NORTH WEST SHELF
JOINT ENVIRONMENTAL
MANAGEMENT STUDY

Review of research and data relevant to marine environmental management of Australia's North West Shelf

NWSJEMS

TECHNICAL REPORT No. 1

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CSIRO

Government of Western Australia
Department of Environment

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ACRONYMS

ACOM	Australian Community Ocean Model
AFMA	Australian Fisheries Management Authority
AFZ	Australian Fishing Zone
AGSO	Australian Geological Survey Organisation now Geoscience Australia
AHC	Australian Heritage Commission
AIMS	Australian Institute of Marine Science
AMSA	Australian Maritime Safety Authority
ANCA	Australian Nature Conservation Agency
ANZECC	Australian and New Zealand Environment and Conservation Council
ANZLIC	Australian and New Zealand Land Information Council
APPEA	Australian Petroleum, Production and Exploration Association
AQIA	Australian Quarantine Inspection Service
ARMCANZ	Agricultural Resources Management council of Australia and New Zealand
ASIC	Australian Seafood Industry Council
ASDD	Australian Spatial Data Directory
CAAB	Codes for Australian Aquatic Biota
CAES	Catch and Effort Statistics
CALM	Department of Conservation and Land Management (WA Government)
CAMBA	China Australia Migratory Birds Agreement
CDF	Common data format
CITIES	Convention on International Trade in Endangered Species
CTD	conductivity-temperature-depth
CMAR	CSIRO Marine and Atmospheric Research
CMR	CSIRO Marine Research
COAG	Council of Australian Governments
ConnIe	Connectivity Interface
CPUE	Catch per unit effort
CSIRO	Commonwealth Science and Industrial Research Organisation
DCA	detrended correspondence analysis
DIC	Dissolved inorganic carbon
DISR	Department of Industry, Science and Resources (Commonwealth)
DEP	Department of Environmental Protection (WA Government)
DOM	Dissolved organic matter
DPIE	Department of Primary Industries and Energy
DRD	Department of Resources Development (WA Government)
EA	Environment Australia
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
EPP	Environmental Protection Policy
ENSO	El Nino Southern Oscillation
EQC	Environmental Quality Criteria (Western Australia)
EQO	Environmental Quality Objective (Western Australia)
ESD	Ecologically Sustainable Development
FRDC	Fisheries Research and Development Corporation
FRMA	Fish Resources Management Act
GA	Geoscience Australia formerly AGSO
GESAMP	Joint Group of Experts on Scientific Aspects of Environmental Protection
GIS	Geographic Information System
ICESD	Intergovernmental Committee on Ecologically Sustainable Development
ICS	International Chamber of Shipping
IOC	International Oceanographic Commission
IGAE	Intergovernmental Agreement on the Environment
ICOMOS	International Council for Monuments and Sites
IMO	International Maritime Organisation

IPCC	Intergovernmental Panel on Climate Change
IUNC	International Union for Conservation of Nature and Natural Resources
IWC	International Whaling Commission
JAMBA	Japan Australian Migratory Birds Agreement
LNG	Liquified natural gas
MarLIN	Marine Laboratories Information Network
MARPOL	International Convention for the Prevention of Pollution from Ships
MECO	Model of Estuaries and Coastal Oceans
MOU	Memorandum of Understanding
MPAs	Marine Protected Areas
MEMS	Marine Environmental Management Study
MSE	Management Strategy Evaluation
NCEP - NCAR	National Centre for Environmental Prediction – National Centre for Atmospheric Research
NEPC	National Environmental Protection Council
NEPM	National Environment Protection Measures
NGOs	Non government organisations
NRSMPA	National Representative System of Marine Protected Areas
NWQMS	National Water Quality Management Strategy
NWS	North West Shelf
NWSJEMS	North West Shelf Joint Environmental Management Study
NWSMEMS	North West Shelf Marine Environmental Management Study
ICIMF	Oil Company International Marine Forum
OCS	Offshore Constitutional Settlement
PFW	Produced formation water
P(SL)A	Petroleum (Submerged Lands) Act
PSU	Practical salinity units
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SOI	Southern Oscillation Index
SMCWS	Southern Metropolitan Coastal Waters Study (Western Australia)
TBT	Tributyl Tin
UNCED	United Nations Conference on Environment and Development
UNCLOS	United Nations Convention of the Law of the Sea
UNEP	United Nations Environment Program
UNESCO	United Nations Environment, Social and Cultural Organisation
UNFCCC	United Nations Framework Convention on Climate Change
WADEP	Western Australian Department of Environmental Protection
WADME	Western Australian Department of Minerals and Energy
WAEPA	Western Australian Environmental Protection Authority
WALIS	Western Australian Land Information System
WAPC	Western Australian Planning Commission
WHC	World Heritage Commission
WOD	World Ocean Database
www	world wide web

TECHNICAL SUMMARY

Structure of this review

The region of interest for this study was Australia's North West Shelf, extending from the inter-tidal zone to the continental shelf break, with particular focus on data relevant to the area between North West Cape and Port Hedland. The principal resource used for identification of existing data and information was the bibliography assembled by Jernakoff et al. (2006).

This document provides an overview of the relevance of existing information to the North West Shelf Marine Environmental Management Study (NWSMEMS). It identifies gaps in knowledge that are likely to be important to the NWSMEMS and makes recommendations for addressing these gaps. The review presents information on the marine environment, grouped into physical, chemical and biological themes. This summary at the beginning of the document presents our major conclusions about the relevance of existing knowledge and about major gaps in information, and our recommendations for future research.

Relevance of existing data to the North West Shelf Marine Environmental Management Study

It is clear that a very large amount of research has been conducted on the North West Shelf and that the volume of information potentially relevant to the NWSMEMS is increasing each year. The information, from diverse private and public sources, has generally been collected to service the needs of particular industries or site-specific activities. It will be a major challenge to access, standardise and integrate this information, so that it provides useful support for management decisions about the marine environment at a range of spatial scales that go beyond individual stakeholder interests. It is likely that the NWSMEMS will need to standardise and integrate the existing datasets, and it should also encourage consensus on a format for future reporting by stakeholders in the region.

The existing data and reports only cover parts of the region: the density and diversity of information are correlated with the accessibility and/or the economic value of particular locations. This bias in information distribution towards locations supporting past and present human activities facilitates short-term environmental management, but the management of regional scale issues and the future expansion of human activities will require additional data and more complex modelling of ecosystem responses to these pressures. For circulation models, gaps in information over distances ranging from a few kilometres to tens of kilometres may not be very important, but similar gaps may significantly hamper our understanding of patterns of biodiversity and temporal variability in the abundance of species. Shallow water marine habitats <20 m deep, such as those around the larger emergent reef and island systems, have been most studied adjacent to towns, petroleum operations or terrestrial park areas. Knowledge of deeper continental shelf waters, particularly areas deeper than 50 m, has been principally derived from research related to fisheries and petroleum. Areas remote from development, and large areas 20 to 50 m deep, are relatively poorly understood. It is clear that, as a first step, the NWSMEMS should apply geographic information system

(GIS) technology to existing data on habitats and infrastructure development, and thereby identify the major areas that lack ecosystem information.

With regard to biological processes, there have been very few detailed long-term studies to provide insight into the intra- and inter-annual dynamics of most organisms. The range of natural variability inherent in the major biological communities of the region remains to be described. In the short term, the NWSMEMS is likely to depend on assumptions based on the limited data from the region for a few major organisms such as some corals and fish and on inference from other tropical ecosystems where the same or similar species occur.

Important physical oceanographic data have provided the basis for continental shelf circulation models that agree well or reasonably well with observed regional scale flows. Existing research programs, both public and privately funded, continue to refine and validate these models at a variety of spatial and temporal scales. The NWSMEMS will be able to incorporate estimates of the seasonal and inter-annual variability of general circulation into management decisions, using the models as a framework.

Our report has relied heavily on the North West Shelf bibliography (Jernakoff et al. 2006) developed for the NWSMEMS. It is the most complete bibliography existing for the North West Shelf, although it is continually developing as more private sector data and reports are included and as unpublished data are identified in the public sector. Our brief review document summarises key information from over 1700 references, and identifies gaps in management tools, knowledge and data, and makes recommendations for further research (in this summary only). With this information, combined with a risk-and-threat analysis and a GIS approach, scientists and managers should be able to rank future research needs for the North West Shelf.

Gaps in management tools, knowledge and data

Management tools and models

There are management plans and compliance requirements for nearly all the activities that involve economic, social or scientific uses of the Pilbara marine and coastal area. Most of these activities require the proponents to produce documents related to environmental management (Environmental Management Programs, Consultative Environmental Reviews, CALM Management Plans, Aquaculture Development Proposals). Self-regulation for compliance is a common practice, and consultants are used extensively for the production of research and monitoring documents. These private sector environmental reports are a valuable source of information about the North West Shelf environment. However, the compliance reporting requirements do not generally stipulate methods or reporting formats. Typically, the relevant government department receives only hard-copy reports containing only summary data. The acquisition, sharing and use of industry-funded data from the North West Shelf would be much more efficient if there were standardised methods and reporting formats, including a requirement for electronic submission.

Notable exceptions to the practice of individual reporting of environmental performance have been wild fisheries operators, who have not been required to document their potential environmental impacts and subsequent environmental management plans before starting their operations. WA Fisheries and CSIRO have assessed the impact of trawl fisheries operating on the continental shelf; the studies find there has been

significant alteration of benthos and fish community structure. If the commercial fisheries should seek to demonstrate conservation and sustainability, both of target and of non-target species, along the lines of the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*, new data of great relevance to the NWSMEMS could become available.

A number of models developed for circulation, wave analysis and particle dispersion on the North West Shelf have been validated over small areas at specific locations. Wave, tide and cyclone modelling has been applied to the engineering of offshore structures and pipelines and to events such as storm surges and their effects on coastal communities. The circulation patterns at Exmouth Gulf (AIMS), the Lowendal Islands (Apache Energy) and the Dampier Archipelago (WA DEP), among other sites, have been modelled at a fine spatial scale. Now the data and uncertainties defined by these models and by more general circulation models, should be integrated into one scalable circulation system for the region.

For its risk management strategy for the North West Shelf, the petroleum industry incorporates circulation-type models into decision support systems. Commercially available decision support systems, such as OILMAP and MUDMAP, are commonly used in the region for oil spills and routine discharges, respectively, and may be readily linked to general circulation models. Additional models have been used to predict cyclone related storm surges. There has been little commercial incentive to integrate models across disciplines — that is, to combine physical, geological, chemical, and biological processes — and no attempt has been made to model ecosystems in the region. The NWSMEMS is likely to provide the impetus for integration of the modelling of ecosystem processes.

Oceanography

Data on currents have been collected from the region since the 1970s. They provide a vast database with which to model circulation. Yet, with the exception of studies focused on internal waves, tides and tropical cyclones, there have been few investigations of general circulation on the North West Shelf. In addition, a strong focus of this work has been on the mid to outer continental shelf and slope, with particular interest in large-scale ocean circulation patterns such as the Leeuwin Current and in the fine-scale extreme phenomena of tropical cyclones. Internal waves and tides feature prominently in the literature on physical oceanography of the North West Shelf because they generate strong, depth-dependent currents, particularly on the outer shelf. The roles of tidal forcing and wind forcing in the nearshore habitats have received less attention, but they may be particularly important for understanding nutrient inputs and for predicting the transport of larvae between shallow water communities.

The water properties and circulation of the North West Shelf are affected by seasonal, inter-annual and decadal-scale variation in the eastern Indian Ocean and the Indonesian Throughflow. The effects need to be clarified at local scale, regional scale and oceanic scale. Inter-annual warming reversals may occur in the Indian Ocean with a frequency similar to that of El Niño in the Pacific. Historical data show that reversals in temperature patterns in the equatorial regions of the Indian Ocean have happened six times in the past 40 years, with no clear link to El Niño. Recent observations suggest that El Niño–Southern Oscillation (ENSO) events in the south-eastern Indian Ocean are correlated with large-scale regional warming. The implications of these inter-annual

variations, for example the potential for impacts on thermally sensitive organisms such as corals, need to be studied further.

A large effort has gone into the modelling of physical oceanic responses to tropical cyclones on the North West Shelf, but the modelling could be further developed so as to include coupled atmosphere–ocean models and an improved atmospheric model of winds. As well, the initial oceanographic conditions could be defined better, and the models' handling of internal mixing could be improved. The region's natural disturbance regime in response to tropical cyclones would be better understood if there existed a complementary GIS of cyclone tracks and the resultant forces (waves and wind) influencing various habitats, particularly shallow water and emergent habitats.

Upwelling and internal wave or tide mixing appear to be important factors in the delivery of nutrients to the mid and outer North West Shelf. There is nutrient enrichment and subsequently enhanced primary and secondary productivity close to the shelf break, but researchers do not know the extent of these influences across the continental shelf. For example, would these types of processes influence the shallow water ecosystems around mid shelf islands such as the Monte Bellos? Circulation models are required, to explain or elucidate the relationship of nearshore and offshore waters and the relative importance of tidal, wind, wave and upwelling forces on mixing, at locations where the shelf width varies greatly, e.g. Ningaloo versus Port Hedland.

A comprehensive bathymetric and sediment distribution database exists within the Australian Geological Survey Organisation (AGSO) and other organisations, but it needs links to biological and circulation models. A general model of sediment dynamics could be developed for the region if there were data that related sediment distribution, benthic habitat and the frequency and intensity of episodic natural disruptions to the habitat.

