grounds around Rosemary Island, the green turtle feeding ground near Legendre Island as well as those segments of the migration corridor that pass though the Dampier Archipelago region. The reserve boundaries do not extend far enough offshore between the Archipelago and Cape Preston to incorporate the migratory pathways used by green turtles and hawksbills moving inshore from Barrow and Varanus or the hawksbills moving between Rosemary Island and the coastal island chains south west of Cape Preston.

This study has highlighted the importance of the Dampier Archipelago for both green and hawksbill turtles on migration. The migration pathways for 8 of the 17 turtles tracked from Pilbara nesting sites passed through this area. This concentration of turtles within the areas is of significance given that the port of Dampier is one of the largest in Australia, with over 2000 ship movements per year transiting the waters of the Archipelago (Dampier Port Authority, www.dpa.wa.gov.au). This concentration of turtles and ships within a confined area increases the risk of collision between the two, particularly as turtles have been shown to swim just under the water surface (Godley, B.J. *et al.* 2002) whilst on migration. The drag on swimming animals is minimized once the depth is 2.5 times the animal's diameter (Hertel 1966 in Godley et al 2002) which would place an adult turtle approximately 4m under water. This depth is safe from shallow draft recreational boats but not from the keel of the large ships that traverse Mermaid Sound.

Dredging is also recognized as a threat to sea turtles (Lutcavage *et al.* 1986; Slay and Richardson 1988). Some sea turtles such as loggerheads (Carr *et al.* 1981), green turtles (Moein *et al.* 1994) and potentially flatback turtles may be at risk from hopper dredging. While little data are available, field observations suggest that some species may hibernate over winter in the soft sediment at the bottom of shipping channels (Felger *et al.* 1976; Carr *et al.* 1981). Flatback turtles are known to favour soft bottom habitat in shallow turbid near shore areas and are therefore at risk from dredging.

The increase in industrial development within the Dampier Archipelago region has included increased requirements for dredging. As recently as October 2003 two proposals for dredging that were assessed by the Western Australian Environmental Protection Authority failed to recognize the risks to sea turtles within Dampier Archipelago (EPA 2003a, 2003b). The confirmation of the Archipelago as both a migration route and a feeding ground for sea turtles suggest these animals may be at risk from dredging activity.

Migratory pathways north of Dampier Archipelago fall inshore of the 30m isobath and do not pass through any conservation zones. The feeding areas at the De Grey River areas are similarly unprotected. The waters around North Turtle and Bedout Island were proposed for consideration for reservation by the Marine Parks and Reserves Selection Working Group (Wilson 1994). The current study has confirmed this area as an important foraging ground for the Pilbara Islands hawksbill and green turtles and provides strong support for the recommendations made by the above Working Group.

The single green turtle that continued along the coast from the De Grey River area to a foraging ground off Cape Jaubert at the north end of 80 Mile Beach also migrated through unprotected waters. Both her migration path and feeding grounds are outside of any existing or proposed marine conservation areas.

The migratory path reconstructed for Lyn, a green turtle from Barrow Island, probably passed through the Ningaloo Marine Park. Her feeding ground in Freycinet Estuary is encompassed within the shark Bay Marine Park, and falls within the Freycinet Special Purpose Zone which allows for various recreational activities. The World Heritage Area zoning of Shark Bay adds an additional level of protection to this feeding area.

The most important hawksbill foraging ground identified by this study are the extensive and diverse coral, macroalgal and limestone reef assemblages that occur throughout the island chains west of Cape Preston, extending as far south as Onslow (Tap 1998). The conservation values of the islands (all land above the low water mark) of the Passage Group and the northern half of the Mary Anne Group are protected under the umbrella of the Sandy Island Nature Reserve. Four of the 9 hawksbills tagged at Varanus and Rosemary Islands migrated to this region. The waters and subtidal habitats of this area are currently unprotected and no plans are in place to create a marine reserve over the area. This area should be assessed for conservation as a matter of priority.

One of the green turtles from Sandy Island travelled to foraging grounds contained within the protection of the Cobourg Marine Park. The two green turtles with feeding grounds off Melville Island and Anson Bay are not similarly protected. The migration pathways taken by these animals between Scott Reef, the Bonaparte Archipelago, the Joseph Bonaparte Gulf and the endpoint feeding grounds are also unprotected. An additional threat to turtles in the Kimberley and Northern Territory waters is the increased risk of aboriginal hunting.

Threats to adult green and hawksbill turtles at their nesting grounds include; boat strike where turtles are concentrated (mating and internesting) such as off the west coast of Barrow Island prior to and during the nesting season (see Section 7.2), disturbance of internesting females during egg formation from seismic discharges and disruption of females nesting (night time), and human disturbance of animals basking on shorelines (day time).

Threats during migration include boat strike, particularly where animals are concentrated in migration corridors such as through the Dampier Archipelago. It is also possible that the migrations made by the early summer nesting window of hawksbills will overlap with the end of the prawn trawling season in July each year. High risk areas are the trawl grounds in the shallow near shore waters adjacent to river deltas along the coast between the Ashburton River and the De Grey River.

Threats on feeding grounds include all of the above in addition to the loss of food resources resulting from destruction of seagrass and algal beds or reef habitat. This includes physical removal of habitat by dredging, trawling or construction activities associated with pipeline installation as well as losses associated with pollution reducing water quality.

Chapter 8 General Discussion

Three species of sea turtle nest routinely within the Barrow, Lowendal, Montebello (B-L-M) Island complex. These are *Chelonia mydas* (green turtle), *Eretmochelys imbricata* (hawksbill turtle) and *Natator depresssus* (flatback turtle). Historical records of sea turtle activity in the region suggest that these populations have been exposed to hunting pressures, while large numbers of turtles from all life stages were also killed following the British atomic bomb testing in the Montebello Islands during the 1950's. In recent years, the exposure of the local sea turtle populations to the potential impacts of industrial development has been recognised as an issue requiring further investigation and management.

As a case study this thesis has demonstrated that a variety of aspects of sea turtle biology must be considered when looking at the potential impacts of industry on sea turtle population conservation. Both the spatial variability in developmental habitats and the longevity of sea turtles means that impacts on hatchlings and juveniles are difficult to monitor and will take a long time to manifest themselves in the adult population. The light environment of the nesting beaches is clearly critical to the success of hatchling reaching the ocean.

It is important to have a general feel for the population structure of the sea turtle species and some measure of the breeding output of beaches over a wide area to be able to quantify the proportion of the population impacted. It is also important to be able to identify the geographically remote location of the foraging habitats used by the animals being monitored at nesting beaches so that any stressors can be identified and put into context when monitoring nesting population levels.

Currently both resident and breeding sea turtle populations share the region with pearling, tourist and oil and gas industries. The oil and gas industry dominates the region with infrastructure currently centred on Barrow Island and Varanus Island, supporting 10 offshore oil and gas production monopods and platforms and 2 tanker loading facilities. Oil and gas exploration commenced in the mid 1980's and has grown rapidly since that time. This growth is expected to continue with plans for large scale exploration and development activities currently proposed by Apache Energy at Varanus Island and ChevronTexaco at Barrow Island.

Studying sea turtles at the B-L-M Islands nesting beaches has provided an insight into a small (~1%), but critical, aspect of the life cycle of hatchlings and sexually mature adults . Identifying the at-sea habitats that are also used by the sexually mature sea turtles has provided a basis upon which the stress on these populations may be more confidently assessed. Specifically, information on sea turtle nesting demographics has been compiled from the current study and then used, along with the experimental results on hatchling light preferences to assess the proportions of the local populations exposed to local, industrial based, light sources. These results, when viewed in conjunction with the information on internesting grounds, migratory routes and foraging ground locations allow a detailed picture to be built of the potential stressors that the sexually mature sea turtles that use Barrow, Lowendal and Montebello beaches, are exposed to.

The three species found in the B-L-M region show distinct spatial and temporal nesting characteristics. The densest hawksbill turtle nesting was documented on small, rubbly, shallow sand beaches characterised by coral reef habitat in the foreshore zone. The concentration of hawksbill nests on these beach types may also be a factor of the shallow sand depth precluding green turtle and flatback turtles from using these beaches. Hawksbills appear to also use the larger, deep sand beaches favoured by green and flatback turtles however the higher density of green turtle and flatback tracks probably obscure the less dense hawksbill tracks. Green turtles favour larger, high energy beaches with deep sand and an open foreshore approach. Flatback turtles are more susceptible to mechanical damage due to low keratin levels in their shells and were found in highest numbers on narrow, low energy beaches that may or may not have an obstructed foreshore approach.

The nesting season for the three species varied. Flatback turtles appear to nest over a relatively short two month period in December and January, 86% of the mean number of tracks counted was in these two months. Green turtles commenced nesting on November and peaked in January and February, systematic survey data was unavailable for March but limited beach inspections in March 2001 suggest numbers declined that month. Hawksbill nesting shows a similar spread as green turtles though shifted two months earlier. Nesting takes place over 5 months between September and January, peaking between October and December. These data, along with hatchling emergence peaks, clearly identify the period when sea turtles are most at risk from industrial activity near nesting beaches and should be used to design management plans to reduce impacts.

The high density nesting beaches within the Barrow, Montebello, Lowendal complex provide nesting habitat for ~ 40,000 green turtle, ~ 6,500 flatback and ~ 2,600 hawksbill turtles. These estimates are based on track count data and subject to the limitations and biases inherent in this monitoring method, *i.e.* they are not representative of absolute animal numbers and may overestimate the number of animals. All three species use beaches on each of the three island groups. The proportional distribution of species tracks within the entire B-L-M region was;

- Green turtles - 50% of tracks on Barrow Island, 50% on the Montebello Island beaches,
- Flatback turtles - 60% of tracks on Barrow Island, 24% on Montebello Island group beaches and 16% on Lowendal Island group beaches.
- Hawksbill turtles - 53% of tracks on the Montebello Island group beaches, 37% on Lowendal group beaches and 10% on Barrow Island.

Barrow Island provides the biggest habitat for green turtle and flatback while the Montebello group are the most important nesting sites for hawksbills.

Estimates of the proportion of nesting turtles potentially exposed to industrial lighting within the island complex suggest flatback turtles are at the greatest risk of exposure (42% of the population) followed by hawksbill turtles (12 % of the population) while none of the green turtle nesting sites currently fall within a 1.5 km radius of industrial based light. Two colour choice experiments confirmed the findings of Witherington (1992). Green turtle, hawksbill and flatback hatchlings selected low wavelength light over high wavelength light more frequently, particularly where the wavelengths are separated by 100 nm or more. Wavelengths separated by ≥ 50 nm produce distinctly different colours, *i.e.* 450 nm light is blue/violet, 500 nm is blue green, 550 nm is bright green, 600 nm yellow, 650 nm orange and 700 nm dark red. As the two wavelengths being tested approached each other, and the difference in the colour of the light was reduced (*i.e.* 550 nm bright green and 570 nm dark green), the lower wavelength was no longer selected 100% of the time. While hatchlings appear to be able to discriminate between primary colours they do not appear to discriminate between hues of a primary colour as consistently.

The results of the green turtle and hawksbill two colour choice experiments were compared with those obtained by (Witherington 1992a), who was able to use larger sample sizes. The behaviour of the Barrow Island green turtle hatchlings was consistent with Witherington's results. The trend in the Varanus Island hawksbill hatchling results was generally similar to Withington's (lower wavelengths selected over higher wavelengths) however the results appeared to be confounded by the small hawksbill hatchling sample size. Flatback hatchings have not been tested against variable light wavelengths before and therefore the Barrow Island results could not be compared with animals tested elsewhere. Instead the flatback results were compared with Witherington's green turtle and hawksbill results. The comparison suggested that flatback hatchlings do not select the lower wavelength over the higher wavelength more frequently for combinations of 500 nm (blue green) and 450 nm (blue/violet) or 480 (bright blue) nm. However they clearly favoured 500 nm over all wavelengths from 550 nm (bright green) to 700 nm (dark red).

This difference in response may be related to the difference in the neonatal habitats used by flatback turtles relative to other sea turtle species. In the near shore turbid waters favoured by flatback turtles the high levels of dissolved organic matter may reduce the transmission of the light in the blue - violet range (300 nm – 450 nm) and in the orange -

red range (600 nm – 700 nm) by up to 90% (Gross 1982). It is possible that the response of the flatback eye to light is adapted to lower light intensities and narrower wavelength range (yellow/orange light) found in turbid water.

The artificial light types used in industrial setting include fluorescent, metal halide, halogen, mercury vapour and high pressure sodium vapour. The flaring of gas from oil and gas facilities also contributes artificial illumination to the night skies. All of these light sources contain light emissions in the low wavelength region of the visible spectrum that has been shown to be the most attractive to sea turtle hatchlings. The level of disruptiveness these light sources pose to sea turtle hatchling orientation range from extremely disruptive for those lights containing a strong concentration of low wavelength light (*i.e.* mercury vapour, metal halide, fluorescent, halogen) to moderately disruptive for sources containing (*i.e.* high pressure sodium vapour and flares). The effects of three types of industrial lights on green turtle and flatback hatchlings, tested under controlled conditions on Barrow Island, showed that higher intensities of sodium vapour light are required to trigger sea finding disruption in both green turtle and flatback hatchlings than fluorescent and metal halide light.

The visibility of these lights on nesting beaches can be reduced by physically shielding the lights, lowering the height of lights, directing lights onto work areas, using long wavelength red, orange or yellow lights and avoiding using short wavelength white lights and filtering the light to reduce short wavelength light. The amount of light reflected into the sky above an industrial site should also be reduced. This can be done by using dark matt non reflective paint on equipment and vessels (instead of the bright shiny white paint that is commonly used). Alternative use of lighting should also be explored, e.g. use of reflective tape on vessels and equipment, embedded street lighting, motion sensors and timers etc. The base design case for a facility should assume dark sky conditions and lighting added as needed, as opposed to illuminating the facility to replicate day light conditions.

Hawksbill hatchlings tested *in situ* under the influence of actual oil and gas artificial lighting from nearby onshore (100m distance) and more distant offshore (2.5 – 3.3 km distance) facility based lighting were disrupted from the most direct line to the ocean by the light emissions. The moderating influence of the moon increased the proportion of hatchlings orienting in a seaward direction from 3% - 8% (no moon) to 35% - 45% (full moon) on two beaches exposed to artificial light from an oil and gas facility. Hatchling orientation was also moderated by beach topography. Hawksbill hatchlings tested under full moon conditions and in the absence of artificial light oriented along the beach, in the opposite direction from the shadow of tall headlands, instead of towards the very bright ocean horizon. These results provide additional evidence to support the hypothesis presented by (Limpus, Colin J. 1971) and elucidated further by (Salmon, M. *et al.* 1992), that hatchlings orient away from an elevated dark silhouette and not towards the region of maximum irradiance.

Emergence fan mapping methods that measure hatchling orientation on nesting beaches were refined and are proposed as an alternative monitoring tool for use on beaches that are logistically difficult to access for large scale experimental orientation studies. The fan mapping methods developed during this study are very similar to those used to develop a "Hatchling Orientation Index", proposed by (Witherington *et al.* 1995). Fan mapping was successful as a monitoring tool for documenting misorientation impacts of artificial light. However, the presence of tall headlands on some of the B-L-M beaches influenced the results. The distance over which the headland effect is exerted was not quantified during this study and awaits further experimental investigation. Similarly the variation in the mean and range of fan spread and offset angles from beaches coded for light (within 1.5 km) suggests that the variability in light intensity has a strong influence on hatchling fan behavior. For example the fan spread angles on beaches exposed to onshore and offshore light ranged from 5° to 360°. Hatchling fans spread around 360° were clearly influenced by artificial light while a spread angle of 5° suggests this nest was not responding to the artificial light. Given the variability in light exposure (onshore and offshore), light type, light intensity and beach topographic features (dunes and headlands) for individual beaches within the B-L-M region it was not possible to develop a single hatchling orientation index that cold be applied to all beaches. Instead, indexes were developed for specific beaches under different light exposure regimes. For example, different indexes were determined for Pipeline Beach (Varanus Island), a brightly illuminated beach (onshore and intermittent offshore light sources) and for east coast Barrow Island beaches, which were weakly illuminated relative to Pipeline Beach, by onshore light sources only.

While the preceding discussion provides heretofore undocumented detail on sea turtle demographics and nesting beach usage within the Barrow, Lowendal and Montebello region as well as additional detail on the effects of industrial lighting on sea turtle hatchlings, it does not provide information on the risks these sea turtles are exposed to during the remaining 99% of their life cycle. Understanding the post-nesting movements of sea turtles provides an indication of the risks these animals are exposed to on remote foraging grounds and puts the nesting demographic data into perspective. For example a reduction in track counts on a light exposed nesting beach may be related to a loss of adults due to hunting and not from light disturbing the nesting females. For the first time in Western Australia, twenty one nesting green and hawksbill sea turtles were satellite tracked (using the ARGOS satellite system) during internesting, on their post-nesting migration and at their remote foraging grounds. Green turtles were tracked from Barrow Island and Scott Reef, while hawksbill turtles were tracked from Varanus Island (Lowendal Island group) and Rosemary Island (Dampier Archipelago). The quality of the ARGOS location data during internesting was poor. However, the data clustering suggests both green and hawksbill turtles remained close (within 5 km) to their nesting beaches.

Green and Hawksbill turtles leaving the Barrow and Varanus Island (Pilbara) region on their post-nesting migration to feeding grounds travel through near shore waters primarily within the 30 m contour and no deeper than 50 m. Scott Reef (Kimberley) green turtles followed similar eastward trending migratory pathways through water > 100 m deep for more than 50% of the time as they crossed from Scott Reef to the Kimberley coast (2 of the 3 turtles) and then across Bonaparte Gulf to the Northern Territory. The migratory pathways for all animals tracked appear to be purposeful. With the exception of one Scott Reef green turtle all left their nesting ground and swam towards shallow coastal water in a constant direction en route to their destination. None of the Pilbara or Kimberley mid migration coastal track segments, for either the green or hawksbill turtles, displayed the degradation in signal quality and clustering of locations that signifies a stationary transmitter. This suggests that the tracked turtles did not pause to forage en route to their feeding grounds.

Foraging grounds for the green turtles tracked from Barrow Island were spread between Shark Bay, 1000 km to the south, and Cape Bossut, 500 km to the north, of their nesting site and are contained wholly within Australian waters. Green turtles at Scott Reef travelled over 1000 km from the edge of the Continental Shelf to foraging grounds in Northern Australia. Foraging grounds for Rosemary Island hawksbill turtles were located within 100 km of their nesting beaches. With the exception of one green turtle from Barrow Island, the foraging and migration pathways for the remaining 20 turtles tracked all fell outside of protected areas.

Green turtles nesting at Scott Reef are at risk from hunting by Indonesian fishermen. Evidence was observed on Sandy Island where bloodied and charred skeletal material was documented. The loss of transmissions from one of the green turtles within 48 hours of ptt deployment and in the presence of over 40 Indonesian fishing boats was probably due to the turtle being taken for food. The three green turtles tracked from this location all migrated to foraging grounds in the Northern Territory where indigenous hunting also takes place. While no systematic surveys of green turtle nesting activity at Scott Reef have been conducted to monitor the fluctuations in nesting population numbers, opportunistic surveys suggest that the numbers using Sandy Island are not large (pers. com. RIT Prince 2002, pers obs. 2002, 2003). It is likely that the hunting of these animals in both their nesting and foraging habitat may, over time, drive this population to extinction.

Green and hawksbill turtles that migrate in a northward direction from their Barrow and Varanus Island rookeries appear to use the Dampier Archipelago region as a navigation aid with seven of the eight turtles passing through these near shore waters. The large number of ship movements and large scale dredging programs that are concentrated in this area put these migrating animals at risk from boat strike or maceration in a dredge hopper. No data are currently available on the level of impact these industrial activities might be causing on migrating turtles. The nesting and internesting sites at B-L-M are now covered by marine and terrestrial conservation reserves which provide legislative protection to these critical habitats. However, the foraging grounds at Dampier Archipelago (one green turtle, one hawksbill) and the Turtle Islands (three Barrow green turtles and two Varanus Island hawkbills turtles) off the De Grey River are not similarly protected by conservation reserves and fall within the Nickol Bay prawn trawling area (Penn *et al.* 2004). The recent introduction of Turtle Excluder Devices on Western Australian prawn trawlers reduces the risks to these turtles from trawling related stress or death. The importance of the Turtle Islands/De Grey River area, used by both green and hawksbill turtles nesting at Barrow and Varanus Island, has been recognised by the Marine Parks and Reserves Working Group (Wilson 1994) and the results of this study provide strong support for the immediate creation of a formal conservation reserve over the area.

The most important hawksbill foraging grounds identified by the tracking program are those located within the coastal islands chain between Cape Preston and Onslow. Hawksbill turtles from Varanus Island and Rosemary Island (Dampier Archipelago) forage in this area which is currently not protected by any conservation reserves. Industrial activity in the region is currently low and confined primarily to oil and gas pipelines transiting the area, prawn trawling and small scale pearling operations. However plans are in place to develop the western coast of Cape Preston as a ship load out facility which will increase the vessel traffic and by extension public access to a currently pristine area. This area is not currently nominated for conservation.

The results of this research has had an important role in environmental management of the oil and gas industry activities situated within the B-L-M Island group. Ongoing process improvements have seen the local oil companies make changes to their operations on the basis of these findings. For example, the management of facility lighting at Varanus Island has reduced light spill onto the hawksbill rookery at Pipeline Beach and resulted in an increase in numbers of hatchlings reaching the ocean (pers comm. Libby Howitt, 2005). Light management audits and plans have been prepared for oil and gas facilities located both within and adjacent to the study area, and the findings have been used extensively in the preparation of the Environmental Review and Management Plan, and associated risk assessment, for the proposed $40 billion Gorgon Gas facility to be based on Barrow Island.

This thesis has specifically identified the gaps in our knowledge of sea turtle demographics in the B-L-M region and has provided a baseline for ongoing sea turtle research on the use of nesting and foraging habitats used by green, flatback and hawksbill turtles both within the region and on a broader scale across northern Western Australia. The research has provided information on the significance of existing industrial light impacts on sea turtle hatchlings. The implementation of light management recommendations arising from this research are already being used to enhance the successful migration of hatchlings off rookery beaches in the B-L-M region and have been incorporated into the normal operating conditions of both local, and regional, oil and gas operators (e.g. Apache Energy at Varanus Island and Chevron Australia at Thevenard Island and Barrow Island).

This thesis has also provided a focus for the following specific research programs planned for the 2005/2006 summer nesting season. The data these programs will be useful in designing and managing industrial facilities in the vicinity of sea turtle rookeries. Additional controlled light arena studies on the effects of artificial light glow on green turtle and flatback hatchlings will be carried out to attempt to quantify the intensity of light glow most disruptive these species. Adult flatback turtles will be satellite tracked during internesting, migration and at foraging grounds for the first time in Western Australia. Accurate data on the size and demographic parameters of the flatback nesting population using the east coast beaches at Barrow Island will be gathered by way of a large scale saturation tagging program. This program will yield data that will allow that population to be placed in a regional and national perspective. Finally, these data will be used in conjunction with the ongoing census beach track count surveys (initiated as part of this PhD) to further refine the census methods and data analysis for ongoing routine sea turtle monitoring programs.

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APPENDIX 1

Beach dimensions, physical characteristics and proximity to anthropogenic light emissions (1998-2003) for Barrow Island, Montebello Islands and Lowendal Islands

Table A1.1: Barrow Island nesting beach habitat characteristics

Beach name	**Beach code**	**Length (m)**	**Width (m)**	**Foreshore topography 1=wide 2=narrow 3=coral**	**Sand depth 1=deep 2=shallow**	**Slope 1=high 2=low**	**Light within 1.5 km (1=yes, 2=no)**
Northern region – 4.5 km total coastline length							
Surf Point	11	440	28	2	1	1	2
	12	200	15	2	2	1	2
	13	340	28	2	1	1	2
	14	100	10	2	1	1	2
	15	650	18	2	1	1	2
Ti Tree	16	106	10	2	2	2	2
North West region – 16.5 km total coastline length							
V	17	58	30	2	1	1	2
Perched	18	140	15	2	2	2	2
Tortuga	19	412	36	2	1	1	2
Olivia	20	680	13	2	1	1	2
Tania	21	415	10	2	1	1	2
Max’s coast	22	350	5	2	2	2	2
Whites N	23	320	23	2	2	2	2
Whites S	24	390	25	2	1	1	2
Obes	25	110	40	2	1	1	2
Y Station	26	120	43	2	1	1	2
Cave Sth	27	450	55	2	1	1	2
Butlers	28	80	10	2	1	1	2
Flacourt	29	200	70	2	1	1	2
Petal	30	340	50	2	1	1	2
John Wayne E	31	300	37	2	1	1	2
John Wayne W	32	500	50	2	1	1	2
Silver	33	450	20	2	1	1	2
Tonto coast red	34	1100	5	2	2	1	2
Turtle Bay N	35	488	10	2	1	1	2
Turtle Bay S	36	510	10	2	1	1	2
Parking lot	37	100	20	2	1	1	2

Beach name	Beach code	Length (m)	Width (m)	Foreshore topography 1=wide 2=narrow 3=coral	Sand depth 1=deep 2=shallow	Slope 1=high 2=low	Light within 1.5 km (1=yes, 2=no)
South West region – 14.8 km total coastline length							
Biggada	38	83	66	2	1	1	2
Boggs	39	150	68	2	1	1	2
	40	132	30	2	1	1	2
The Ledge	41	41	15	2	1	1	2
Groper	42	200	15	2	1	1	2
Whale	43	600	40	2	1	1	2
Loop	44	670	14	2	1	1	2
Satellite N	45	1000	10	2	1	1	2
Satellite S	46	880	10	2	1	1	2
S W ledge	47	260	5	2	2	2	2
Eagles Nest N	48	475	30	2	1	1	2
Eagles Nest S	49	120	10	2	2	2	2
South End West	50	2300	10	2	1	1	2
Southern region – 13 km total coastline length							
South End SE	51	540	5	2	2	2	2
South End East	52	1400	5	2	2	2	2
South End north	53	1300	5	1	2	2	2
LBB N	54	1400	5	1	2	2	2
Causeways	55	2500	3	1	2	2	1
Lone Mangrove	56	2500	3	1	2	2	2
Sea Eagle Beach	57	300	3	1	2	2	2
South East region – 13.8 km total coastline length							
Weather Station	59	150	3	1	2	2	2
Airport	60	100	3	1	2	2	1
Heliport	61	150	3	1	2	2	1
Shark Point N	62	200	3	1	2	2	1
Pole A07	63	400	3	1	1	2	2
Junction	64	720	3	1	2	2	1
Camp	65	300	10	1	2	2	1
Mid East region – 5.54 km total coastline length							
YC S	66	1200	15	1	1	2	1
YC N	67	925	10	1	1	2	1
Inga	68	800	20	1	1	2	2
Bivalve	69	600	13	1	1	2	2
Terminal	70	500	20	1	1	2	1
Tank	71	23	10	1	2	2	1
Mushroom	72	810	10	1	1	2	1
Mattress S	73	540	10	1	2	2	2
Mattress Pt	74	140	20	1	1	2	2
Donald River	75	830	5	1	2	2	2
Boomerang Is	76	110	15	2	1	2	2
Boomerang coast	77	150	5	1	2	2	2

Beach name	Beach code	Length (m)	Width (m)	Foreshore topography 1=wide 2=narrow 3=coral	Sand depth 1=deep 2=shallow	Slope 1=high 2=low	Light within 1.5 km (1=yes, 2=no)
The Landing	78	100	10	2	2	2	2
North East region - 11.2 km total coastline length							
Whitlock	1	150	25	2	1	2	2
	2	500	25	2	1	2	2
	3	470	15	1	2	2	2
	4	340	10	1	1	2	2
	5	260	13	2	1	2	2
Square Bay	6	240	5	1	2	2	2
	7	490	13	1	1	2	2
	8	180	16	1	2	2	2
	9	370	20	2	1	2	2
Sth Surf Point	10	55	5	2	2	2	2

Table A1.2: Montebello Group nesting habitat characteristics

Island and beach name	Beach code	Length (m)	Width (m)	Foreshore topography 1=wide 2=narrow 3=coral	Sand depth 1=deep 2=shallow	Slope 1=high 2=low	Light within 1.5 km (1=yes, 2=no)
Ah Chong Island							
South East	1	300	11	2	1	1	2
North East	2	250	20	2	2	2	2
North	3	186	11	2	2	2	2
West	4	96	11	2	2	2	2
Hermite Island							
Wilsons	5	700	20	2	1	1	2
North West Island							
	1	100	25	1	2	2	2
	2	50	5	2	2	2	2
	3	555	50	2	1	1	2
	4	180	47	2	1	1	2
	5	730	30	2	1	1	2
	6	2500	3	2	1	2	2
	7	355	30	2	1	1	2
Trimouille Island							
	1	760	5	2	2	2	2
	2	40	2	2	1	2	2
	3	100	20	2	1	2	2
	4	470	40	2	1	1	2
	5	450	50	2	1	1	2
	6	480	53	2	1	1	2
	6a	200	20	3	2	2	2
Main	7	1100	3	2	1	2	2
Cocoa	14	300	5	2	1	2	2
	8	250	15	3	2	2	2
	9	330	20	2	1	2	2
	10	630	56	2	1	2	2
South East Island							
Reef	1	400	25	3	1	2	2
Spit	2	120	25	2	1	1	2
Cliff	3	144	10	2	2	2	2

Table A1.3: Lowendal Group nesting habitat characteristics

Island and Beach name	**Beach code**	**Length (m)**	**Width (m)**	**Foreshore topography 1=wide 2=narrow 3=coral**	**Sand depth 1=deep 2=shallow**	**Slope**	**Light within 1.5 km (1=yes, 2=no)**
Bridled Island							
Kaia	9	160	15	2	1	1	2
Pocket	10	10	<5	2	2	2	2
Rose	11	120	10	1	1	2	2
Ike	12	230	<5	1	2	2	2
Scott	13	160	15	2	1	2	2
Ben	14	30	<5	2	2	2	2
Beacon Island	15	200	15	2	1	1	2
Abutilon Island							
Shark	16	170	15	1	1	2	2
Trunk	17	55	20	1	2	2	2
NW	18	50	15	2	1	1	2
SW	19	42	<5	2	1	1	2
Varanus Island							
Cooks	1	235	30	2	1	2	2
Pipeline	2	200	27	2	1	2	1
Amenity	3	60	30	2	2	2	1
Harriet	4	290	50	2	1	2	1
Andersons	5	90	23	2	1	2	1
Mangrove	6	240	<5-8	2	2	2	1
Tannys	7	80	15	2	1	2	1
Cliff	8	40	10	2	1	2	1
Parakeelya Island	20	261	16	2	1	2	2

APPENDIX 2

Mean number of BHT track counts per day, 1998 – 2005, from all survey beaches within each island group, during the peak nesting months January for green turtle and flatback and November for Hawkbills. Range shows the number of tracks counted on individual beaches, n is the number of beach survey days on each island.