Toxicology

The total loading of pollutants to the marine environment from industrial and domestic point sources on the North West Shelf cannot be calculated until the WA Department of Environmental Protection (DEP) completes a comprehensive inventory of contaminant inputs. Coastal issues related to domestic waste, such as sewage disposal, have been perceived as less significant in this region than elsewhere because of its low population density.

Recurring pollutants from diffuse sources in the region include heavy metals from antifoulants on shipping, harbour works, shore-based plants and cross-shelf pipelines. Several studies using local invertebrates, such as oysters and intertidal gastropods, have detected elevated levels of some metals. A broader range of local animal and plant species will need to be used before ecological impacts can be inferred from toxicology testing.

Significant dredging activity occurs in the region, particularly in the major ports Dampier and Port Hedland. During dredging operations, suspended sediment concentrations are very high for sustained periods. Monitoring suggests that the impact on existing adjacent macro-benthos communities is minimal, but there are no data to show the effects of suspended sediment on very small organisms and on new recruits such as juvenile corals.

When synthetic olefin- and ester-based drilling muds are adopted for exploration purposes their effects will need to be studied, particularly in more sensitive areas. Little is known about the transport of cuttings on the North West Shelf or about the implications for dispersion and degradation of the fluids.

We do not fully understand the effects of aromatic components of the Produced Formation Water (PFW) plume on the water column, and the fate of these compounds in the sea surface microlayer, given the high possibility of photo-oxidation. The volume of PFW released will increase with the number and age of drilling platforms on the North West Shelf. The fate and effects (if any) of the components other than hydrocarbons, including added chemicals such as corrosion inhibitors, must be studied.

There are some data that assess the acute toxicity of potential pollutants such as PFW and heavy metals, but the environment's capacity to incorporate these loads is unknown. Research will be required to determine the effects of chronic, low-level pollution loads on the North West Shelf.

Plankton and nutrients

The major phyto- and zooplankton groups have been described, but little is known of microbial plankton communities. There has been only minimal sampling of the plankton communities, across multiple seasons and at fine scale, to detect spatial and temporal variation in their abundance and diversity.

Very rapid cycling of nutrients can occur in phytoplankton communities on the North West Shelf, and bacteria also have rapid carbon metabolism. Few data assess the trophic links between the plankton and the benthos. So far, the major source of nutrients that has been identified for the North West Shelf is related to the mixing and upwelling of deeper offshore waters, near the shelf break. Upwelling on the North West Shelf is unusual because it may not show on the surface. There is some evidence that enriched water masses move from the shelf break into the water at 50 m depth, but their influence on ecosystems across the shelf is not well understood.

It will take much more work on the nutrient cycle to determine the relative importance of alternative processes. The availability of nutrients may be strongly influenced by tidally-forced mixing or cyclone-forced mixing. In addition, nitrogen-fixing microbes such as the planktonic bloom-forming *Trichodesmium* or the mangrove mud-flat cyanobacteria may contribute nutrients.

A key aspect of coastal ecology that warrants further investigation relates to nutrient input and trophic links in the nearshore environment. The roles of tidal flushing or mixing, and of inputs from the supra- and intertidal zones, need to be studied. The region is in the arid tropics and it has not been proved that its coastal eco-chemistry and ecology function in the same way as those of the wet tropics, where mangroves have a major role.

Fish and fisheries

Good taxonomic information exists for the piscine fauna of the North West Shelf region, but there are limited studies providing ecological information on the nearshore and intertidal fish communities. There are large gaps in our understanding of the life history and population dynamics of numerous fish and invertebrate species throughout the region.

Benthic trawling appears to be the major human activity affecting large epibenthic organisms on the mid- and outer areas of the continental shelf. In this region we know little about the regeneration rates of the epibenthos and the interactions of fish populations with the benthic fauna. Many useful data are held by CSIRO and WA Fisheries, but to help us understand the dynamic processes that maintain benthic communities it is likely that a sustained sampling regime, more intensive than current efforts, will be necessary. WA Fisheries collates commercial data and undertakes its own research, but it focuses on a limited number of commercial scalefish species; this may be a missed opportunity to better characterise the biodiversity of the continental shelf.

Recreational fishing effort has not been quantified, but is likely to have a significant effect in areas surrounding regional towns. The Dampier Archipelago is primarily a recreational fishing area, with the highest per capita boat ownership in Australia. Anecdotal evidence indicates that stocks of demersal fish have been greatly depleted over the last two decades in this area. Resource conflicts exist in this region between commercial fishing, aquaculture and recreational fishing.

There are few studies of fish ecology, apart from the significant fisheries data of CSIRO and WA Fisheries, and they tend to be short-term. At present, AIMS is running a fish project focused on seasonal recruitment and productivity across the shelf, which will provide insights into the ecosystem dynamics of early stages in life cycles. It is likely that very useful further data can be extracted from the existing sampling collections of WA Fisheries and CSIRO. If we knew the full extent of these collections we could evaluate their potential to improve our knowledge of fish ecology on the North West Shelf.

Mangroves

The mainland coast has a thin fringe of mangroves, flanked by intertidal and supra-tidal sand and mudflats, broken periodically by rocky headlands and beaches. The diversity of the mangrove tree communities is diminished (five species) relative to the wet tropics, but can be structurally complex in some areas of the mainland. Lesser mangrove systems occur around the numerous islands such as the Monte Bello–Lowendal–Barrow group.

The coastal mangroves are the only closed canopy forest in the region and therefore they provide a major habitat type for birds and marine organisms, although the ecology of many species associated with the mangroves remains to be investigated.

The Pilbara mangroves are scientifically important because they are key examples of arid zone mangle. Gaps exist in our understanding of the physiology of these mangroves in response to high temperatures and salinities and of their sensitivities to various human pressures.

The ecological role of these mangroves in the coastal ecosystem is poorly understood in comparison to wet tropic mangroves. It is presumed, based on wet tropics data that they are important, but some data suggest that they differ and may be less effective than wet tropics mangroves as nursery areas, for example. Theories that mangroves have a role in supporting secondary coastal production on the Pilbara are often assumptions transferred from studies of mangrove forests elsewhere in the wet tropics, and may be misleading because of the arid nature of the region. More studies are required of the biological and chemical processes in the Pilbara mangroves and their adjacent sub and supra-tidal mudflats.

Biodiversity

Species richness is the aspect of biodiversity best documented for the North West Shelf, but there is little information on spatial patterning. A majority of species are likely to be panmictic, but there is evidence of endemism in several benthic invertebrate groups in the region, although the spatial scales involved are not always known. The range of genetic information is very limited. For most species we do not know how much interconnection there is between similar habitats throughout the region and at what spatial scales.

On the deeper mid- and outer continental shelf a major source of data about species richness has been the fisheries-related research programs of CSIRO and WA Fisheries on the major trawling grounds seaward of the 50 m isobath. Data from historical and ongoing fisheries studies could be used in a broader, landscape-ecology approach to better describe the benthic and demersal communities on the shelf. This is one area where broadscale rapid assessment technologies would deliver useful information if they were developed.

Benthos

Cyclones, particularly the patterns of disturbance and the return frequency of impacts on individual coral reefs, mangroves and other shallow water habitats, are likely to be a major agent of change for benthic communities on the North West Shelf. Models of disturbance and recovery intervals could be developed and tested for the region to allow comparison with Australia's tropical east coast where there are better long-term monitoring data for benthic habitats. The Bureau of Meteorology maintains a database on tropical cyclones which includes detailed satellite data since 1970, reliable ground data since 1960 and less reliable, but often useful, information on storms since 1939.

Given the size of the region, rapid survey tools would be a great help in the mapping of benthic habitats. For example, with acoustic survey techniques, the distribution and associations of bottom types and habitat and biodiversity can be inferred. Further research would be required to validate and fully characterise such proxies for habitat and biodiversity. Light can penetrate to the seafloor over large areas of the North West Shelf where the sediments are unconsolidated. Mapping of the distribution of light-influenced seafloor, whether rock or unconsolidated sediments, would be a first step in assessing the potential importance of benthic primary production around reefs, between reefs and in the broad shelf zones.

Little is known about the growth rates of sessile benthos and the time needed for recovery after natural or human-induced disturbance of benthic habitats. CSIRO and WA Fisheries have made some observations from shelf trawling and benthic video data at 50 to 200 m depth, while AIMS and other research groups are gathering this type of data from shallow water areas <30 m deep. At present, the resilience to disturbance and probable recovery times of benthic communities can only be modelled in very general terms for a few taxa on the North West Shelf.

Macro-algae are poorly described in general, but are an obvious major component of some habitats, with large seasonal fluctuations in biomass. Spatial data on abundance, diversity and population dynamics of dominant species are generally lacking.

For the key organisms, we know little about the timing of potentially sensitive life cycle phases, with a few exceptions. For most organisms and locations, we can only infer

patterns of supply of larvae for recruitment because there have been no long-term studies that sample frequently enough to detect seasonal patterns in recruitment. Studies similar to those by AIMS for fish and corals are required. The population dynamics of most organisms have not been investigated or verified with regionally based studies. In general, the processes of renewal following a disturbance can only be inferred from data for similar species elsewhere.

Microbial ecology

Microbial ecology in pelagic, benthic, intertidal and supra-tidal habitats is poorly described. A few papers suggest that planktonic bacteria are very important in carbon cycling and that the bacteria of the mudflats may be a major source of nutrients to the inshore ecosystem.

Birds, turtles and cetaceans

Seabirds, turtles and whale species subject to international agreements occur through the State and Commonwealth waters in the region.

Many waders and seabirds use the islands for nesting. Some data show large foraging ranges for species such as shearwaters, but for most seabirds their place in the food chain and in the region's general ecology are not well described. Petroleum companies have useful data on seabirds and Murdoch University maintains an unpublished database on them.

The Pilbara coast and islands provide major nesting grounds for loggerhead, green, flatback and hawksbill turtles. The residence times, local ecology and migration patterns of these animals are not well understood.

Three species of baleen whale and six species of toothed whale are reported from the region. Of these the Group IV humpbacks in particular are of international significance. For the humpbacks, the general seasonality and patterns of migration have been described, but more needs to be known of their movements, residence times and ecology in the region.

Cave fauna

A stygofauna of world significance exists in the limestone of Cape Range near North West Cape and may extend, in varying degrees, through some of the offshore islands in the region. The extent, composition and sensitivities of this fauna require further elaboration.

Recommendations for future work

The NWSMEMS should establish procedures and agreements for the exchange of data between the major custodians of data in the public and private sectors. In the process there may be the opportunity to promote standardisation of data platforms and reporting formats between all industries and government departments active in the region.

A comprehensive GIS for the North West Shelf should be developed. This information system should be capable of managing all major existing data and should also form the key repository for future data derived from the NWSMEMS and other sources in the region.

Once a GIS has been set up to incorporate existing habitat data, a new program of habitat studies should be supported, to work on areas that have been missed before.

The NWSMEMS may benefit from the acquisition or development of computer-based models that will provide decision support, in particular:

- models that estimate circulation at a variety of spatial scales. Finerscale modelling and validation have already been undertaken by other organisations at several locations. These should be integrated into a general circulation model. The circulation models should be capable of describing key phenomena of importance to management, such as the principal vectors in contaminant dispersal or during the major spawning seasons of key organisms, so that NWSMEMS can gain a holistic appreciation of patterns operating in the region;
- models that integrate existing databases of sedimentary and bathymetric data and can be used to predict sediment transport. To calibrate and verify the models, the frequency, rate, and direction of sediment transport (for natural sediments, drill cuttings, and dredged material) should be measured at key sites;
- models that incorporate existing knowledge on the population dynamics and temporal and spatial variability of key species, so that their responses to natural and human disturbances can be predicted;
- models that integrate the available data on sedimentary environments, benthic habitat, and fish ecology; and
- models that incorporate data about existing and proposed pressures throughout the region, so that scalable sensitivity analyses can be made for major habitats and key species.

The NWSMEMS should support the collection and analysis of data on biodiversity for this region. There are gaps in the spatial information about species richness on the North West Shelf that need filling. The GIS should incorporate details of collection locations and lists of taxa, derived from field programs such as those of the WA Museum, AIMS and CSIRO. The diversity and distribution of the stygofauna and the local ecology of the birds, turtles and whales need to be described.

Existing research programs on fisheries provide an opportunity for the acquisition of general data about biodiversity. The NWSMEMS should consider accelerating the processing and analysis of data collected by WA Fisheries and CSIRO in the 50 to 200 m trawl zone of the continental shelf. These sample collections may contribute valuable information on habitat distribution, reproductive seasonality of fish species and benthic dynamics. It would be useful if there were collaboration in future in field programs to collect data on species that are not fishing targets.

The NWSMEMS should support the development of appropriate performance indicators of environmental management. For example, suitable bio-indicators need to be identified for acute and chronic toxicology studies.

There should be more research into nutrient delivery and cycling in the mid–outer shelf and in nearshore environments. Upwelling and tidal mixing appear to be important for nutrient supply on the mid- to outer continental shelf but their extent, seasonality and significance may vary from place to place. Processes at the shelf edge may be more or less important to the nearshore habitats according to the width of the shelf, e.g. north or south of the Monte Bello Islands. In the nearshore environment the nutrient cycle and its

links to microbial activity on tidal flats and mangroves are not fully understood. Across the shelf we need to clarify the role of the planktonic, bloom-forming *Trichodesmium* in the nutrient cycle.

More detailed data could fill in our knowledge of the dynamic processes supporting primary and secondary productivity. The NWSMEMS should consider accelerating the processing and analysis of AIMS data derived from intensive fine-scale surveys of primary and secondary productivity in the North West Cape region.

Tropical cyclones are a recurring feature of the region. The scale, spatial distribution and return frequency of effects related to cyclones need to be described, across the North West Shelf.