Island	statistic	Flatback	Green turtle	Hawksbill
BWI East	mean	7.78	0.08	0
	stdev	8.02	0.33	0
	se	0.74	0.03	0.00
	range/beach	0-40	0.2	0
	n	119	120	116
BWI West	mean	0.11	9.3	0
	stdev	0.41	15.25	0
	se	0.04	1.56	0.00
	range/beach	0-3	0.105	0
	n	95	97	96
Varanus	mean	1.61	0	1.16
	stdev	2.78	0	1.71
	se	0.38	0.00	0.19
	range/beach	0.11	0	0-8
	n	54	54	80
Bridled	mean	2.94	0.1	1.9
	stdev	4.48	0.54	2.99
	se	0.80	0.10	0.48
	range/beach	0-17	0-3	0-13
	n	32	32	40
Hermite	mean	4.56	2.76	0.47
	stdev	6	4.2	0.64
	se	1.46	1.02	0.17
	range/beach	0-22	0-15	0-2
	n	18	18	15
Ah Chong	mean	0.54	0.04	2.27
	stdev	0.91	0.29	3.87
	se	0.14	0.04	2.23
	range/beach	0-3	0-2	0-16
	n	46	46	4
SE	mean	0.91	0.36	1.73
	stdev	1.14	0.67	2.1
	se	0.36	0.21	0.66
	range/beach	0-3	0-2	0-6
	n	11	11	11

Island	statistic	Flatback	Green turtle	Hawksbill
Trimouille	mean	1.5	3.93	0.65
	stdev	4.53	6.73	1.53
	se	0.38	0.55	0.15
	range/beach	0.37	0-39	0-14
	n	142	153	110
NW	mean	0.49	3.51	0.38
	stdev	1.34	5.74	0.75
	se	0.14	0.62	0.09
	range/beach	0-9	0-30	0-3
	n	88	88	68
Beacon	mean	1.57	0	2.91
	stdev	2.51	0	3.22
	se	1.02	0.00	1.02
	range/beach	0-7	0	0-10
	n	7	7	11
Abutilon	mean	2.44	0.05	0.1
	stdev	4.57	0.22	0.32
	se	1.11	0.05	0.11
	range/beach	0-19	0-1	0-1
	n	18	20	10

Satellite tracking results for individual animals

1 Introduction

Sufficient LC 1,2,3 transmissions were received to reconstruct the migration route and foraging ground location for 13 of the 21 turtles (last column, Table 7.2). These are the default locations used by the STAT mapping program to filter and map the track data. These positions appear as large circles joined by a track line on each map. Where LC 1,2,3 positions were unavailable (*i.e.* for the remaining 8 turtles) selected lower quality (LC 0, A and B) positions were used and these appear on the maps as smaller dots that are typically clustered around the internesting and feeding ground locations and scattered along the migration path. This allowed details on track and foraging grounds locations to be mapped which otherwise would have been discarded during the STAT program filtering process.

2 Hawksbill results

2.1 Emma

Emma (Figure A3.1) was found and tagged at Pipeline Beach, Varanus Island on the 16th December 2000. She spent 16 days in the vicinity of Varanus Island before leaving the area on the 1 January 2001. After Emma departed the Varanus Island area on 1 January 2001, she travelled east towards the mainland tracking along the 20m isobath and passing through Dampier Archipelago around 6 January 2001. She took 21 days to reach her endpoint east of the De Grey River. She remained in this area for 56 days after which no further transmissions were received.

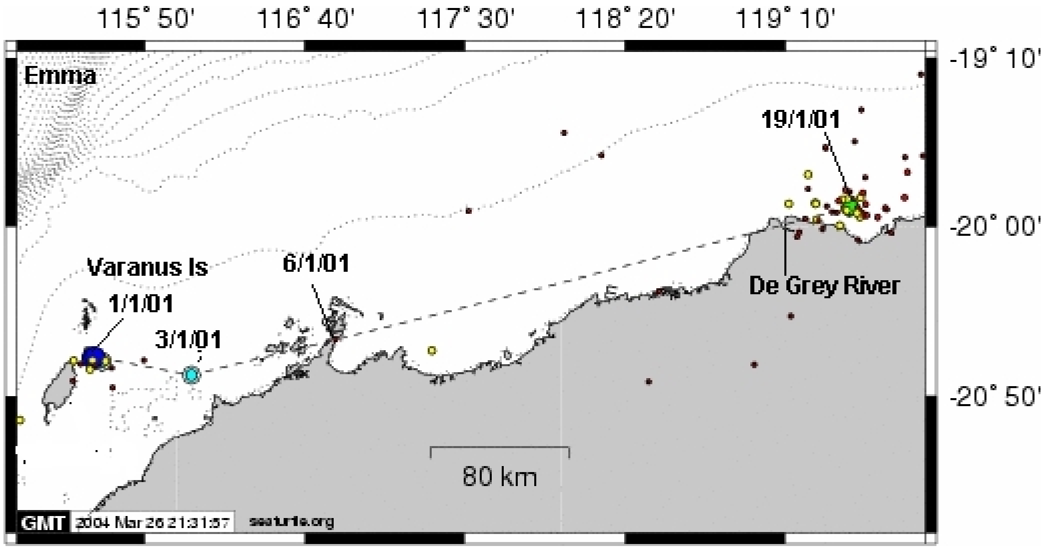

Figure A3.1: Emma migration pathway and foraging ground

2.2 Erica

Erica (Figure A3.2) was found on Pipeline Beach however she was transported to Harriet Beach for ptt attached and release. Only 8 of the 143 transmissions for Erica were LC1, 2 or 3. Her first fix (LC 3) 18/12/01 was while I had her on Pipeline Beach attaching the ptt. The fix location was 1km west of the actual position. All internesting locations are clustered around Varanus. The last fix received was a LCB on 24/2/01, notionally near Dampier Archipelago. This data represents 2 months in the VI region. There is no sign of an apparent migration and the data appears to represent the nesting and internesting period of the reproductive cycle for this turtle.

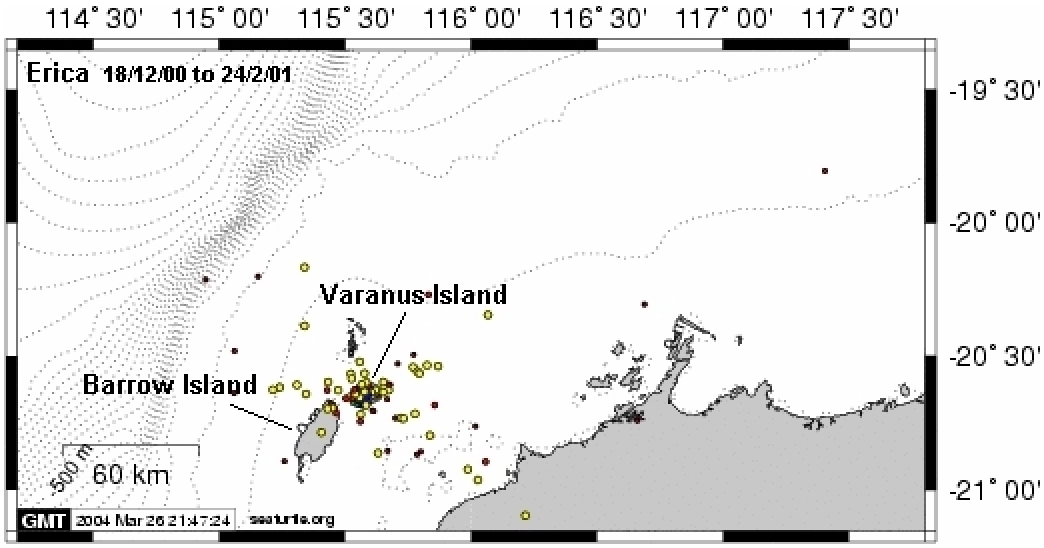

Figure A3.2: Erica internesting ground.

2.3 Marnie

Marine was tagged (after transport from Pipeline Beach to Harriet Beach) on 20/12/00, 20 days after a previous nesting event (Figure A3.3). On the 10/1/01 she moved southward away from VI towards the mainland. Her first position for the area east of Great Sandy Island was on the 12/1/01. Her swimming speed was calculated, using LC 2 and 1 data only, at an average of 1.5 km/hr. Her path was direct with no deviations from the line shown in Figure A3.6. A LC 1 fix was recorded for her on 18/1/01, the data for the period Jan 12 until transmissions ceased on 4 Feb (LC A and 0) shows her locations clustered around Great Sandy Island, 65 km south of Varanus Island. This area has extensive intertidal and subtidal reef habitat (K Pendoley field notes 17 July 2000). The data represents 24 days in this area, it is reasonable to assume this is her feeding ground.

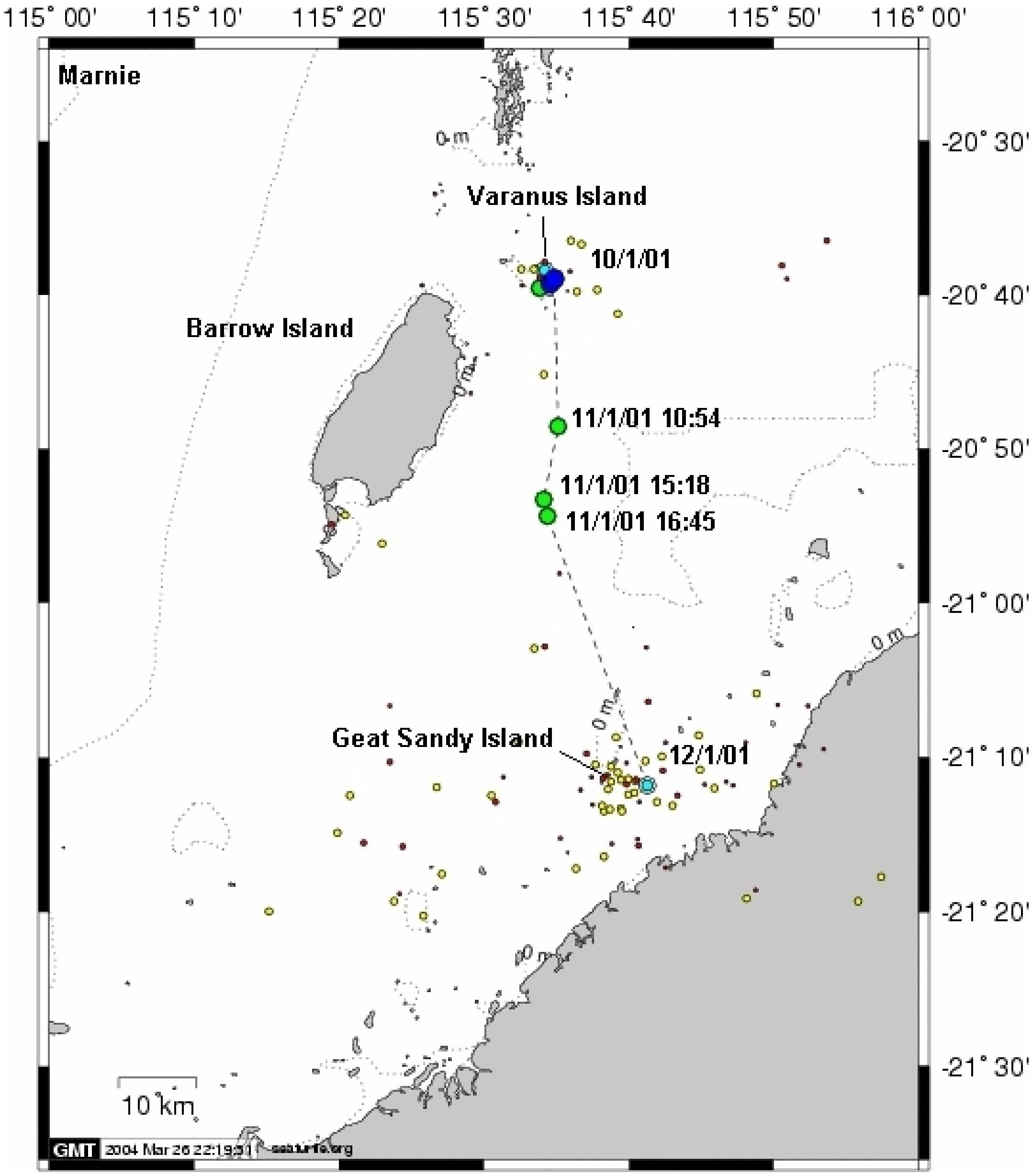

Figure A3.3: Marnie migration pathway and foraging ground.

2.4 Marilyn

Marilyn was found on North Mangrove Beach on the west coast of Varanus Island. She was tagged and released from Harriet Beach on the 21/12/00. A LC 3 fix was obtained for her on 23/12/00 that showed her ashore on Tannys Beach on the west coast of Varanus Island. Her presence on the beach at that time was confirmed by an oilfield worker who found her and noted her ptt number, date and time of observation (2100 hrs). A second LC 3 fix was obtained for her on 10/1/01 on Tannys Beach giving her an 18 day interesting period. There was no further data for Marilyn until she reappeared 11 days later in the vicinity of the Mary Anne Island group, 85 km to the south of Varanus Island (Figure A3.4).

No further LC 1,2,3 fixes were obtained for her in this region. The rest of the data was classes 0, A and B. All were clustered around the Mary Anne Group through to the end of January 2001. No further data was obtained until July 2001 when several LC 0 and A fixes were received just prior to the programmed termination of the ptt transmissions. This indicates a 6 month period in this region for this animal. It is reasonable to assume this is her feeding ground.

The Mary Anne Island Group is characterized by huge areas of subtidal and intertidal shoal reef habitat. In July 2000 an adult Hawksbill turtle was found on an exposed section of this intertidal area during a biological survey of the coastal islands from Cape Preston to Onslow. She measured 81 cm CCL and 69 cm CCW (K Pendoley field notes 15 July 2000). The habitat was a perched lagoon reef system, rich in sponges, the preferred food of hawksbill turtles.

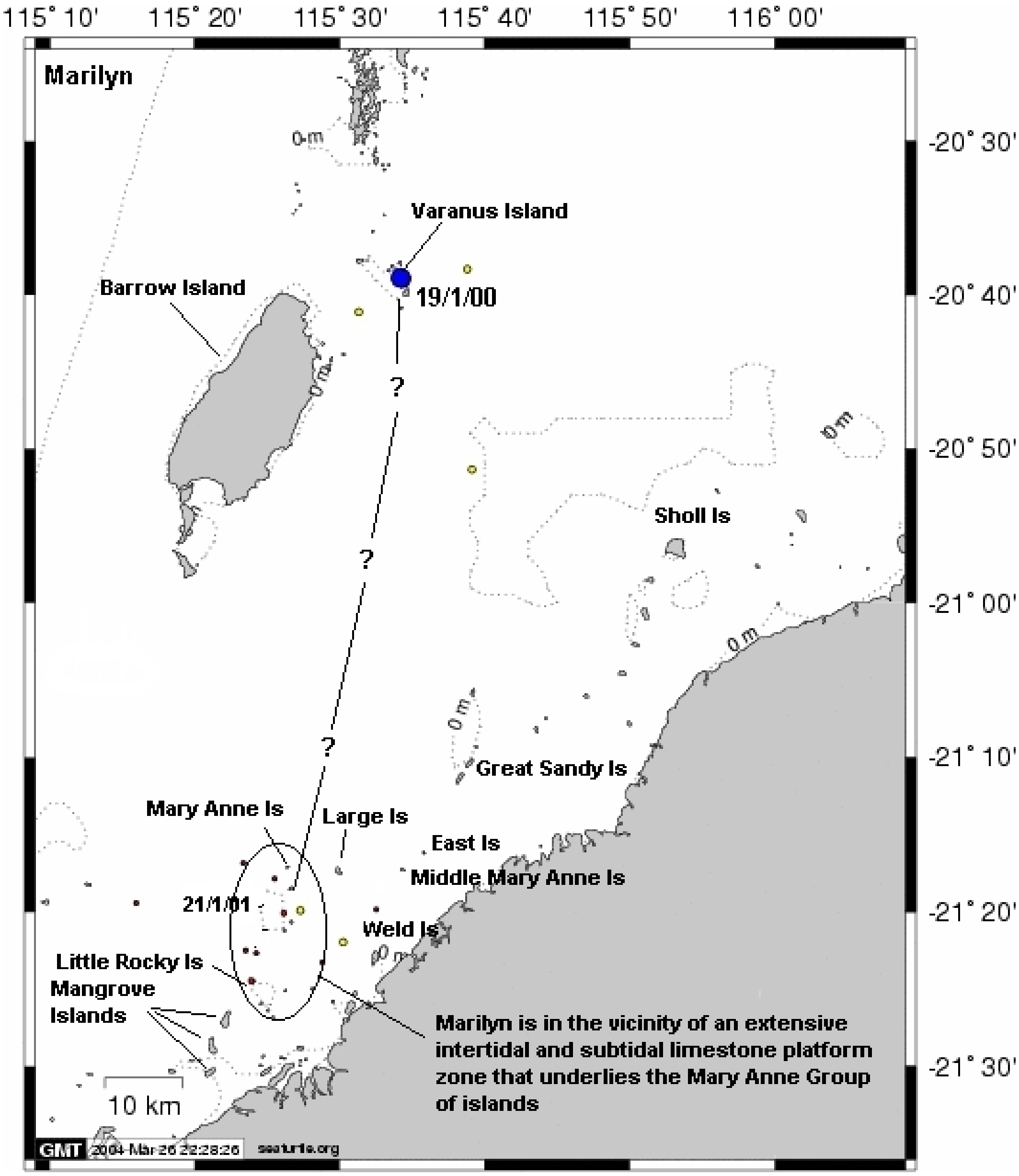

Figure A3.4: Marilyn foraging ground.