1. INTRODUCTION

1.1 Background

The Western Australian (WA) Department of Environmental Protection (DEP) has initiated a North West Shelf Marine Environmental Management Study (NWSMEMS). Broadly, the goals of the study are to provide information that will support:

- ecologically sustainable development of marine-related industries;
- the conservation and reservation of representative marine ecosystems; and
- the management of multiple uses.

Specifically, the study has two aims. The first is to ensure that adequate environmental data, improved scientific understanding, and predictive capabilities are available to support sound environmental planning, management and decision-making on the North West Shelf, both in the private and in the public sectors. The second is to ease the implementation (in consultation with stakeholders and the community) of more effective and efficient environmental management frameworks, under existing statutory arrangements.

This report, commissioned by the DEP as a component of the NWSMEMS, is a compilation and overview of scientific research and data related to the North West Shelf marine environment. In it, we discuss aspects of North West Shelf marine research, list sources of data, provide critical assessment of the existing knowledge and understanding of marine environmental systems on the North West Shelf, and identify gaps in that knowledge. The report identifies research opportunities that we believe will provide the information or capabilities needed to accomplish the goals of the NWSMEMS and manage the marine environment on the North West Shelf.

The region of interest for this review lies between North West Cape and Port Hedland, and extends from the inter-tidal and nearshore zones to the shelf break which generally occurs near the 200 m depth contour (figure 1). Most of this area lies within the Pilbara region, where significant resource development and exploitation is most active, more so than the IMCRA-defined North West Shelf region which comprises adjacent waters extending seaward and northward from Port Hedland.

1.2 Methods

Our review focuses almost exclusively on information identified in the bibliography recently compiled by Jernakoff et al. (2006) for the DEP as part of the NWSMEMS. The bibliography was compiled using on-line literature searches, review of citations in literature, and discussions with scientists, data managers and librarians at AGSO, APPEA, BHP Petroleum, CALM, CSIRO, Curtin University, Fugro Survey Pty Ltd, Gorgon Australia LNG, Hamersley Iron, Land Corp, Mobil, Murdoch University, the Museum of Western Australia, Pendoley Environmental, the University of Sydney, Water and Rivers Commission, West Australia Petroleum Pty Ltd (WAPET), Western Australian Fisheries, Western Australian Research Laboratories, WNI, Woodside Offshore Petroleum, and the WA departments of Minerals and Energy (DME), Land Adminstration (DOLA), Resources Development (DRD), and Transport (DOT). The bibliography contains more than 1700 references found in public and corporate

libraries, but it is still incomplete because there are hundreds of reports and manuscripts that are not publicly available. Nonetheless, it characterises the marine research that has been conducted on the North West Shelf, and it can be used to identify gaps in the scientific knowledge and understanding needed to manage the marine environment.

Figure 1: Location map for the Study area.

2. MARINE ENVIRONMENTAL RESEARCH ON THE NORTH WEST SHELF

The diverse marine environmental data available for the North West Shelf are a consequence of the history of development and scientific research in the region. In most instances, development pressures spawned research designed to evaluate the economic or technical feasibility, or the environmental consequences, of specific projects. The impetus of oil and gas exploration and development is clear in figure 2: many of the citations found relate to this industry.

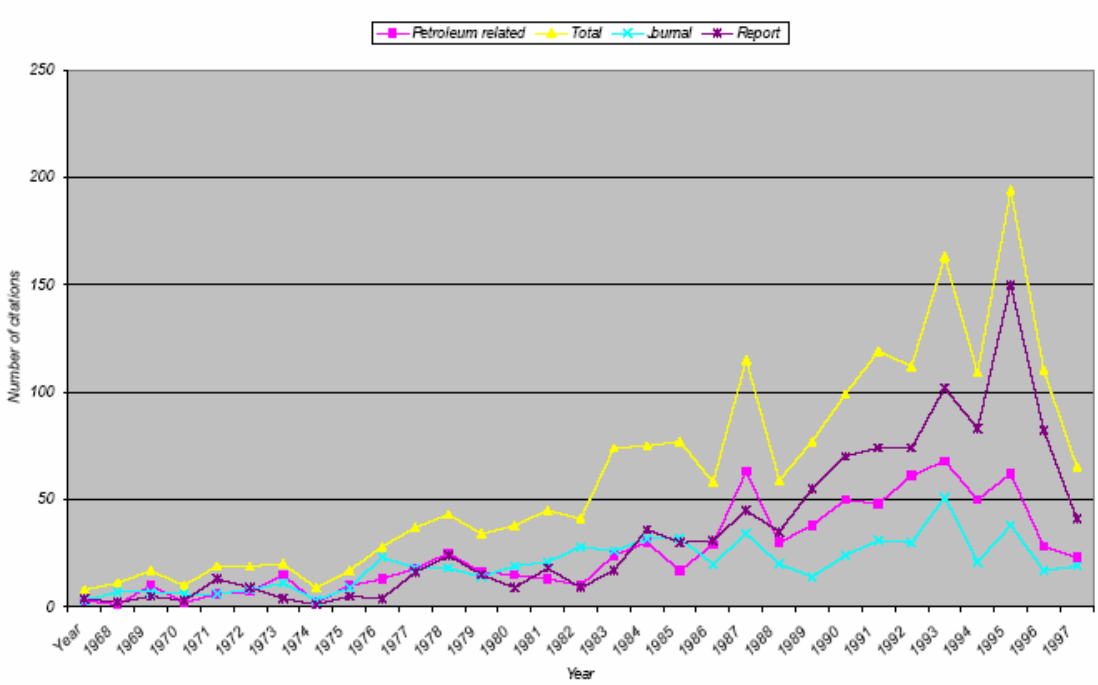

Figure 2: Annual numbers of citations since 1968, according to category, in the NWSMEMS bibliography by Jernakoff et al. (2006).

2.1 Literature reviews and compilations

There have been several reviews and compilations of data relevant to marine environmental management on the North West Shelf. Compilations and reviews of marine management were made by Burbidge (1989) and Donaldson et al. (1995). Pearce (1983) provided one of the first comprehensive reviews of the physical oceanography and meteorology of Western Australia, with emphasis on regional oceanography and the Leeuwin Current. Harris et al. (1991b) compiled a bibliography of (mostly published) physical marine sciences, and Church and Craig (1998) summarised the regional oceanography of Australian shelf seas and included a valuable reference list. Buchan and Stroud (1993) compiled a concise and pragmatic review of physical oceanography on the North West Shelf and in the Timor Sea. Their summary describes general oceanographic conditions (winds, waves, and currents) on the North West Shelf and reviews efforts made towards numerical modelling of cyclones, oil spill trajectories, internal tides, wastewater dispersion, and regional scale oceanography. Notably, their summary gives examples of data archived by WNI from studies

performed on the North West Shelf. Hamilton (1997a) describes sources of wave data for the whole of Australia, including the North West Shelf.

A large collection of papers describing the subsurface geology of the North West Shelf appear in a special edition of the AGSO Journal (Exon, 1994) and in the Proceedings of the North West Shelf Symposium (Purcell & Purcell, 1988). A general review of bottom sediments appears as a chapter in Harris et al. 1991a.

Crossland and Wells (1985) developed a bibliography of marine and estuarine studies for the whole of Western Australia. Jones (1986) catalogued marine resources of Western Australia; and the so-called Wilson Report (Marine Parks and Reserves Selection Working Group, 1994) describes the distribution and extent of marine habitats. Site-specific literature surveys of marine resources and habitats include those for the Monte Bello and the Lowendal Islands by Deegan (1992a,b) and Berry (1993), the assessment of marine resources at Barrow Island by WAPET (LeProvost Environmental Consultants, 1991), and several assessments for the Dampier Archipelago (Burbidge & Prince, 1972; Chittleborough, 1981; Semeniuk et al. 1982).

Fish of the North West Shelf are described by Allen and Swainston (1988). The history of biological and management issues pertaining to particular fisheries is dealt with by several authors and remains highly relevant. For the trawl fisheries of the region, see Sainsbury (1988), Jernakoff and Sainsbury (1990) and Moran et al. (1995); for overviews of specific fisheries such as Exmouth Gulf prawn trawling, see Penn and Caputi (1986); for the Pilbara line and trap fisheries see Moran et al. (1988) and Looby (1997), and for a general review of North West Shelf fisheries see Camkin (1992). A recent national review of fisheries habitat (Cappo et al. 1998) gives a broad view of the region's major habitat zones and follows the lead of Wilson et al. (Marine Parks and Reserves Selection Working Group, 1994) in differentiating between a distinct shallow water nearshore habitat (<10 m deep) and the deeper shelf waters. WA Fisheries maintains extensive data on fisheries for the region and summaries are published as State of the Fisheries annual reports. More detailed information is compiled annually in the WA Fisheries Research reports, but these are confidential to that department. Aquaculture in the region is dominated by the pearling industry, which has recently completed a review of its environmental practices. General aquaculture activities and opportunities have been reviewed (Makaira Pty Ltd & Ecologia Environmental Consultants, 1997) in a report to WA Fisheries.

The shallow water habitats have been broadly reviewed (Marine Parks and Reserves Selection Working Group, 1994; Bowman Bishaw Gorham, 1995a,b). More detailed descriptive information is available about important nearshore and island locations such as the Monte Bello Islands region (Deegan, 1992b; Wells et al. 1993; Berry, 1993; Mobil Exploration & Producing Australia Pty Ltd, 1994; V. & C. Semeniuk Research Group, 1995; Sinclair Knight Merz, 1996; The Ecology Lab Pty Ltd, 1997) and the Dampier Archipelago (Hutchins et al. 1978; Marsh, 1978; Aboriginal Sites Department, 1979; Meagher & LeProvost, 1979; Semeniuk & Wurm, 1982; Chittleborough, 1983; Simpson, 1988). Lord et al. (1998) examine seagrass habitats and reclamation projects for the whole of Australia, Creagh (1985) discusses the blue–green algae literature and Semeniuk (1983) and Carr et al. (1996a,b,c) review the distribution and ecology of mangrove habitats in the Pilbara. The number of process-related studies is limited, nonetheless, and comprehensive review of ecosystem ecology for the region is lacking.

Environmental effects of oil and gas development have been summarised by Swan et al. (1994), and Jones (1986a) specifically discusses impacts on marine organisms. APPEA is compiling a comprehensive electronic database of recent and on-going marine research projects undertaken on the North West Shelf by the petroleum industry (P. Cochrane, pers. comm.), which should be available during 1999. It is hoped that this database will promote awareness of the extensive environmental data holdings of the industry, and facilitate access to them.

3. PHYSICAL OCEANOGRAPHY OF THE NORTH WEST SHELF

3.1 Leeuwin Current and the Indonesian Throughflow

A significant fraction of the research into physical oceanography in the region has been related to the Leeuwin Current and the Indonesian Throughflow. The Leeuwin Current is a warm surface current that flows from the tropics to the waters of southern Western Australia. It is unusual because it is both narrow (~50 km wide) and strong (1 to 3 knots), whereas currents on the western sides of all other continents are broad and weak (Pearce & Cresswell, 1985). Investigations into the Leeuwin Current have resulted in numerous publications (Hall, 1972; Andrews, 1977; Rochford, 1977; Golding & Symonds, 1978; Cresswell & Golding, 1980; Andrews, 1983; Thompson & Cresswell, 1983; Thompson, 1984; Godfrey & Ridgway, 1985; Griffiths & Pearce, 1985; Holloway & Nye, 1985; Lynch et al. 1986; Borland et al. 1988; Pearce & Phillips, 1988; Weaver & Middleton, 1988; Church et al. 1989; Prata, 1989; Batteen & Rutherford, 1990; Godfrey & Weaver, 1990; Weaver & Middleton, 1990; Bayler, 1991; Cresswell, 1991; Hatcher, 1991; Pearce & Griffiths, 1991; Smith et al. 1991; Batteen et al. 1992; Buchan & Stroud, 1993; Holloway, 1995; Caputi et al. 1996). The Leeuwin Current incorporates water from the eastward-flowing gyre of the Indian Ocean and from the North West Shelf, and many of the processes that influence the Leeuwin Current are also important on the North West Shelf. The warm North West Shelf water may be an important influence on the dynamics of the Leeuwin Current (Weaver & Middleton, 1988; Batteen & Rutherford, 1990; Batteen et al. 1992). Several publications have investigated the effects of North West Shelf processes on the Leeuwin Current (Godfrey & Ridgway, 1985; Holloway & Nye, 1985; Lynch et al. 1986), but there has been little examination of the processes linking the Leeuwin Current and the Indonesian Throughflow across the North West Shelf.

As a result of flow through the Indonesian archipelago, water in the upper 200 m of the Timor Sea and outer North West Shelf resembles western Pacific water, and is warm and relatively fresh. This warm pool of water contributes to the South Equatorial Current and is the reason that the poleward-flowing, density-driven Leeuwin Current exists off Western Australia instead of a wind-driven current that flows toward the equator, as is found in the eastern Atlantic or Pacific. It also partially explains why winds that favour upwelling do not appear to generate much upwelling south of the North West Shelf. The supply of warm, relatively fresh water to the North West Shelf varies between seasons and between years in a manner comparable to the variations due to average transport (Cresswell et al. 1993; Meyers et al. 1995; Bray et al. 1996; Wijffels et al. 1996; Meyers, 1996). This variability at 30 to 60 day periods makes the interpretation of short-term data very difficult (Molcard et al. 1994, 1996). The variability may affect the Leeuwin Current across the North West Shelf, as well as water properties on the North West Shelf, with implications for mixing, upwelling and response to tropical cyclones. CSIRO (Godfrey & Ridgway, 1985) and international programs (WOCE, TOGA/TAO) have important data sets describing the behaviour of the Indonesian Throughflow and large-scale regional oceanography. Meyers and co-workers at CSIRO are developing global ocean models with improved resolution in the tropics to study the Indonesian Throughflow and tidal mixing in the North West Shelf and Timor Sea regions.