2.5 Sharon

Sharon was found on Pipeline Beach on the 25/11/02. She was tagged and released on the 26/11/02. Sharon was found on Pipeline Beach 18 days later on the 14 December 2002. She emerged from the water at 2000 hrs and attempted to nest in the shallow sand under and adjacent to the pipelines crossing Pipeline Beach. Inspection of the ptt showed the fibreglass resin and tape used to attach the ptt to her shell was heavily scratched and much of it was lifting and had been broken away in the region behind the transmitter. The salt water switches looked clean with no fouling noted. This ptt was one of two deployed without tygon tubing protecting the antennae. The antennae were bent sideways. The damage observed appeared consistent with mating behaviour. Sharon appeared very determined to nest and was not dissuaded from this objective by the presence of people or torch light.

Sharon remained in the vicinity of Varanus Island until 16/12/02 when she left the island in an easterly direction travelling along the same 20 m isobath pathway taken by Emma 13 months earlier (Figure A3.5). Her pathway took through Dampier Archipelago and along he coast to North Turtle Island. The filtered track suggests she travelled offshore from Dampier however the clustering of the LC 0, A and B data along an inshore line suggests she actually travelled closer to the coast along a similar course taken by Julie. She arrived in the vicinity of North Turtle Island on 31/12/02, a straight line distance of 369 km, and remained in the area for the next the next 115 days until the transmitter ceased operating. The extended residency in the area is an indicator that this is her feeding ground.

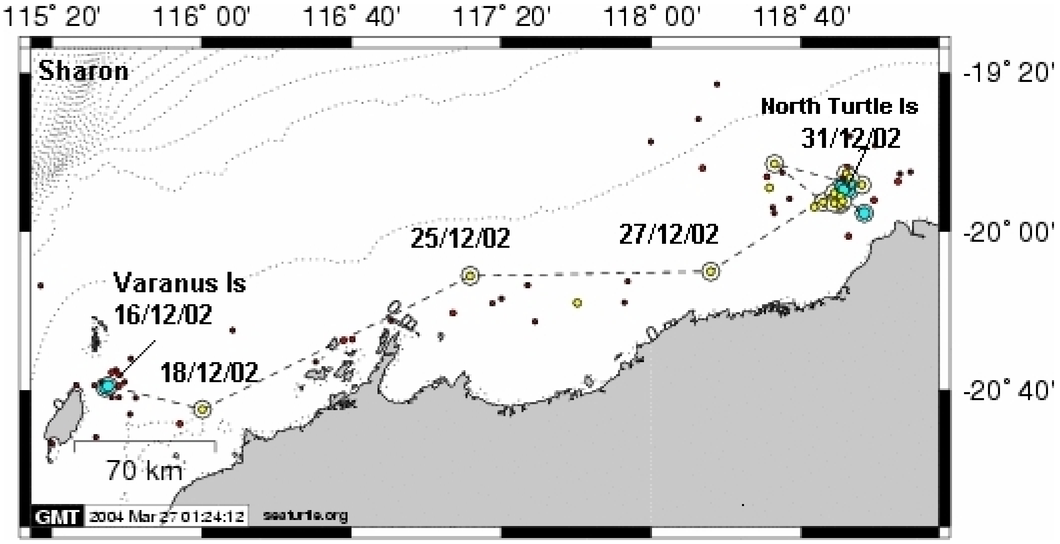

Figure A3.5: Sharon migration pathway and foraging ground.

2.6 Julie

Julie was released from Pipeline Beach, Varanus Island on 27/11/02. Julie was found emerging from the water at Pipeline Beach on the 14 December 2002, 17 days after being tagged. She emerged at approximately the same place and a half an hour after Sharon (2030 hrs). She attempted to nest within 10m of Sharon however she returned to the water after a single attempt. Damage to the fibreglass resin attaching her ptt was less extensive than on Sharon. Her tygon protected antennae was undamaged and the salt water switches clean.

Julie remained in the Varanus Island region until 17/12/02 when she headed east along a similar path taken by Emma (January 2001) and Sharon (1 day earlier) towards Dampier Archipelago (Figure A3.6). She approached the area from the east of Enderby Island, passing to the south of Rosemary Island and around the top of the Burrup and Legendre Island. She took a direct easterly path from here towards Cape Thouin and then onto an area east of the De Grey River mouth, arriving on the 2/2/03. She remained in this area for the next month until transmissions ceased on 2 March 2004. This endpoint was in the same area as Emma tracked 12 months earlier.

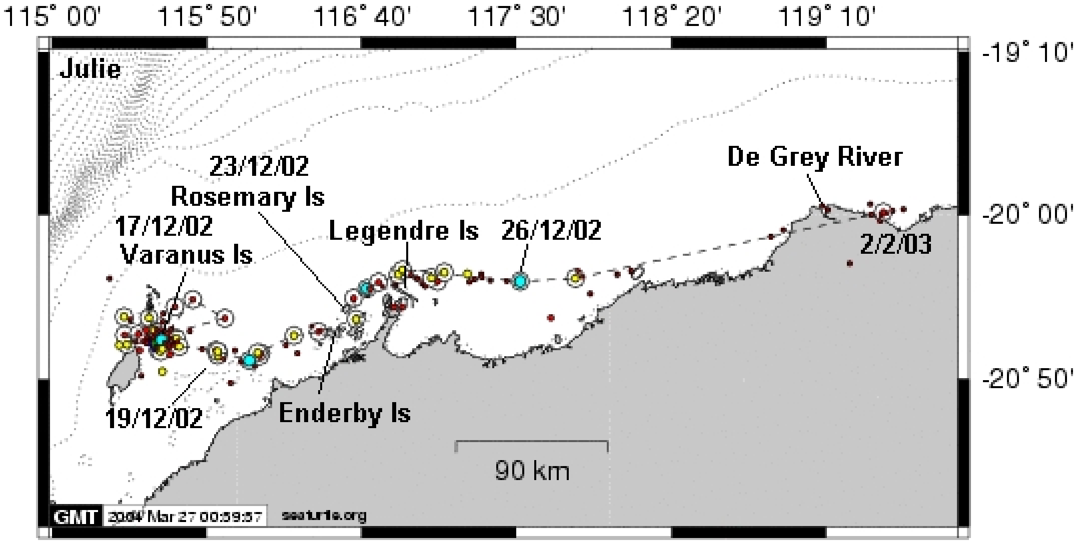

Figure A3.6: Julie migration pathway and foraging ground.

2.7 Fran

Fran was tagged on 6 November 2004 at Rosemary Island within the Dampier Archipelago (Figure A3.7). She left Rosemary Is after nesting on the 9/11/02 and travelled east across Mermaid Sound, through Searipple passage and on into Nickol Bay (first fix here 13 November 2002). Relatively few low quality transmissions were received for this turtle however the final position for her in this area was on the 28/12/02, giving her 45 days of presence in the Nickol Bay area, it is therefore reasonable to assume this is her feeding ground.

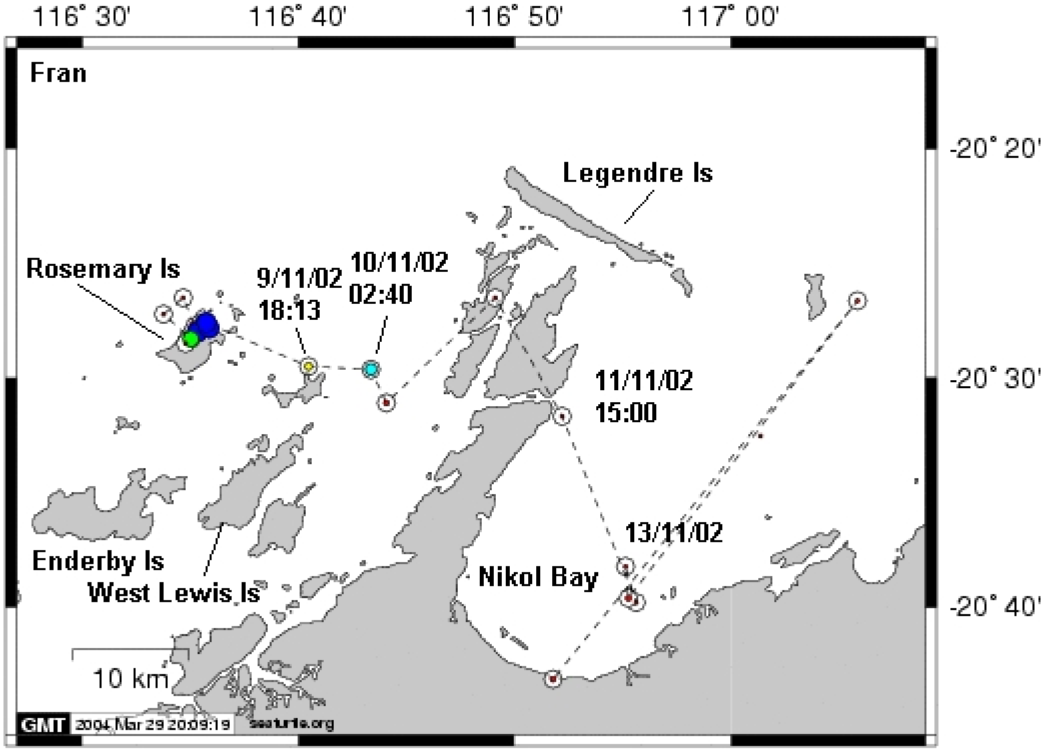

Figure A3.7: Fran migration pathway.

2.8 Vicky

Vicky was tagged the same day as Fran at Rosemary Island. She departed the island on the day before Fran on the 8 November 2002, heading in a south westerly direction. She arrived at her endpoint on 15 November 2002 and remained in this area, off the north coast of Sholl Island until transmissions ceased 7.5 months later on the 27 June 2002. The locations for the migration path and feeding ground area are plotted on Figure A3.8 and show a clustering on the subtidal platform off the north west coast of Sholl Island. The extended time in this area suggests this is her feeding ground.

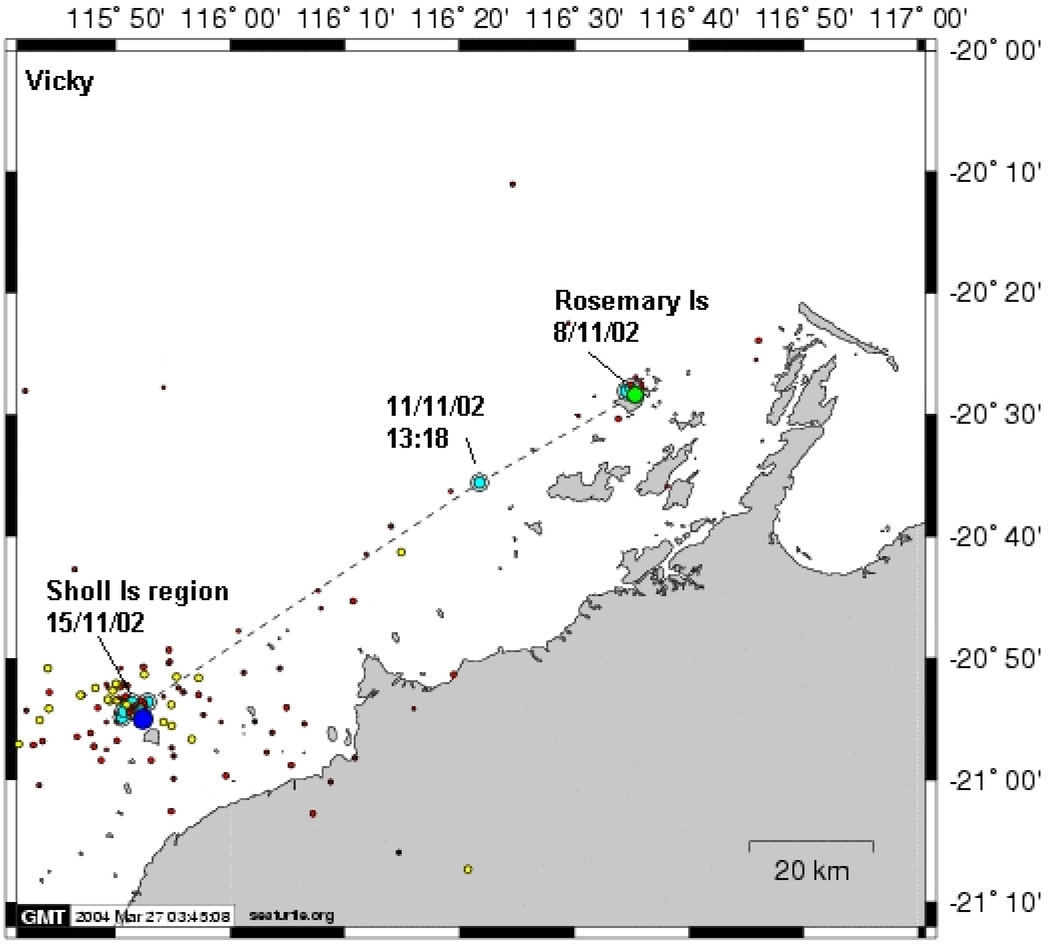

Figure A3.8: Vicky migration pathway and foraging ground.

2.9 Anna

Anna was tagged the day after Fran and Vicky at the same location on Rosemary Island. Unlike the other two she remained around Rosemary Island for an additional 38 days. She departed the island on 15 December 2002 and travelled in the same south westerly direction as Vicky had done the month before (Figure A3.9). Her endpoint was in an area 20 km east of Vicky's feeding ground, 10 km off the mouth of the Fortescue River. Transmissions were received from this location for 24 days indicting this is her feeding ground.