3.2 Shelf circulation

Apart from studies focused on tides, internal waves, and tropical cyclones (discussed below), there have been few investigations of general circulation on the North West Shelf. A very large amount of oceanographic data has been collected by industry in support of offshore structural engineering projects (e.g. Steedman Science and Engineering, 1989; Craig et al. 1992). Hindcasts from numerical models of winds, waves, and storm-driven currents have also played an important role in setting offshore design criteria. Stroud (1996) discusses the development of oceanographic data for engineering design, and makes recommendations for future research and measurement programs.

Provis and Radok (1979) reported that large-scale shelf waves are generated by spatial variations in winds and are propagated along the coast of Australia. Webster (1985a,b) made detailed studies of these and other wind-driven aspects of the circulation on the North West Shelf. Lynch et al. (1986) used sea surface temperature signals to investigate upwelling on the North West Shelf. Upwelling is somewhat unusual on the North West Shelf because it may not show at the surface. Offshore transport of surface waters and their replacement by upwelling of deeper, cooler, nutrient-rich water typically supports high productivity on the western side of continents, and would be expected during the SE monsoon period (Wyrtki, 1973). On the North West Shelf, upwelling is not often observed, and Holloway et al. (1985) suggest that weak upwelling actually occurs during the summer and may provide up to one half of the nitrogen used on the shelf.

3.2.1 Tides and storm surges

Astronomical tides on the North West Shelf are semidiurnal and generally quite large, ranging from 0.95 m near Exmouth to more than 3 m on the inner shelf near Broome (values are the sum of M2, S2, and K1 components; Holloway, 1982, 1983b). The Australian Hydrographic Service produces commercially available tidal predictions of a primary quality at nine locations between Exmouth and Port Hedland which indicate maximum spring tide amplitudes of just over 2 m at Exmouth, 2.5 m at Onslow, 4.5 m at Dampier and close to 6 m at Port Hedland. The increase in tidal amplitude from south to north in the study region is most marked north of the Monte Bello Islands, where the width of the continental shelf increases significantly. It is noteworthy that the spring low tides, which expose large areas of intertidal habitat in some locations, occur in the early morning and late afternoon rather than during the hottest part of the day (Heyward, personal observations).

Easton (1970) gave the first general description of tides on the North West Shelf and analysed tidal harmonic constituents using the data of Nikpalj and Radok (1972). Holloway (1983a,b) explained important features of tidal response on the North West Shelf with a simple analytic model using tidegauge data from Carnarvon, Point Murat, Dampier, Cape Lambert, Port Hedland and Broome. The tidal velocities are essentially barotropic with flow predominantly in the cross-shelf direction at the shelf break; it changes to a predominantly along-shelf direction near the coast (Holloway, 1983a,b). Tides on the outer and mid shelf are generally well predicted by world tidal models (Schwiderski, 1980; LeProvost et al. 1994). Numerical tidal circulation modelling and validation has been undertaken in several shallow water areas, including the Dampier Archipelago (Mills, 1985) the Lowendal Islands (S. Langtry pers. comm. 1999) and

Exmouth Gulf (Massel & Brinkman, 1997). Spatial variations in tidally forced current regimes may be very complex around some of the nearshore habitats such as the Dampier Archipelago. Tides are now routinely measured by WA Transport at Broome (with historical data from 1982; Rob Kay, pers. comm. 1998), Cape Lambert (since 1983), King Bay (since 1991), Onslow (since 1985), and Exmouth (since 1989).

Low-frequency variations in sea level were evaluated by Provis and Radok (1979) using the data of Nikpalj and Radok (1972). Storm surges and currents associated with tropical cyclones have been modelled using two and three-dimensional barotropic models (Fandry et al. 1984; Hearn & Holloway, 1990; Fandry & Steedman, 1994; Hubbert & McInnes, 1999). Near real-time predictions of storm surge derived from a statistical match between winds and Topex/Poseidon altimeter data on the North West Shelf can be viewed on the World Wide Web.

3.2.2 Internal waves

Internal-waves and tides feature prominently in the literature on the physical oceanography of the North West Shelf because they generate strong, depth-dependent currents, particularly on the outer shelf. Surface expressions have been observed from ships (Holloway, 1994) and in Landsat, ERS-1 SAR, and Radarsat imagery (Baines, 1981; Burrage et al. 1996a,b; Cresswell, 1991). Holloway has collected and collated an important body of information, including current, salinity and temperature profile data related to internal tides in the region (see Wallace & Wilkinson, 1981; Holloway, 1982; Holloway et al. 1982a,b; Holloway, 1983a,b, 1984, 1985; Holloway et al. 1985; Holloway, 1987, 1988; Smyth & Holloway, 1988; Holloway, 1994). Craig (1988) found that the region of strongest internal tidal generation was in deeper water beyond the shelf break. Numerical models of internal waves have been qualitatively successful, but are not very reliable for predictions (Craig, 1987a,b; Craig, 1988; Holloway, 1996; Walker, 1997). Internal waves and tides give strong but variable signals along the North West Shelf, and more research is needed before they can be modelled successfully in realistic ocean situations.

3.3 Tropical cyclones

It is particularly important to predict the impacts of tropical cyclones when planning offshore operations and setting design criteria for offshore structures. The petroleum companies have been collecting meteorological and oceanographic information on the North West Shelf since the 1970s, and a number of numerical modelling studies have addressed oceanographic response to tropical cyclones. The Bureau of Meteorology maintains a database on tropical cyclones which includes detailed satellite data since 1970, reliable ground data since 1960 and less reliable, but often useful, information on storms since 1939 (Coleman, 1972; Holland, 1981; Lourensz, 1981). Nicholls (1979) recognised that tropical cyclone activity was correlated with global-scale pressure gradients, and more recent work has better defined the relationship between cyclone activity, sea surface temperature distributions, and El Niño (Nicholls, 1984, 1985; Revell & Goulter, 1986; Hastings, 1990; Nicholls, 1992; Evans & Allan, 1992; Broadbridge & Hanstrum, 1998).

Oceanographic models of tropical cyclones have been developed and/or applied by Holloway and co-workers, researchers at the University of Western Australia, CSIRO and WNI, and have been used to simulate tropical cyclones for design purposes. Models used by WNI (previously called Steedman Science and Engineering) are described by

Stroud (1978), Fandry and Hart (1988), Fandry and Steedman (1989, 1994). More recently, WNI has used the three-dimensional hydrodynamic model of Walker and co-workers at CSIRO (Waring et al. 1988; Reid et al. 1996, 1997; Walker, 1997; Condie et al. 1998) to hindcast recorded cyclones.

3.4 Waves

Wave data for the North West Shelf have been collected at several locations by consultants for the shipping and oil and gas industries, at two locations by the WA Department of Transport, and in the Exmouth Gulf and Ningaloo Reef area by AIMS. Massel and Brinkman (AIMS, unpublished data) have validated models of wave regimes in Exmouth Gulf and at Ningaloo Reef. Buchan and Stroud (1993) summarise the wave climate on the North West Shelf, noting that the sea state may depend on contributions from Southern Ocean swell, summer monsoonal swell, winterly easterly swell, 'West Coast' swell, tropical cyclone swell, and locally wind-generated seas. The effects of these wave-generation mechanisms on wave spectra at Port Hedland and Dampier have been investigated by Hamilton (1997a). Hamilton (1997b), in his compilation of sources of wave data around Australia, tabulates (p.138) data collected by WNI on the North West Shelf. A program of real-time wave monitoring called the Remote Offshore Warning System (ROWS) is conducted for Woodside by WNI each cyclone season, and the WA Department of Transport has historical data from waverider deployments near Ningaloo and Exmouth.

3.5 Regional examples of intensive oceanographic sampling

3.5.1 Dampier Archipelago

The Dampier Archipelago has been the focus of several studies because shipping has grown to make the Port of Dampier Australia's largest tonnage port. A brief history of the port at Dampier is given in the Dampier Port Authority Environmental Management Plan (Bowman Bishaw Gorham, 1994). It was built in 1963 as a private port for the export of iron ore by Hamersley Iron Pty Ltd. Additional traffic was added when Dampier Salt began exports in 1972, and again when Woodside Offshore Petroleum Pty Ltd began shipping LNG and condensate from their site on Mermaid Sound.

The DEP undertook a marine environmental study of the Dampier Archipelago in the early 1980s. Current meter measurements were made at 21 locations (Mills et al. 1986) and wind data were recorded at Conzinc Island between September 1981 and July 1985 (Pitt & Mills, 1985). The current-meter data were used to test a numerical model for simulating depth-averaged tidal and wind-driven circulation (Mills, 1985), and the wind data were used as input. Model experiments demonstrated that the strength and direction of tidal currents in the archipelago depended on the along-shelf water-surface slope associated with regional diurnal tides. The model was to be used for estimating flushing times within the archipelago, but it is not clear how it has been used since 1985.

3.5.2 Exmouth Gulf

In 1993, AIMS began studies in Exmouth Gulf as one of several long-term research programs on the North West Shelf (Australian Institute of Marine Science, 1997). Physical oceanographic measurements performed by Dr S. Massel and co-workers included a series of tide-height measurements, and current measurements across sixteen transects throughout the gulf. These measurements have been used in conjunction with

numerical models to provide insight into tidal and wind-driven flushing of the gulf (Massel & Brinkman, 1997). In addition, a rich set of cross-shelf hydrographic transects is being collected in conjunction with the water-column chemistry and biological studies being made by AIMS.

Additional data have been collated by the RAN in evaluating the potential for development of an underwater tracking range in the Exmouth region. As part of this process the DSTO have summarised oceanographic conditions in the region west and north of North West Cape (Scott, 1998).

3.5.3 Ningaloo Reef

AIMS measured water elevations, waves and currents on a section of Ningaloo Reef in 1997 as part of a circulation study (Brinkman, 1998). Additional oceanographic measurements have continued nearby during 1998 and 1999 as part of continuing AIMS research into biological and physical oceanography across the continental shelf in the region of North West Cape.

3.5.4 Monte Bello, Lowendal and Barrow Islands region

Extensive oceanographic and habitat data have been collected in this region by the petroleum industry because it is a key centre of development activities in this region. In particular, the emergent and shallow water habitats around the Barrow–Lowendal–Monte Bello Islands region, where WAPET and Apache Energy Pty Ltd are primary operators, have been intensively studied. This Monte Bello Islands region has been identified as a sensitive and valuable marine resource used by multiple sectors of the community and will be considered a high priority region for marine conservation (APPEA, 1997).

4. SATELLITE AND OTHER REMOTE SENSING DATA

The application of remote sensing technologies has particular appeal in the North West Shelf region, a large and sparsely populated area which is expensive to operate in, whether on the coast or at sea. However, to interpret and apply essential remote sensing tools such as satellite data to the region remains a major challenge. A range of existing satellite databases contain historical information, but there is also considerable interest in evaluating the potential of several very recent satellites that are now providing coverage of the North West Shelf.

The main access group for satellite-related data products in Western Australia is the Western Australian Satellite Technology and Applications Consortium (WASTAC) which consists of the Bureau of Meteorology, Curtin University of Technology, CSIRO Office of Space Science and Applications (COSSA) and the Western Australian Government's Department of Land Administration.

4.1 Remotely sensed physical oceanography

Regional scale remote sensing data have been used in the north-west for measurement of ocean circulation (Griffiths & Pearce, 1985; Pearce & Griffiths, 1991; Murtugudde et al. 1998), internal wave activity (Baines, 1981; Burrage et al. 1996a,b) and sea surface temperature (Lynch et al. 1986; Prata, 1989; Walker & Wilkin, 1998). These studies have taken advantage of a range of satellite-based sensors, including Landsat (1 & 2) and ERS (1 & 2) for studies of surface and internal waves, AVHRR for sea surface temperature and Topex/Poseidon for currents. Additional remotely sensed data on surface wave spectra in the north-west may be obtained from land-based radar (see Hamilton, 1997a). Satellite tracking of drifting buoys has also been applied on the North West Shelf to studies of regional scale circulation (Cresswell, 1981; Matsuura et al. 1997) and to local-scale dispersion modelling (e.g. WNI, 1995).

Altimeters on board the Topex/Poseidon satellite can measure any sea surface height anomaly to within a few centimetres, e.g. Walker and Wilkin (1998). The capability is available in near real time interpolated onto a one degree grid and can be used to calculate surface geostrophic currents if the mean sea surface height fields are known. This type of altimeter data can add a valuable near real-time input into general circulation models of the North West Shelf. Regional profiles of temperature, salinity, dissolved oxygen, nitrate, silicate and phosphate have been collated and interpolated in the Climatology of Australian Regional Seas (CARS) database (contact Jeff Dunn, CSIRO Marine Research) and are available for use in general circulation models.

Recently, global-scale rises in sea surface temperatures have been implicated in extensive coral bleaching, some of which has been observed on reefs along the North West Shelf (Heyward, personal observation). On the Great Barrier Reef, NOAA, GBRMPA and AIMS are coordinating a study of satellite-derived sea surface temperature (SST) and coral bleaching. Alan Pearce at CSIRO has processed NOAA-AVHRR (Advanced Very High Resolution Radiometer) SST satellite data for Western Australia (including the North West Shelf), using locally received imagery from mid-1983. The image-processing software works on standard 512-line by 512-pixel areas at various spatial resolutions: the whole west coast at 4.4 km resolution, North West Shelf at 2.2 km, and various subareas south of Exmouth Gulf at full (1.1 km) resolution. Averaged daily SST data at a resolution of 9 km, calculated from the NOAA/NASA

Pathfinder reanalysis of AVHRR data, have been optimally interpolated in time to provide a cloud-free record for the Indo-Australian region at 10 day intervals (Walker & Wilkin, 1998).

4.2 Remotely sensed ocean colour

Ocean colour can be an indicator of important biological and physical processes, including primary productivity and sediment loading in surface waters. Considerable effort is being put into developing and validating appropriate algorithms for ocean colour satellite data. Historical ocean colour data were collected at ~1 km resolution with the coastal zone colour scanner (CZCS) between 1978 and 1986 by the NASA Nimbus-7 satellite. More recently the *SeaWiFS* satellite has stimulated the interest in ocean colour.

The *SeaWiFS* ocean colour sensor was launched in August 1997 and has been operational since October 1997. *SeaWiFS* measures upwelling radiance in eight spectral bands in the VIS/NIR with very high signal to noise ratio, allowing for accurate retrieval of water-leaving radiance, and estimates of chlorophyll pigment concentrations in surface waters. Spatial resolution is about 1 km, and repeat coverage over the North West Shelf should be every two days under clear skies, although summer coverage may be affected by sun-glint. There are important scientific remote sensing issues to be addressed in the interpretation and application of *SeaWiFS* data on the North West Shelf. The standard *SeaWiFS* algorithms have been developed for open ocean (so-called CASE 1) waters, where there are negligible effects of reflectance from shallow bottom sediments and suspended sediments derived from either resuspension or runoff. Errors are likely if these algorithms are applied on the inner part of the North West Shelf, where strong tidal currents produce high turbidity levels. *SeaWiFS* images for the North West Shelf are now available (see figure 3) and continuing collaborative work between AIMS, CSIRO and others has begun ground-truthing *SeaWiFS* data in the region of North West Cape.

This research will develop modified regional algorithms for these coastal waters and robust techniques for estimating primary production in the water column from ocean colour data and ancillary data.

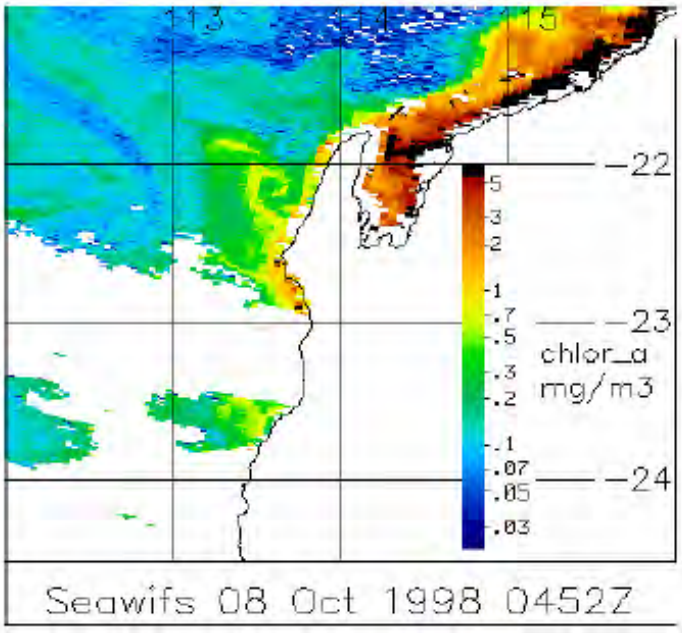

Figure 3: *SeaWiFS* ocean colour image, centred on the North West Cape region. This image is *SeaWiFS* data, collected by WASTAC in Perth under a NASA research agreement and processed by CSIRO. William Skirving (AIMS) provided the image, Professor Merv Lynch provided the data and Chris Rathbone helped with the processing.

5. GEOLOGY, SEDIMENT TRANSPORT, GEOTECHNICAL ENGINEERING

Information on geological aspects of the North West Shelf is extensive, although considerable knowledge gained in the exploration and development of hydrocarbon reserves remains commercially sensitive and confidential. Harris et al. (1991a,b) reviewed and summarised the physical sedimentology of the entire Australian shelf. The Bureau of Mineral Resources performed geological reconnaissance surveys of the North West Shelf in 1967 and 1968 and collected 353 grab samples on a 10 nautical mile grid. On the basis of these samples, bottom photographs, and large-scale bathymetric data from shipboard echo sounders and RAN charts, Jones (1973) provided the first overview of marine geology and sedimentology of the North West Shelf.

The Australian Geological Survey Organisation (AGSO; formerly the Bureau of Mineral Resources) holds major data on sediments and bathymetry for the North West Shelf region. AGSO has recently commenced production of the Offshore Resource Map Series (e.g. AGSO, 1994) and can rapidly produce three-dimensional bathymetric and sedimentary maps of the region (contact Dr Geoff O'Brien, AGSO, Canberra) from their computer database. In addition, a comprehensive database of grain-size data from the North West Shelf is maintained at the University of Sydney (contact Dr Chris Jenkins, Ocean Sciences Inc.) which can be readily developed into bottom sediment maps. The data archive includes historical and recent samples, including Jones's (1973) samples, data from hydrographic surveys, and data from commercial surveys.

McLoughlin (1981) and McLoughlin and Young (1985) analysed samples obtained during CSIRO fisheries research cruises with a 30 cm diameter dredge on a 10 km grid covering the shelf (at 20 to 150 m depth) between Dampier and Port Hedland. They found an along-shore gradation from coarse skeletal sands in the south-west to accretionary oolitic and infilled biogenic particles in the north-east, and an across-shelf decrease in grain size. A later paper presents analysis of sediment samples and bottom photographs obtained from the shelf-edge (at 150 to 200 m depth) between Dampier and Scott Reef (McLoughlin et al. 1988). These data, associated data on benthic habitats, and fisheries data have been archived and partially published by Dr Keith Sainsbury and co-workers at the CSIRO Division of Fisheries (now part of CSIRO Marine Research). There has been no comprehensive attempt to integrate the available data and link sedimentary environments, benthic habitat, and fisheries ecology.

Geological and geotechnical studies have been performed during the design and installation of offshore structures and gas pipelines. In particular, there were extensive geotechnical investigations during the construction of North Rankin 'A' (NRA; Jewell & Khorshid, 1988). Also, there was very detailed survey of installed and prospective gas pipeline routes, following nearly catastrophic scour around the gas pipeline to NRA by cyclone-induced waves and currents. Pipeline studies have included detailed bathymetric surveying with multibeam equipment; high-resolution sub-bottom acoustic profiling; side-scan sonar; examination of bottom samples obtained with dredges, grab samplers, and hydraulic piston corers; and cone-penetrometer measurements that determine the sediment strength. Geological interpretations of subsets of these measurements have been made along potential pipeline routes (Apthorpe, 1998; Logan, 1998). Most of these data have remained proprietary, e.g. Gorgon, Second Trunkline Project (WAPT), or with consulting geologists, geophysicists, and engineers.

Additional, but less obvious, sources of data on geology and seabed sediments include reports from every drilling site on the North West Shelf and background environmental reports on drilling and pipeline routes, e.g. LeProvost Environmental Consultants (1990), Bowman Bishaw Gorham (1991).

6. POTENTIAL THREATS

6.1 Risk and impact assessments

Moving from uncertainty to defined risks is common business practice and is seen in a variety of environmental impact and decision support models adopted by the private sector on the North West Shelf. In many cases risk assessments conducted during the planning and approval stages of developments are desktop studies that apply previously tested models without collecting new field data, e.g. Steedman Limited (1984), Russell (1988), Brown (1992), Buchan (1992), Steedman Science and Engineering (1992). Nonetheless, a large volume of meteorological and physical oceanographic data has been acquired and used as input for testing numerical models, e.g. of oil spill trajectories, of the fate of discharged formation waters, and of the transport of drilling muds and solids. Less effort has gone into empirical or experimental studies of actual ecological effects. Near environmentally sensitive areas, these transport and dispersion studies have sometimes provided detailed, site-specific oceanographic data for a short period. For example APPEA, Apache, and BHP have applied the MUDMAP model (e.g. King & McAllister, 1997) using currents modelled with GCOM3D (e.g. Hubbert, 1993; Apache Energy, 1997) to estimate oil spill trajectories and dispersal of produced formation waters. Comparison of the results with field measurements (e.g. King, 1994; Furnas et al. 1995; GEMS, S. Langtry pers. comm. to A. Heyward; Burns & Codi, 1998; King & McAllister, 1997, 1998; Furnas & Mitchell, 1998) indicated that, when appropriately forced, MUDMAP models provided a reasonable representation of the plume location and concentrations.

6.2 Introduced species

One perceived threat to planktonic and benthic communities is the introduction of exotic species via ballast water. International shipping frequents the region, both in transit and to load oil. Port matching (identifying source and destination ports with similar general water quality) has not been attempted for the tankers, but some arrive from Asia and deliver loads to SE Asia (APPEA, 1997). Consequently, exchange of organisms, via ballast water or hull fouling, from one tropical port to another is an obvious possibility. Additional vectors to the Monte Bello Islands area include the frequent barge traffic from the Port of Dampier, which experiences very heavy international tanker traffic. Nonetheless, there are no published baseline data yet against which to measure or detect introduced species, although recent studies by CRIMP at the Port Hedland area provide a starting point.

6.3 Oil spills

A previous review (Swan et al. 1994) has shown small historical incidence, and little likely future risk of oil spills from the exploration and production industry. If an incident did occur and oil was released, North West Shelf oils are generally light in nature and are therefore likely to evaporate rapidly (Kagi, 1983). The greatest risk is associated with shipping activity (Flood, 1992; May, 1992) which is likely to result in a spill of bunker oil. These oils are heavy in nature and likely to be persistent. Studies currently underway are looking at the effect of these oils on mangroves (Duke et al. 1998a,b,c). There are few data on the likely short- and long-term effects on corals (see Negri & Heyward, in review(a)), and it is not easy to perform field studies in these sensitive areas. There have been attempts

to classify habitats in terms of sensitivity, to allow management plans to be formulated (Hancock et al. 1979). Sensitivities of habitats are an aspect of risk management that have been incorporated into decision support tools such as OILMAP (for example King & McAllister, 1996a,b; King et al. 1996) Oil spill trajectory modelling is potentially an important tool for identifying areas likely to be affected by oil spills, especially when the modelling is combined with habitat maps and toxicology information. The data requirements for some models, such as OILMAP, have been explored (King et al. 1999), but there is relatively little understanding of the distribution of habitats, the composition of the biological communities and their responses to oil. These models appear to work well in tide-dominated conditions, but during strong winds and swells they are less successful because we know less about these conditions. For example, in the Kirki incident, despite an on-shore wind the oil was carried parallel to the shore by the Leeuwin Current, something that is only now being modelled with any degree of success. Radarsat images, often used in oil exploration to identify hydrocarbon seeps, may be useful in tracking persistent releases from offshore operations (G. Cresswell, pers. comm.).

6.4 Drilling fluids and drill cuttings

The environmental impact of drilling fluids and cuttings is an important issue for the Australian petroleum industry e.g. Stejkal (1998). Although most of the wells on the North West Shelf have been drilled with water-based fluids, drilling engineers argue that, for some wells, synthetic (hydrocarbon-based) fluids are safer and more efficient. Some research has been determining the distribution of oil-based mud and cuttings near wells (Chegwidden et al. 1993; Phatak & Palmer, 1998; Oliver & Fisher, 1999). These studies indicate that drill cuttings and mud are rapidly and widely dispersed, but as yet there has been no concerted effort to understand the long-term fate and environmental impact of these fluids beyond the detectable cuttings pile, or at low but chronic levels of exposure.

In the absence of research directly applicable to the tropical carbonate environment of the North West Shelf, the WA Department of Minerals and Energy (DME) has adopted a risk-based case-by-case approach to the regulation of drilling fluids and treatment of cuttings piles (Cobby & Craddock, 1999). This approach is consistent with new environmental regulations implemented in October 1999 that require oil and gas companies to demonstrate the risk to the environment for proposed activities. The new regulations will stimulate additional research into the acute and chronic effects of drilling fluids. Well-defined guidelines are needed so that there can be sustainable use of the public marine resources of the North West Shelf, with minimal effect on the generation of wealth by the extraction of oil and gas resources. It will take careful and objective research to define these guidelines.

We do not adequately understand the effects of synthetic-based fluids such as esters, linear alpha olefins and iso olefins. We know little about the transport of cuttings on the North West Shelf and the implications this has for possible dispersion and degradation of the fluids. For wells drilled in sensitive areas, the DME requires drilled cuttings and adhering fluids to be disposed of down the well. Future oil and gas exploration and production will focus on deep water (>100 m) areas offshore Western Australia. Little is known about the chronic effects of these fluids on deep-water benthic communities. In addition, more research is needed to better understand the biodegradation rates of synthetic drilling fluids and the effects of the associated breakdown components as part of that biodegradation process.

6.5 Produced formation waters (PFW)

Produced formation waters (PFW) are among the few contaminants on the North West Shelf which have been subjected to an integrated study. The study was carried out by AIMS and AGSO in 1994 and 1995 (Holdway et al. 1995; King & McAllister, 1997; Burns & Codi, 1998; Holdway & Heggie, 1998; King & McAllister, 1998), centered on the Harriet A platform. It examined the distribution of hydrocarbons in the discharge plume and in the sediments immediately around the platform. Water column data gathered to track the plume showed a half-dispersion distance of 3.5 km, and the plume was vertically mixed after travelling one kilometre (Holdway & Heggie, 1998). There appeared to be little accumulation of hydrocarbons in the sediments immediately around the platform (Burns & Codi, 1998) even though surface plumes were readily visible.