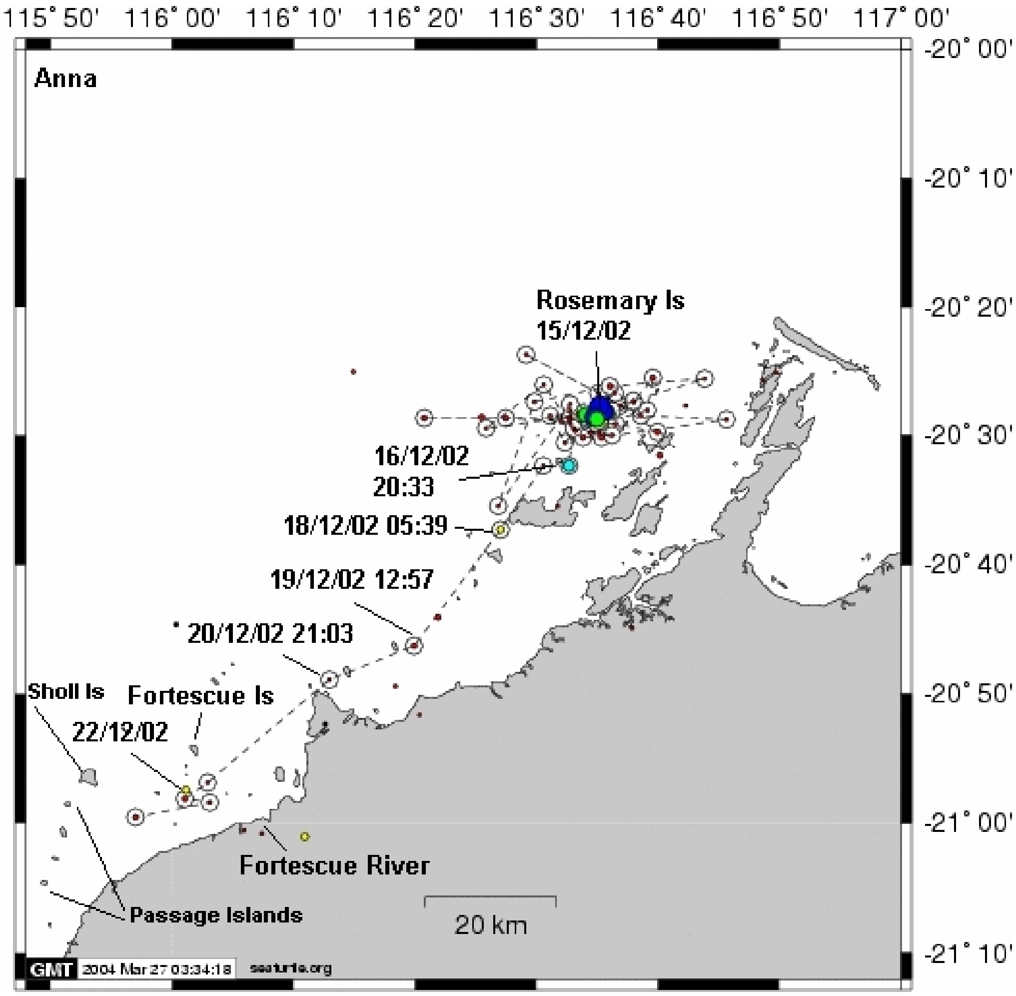

Figure A3.9: Anna migration pathway and foraging ground

3 Green turtle results

3.1 Rachel

Rachel was tagged on John Wayne Beach on 8 January 2001. She spent the next 30 days in the vicinity of John Wayne Beach prior to travelling northward along the western edge of the Montebello Islands (Figure A3.10). Her reconstructed track shows her turning east around the top of North West Island in the Montebello group and tracking due east inshore of the 50m isobath to Legendre Island in the Dampier Archipelago arriving 3 days later on 22 February 2002. She then travelled in an east northeast direction arriving at North Turtle Island 12 days later on the 6 March 2002. Only 2 additional days of transmissions (LC 1, A, B) were received at this location so I am unable to determine if this was her feeding ground. She took a total of 19 days to travel the 420 km to this location. The migratory data showed that after leaving Barrow Island Rachel kept moving steadily eastward, without pausing along the way, until she reached North Turtle Island where she paused for 3 days (before the ptt stopped transmitting), suggesting this may be her feeding ground.

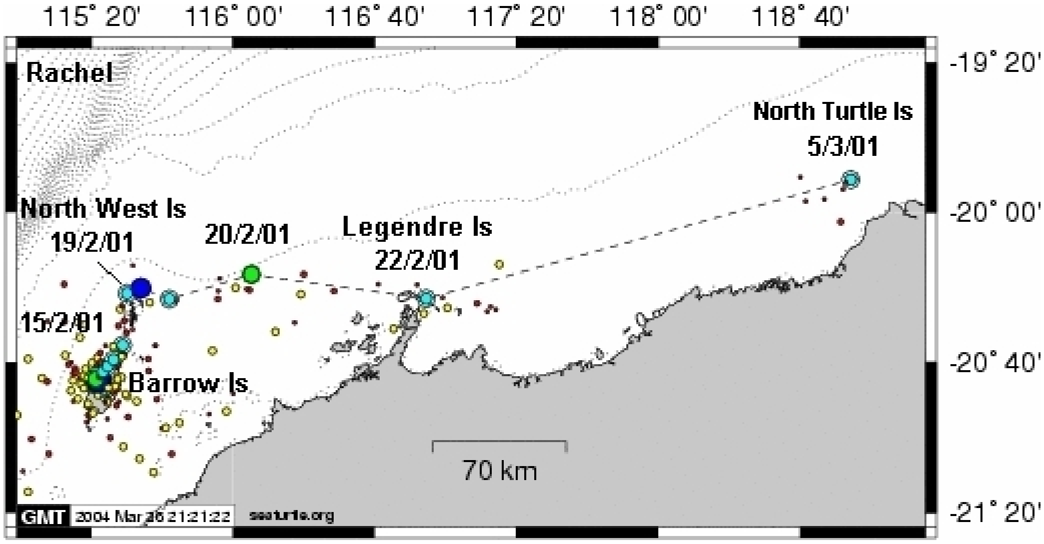

Figure A3.10: Rachel migration pathway and foraging ground

3.2 Eugenie

Eugenie was tagged and released on John Wayne Beach on the 9 January 2001. She spent the next 37 days in the vicinity of John Wayne Beach before departing in a southerly direction on the 7 February 2001. No LC1, 2 or 3 transmissions were received after she left Barrow Island however the LC A, B and 0 data has been hand filtered and is shown in Figure A3.11. The final transmission for this turtle was received on 11/2/01 when she was just east of Locker Island. She appeared to be tracking southwards along the coast and towards Exmouth Gulf at this time. This track represents a partial migration track and her endpoint cannot be determined.

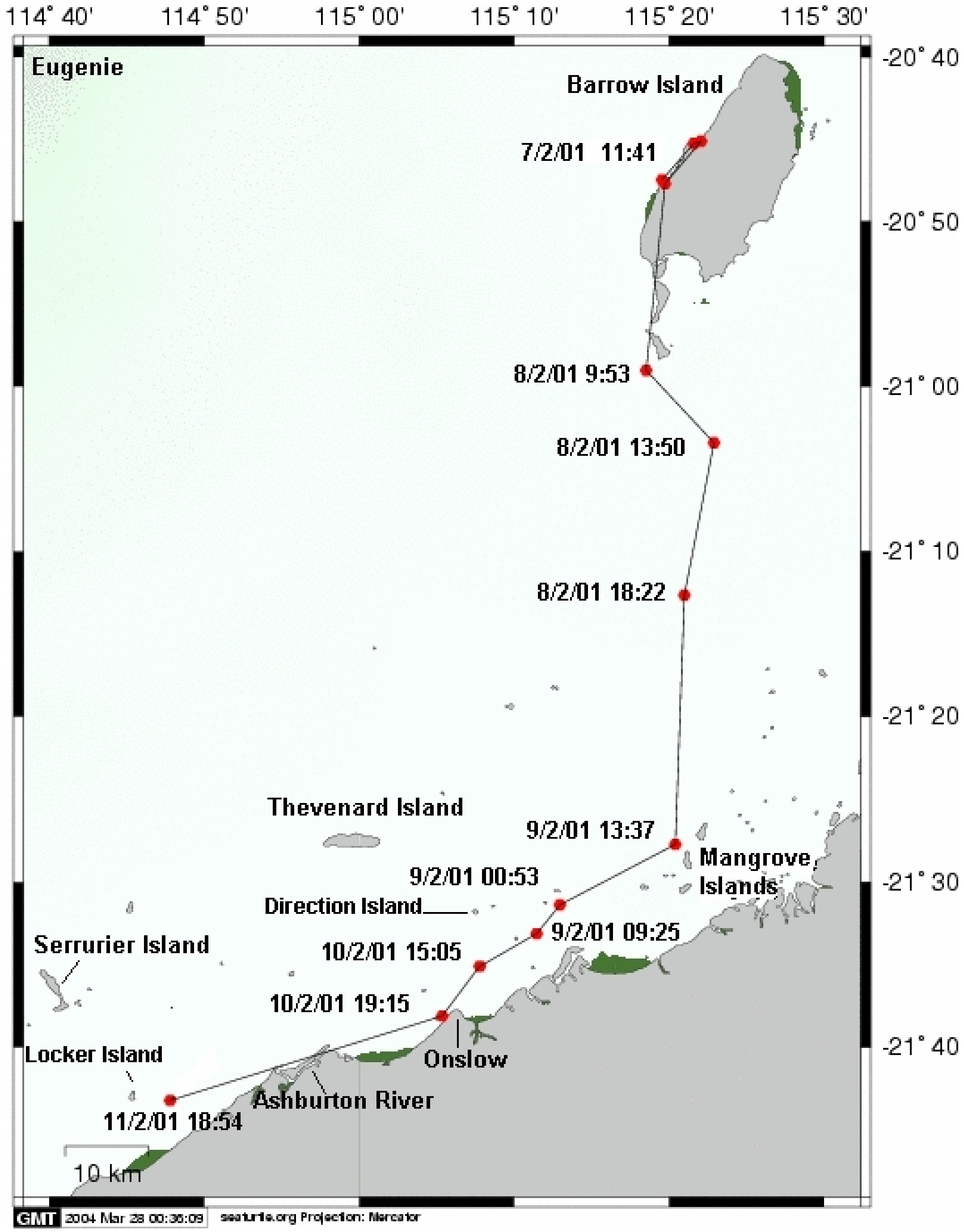

Figure A3.11: Eugenie partial migration pathway

3.3 Isobel

Isobel was tagged on the 10 January on John Wayne Beach. Her subsequently locations showed her in the vicinity of John Wayne Beach and Cape Dupuy on Barrow Island until she left the island on 4 March 2001 travelling north east for 4 days and then turning east and south until her transmissions ceased abruptly west of Cape Thouin on the 11 March 2001 (Figure A3.12). Her track took her well offshore from Dampier Archipelago tracking out to, and along, the 50m isobath before turning inshore. The lack of long term data from the end point suggests she had not completed her migration.

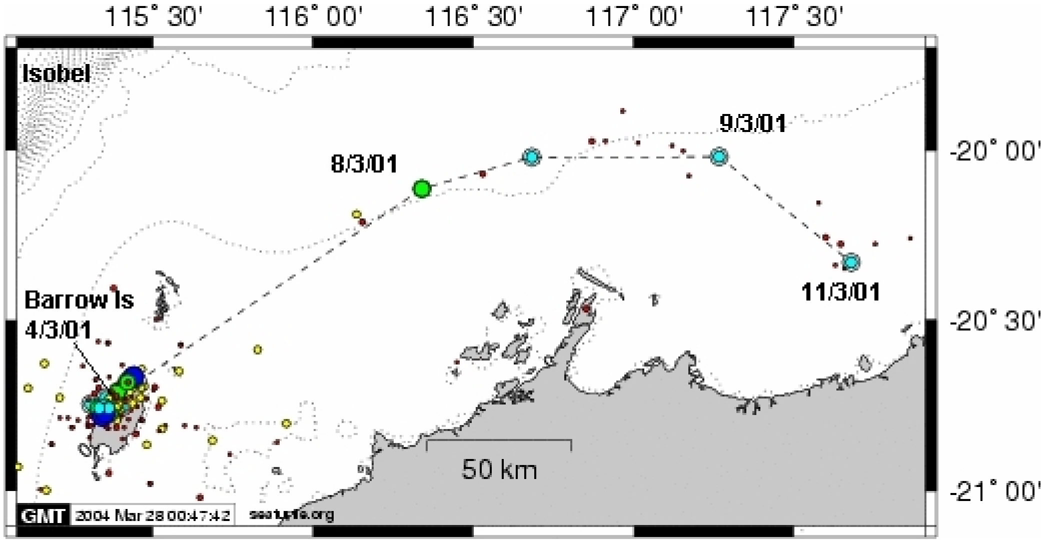

Figure A3.12: Isobel partial migration pathway.

3.4 Sylvia

Was found nesting on John Wayne Beach on 12/1/00, she was tagged and released the same day. Sylvia departed Barrow around December 26th following the inshore 20m isobath track previously taken by the hawksbills from Varanus Island (Emma, Sharon and Julie). She skirted around the top of the Dampier Archipelago, before turning due east at Legendre Island (Figure A3.13). Her reconstructed track then crossed 100 km of open water before intersecting with the mainland just west of Cape Thouin, she then turned north and travelled 400km over 12 days until she reached her endpoint just off Cape Jaubert south of Broome. The scattering of the lower quality data (LC 0, A, B) along her migratory path between Cape Thouin and Cape Jaubert suggests that she may have travelled further inshore than the LC 3,2,1 transmission suggest.

She remained in the area off Cape Jaubert for 33 days prior to transmissions ceasing on 28 March 2001. Her continued presence in this area for 4 weeks suggests that this is her feeding ground.

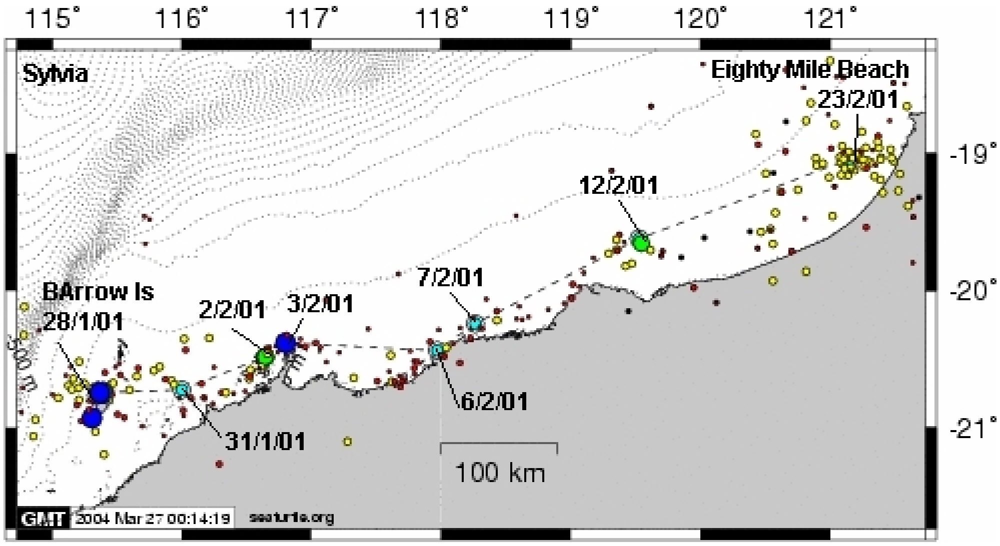

Figure A3.13: Sylvia migration pathway and foraging ground

3.5 Rosie

Rosie was tagged on John Wayne Beach on 6 January 2001 one year after Rachel, Eugenie, Isobel and Sylvia. She remained in the vicinity of John Wayne Beach until leaving he island 12 days later on 18 January 2002. She travelled in a north east direction around the outside of Dampier Archipelago before turning southwards toward the coast briefly (Figure A3.14). She then travelled in a direct line to feeding grounds at and near North Turtle Island. Her LC 321 positions at the feeding grounds were clustered around two points, one to the east of North Turtle Island at the eastern end of a north east – south west lying ridge in 8-10m of water (19 January 2002 to 23 March 2002), the second area of clustering is around North Turtle Island (19 January 2002 to 15 June 2002).

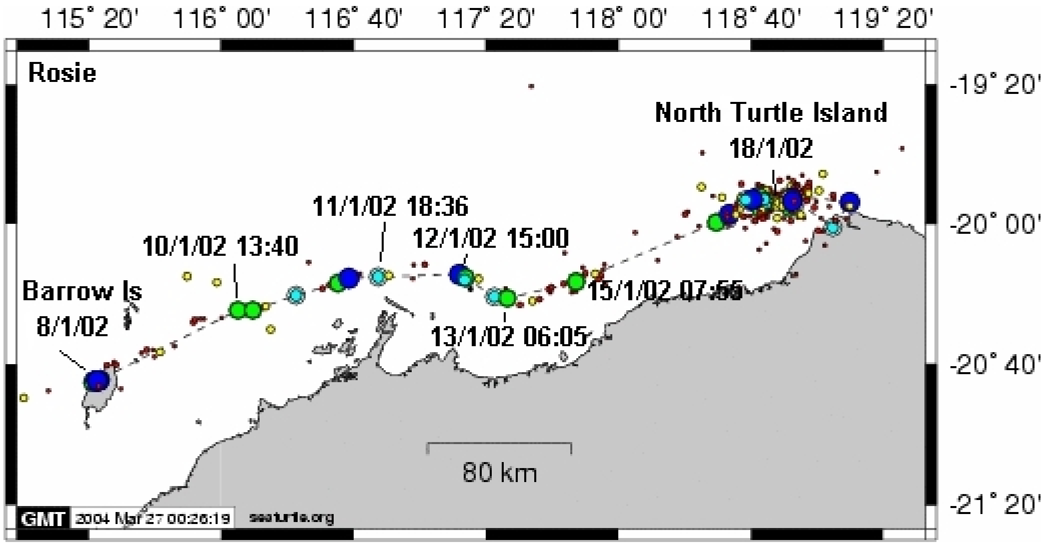

Figure A3.14: Rosie migration pathway and foraging ground.

3.6 Chloe

Chloe was tagged at John Wayne Beach on the 7 January 2002. The ensuing 33 days she spent internesting/nesting at Barrow Island. Her (very good data) positions show her nesting and or internesting at John Wayne Beach as well as Whites Beach and south of Cape Dupuy. She left Barrow Island on 9 February 2002, tracking around the north end of Barrow and Varanus Island before curving south towards Cape Preston and then north along the 10m isobath to Dampier Archipelago (Figure A3.15). She tracked through the Archipelago between Enderby and Rosemary Islands before reaching her end point at Legendre Island. Chloe transmitted for an additional 57 days at this Legendre Island endpoint until her signals ceased in March 2002. It is reasonable to assume this is her feeding ground.

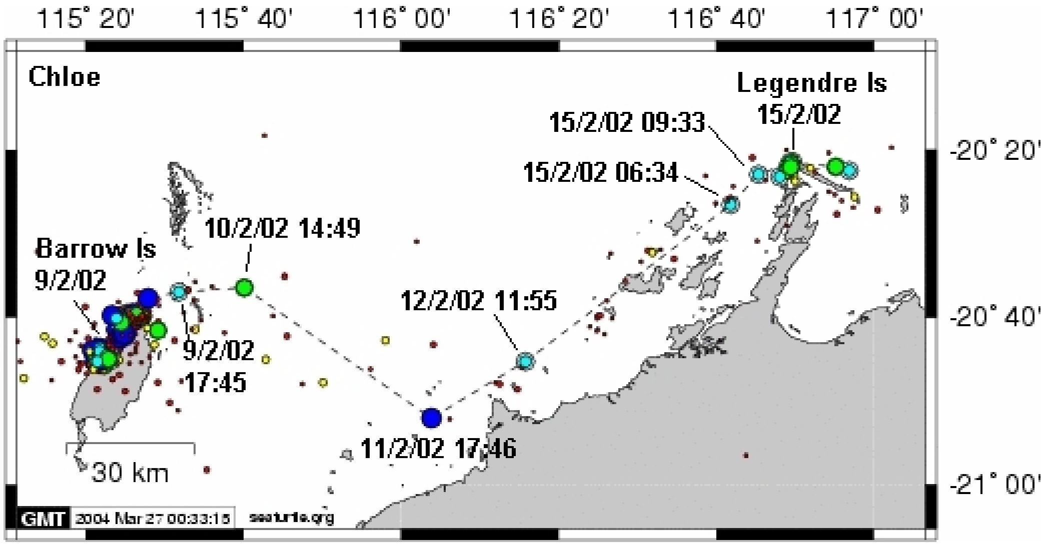

Figure A3.15: Chloe internesting, migration pathway and foraging ground.

3.7 Lyn

Lyn (and Desiree) were tagged one year after Rosie and Chloe and two years after Rachel, Isobel, Eugenie and Sylvia were tagged at John Wayne Beach. She remained around Barrow for 28 days, most closely associated with beaches on the northern coast of Barrow east of Cape Dupuy. Scattering of low level location class transmissions also showed an association with beaches on the east coast, something not seen with any of the other green turtles tracked. Field surveys I carried out in 2002 confirmed the use of these north eastern Barrow beaches by nesting and internesting green turtles (K Pendoley field notes 14 November 2002 and Chapter 3).

Lyn left Barrow Island on the 2 February 2003 and travelled south towards the mainland, as Eugenie had done 2 years earlier (Figure A3.16). Her transmitter stopped operating on 5 February 2003 near Coolgra Point; however two months later she reappeared in the bottom end of Freycinet Estuary at Shark Bay. She remained in this area for 8 months until her transmitter ceased operating.

Whilst on her feeding ground her positions (LC321 only) remained tightly clustered within a small area approximately 6k m x 3 km. This is either an indication of the limits of her feeding ground or is a function of shallow water depths that increase her chances of being on the water surface.

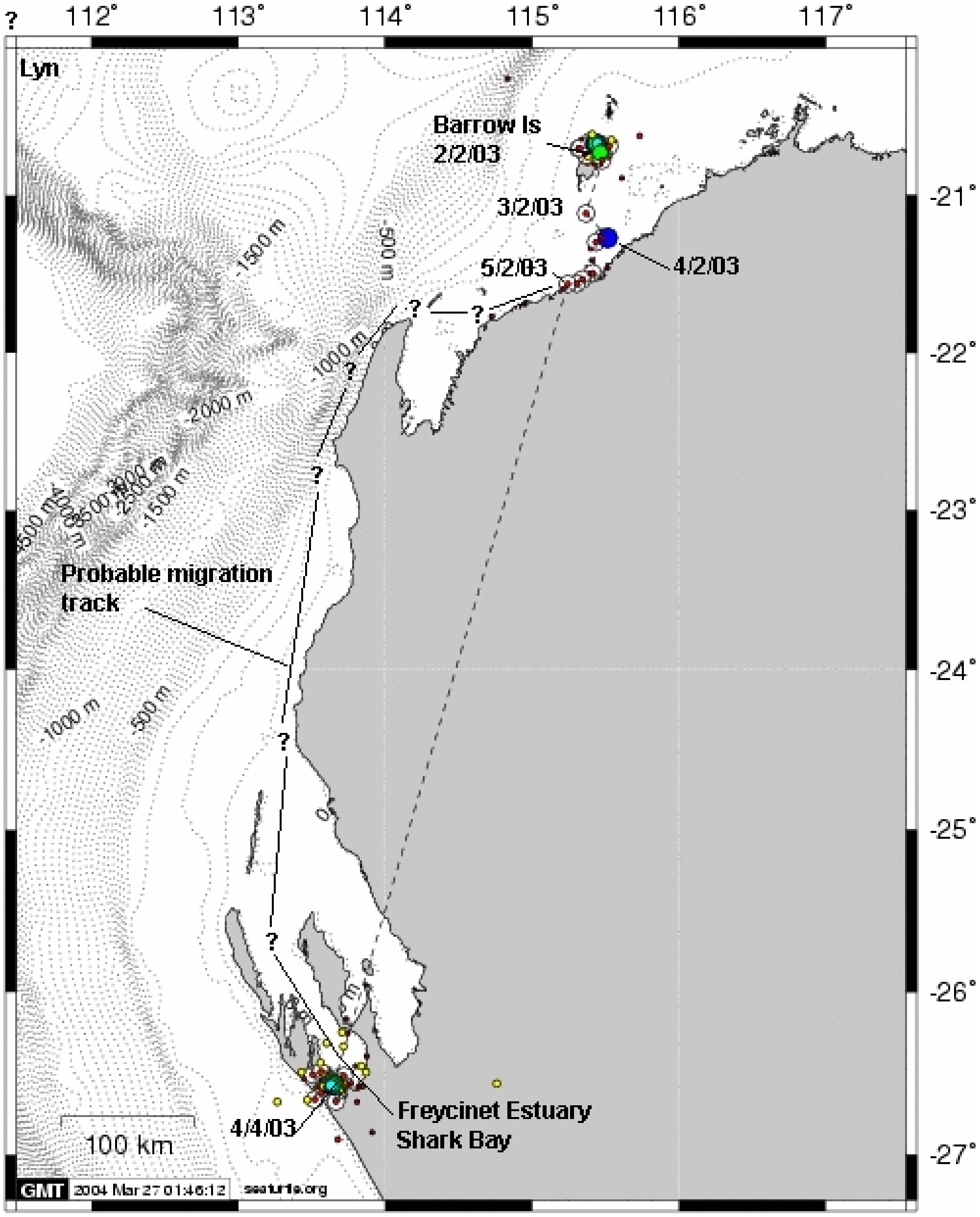

Figure A3.16: Lyn partial migration pathway and foraging ground

3.8 Desiree

Desiree was tagged the same day as Lyn, however unlike Lyn she departed the Barrow are within hours of being tagged and travelled along the same path taken by the hawksbills Emma, Sharon and Julie, and the green turtles Sylvia and Chloe as they traversed the waters along the 20m isobath between the offshore islands and Dampier Archipelago (Figure A3.17). Desiree reached Legendre Island 5 days after leaving Barrow and then travelled east towards Cape Thouin where she turned to the north east swimming directly towards North Turtle Island. The clustering of lower quality positions along her migrations path suggests she remained offshore and followed the 20m isobath to her foraging grounds at North Turtle Island.

The high number of LC 321 transmissions from the feeding ground allowed fine detail to be seen in Desiree's movements. Using only LC 3, 2, 1 fixes she appears to have spent 12 days in a small area north east of North turtle Island (possibly on a pearling holding site/dump area active between March and November annually, ref AUS 739). Before moving onto the subtidal area north of North Turtle Island where she remained until the transmitter ceased operating on 12 March 2003.

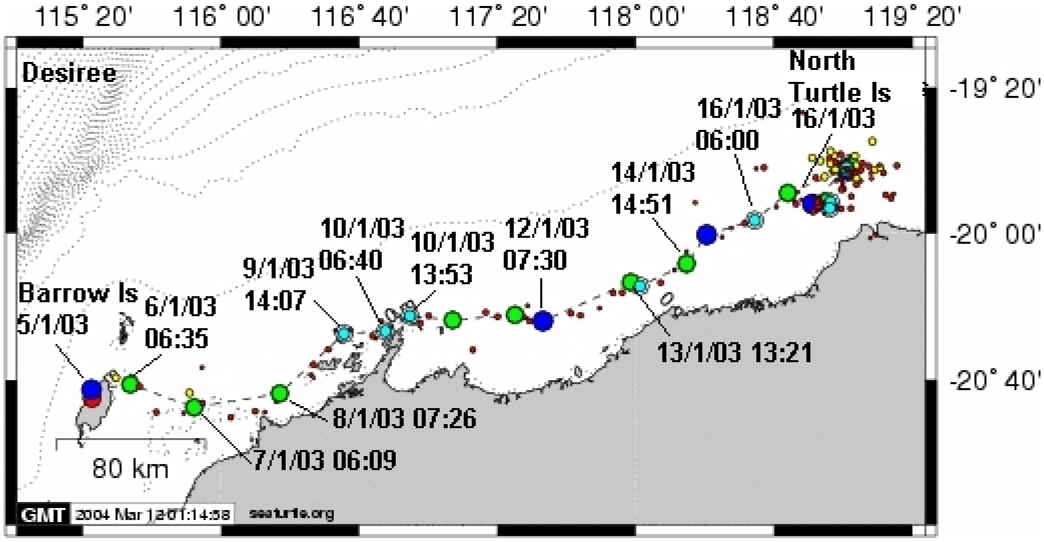

Figure A3.17: Desiree migration pathway and foraging ground.

3.9 KellyB

KellyB was one of 4 turtle tagged at Scott Reef over two consecutive summer periods. She was tagged on Sandy Island at Scott Reef on the 21 October 2002. The behaviour of KellyB is very different to the other 20 turtles tracked during this project. Her tracks fell into two segments, one a large loop around Sandy Island between apparent nesting events 24 days apart followed by a beeline track from Scott Reef to an endpoint at Melville Island (Figure A3.18a).

Within hours of being released KellyB (Figure A3.18b) left Sandy Island and swam west for 100 km before turning south (50 km) and then north east in a large loop around the south of Scott Reef. She tracked along the 200m contour for 3 days (~250 km) before abruptly turning north west for two days and then due south for 4 days. She then turned north west and swam for 3 days before turning south west and back to Sandy Island where she presumably nested.

Two days after returning to Sandy Island KellyB departed in an easterly direction taking a straight line path, across over a 1000 km of ocean and without touching the Kimberley shoreline, to the Clarence Strait south of Melville Island 18 days later. The Clarence Strait is a narrow (20 km wide) channel of water that separates Melville Island from the Northern Territory and joins the Van Diemen Gulf to the east of Darwin with the Beagle Gulf to the west. She passed through the Strait into the Van Diemen Gulf and her endpoint was in the vicinity of Morse Island in the north eastern corner of Van Diemen Gulf. Her transmissions remained centred on this location for 80 days indicating this is her feeding ground.