This study begins to fill in our understanding of this contaminant, but there remain gaps. For example, what are the water column effects of the aromatic components of this plume and the fate of these compounds in the sea surface microlayer, given the high possibility for photo-oxidation. The volume of PFW released will increase with the number and age of platforms on the North West Shelf. In addition, hydrocarbons represent only about 30% of the total organic carbon in PFW and there needs to be more emphasis on the fate and effects (if any) of the other components, including added chemicals such as corrosion inhibitors (Milner, 1995). Studies carried out so far on PFW discharges have shown little influence on general water chemistry (Furnas et al. 1996). There has been acute dose response testing of hermatypic coral fertilisation, larval settlement and adult colony physiology with PFWs from North West Shelf wells. These studies also have found that relatively high concentrations of PFW are required to cause a detectable effect (Negri & Heyward, in review(a); R. Jones, unpublished data). Chronic effects on corals remain to be investigated.

6.6 Ecotoxicology and bioaccumulation

In addition to the toxicology work on PFW, there have been monitoring programs and experimental studies in the region. In general, the studies have found that the zones of acute impact are localised, with few studies indicating contamination beyond 500 m from identifiable sources. Some studies have made use of oysters for estimating petroleum contamination (Tranter, 1958a,b,c,d, 1959; WAIT: The Petroleum Geochemistry Group, 1983; Talbot, 1984; LeProvost Semeniuk & Chalmers, 1986, LeProvost Dames & Moore, 1987; LeProvost Environmental Consultants, 1990 ; Pendoley, 1992; Department of Conservation and Land Management, 1993; LeProvost Dames & Moore, 1993; Geotech, 1998). In studies that analysed oysters and sediments before drilling activities began, it was shown that there was a general low-level background contamination, probably due to shipping activities (Pendoley, 1992) or natural seeps. There has been little evidence to suggest that petroleum-related operations on the North West Shelf significantly add to this contamination outside the obvious zones of effect, but studies on this subject have been limited.

There has been semi-annual (November and May) monitoring of metal concentrations in sediments at sites in the vicinity of the Onshore Treatment Plant and King Bay Supply Base (Burrup Peninsula near Dampier) since 1985, as part of the Woodside Chemical and Ecological Monitoring of Mermaid Sound (e.g. LeProvost Dames & Moore, 1996). A recent assessment of the general Dampier Port area has found localised accumulations of tributyl tin (TBT), and has detected a useful correlation between TBT

levels and imposex frequency in intertidal gastropods. This may be usable as a generic bioindicator for TBT (Reitsema, 1997). Toxicology testing for the effects of TBT and copper on coral reproduction (Negri & Heyward, in review(b)) indicates that the relative toxicity of the two compounds varies with the bioassay employed. Copper is the more toxic to coral fertilisation, while TBT is the more toxic when bioassays involving larval settlement are used.

Major dredging operations periodically produce large loads of suspended sediment in the ports. While some 'before and after' studies of macroepibenthos have failed to detect impacts (K. Grey, pers. comm.), Gilmour (pers. comm. to A. Heyward) finds that elevated concentrations of suspended sediments can reduce coral reproductive success during the early larval development phases that take place in the water column. Very recent research on east coast reefs suggests that the nutrient loading can strongly influence the impacts of suspended sediments on macro-benthos such as corals (K. Fabricius, E. Wolanski, pers. comm.).

Many laboratory-based ecotoxicology studies have used 96-hour acute tests that give little information about long-term chronic effects (Curtin University, 1993; Environment and Resource Technology, 1994a,b; Bidwell et al. 1994, 1995; Bidwell & Tsvetnenko, 1995; Evans et al. 1996; Tsvetnenko et al. 1996a,b; Tsvetnenko & Evans, 1996a; Curtin University, 1997, H118, H149). However, it is difficult to keep sediment invertebrates alive for a prolonged period of time, so at present there appear to be no successful methods available for assessing chronic impacts on them. The lack of a regionally based toxicology facility with flow-through seawater supply has made the task more difficult, because tropical marine organisms have had to be kept in Perth suburban laboratories.

7. FISHERIES BIOLOGY

Commercial fishing is an important activity on the North West Shelf. The Fisheries Department of Western Australia manages fisheries in the Pilbara. These include the Exmouth Gulf, Onslow and Nickol Bay prawn fisheries, the Exmouth Gulf beach seine fishery and the Pilbara finfish fishery. The finfish fishery consists of trawl, trap and line fisheries. Total value to the fishers of all these industries in 1996 was estimated to be approximately $25.4 million; the Exmouth Gulf prawn trawling and Pilbara finfish trawling dominated this with notional values of the order of $10 million each (Penn, 1997).

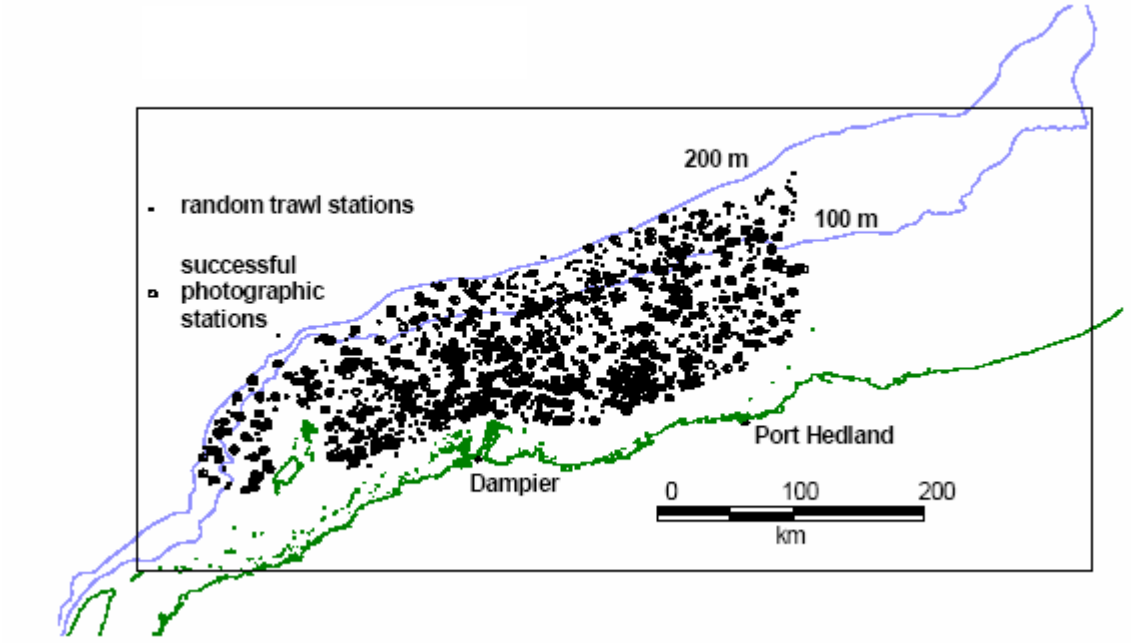

Figure 4: Cumulative sample locations from CSIRO research since 1979 that may provide further data on biota and habitat diversity.

In the bibliography (Jernakoff et al. 2006), 237 references pertain directly to fish or fisheries research, and of these at least 60% contain professional quality scientific research data. The overwhelming majority of this research has been conducted since 1980. Most of it is associated with investigations into trawl and trap fisheries of the region and, in particular, with activities related to commercial fisheries between the 50 and 200 m depth contours. The major contribution to published fisheries-related information has been a CSIRO research program (90 references), which began at about the time when the Australian fishing zone was declared in 1979 and was particularly strong in the early to mid 1980s. In 1982, CSIRO initiated a study of demersal trawling on the North West Shelf. Every second month the study examined: a) water column characterisation and its flora and fauna; b) bottom sediment characteristics, flora and fauna; c) fish reproduction and recruitment; d) fish diet; e) fish growth and mortality; and f) industry aspects. This research is an important survey of a tropical continental-shelf ecosystem, and over time it has covered an increasingly large area (see figure 4). Even so, the replication of samples is often limited, particularly with regard to repeated sampling of the same locations over multiple seasons for multiple years.

Campbell (1994) describes CSIRO databases related to the North West Shelf. Research data collected by WA Fisheries, e.g. figures 5 and 6, has been more tightly focused on commercial species and the interpretation of commercial-sector data within specific fisheries management zones. Given the amount of field effort both organisations have expended it is inevitable that large volumes of data remain to be analysed and published.

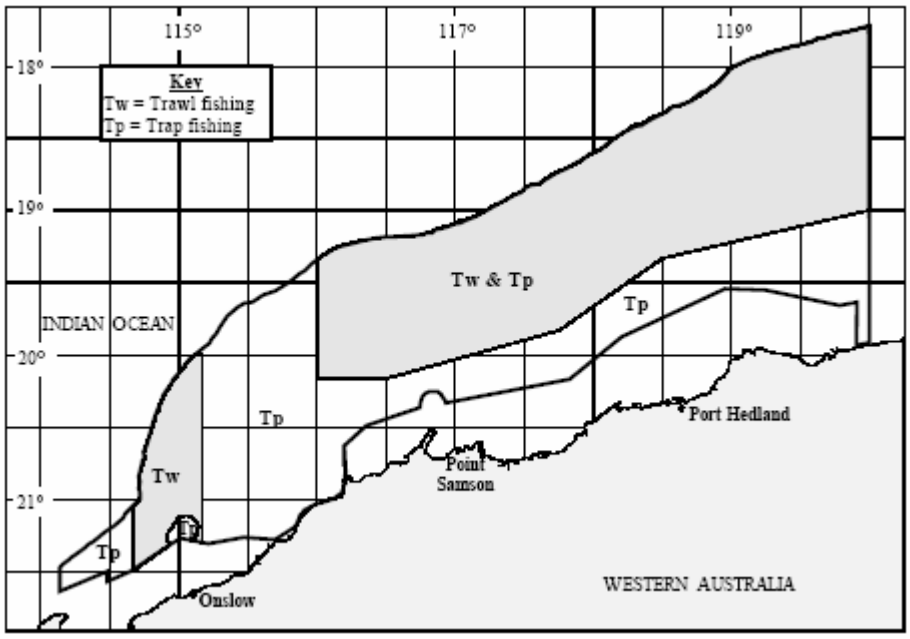

Figure 5: Management zones for the Pilbara finfish fishery. In addition to trap and trawl fishing, line fishers may operate throughout the region. Map provided by WA Fisheries.

Trawling in the region appears to have the potential to be very destructive to large epibenthic organisms (Sainsbury et al. 1993; Moran et al. 1995). Anecdotal information suggests it may also have similar effects in the Exmouth Gulf prawn fishery (Bowman Bishaw Gorham, 1990). Consequently benthic trawling appears to be the major human impact on the mid- and outer areas of the North West continental shelf. It may pose threats to biodiversity in areas with highly diverse invertebrate species and localised endemism (see section 9, Biodiversity). It may also lead to shifts in fish community composition, either directly or by trawling effects in the habitats that are nursery grounds for many of the abundant fish species (Young & Sainsbury, 1985). The regeneration rates of epibenthos and the interactions of fish populations with the benthic fauna are poorly known in general, but are best understood for the shelf trawl grounds (see Sainsbury & Lindholm, in prep.; Sainsbury, 1982a; Sainsbury & Lindholm, 1986; Sainsbury, 1987; Sainsbury et al. 1993).

The spatial extent of data is considerable for the trawl areas deeper than 50 m, but very few studies provide information about the nearshore and intertidal fish communities (e.g. Blaber et al. 1985). This gap in knowledge coincides with poor fisheries data for the inshore commercial fishing effort and recreational line fishing. Data from commercial line fishers can be difficult to resolve at fine spatial scales. Recreational fishing is also difficult to quantify, but it can have a significant effect. The Dampier Archipelago is primarily a recreational fishing area, with the highest per capita boat

ownership in Australia (1600 boats for 9000 people; Driscoll, 1996). Moran et al. (1995) report anecdotal evidence suggesting that stocks of demersal fish have been greatly depleted over the last two decades in this area.

There are major gaps in our knowledge of fish ecology, despite the large amounts of data related to some fisheries in the region, and the significant work by CSIRO in the early 1980s (e.g. Young et al. 1986). Few studies have addressed seasonality of recruitment, larval dispersal, seasonality of spawning, location of spawning and so forth, all of which are relevant to sustainable environmental management. This is probably because of the sampling frequency required to obtain such information. The few exceptions, such as data for the tiger prawn in Exmouth Gulf (White, 1975, cited in Penn & Caputi, 1986), and other detailed studies of single species biology (e.g. Dews et al. 1988), are generally incomplete or short-term studies. Recent extremely intensive sampling of fish and invertebrate recruitment by AIMS (Doherty & McIlwain, 1996, 1997; M. Meekan pers. comm.) in the North West Cape region will provide much needed additional data, but most of this work remains to be analysed and published.