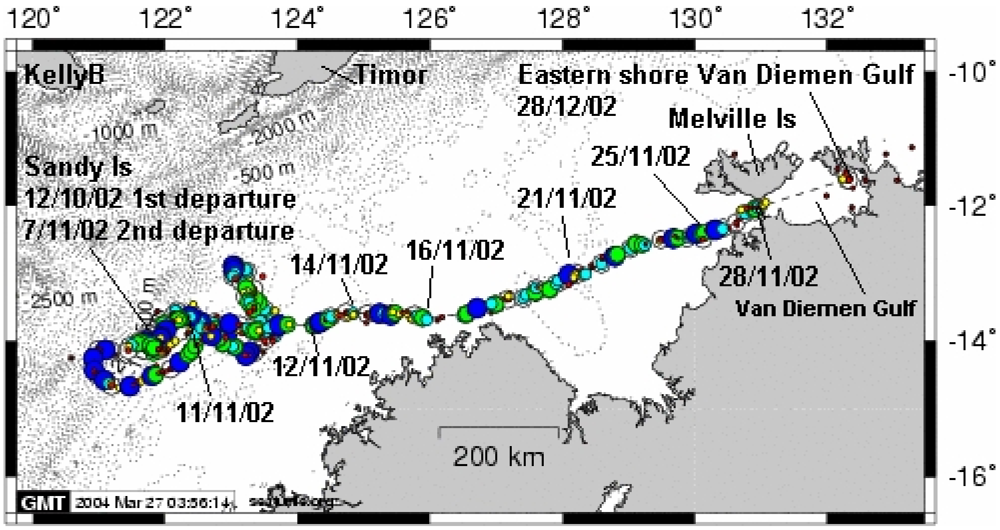

Figure A3.18a: KellyB complete migration pathway

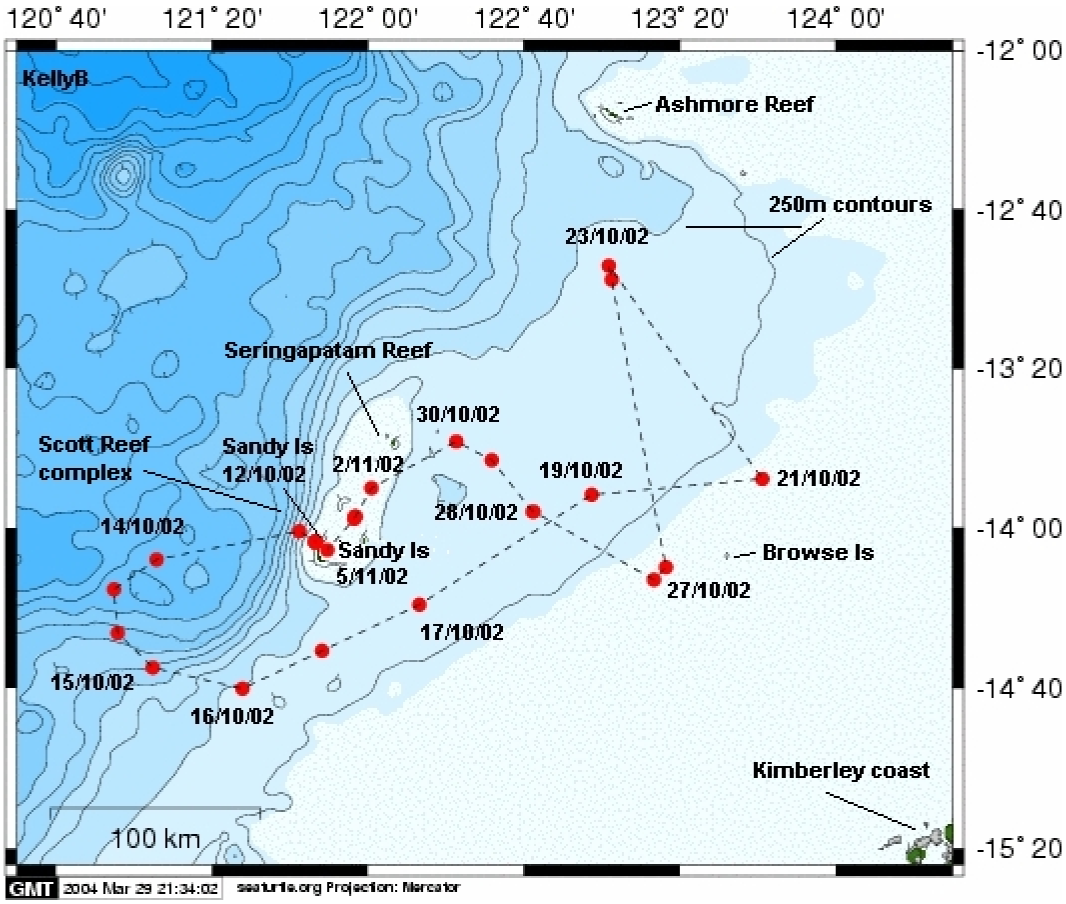

Figure A3.18b: KellyB loop segment of track

3.10 Trouble

Trouble was tagged and released at the same time as KellyB, however she remained in the vicinity of Sandy Island for a further 44 days.

She left Scott Reef on 25 November 2002 and after taking an initial north easterly course she turned south east and swam directly for the Kimberley coast (Figure A3.19a). She arrived at Bigge Island 8 days later on 3 December 2002. She then tracked along the coast for 11 days until she reached Cape Londonderry when she veered away from the coast (Figure A3.19b), swam 500 km across the Joseph Bonaparte Gulf until she reached the her endpoint at Cape Gambier on the southern tip of Melville Island on 9 January 2003. She remained in this area of 56 days. The prolonged presence here is indicative of her feeding ground.

Trouble's complete migratory path cannot be reconstructed as her ptt transmissions ceased temporarily (as programmed) when she was part way across Joseph Bonaparte Gulf.

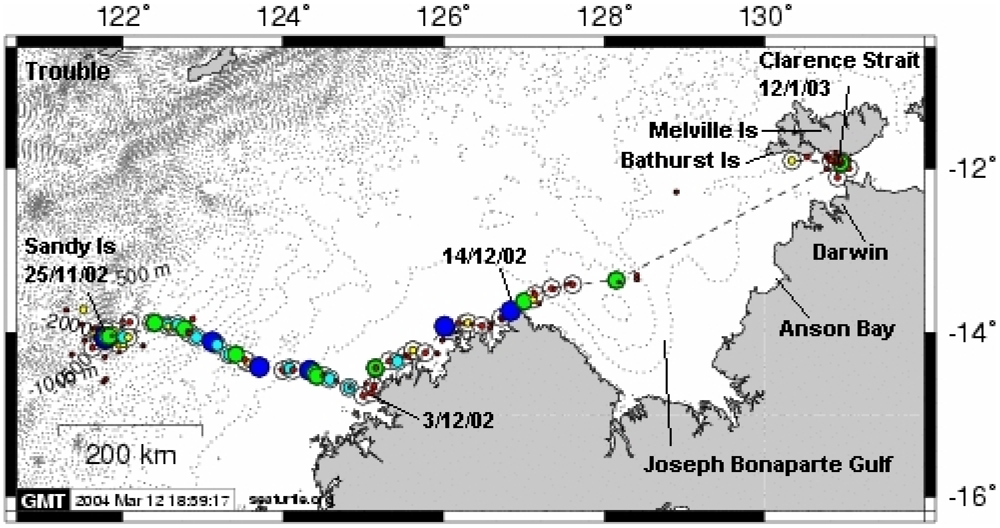

Figure A3.19a: Trouble complete migration pathway

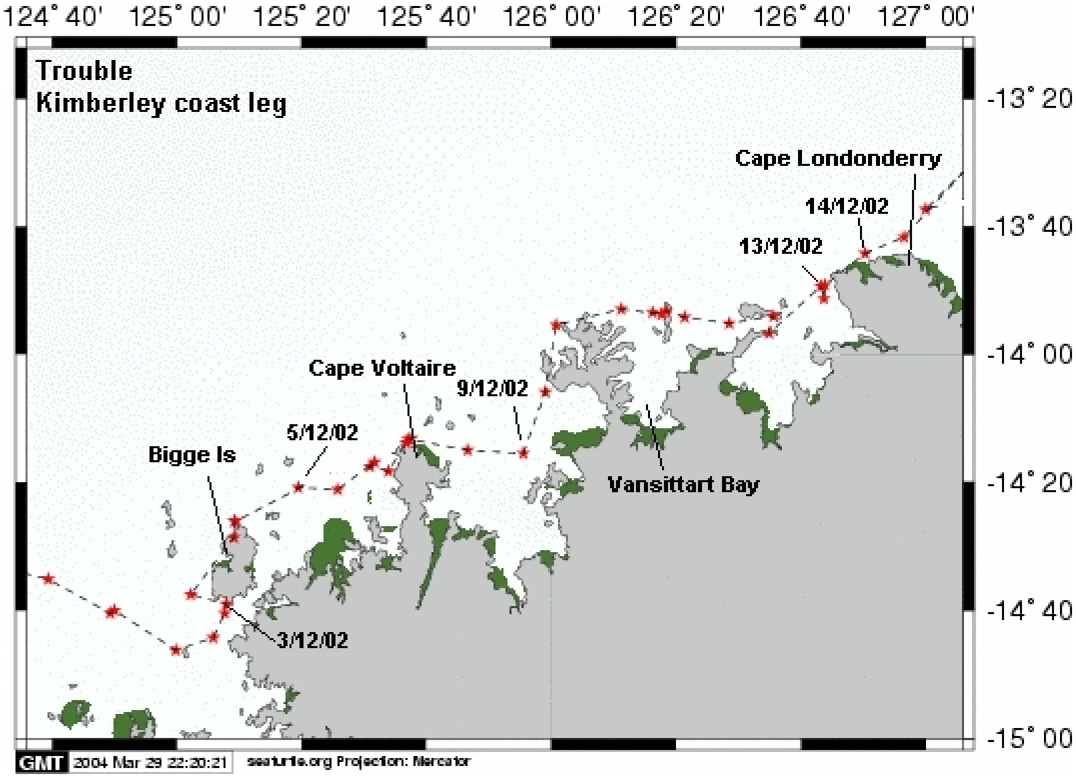

Figure A3.19b: Trouble mid migration path segment along Kimberley coast

3.11 Manari

Manari was the only turtle that visited Sandy Island during the three days I spent at the island in September 2003. She was tagged using the faster 2 part epoxy adhesive and released within 2 hours of capture on the 22 September 2003. Her positions for the two days following release are shown in Figure A3.20. Her transmissions ceased at 23:42 hours the next night on Sandy Island.

This is the first transmitter to cease operating so quickly. Initially I thought it may have fallen off prematurely as a result of the new adhesive being trialled however an alternative possibility is that she was taken by one of the 20+ Indonesian fishing boats present at the reef during this period. The loss of the signal whilst she was on or close to Sandy Island makes this a strong possibility.

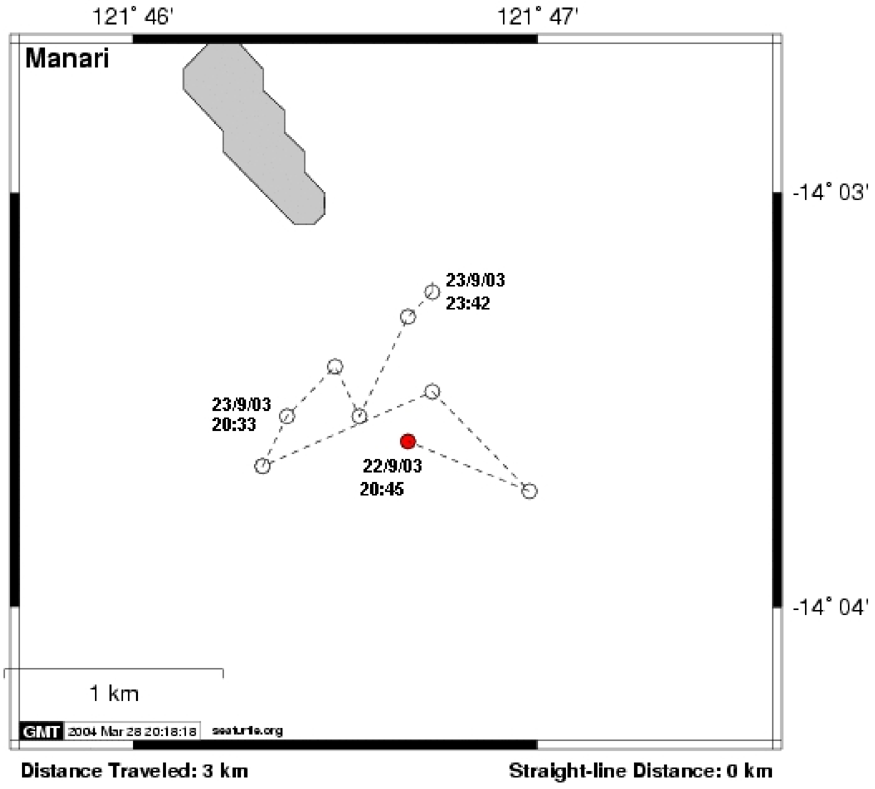

Figure A3.20: Manari partial internesting ground.

3.12 Eden

Eden was the last sea turtle tagged as part of this program and the only animal tagged by someone other than myself. She was captured and tagged on the 5 January 2004 by

Luke Smith (AIMS WA) and Emma Barr during an AIMS field survey at Scott Reef. The 2 part epoxy trailed on Manari was again used. There were no Indonesian fishing boats at the reef at the time as they traditionally do not visit the reef during cyclone season.

Eden remained in the vicinity of Sandy Island for a month. Eden left the reef on 15 February 2004 and swam directly toward the Kimberley coast intersecting it at Cape Voltaire, 60 km north of Trouble's landing point on Bigge Island (Figure A3.21a). Eden tracked closely along the coast in the same manner as Trouble did, however she left the near shore waters sooner at Cape Vansittart and swam directly to Anson Bay in the Northern Territory crossing the 400 km of Joseph Bonaparte Gulf in 6 days. She arrived at Anson Bay on the 5 March 2004, her final transmission was from Bynoe Harbour on 30 April 2004 (Figure A3.21b)