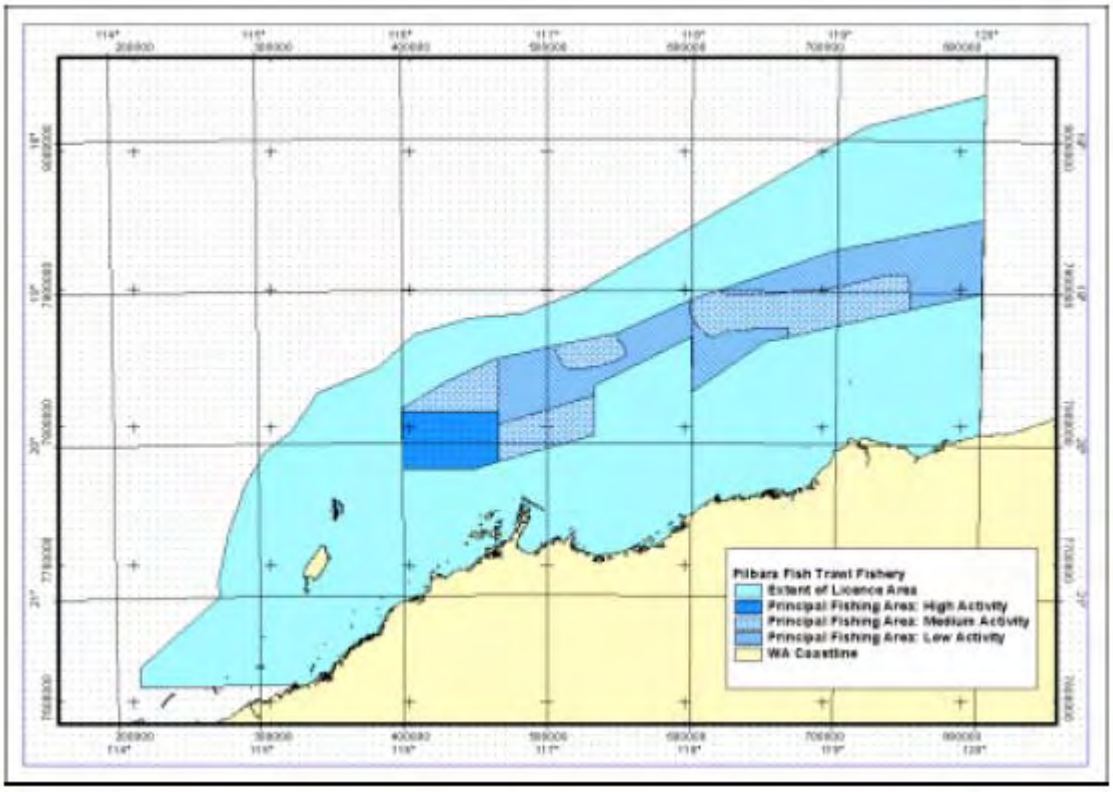

Figure 6: Principal fishing areas in the Pilbara Fish Trawl Managed Fishery. Data provided by WA Fisheries.

8. GENERAL ECOLOGY

8.1 Plankton ecology

Research into primary and secondary productivity of the North West Shelf has been episodic or expeditionary, mainly because there have been no marine research stations or institutions in the region. The principal data sets are those from early CSIRO expeditions in the 1960s to 1980s, and the 1990s results of continuing research by AIMS. Data from the 1960s (CSIRO, 1962a,b; 1964a,b,c; 1965a,b) cover a limited number of sites over the North West continental shelf and provide only a very broad view of seasonal primary productivity with some speculation about underlying processes of enrichment on the North West Shelf. The study by Kabanova (1968) did not systematically investigate the coastal waters off north-west Australia throughout a full year, but subsequent investigation identified seasonally repeated patterns of circulation and nutrient flux, with an apparent disjunction between inner and outer shelf water quality along approximately the 80 m isobath (Bulleid, 1984). A further change occurs around the 200 m isobath, across which sub-tropical and tropical waters migrate seasonally. These studies looked at the broad shelf 15 to 20°S. Rochford (1984) recognised a northern 'tropical' zone and a southern 'subtropical' zone separated for part of the year by a tropical convergence at 18 to 20°S.

There is good taxonomic information available for plankton from the general region of the North West Shelf. The relatively high diversity of some phytoplankton groups, such as diatoms, coccolithophorids and dinoflagellates, has been clarified by Hallegraeff and co-workers (Hallegraeff & Jeffrey, 1984; Hallegraeff, 1984a,b, 1992, 1994). Toxic algal blooms do not appear to be a problem in the region. Blooms of Trichodesmium, some very extensive, occur throughout the region during the warmer months, but its role in nutrient cycling and the trophic system is not known (Creagh, 1985), although it might contribute significantly to the nitrogen budget. Our general understanding of the region's zooplankton abundance, biomass and the taxonomy of selected groups (see Tranter, 1977 and related references in the same journal issue) derives from broadscale surveys done by CSIRO in 1962 to 1963. Recently, AIMS has sampled intensively, at fine scale, for primary and secondary productivity in the nearby region of North West Cape and the Murion Islands, with some additional studies adjacent to the Monte Bellos (McKinnon & Ayukai, 1996; Furnas & Mitchell, 1998). Much of this 1997 to 1999 survey work remains to be published (contact Dr Miles Furnas and Dr David McKinnon, AIMS, Townsville).

The dynamic processes behind primary and secondary productivity on the North West Shelf continue to be described, but the various studies cover small areas, and there are no available long-term (ENSO cycle duration) data collections that have used high frequency sampling. Some studies indicate that standing crop of phytoplankton is not particularly high (approx 20 to 40 mg Chl*a*/m^3); similar to the Arafura Sea and less than the Gulf of Carpentaria (Hallegraeff & Jeffrey, 1986; Tranter & Leech, 1987). The Leeuwin Current may minimise the intrusion of high-nitrate slope water onto the shelf in winter, thus moderating productivity in winter but not in summer, and reducing seasonal variation in the standing crop of phytoplankton. However, intensive studies show that very rapid recycling can occur in phytoplankton on the North West Shelf, with high carbon metabolism also noted for bacteria (Pollard & Moriarty, 1984; Furnas & Mitchell, 1998).

The distribution of phytoplankton reflects the physical dynamics of the water column, with internal waves and tidal flows being potentially important (Tranter & Leech, 1984). Areas of enhanced production have been found at the interface between stable waters warmed by solar heating and unstable waters mixed by tidal turbulence, but such fronts are rarely found seaward of the 40 m isobath. Early research suggested that at most times of year the bulk of the phytoplankton standing crop on the North West Shelf lies well beneath the surface, either at the base of the thermocline or in the bottom mixed layer adjacent to the seafloor (Tranter & Leech, 1987). This was based on eight cruises in 1982/83 that repeatedly sampled two cross-shelf transects either side of Port Hedland. There is evidence of possible enrichment onto the North West Shelf with nutrients in summer, coinciding with the time of maximum internal wave activity, which gives peaks in phytoplankton just shoreward of the shelf break. The role of tidal mixing remains unclear, although some data show that the standing crop is sporadically much larger at spring tides than at neaps. Intrusions of slope water have been recorded as far across the shelf as the 50 m isobath, but they do not break the surface; they act as vestigial upwellings with fairly mild effects. The tidal and low frequency upwelling events may supply about half the nitrogen requirements of the shelf (Holloway et al. 1985), with additional nitrogen coming from mixing during cyclones, and recycling (see also Rochford, 1988).

These fundamental insights into nutrient supply and flux on the North West Shelf have focused on physical processes, noting that riverine inputs are negligible compared to the wet tropics, but biological processes linking nitrogen-fixing micro-organisms in the plankton and intertidal zones to nutrient inputs have received scant attention.

There are a few data describing the trophic links between the plankton and the benthos. One study suggests there is a mid shelf habitat at 40 to 100 m depth, where sessile filter feeders have direct access to live phytoplankton below the pycnocline. It also suggests there is an offshore habitat >100 m deep, which depends on detrital input from subsurface phytoplankton rather than from phytoplankton living below the pycnocline (Tranter & Leech, 1987).

Few data show inter-seasonal variability in plankton communities. Good spatial data sets were collected during the 1980s CSIRO cruises east of Dampier and Port Hedland, and during the recent AIMS cross-shelf transects at higher sampling frequency, across Exmouth Gulf and past North West Cape. However, there are gaps in our understanding of the processes behind productivity on the mid- and outer shelf, and we do not understand the role of tidal mixing and inputs from rivers, mudflats and mangroves (see section 8.3) in the plankton dynamics of the nearshore. Not much has been done with the picoplankton or bacteria, although research associated with onshore salt production has characterised halophilic types (e.g. Dampier Salt, 1981) and two studies have investigated bacterial productivity in parallel with studies of primary production (Pollard & Moriarty, 1984; Furnas & Mitchell, 1998).

8.2 Coral reefs

Coral reefs and coral-dominated benthic communities are ubiquitous in rocky shallow water areas throughout the region. The locations with significant live coral cover have been described in industry-commissioned broadscale habitat maps covering the region between Dampier and North West Cape (e.g. Bowman Bishaw Gorham, 1995b), with most of these data now managed in GIS format by Apache Energy (E. Stejkal, pers.

comm.). The most common morphology of these reefs is a fringing formation adjacent to mainland rocky shores or emergent islands. Ningaloo Reef tract, extending southward from the North West Cape, is Australia's major fringing reef system and is managed by CALM as a Marine Reserve. The habitat and biological diversity of the coral reef ecosystems around the Monte Bello Islands and Dampier Archipelago have been widely recognised and both areas have high priority for future management as marine reserves under the CALM Act (see Simpson and Bancroft, 1998).

Detailed taxonomic surveys on shallow water coral reefs in the region typically report high biodiversity and fine-scale habitat complexity (Berry, 1993). The scleractinian coral fauna itself is quite diverse, with surveys in the last few years adding species to the list of more than 200 previously reported from the Monte Bello Islands and Dampier Archipelago region (WA Museum, pers. comm; M. Ford, pers. comm.). Good taxonomic data and knowledge exist, principally within the WA Museum, about the region's reef fish, molluscs, echinoderms, sponges and crustacea. Collections and identification of macroalgae and soft corals are more limited. The AIMS biodiversity collections from Commonwealth waters in the region amount to several thousand voucher specimens of macro- and micro-organisms. The museum and AIMS collections require major taxonomic work to get to species level, but an electronic database of location and sample details is maintained at AIMS (contact Dr Chris Battershill) and should be easily adapted to GIS use.

Reproductive activity of the major coral species is known to peak between March and April (e.g. Simpson, 1985), usually occurring 7 to 10 nights after the full moon. AIMS research into the population dynamics of corals throughout the region has been sustained since 1994, focusing on quantifying recruitment (Smith and Heyward, unpublished data), although many of these data are not yet published. In addition to the expected recruitment peak in autumn, coral recruitment occurs throughout the year, with brooding species implicated. There have been recent observations (Heyward, unpublished data) of broadcast spawning of corals along the North West Shelf in October–November also, although this is a minor event relative to the March–April spawning.

The population dynamics of many shallow water reef organisms have not been studied in the region, and the interplay of major benthic groups has been poorly documented. There are known to be large temporal variations in key organisms such as corals as a result of predation, bleaching or cyclones, but the relative responses within the benthic communities have yet to be characterised locally.

8.3 Mangroves and nearshore ecology

The mainland coast has a thin fringe of mangroves, flanked by intertidal and supra-tidal sand and mudflats, broken periodically by rocky headlands and beaches. The diversity of the mangrove tree communities is diminished (five species) relative to the wet tropics (IMCRA, 1997), but the communities can be structurally complex in some areas of the mainland and they are significant scientifically as key examples of arid zone mangle. The ecological role of these mangroves in the coastal ecosystem is poorly understood in comparison to wet tropics mangroves. It is presumed (IMCRA, 1997) that they are important. There are studies inferring important trophic links between mangroves and nearshore fauna (Wells, 1983,1984) but there are also data that suggest that the Pilbara mangroves may be less effective as nursery areas than other mangrove

communities (Blaber et al. 1985). Robertson (1993) advocates caution and points out that we do not understand how climatic, geomorphic, hydrological, biological and biogeochemical processes maintain the mangrove communities in the Pilbara region of Western Australia.

Despite these shortcomings in knowledge of processes, Pilbara mangroves have been extensively investigated, including a major recent review (Carr et al. 1996a,b,c). Difficulties in gaining direct access and the large scale of the Pilbara coast are noted in most reports. There is little species diversity among mangrove trees but high diversity among animals such as birds (15 species), crustaceans and molluscs. There is reasonably good understanding of the biogeography, zonation, structure and physiognomy of north-western mangroves in a regional context (Semeniuk, 1993). This knowledge also extends to mangroves around the regional islands such as the Lowendals and Monte Bellos.

Several papers stress the high primary productivity of mangroves relative to other shallow-water systems in the region, but Robertson (1993) states that there are no data describing relative levels of primary production in shallow-water habitats along the Pilbara coast. This gap in information is being partially addressed (McKinnon & Ayukai, 1996; Ayukai et al. 1997; Ayukai & Miller, 1998). There are a few data that suggest that mangroves are linked to coastal foodchains; e.g. mangroves in the Dampier area are nursery grounds for juvenile fish (Blaber, 1984; Blaber et al. 1985), and mangroves receive nutrient inputs from adjacent salt flats (Paling, 1986). The ecology of birds in mangroves, and their trophic links, are particularly important in the Pilbara because the mangroves are the only closed forest type in the region (Johnstone, 1990). Many assumptions have been made about the role of mangroves in supporting secondary coastal production. However, the assumptions are based on mangrove forests elsewhere in the tropics, and may not prove to be true for the North West Shelf. This warning may also apply to recent experiments on the responses of mangroves to oil spills (Duke et al. 1998a,b) which were done at sites on the east coast.

Key aspects of coastal ecology that need further investigation are the nutrient inputs to, and trophic links within, the nearshore environment. In the Pilbara, non-heterocystous cyanobacterial mats cover a large proportion of the extensive saline flats behind the most landward mangroves *Avicennia marina* (Paling, 1986). These algal mats have been shown to be very important for nitrogen fixation (Paling & McComb, 1994), but we do not know if that finding applies everywhere in the region. There may be widespread leaching of large amounts of fixed nitrogen via tidal inundation and sporadic but intense rainfall. Export of nitrogen from algal mats to adjacent mangroves was shown for Nickol Bay, Dampier (Paling & McComb, 1994). Carbon transfer processes are not well documented, although molluscs and crustaceans are likely to play a key role in the detrital cycle and in trophic links out of mangrove systems (Wells, 1984; V & C Semeniuk Research Group, 1995).

9. BIODIVERSITY

9.1 Benthic and demersal

The aspect of biodiversity best documented for the North West Shelf is species richness, which is noted as high for many taxonomic groups (see e.g. Marsh & Marshall, 1983; Rainer, 1991). A few studies provide data on the spatial heterogeneity of the macrobenthos, but in general this community is not well documented, especially at species level, and certainly has not been integrated across phyla into a cohesive spatial database. The accessible shallow water habitats, particularly the coral reefs and islands of the region, exhibit high species diversity associated with habitat diversity and complexity, as has been well recorded for major macroscopic groups, e.g. Hutchins et al. (1978), Berry (1993). Rainer (1991) noted that diverse microhabitats also have a role in supporting a highly biodiverse infauna. Rainer postulated that physical disturbance and predation both contribute to high diversity on the North West Shelf.

On the deeper mid- and outer continental shelf, the major sources of data on species richness have been the fisheries-related research programs of CSIRO and WA Fisheries. Most of this effort by both organisations has focused on the major trawling grounds seaward of the 50 m isobath (see figures 4, 5, 6). The crustaceans and finfish have been best described (for crustaceans, see George & Knott, 1967; George & Clark, 1972; George & Griffin, 1972; Carter et al. 1983; Davis, 1984; Bruce, 1985; Jones, 1986b; Bruce, 1988; Pearce & Phillips, 1988; Penn & Dybdahl, 1988; Ward & Rainer, 1988; Wadley & Morris, 1990; Bruce, 1992; Garvey, 1992; Garvey et al. 1992; Wadley, 1992; Wadley & Evans, 1992; Rainer, 1992a,b; Hanamura, 1994; Jones & Morgan, 1994; Jones, 1996; Hewitt, 1996, 1997; for finfish, see Newman, in progress; Chen et al. 1979; Williams, 1990; Evans, 1992; Garvey et al. 1992; Williams, 1992; Ramm, 1994). With additional attention to existing collections and further studies during these continuing programs, there is potential for a broader ‘landscape ecology’ picture to emerge for the shelf benthic and demersal communities. Links between biodiversity and economics have not been measured, but they are tacitly acknowledged in trawl fishery interactions with the benthos (e.g. Sainsbury, 1982b; Sainsbury & Lindholm, 1986; Sainsbury, 1988; Sainsbury et al. 1993). The potential economic gain from novel chemicals and biological products is implicit in modern collections of organisms linked to biotechnology development, such as the program commenced by AIMS (contact Dr Chris Battershill), and may drive renewed focus on the biodiversity of the North West Shelf.

High diversity, and significant endemism in some cases, has been reported in several major invertebrate groups, including echinoderms (Marsh, 1976), cnidarians, polychaetes (Rainer, 1991) and sponges (Hooper & Levi, 1994). Marsh and co-workers (Marsh & Marshall, 1983), nonetheless, have noted that in some groups, such as echinoderms, the endemism is most marked in the coastal and shelf areas, while the shelf edge reef systems tend to support widespread Indo-Pacific species. Other allozyme-based studies on a limited number of fish, echinoderms and cephalopods suggest that there are extensive genetic connections over large distances (Johnson et al. 1993; Yeatman & Benzie, 1994; Williams & Benzie, 1996). The range of genetic information is very limited. We do not know how much interconnection there is between similar habitats throughout the region, and at what spatial scales.

9.2 Marine mammals

Dugongs (*Dugong dugon*) are observed throughout inshore waters of the region such as in the Dampier Archipelago. The WA Department of Conservation and Land Management (CALM) is the major custodian of dugong data in Western Australia (e.g. Prince et al. 1981; Kojan, 1984; Prince, 1986), but very little of the information is published. Preen (1998) indicates that the dugong has been exterminated from several areas in the Indian Ocean, and it appears to be particularly threatened by mesh netting and hunting. He considers conservation of the Western Australian dugong stocks, notably those in Shark Bay which contains the largest known Indian Ocean population, potentially crucial to conservation of the species in the Indian Ocean region. The North West Shelf region has not been surveyed systematically and the status, local ranges and migratory paths of dugongs in the region are unknown (Marsh, in prep.). The draft national dugong conservation plan (Marsh, in prep.) recommends that baseline information be obtained on dugong abundance, distribution and habitat, and that regular monitoring be started.

Six species of toothed whale and three species of baleen whale are reported from the area (APPEA, 1997; Higgins Wood & Associates, 1995). The Group IV population of humpback whales, which winter off north-west Australia, (Jenner & Jenner, 1995) is historically the largest population of humpback whales in the southern hemisphere. Northward migrating whales can be expected in the area from June, (BHP Iron Ore, 1991; Scott, 1998), while mothers returning with calves may be seen in September–October and during the following few months. Jenner (1998) describes approximate migration routes. Although the published data on cetaceans in the area are limited, a summary of the state of knowledge for the region is being prepared by the Centre for Whale Research, supported by Woodside Energy Pty Ltd, for delivery in 1999.

9.3 Seabirds and waders

The total bird list based on a monitoring program from the Lowendal Islands (Apache Energy Ltd, 1998b) documents 64 species of birds, with seasonal observations covering the period 1992 to 1996. It would be reasonable to assume that this is a conservative estimate for the North West Shelf region. Management of these birds can involve both State and Commonwealth responsibilities. For example, in the Monte Bello Island area three bird species, the lesser noddy (*Anous tenuirostris melanops*), the beach stone curlew (*Esacus neglectus*) and the fairy tern (*Gygis alba*) appear listed as protected under the Western Australian Wildlife Conservation Act, while the little tern (*Sterna albifrons sinensis*) has protection under both State and Commonwealth legislation. A significant number of migratory species recorded from the North West Shelf area are subject to agreements between the Commonwealth and the governments of China and Japan (see Heyward, 1999). The ecology of seabirds has received some attention, notably from a research group at Murdoch University which has developed a database of seabird information relevant to the region. These data (contact Nick Dunlop) may be suitable for linking to a GIS system. The foraging ranges of some bird species provide tangible evidence of trophic links between wide areas in the region. For example, the preferred feeding range of the Wedge-tailed Shearwater is reported as 40 to 120 km from the nesting colonies (Astron Environmental Pty Ltd, 1997) on mid shelf islands such as the Monte Bello–Lowendal–Barrow group.

9.4 Turtles

Four species of turtle, all of which are migratory, have been reported to inhabit and/or nest in the region (e.g. APPEA, 1997), although few papers provide information on their local ecology. A summary of knowledge for the Monte Bello–Barrow Islands area is provided by Pendoley (1998), while broader ranging data and information, including tagging program data from the Dampier Archipelago, are available from CALM (contact Dr Bob Prince). CALM is the custodian of data on Western Australian turtles, and some important data have been published (e.g. Prince, 1994, 1998), but a large amount of information is only available via personal communication.

There is some separation of nesting grounds; for example, the loggerheads feature strongly in the Murion Islands area, while the green, flatback and hawksbill turtles have a substantial presence in the Monte Bello–Lowendal–Barrow Islands region (Pendoley, pers. comm.; APPEA, 1997; Pendoley, 1998). Nesting occurs between late spring and early autumn, but is principally a summer activity on the offshore islands and some areas of Mainland beach.

We do not know the local feeding ecology and home ranges of these species when they are in the Pilbara. Consequently, we cannot determine if these species spend most time foraging over the extensive shallow areas around nesting beaches or if they range into deeper water, such as the mid shelf areas, foraging for fauna such as the sponges found in these mid shelf habitats. Similarly there is very limited information on the turtles' migratory paths, although links to Indonesia have been proposed for some species (Pendoley, 1998).

9.5 Cave fauna

A cave fauna of international importance exists in the region, extending northwards from Cape Range National Park through at least some of the cavity filled limestone islands (Humphreys, 1996). The fauna appear to be relict rainforest fauna, with origins 60 000 years ago. Humphreys (1996) considers that the troglofauna of Cape Range Peninsula and Barrow Island comprise one of the world's best examples of subterranean fauna. The subterranean water-filled voids contain both marine and freshwater species, which demonstrate extreme levels of endemism.

10. MARINE ENVIRONMENTAL MANAGEMENT

The bibliography (Jernakoff et al. 2006) has 200 citations directly pertaining to environmental management, and the great majority of these are of a supporting nature, describing essential features of natural systems (e.g. Gordon, 1987; Sainsbury, 1988), or human activities that may pose threats to them, or the controls that might be applied (Woods & Lewis, 1990; Novus West Australia Pty Ltd, 1992; Western Mining Corporation, 1995; Ampolex, 1996; Halpern Glick Maunsell, 1996; Paling, 1996; LeProvost Dames and Moore, 1997; Duke et al. 1998a,b,c; Mobil Exploration & Producing Australia Pty Ltd, 1998; Apache Energy Ltd, 1998a,b).

Nearly all the economic, social or scientific uses of the resources in the Pilbara marine and coastal area have management plans and compliance requirements. Planning, evaluation and development phases of industrial activities generate the most documents related to management (EMPs), from both government and private sectors. Ongoing compliance reporting by the developer is a feature of most activities. A notable exception has been the fisheries operators, who have historically not been required to document their potential environmental impacts and subsequent environmental management plans before starting their operations. The industry has funded research into environmental effects, via the Fisheries Research and Development Council (e.g. Moran et al. 1995), but environmental performance requirements appear to differ between the several industry sectors operating in the same ecosystems on the North West Shelf.

A second related group of documents provides information on the environmental management systems used by particular companies and industries. This includes performance audits and quality assurance systems for corporate EMPs (e.g. West Australian Petroleum Pty Ltd, 1994), and several proposed models for fisheries management (Sainsbury, 1988; Stephenson & Dunk, 1996; Looby, 1997).

A range of hydrodynamic models for the North West Shelf (Buchan & Stroud, 1993), including those validated and applied over limited spatial scales, have features of general relevance to environmental management. Models have been developed and compared with observations of water circulation at large spatial scales. Examples include the CSIRO Carnarvon to Darwin model (S. Walker, pers. comm.) and the GEMS barotropic/baroclinic models (GCOM3D, S. Langtry, pers. comm.); models of circulation driven by cyclones (Stroud, 1978; Fandry et al. 1984; Fandry & Hart, 1988; Fandry & Steedman, 1989, 1994); and models of tidal and wind-driven hydrodynamics at specific locations such as the Dampier Archipelago (Mills, 1985), Exmouth Gulf (Massel & Brinkman, 1997) and the Lowendal Islands (GEMS, S. Langtry, pers. comm.). Very fine scale dispersion from point sources (Burns et al. 1999; King & McAllister, 1998 and others) has also been modelled effectively. In combination, these models demonstrate a high level of capability to deal with circulation related problems on the North West Shelf.

There are some examples where these circulation-related models have been further developed into decision support tools, e.g. King et al. (1996). Risk management and response planning for the effects of oil spills and discharges have generated local applications of computer models for the trajectories of spills and point source pollutants, and the models have been completely validated on the North West Shelf (e.g. Apache Energy Ltd, 1998b). Of these, the OILMAP and MUDMAP systems have been adopted

by several petroleum industry operators on the North West Shelf. Integrated ecosystem management has not been attempted on the North West Shelf, but reform appears imminent at the State level (Donaldson et al. 1995; Kay & Lester, 1997; Kay et al. 1997) and a third category of management related models is likely to be used in this context.

CALM is refining a consensus-building decision support tool (Simpson & Bancroft, 1998) for the management of multiple use marine protected areas. A key element for such an approach is spatial information about values and uses in the context of marine areas. It has been noted that such information is generally lacking for important ecosystems along the Western Australian coast (Marine Parks and Reserves Selection Working Group, 1994). It is apparent that for certain areas of the North West Shelf, industrial activity has enabled a significantly higher proportion of information relevant to the environment to be captured than for most other areas. The challenge will be to integrate this resource into a functional model for management.

11. CONCLUSION

The history of development and scientific research on the North West Shelf has created unique challenges in data integration. Published scientific literature is only the tip of the 'iceberg' of North West Shelf studies. Research by industry or consultants has collected most of the data relevant to marine environmental management, the majority of which have not been published in peer-reviewed literature, and little has been released to the general public. Some valuable information exists only as the personal knowledge of individual researchers, consultants, fishers and local residents.

In addition, the pressure on State and Commonwealth agencies to recover costs has meant that much of the data collected by the Bureau of Meteorology, the Royal Australian Navy, AGSO, CSIRO, AIMS, WA Transport, CALM, Curtin University, the University of Western Australia, the Australian Defence Force Academy, and the DEP is considered intellectual property. One significant contribution that the NWSMEMS can make is to broker agreements among the various stakeholders to allow access to a wider range of data. Removal of economic and administrative barriers will allow these rich but presently disparate data holdings to be incorporated into databases and geographic information systems and integrated scientifically.

There are several aspects of marine management for which additional research is needed before decisions can be made on a sound scientific basis. The data already collected by industry, state agencies, AIMS and CSIRO will meet some of these research needs, but numerous additional studies are required or desirable. They have been listed in the Summary at the beginning of this report. This brief review should help scientists and managers set priorities for future research for the North West Shelf.

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