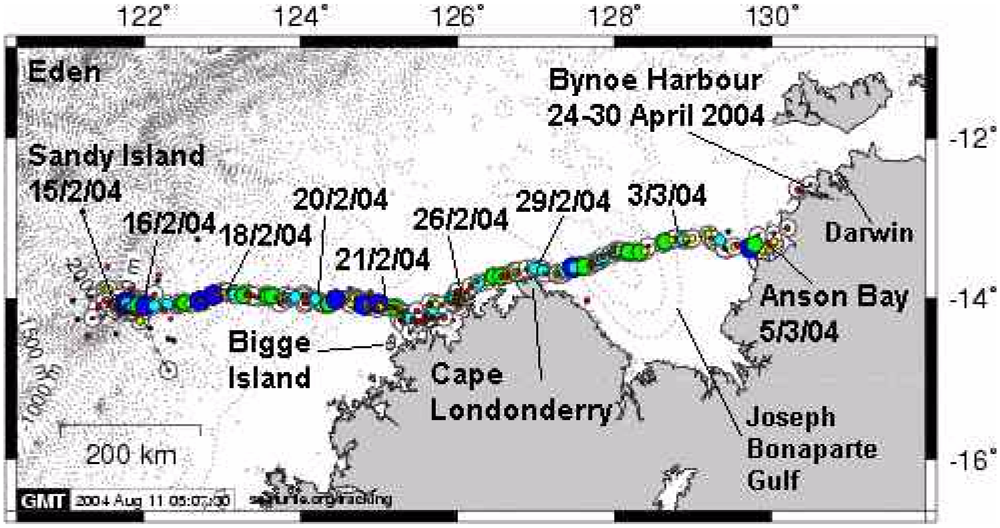

Figure A3.21a: Eden complete migration pathway

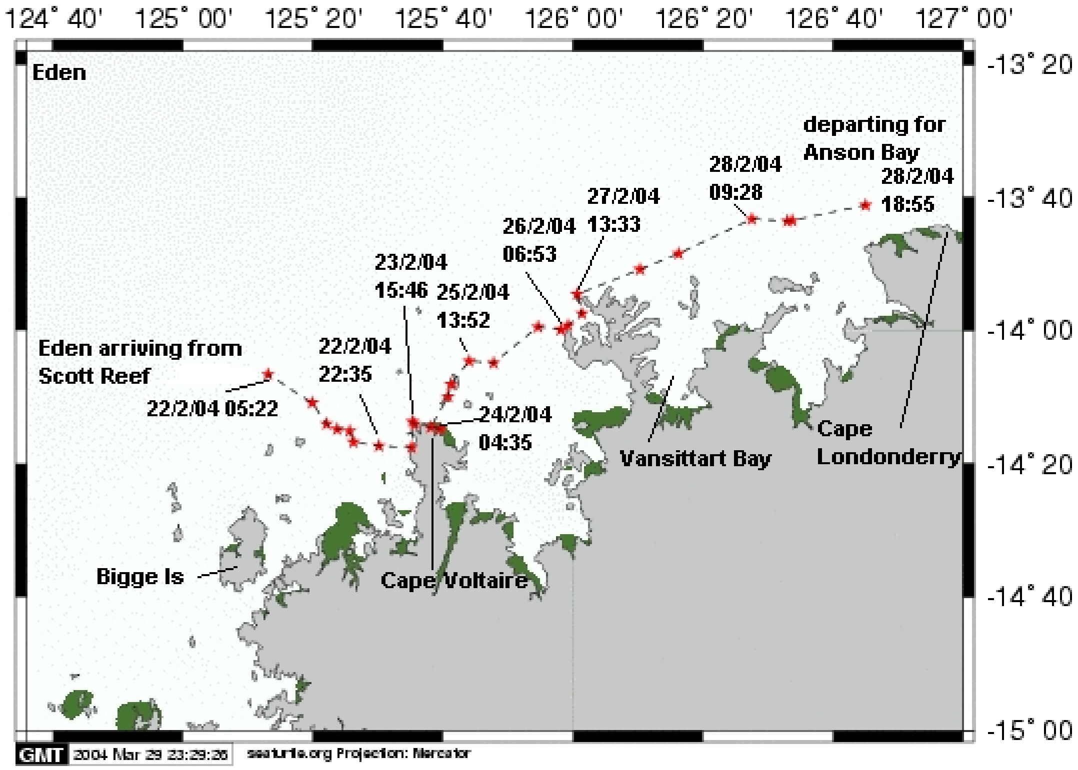

Figure A3.21b: Eden mid migration path segment along Kimberley coast

4 Foraging grounds

The detailed maps of foraging grounds and approximate ranges are shown below

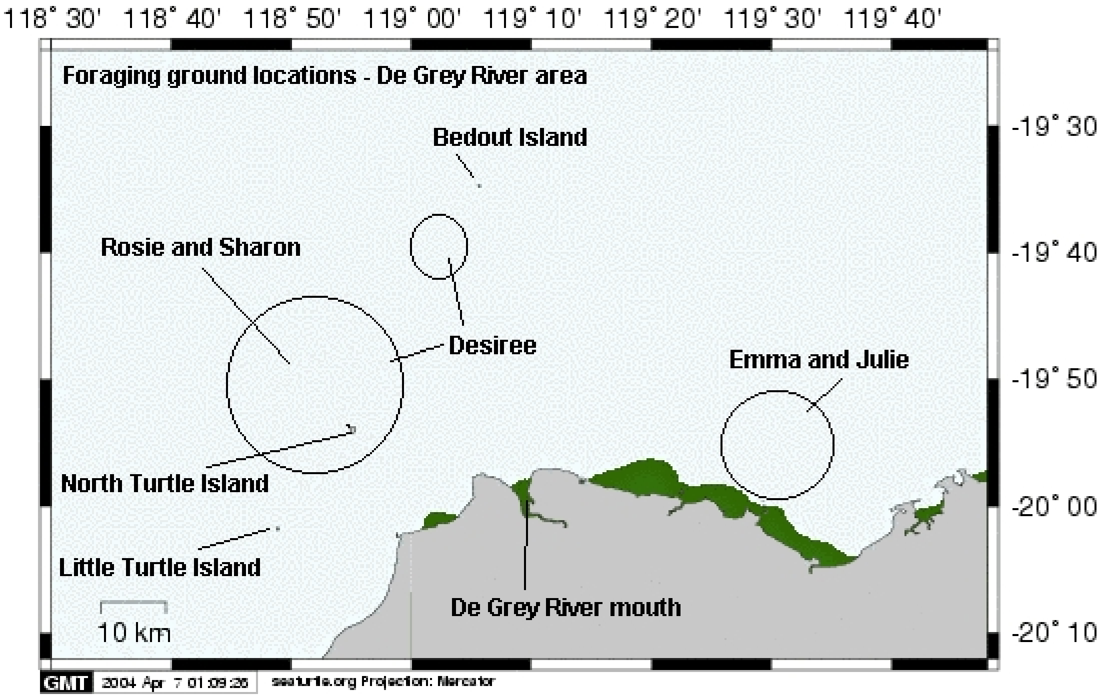

Figure A3.22: De Grey River mouth region foraging grounds for Barrow Island green turtle (Emma, Rosie, Desiree) and Varanus Island hawksbill (Sharon, Julie) turtles.

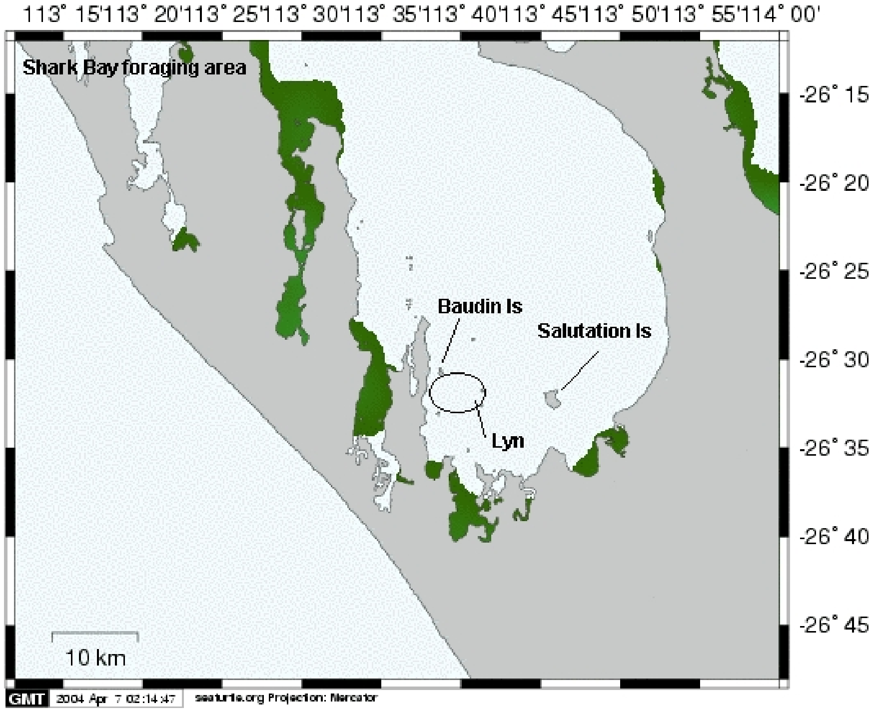

Figure A.3.23: Shark Bay foraging grounds for a Barrow Island green turtle (Lyn).

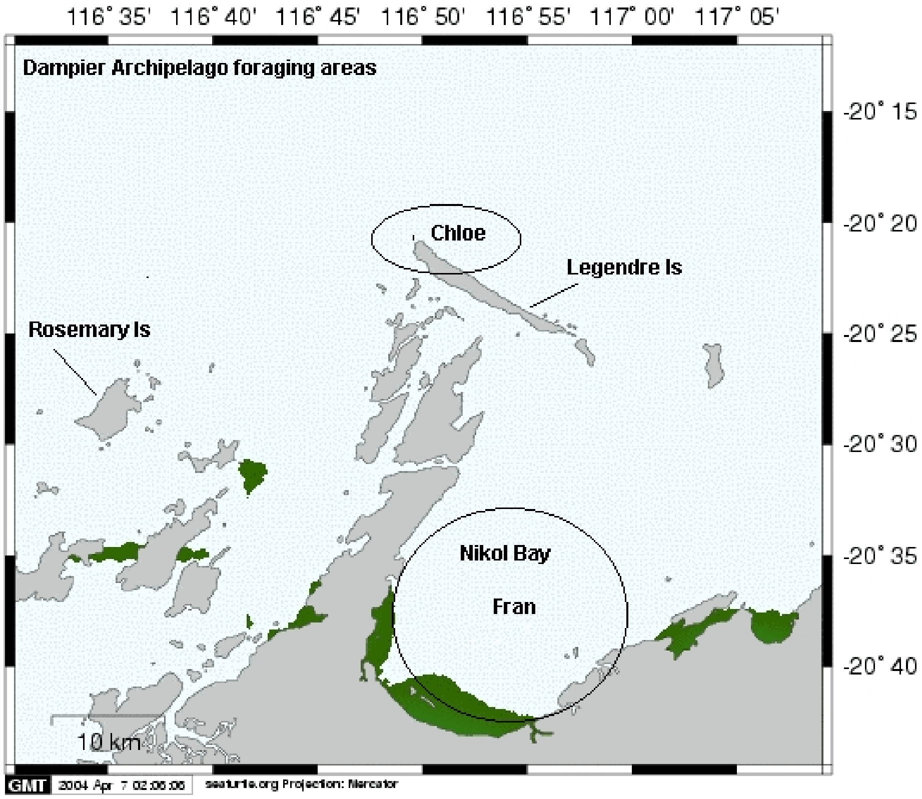

Figure A3.24: Dampier Archipelago foraging grounds for Barrow Island green turtle (Chloe) and Rosemary Island hawksbill (Fran) turtles.

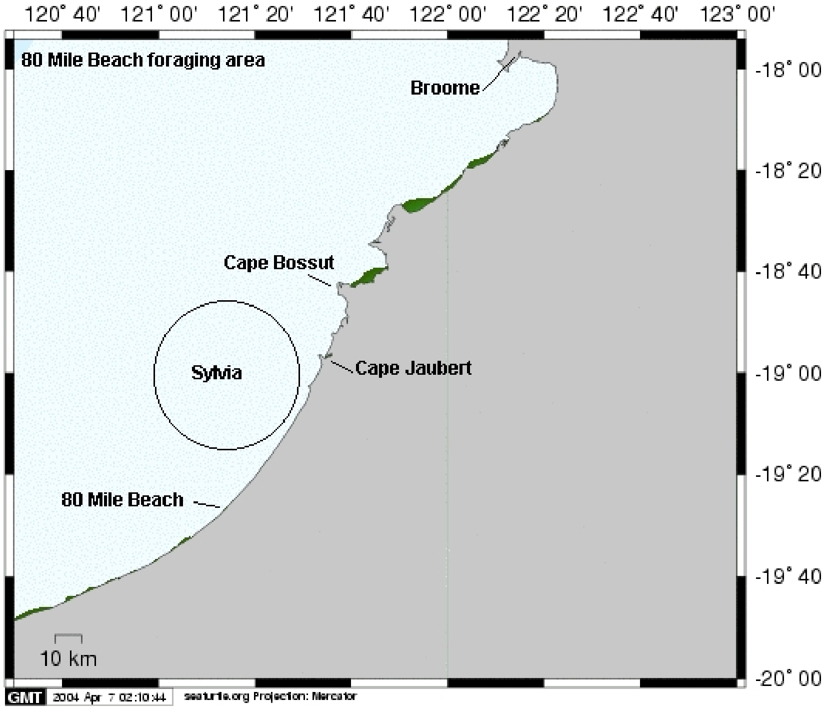

Figure A3.25: Eighty Mile Beach foraging ground for a Barrow Island green turtle (Sylvia).

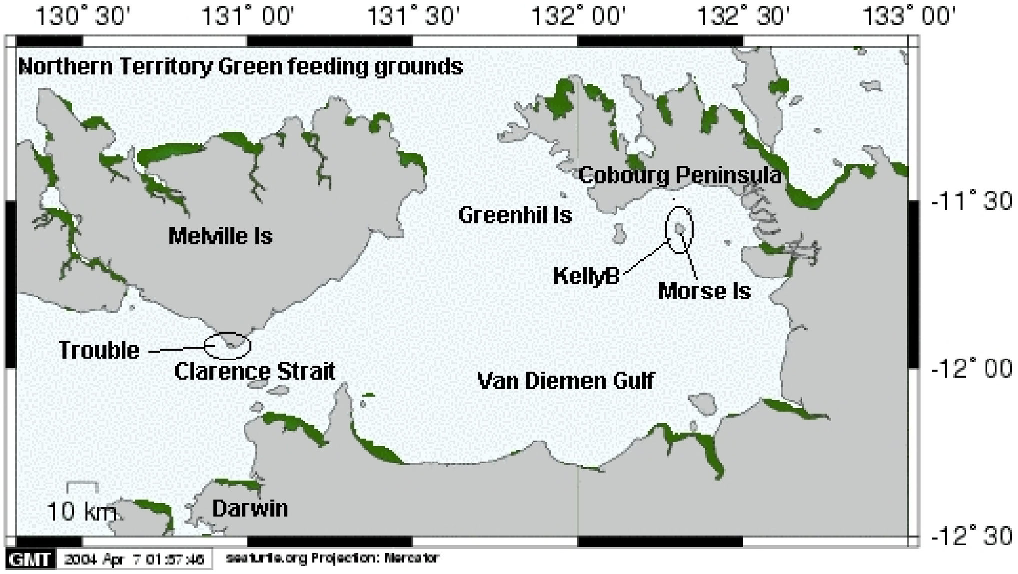

Figure A3.26: Northern Territory foraging grounds for Sandy Island (Scott Reef) green turtles.

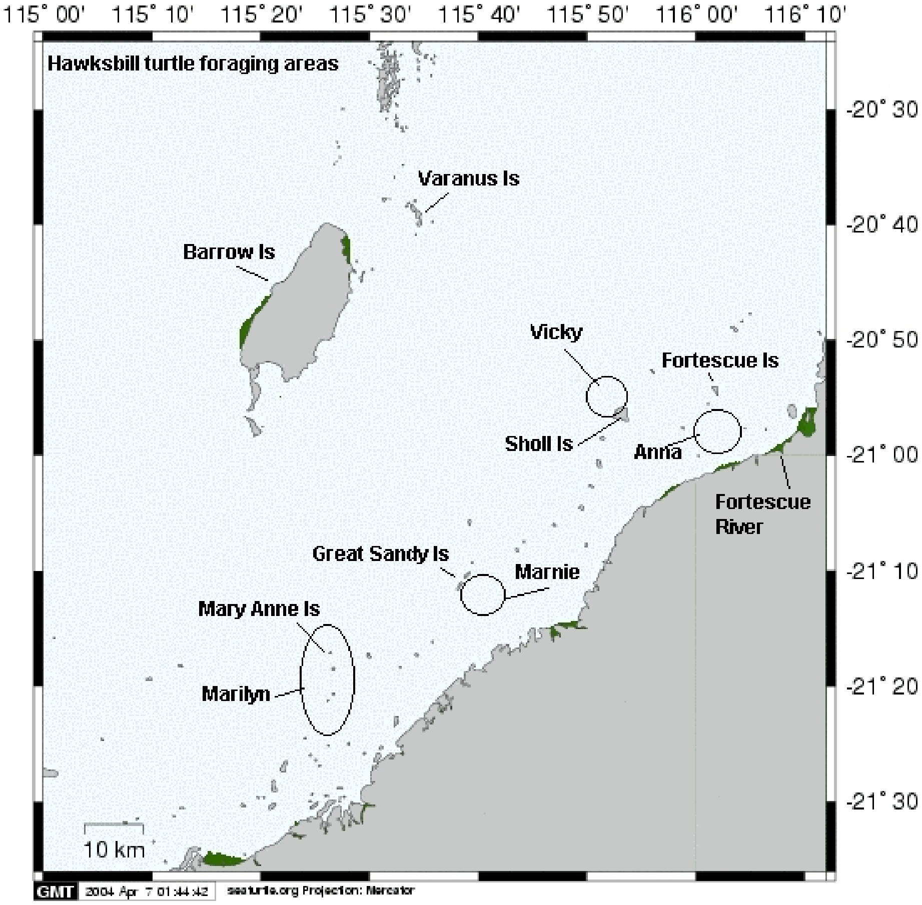

Figure A3.27: Coastal Pilbara Islands foraging grounds for Varanus (Marnie, Marilyn) and Rosemary Island (Vicky, Anna) hawksbill turtles.