NORTH WEST SHELF
JOINT ENVIRONMENTAL
MANAGEMENT STUDY

Final report

NWSJEMS

North West Shelf
Joint Environmental Management Study

June 2007

CSIRO

Government of Western Australia
Department of Environment

National Library of Australia Cataloguing-in-Publication data:

North West Shelf joint environmental management study final report.

Bibliography.
Includes index.
ISBN 9781921232800 (web).

1. Ecosystem management - Western Australia - North West Shelf. 2. Marine ecology - Western Australia - North West Shelf. 3. North West Shelf (W.A.) - Environmental aspects. I. Western Australia. II. CSIRO. Marine and Atmospheric Research. III. Title.

577.709941

North West Shelf joint environmental management study final report.

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ISBN 9781921232817 (hbk.).

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List of technical reports

NWSJEMS Technical Report No. 1
Review of research and data relevant to marine environmental management of Australia's North West Shelf.
A. Heyward, A. Revill and C. Sherwood

NWSJEMS Technical Report No. 2
Bibliography of research and data relevant to marine environmental management of Australia's North West Shelf.
P. Jernakoff, L. Scott, A. Heyward, A. Revill and C. Sherwood

NWSJEMS Technical Report No. 3
Summary of international conventions, Commonwealth and State legislation and other instruments affecting marine resource allocation, use, conservation and environmental protection on the North West Shelf of Australia.
D. Gordon

NWSJEMS Technical Report No. 4
Information access and inquiry.
P. Brodie and M. Fuller

NWSJEMS Technical Report No. 5
Data warehouse and metadata holdings relevant to Australia's North West Shelf.
P. Brodie, M. Fuller, T. Rees and L. Wilkes

NWSJEMS Technical Report No. 6
Modelling circulation and connectivity on Australia's North West Shelf.
S. Condie, J. Andrewartha, J. Mansbridge and J. Waring

NWSJEMS Technical Report No. 7
Modelling suspended sediment transport on Australia's North West Shelf.
N. Margvelashvili, J. Andrewartha, S. Condie, M. Herzfeld, J. Parslow, P. Sakov and J. Waring

NWSJEMS Technical Report No. 8
Biogeochemical modelling on Australia's North West Shelf.
M. Herzfeld, J. Parslow, P. Sakov and J. Andrewartha

NWSJEMS Technical Report No. 9
Trophic webs and modelling of Australia's North West Shelf.
C. Bulman

NWSJEMS Technical Report No. 10
The spatial distribution of commercial fishery production on Australia's North West Shelf.
F. Althaus, K. Woolley, X. He, P. Stephenson and R. Little

NWSJEMS Technical Report No. 11
Benthic habitat dynamics and models on Australia’s North West Shelf.
E. Fulton, B. Hatfield, F. Althaus and K. Sainsbury

NWSJEMS Technical Report No. 12
Ecosystem characterisation of Australia’s North West Shelf.
V. Lyne, M. Fuller, P. Last, A. Butler, M. Martin and R. Scott

NWSJEMS Technical Report No. 13
Contaminants on Australia’s North West Shelf: sources, impacts, pathways and effects.
C. Fandry, A. Revill, K. Wenziker, K. McAlpine, S. Apte, R. Masini and K. Hillman

NWSJEMS Technical Report No. 14
Management strategy evaluation results and discussion for Australia’s North West Shelf.
R. Little, E. Fulton, R. Gray, D. Hayes, V. Lyne, R. Scott, K. Sainsbury and D. McDonald

NWSJEMS Technical Report No. 15
Management strategy evaluation specification for Australia’s North West Shelf.
E. Fulton, K. Sainsbury, D. Hayes, V. Lyne, R. Little, M. Fuller, S. Condie, R. Gray, R. Scott, H. Webb, B. Hatfield, M. Martin, and D. McDonald

NWSJEMS Technical Report No. 16
Ecosystem model specification within an agent based framework.
R. Gray, E. Fulton, R. Little and R. Scott

NWSJEMS Technical Report No. 17
Management strategy evaluations for multiple use management of Australia’s North West Shelf – Visualisation software and user guide.
B. Hatfield, L. Thomas and R. Scott

NWSJEMS Technical Report No. 18
Background quality for coastal marine waters of the North West Shelf, Western Australia.
K. Wenziker, K. McAlpine, S. Apte, R.Masini

CONTENTS

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

SUMMARY

Results of the North West Shelf Joint Environmental Management Study (NWSJEMS) have been documented in a series of 18 Technical Reports (listed at the beginning of this report and available at http://www.marine.csiro.au/nwsjems). This final summary report attempts to provide a broad overview of the study, its products, and the enhanced scientific understanding that has emerged from the work.

Western Australia's North West Shelf is one of the most economically significant coastal and sea regions in Australia. It produces the majority of Australia's domestic and exported oil and gas and its ports carry most of the nation's iron ore exports. The infrastructure supporting these and other industries is concentrated along the coastal fringe or in offshore facilities. These areas are also characterised by habitats of high ecological value, such as mangrove forest, seagrass beds, coral reefs, and sponge beds. These habitats support a diverse fish community, as well as listed species such as dugongs, turtles and whale-sharks.

Maintaining the region's environmental assets during a period of rapid industrialisation poses major challenges for all stakeholders in the North West Shelf region. The Western Australian Government recognises that a collaborative and informed approach is essential in balancing and managing multiple-uses of the North West Shelf ecosystem. As a result, NWSJEMS was established to support ecologically sustainable development of the North West Shelf region.

NWSJEMS was a A$7.7m marine environmental study of the North West Shelf, jointly funded by CSIRO and the Western Australian Government. The overarching objective was to develop and demonstrate practical science-based methods that could support integrated regional planning and multiple-use management of the North West Shelf marine ecosystems.

The first major component of the study was compiling, extending and integrating information and understanding of the ecosystems and human activities of the North West Shelf. This included reviews of existing information, collation of existing data, filling key gaps through collection of new data, and development of new data products such as maps and habitat classifications.

The second component was the development of a range of ecological models that combined data products with process understanding to generate new insights into the dynamics of the North West Shelf system and provide a predictive capability. The models included ocean currents and connectivity, sediment transport, nutrient cycling and primary production, food web interactions, and habitat dynamics.

The third component was the development of a new modelling framework for evaluating the effectiveness of strategies for managing major sectors operating on the North West Shelf. This required representation of the ecosystem, the human sectors, and a simulated monitoring and management decision process. The framework was used to evaluate management strategies under various scenarios, taking into account known uncertainties, so as to identify strategies that could robustly meet management objectives.

The fourth component was integral to the success of the study. It was the development of tools that allowed both study participants and a broader user group to access, explore and retrieve study results, including data products and model outputs. Where feasible, these were developed as online interactive tools or distributed on DVD.

1. INTRODUCTION

1.1 Background and rationale for the study

The North West Shelf Joint Environmental Management Study (NWSJEMS) was a A$7.7m marine environmental study of Australia's North West Shelf (NWS) jointly funded by the Western Australian Government and the CSIRO. The study focused on the region from the Pilbara coastline out to the edge of the shelf as represented by the 200 m isobath (figure 1.1.1).

Western Australia's North West Shelf is one of the most economically significant coastal and sea regions in Australia, contributing more than A$15 billion annually to the national economy. It produces the majority of Australia's domestic and exported oil and gas, and its ports carry more than 95% of the nation's iron ore exports. The region also hosts a number of other important industries including salt production, commercial fisheries, and a rapidly expanding tourism industry. With this development comes a larger human population and increasing demand for infrastructure and services, which in the arid Pilbara region tends to be strongly concentrated along the coastal fringe.

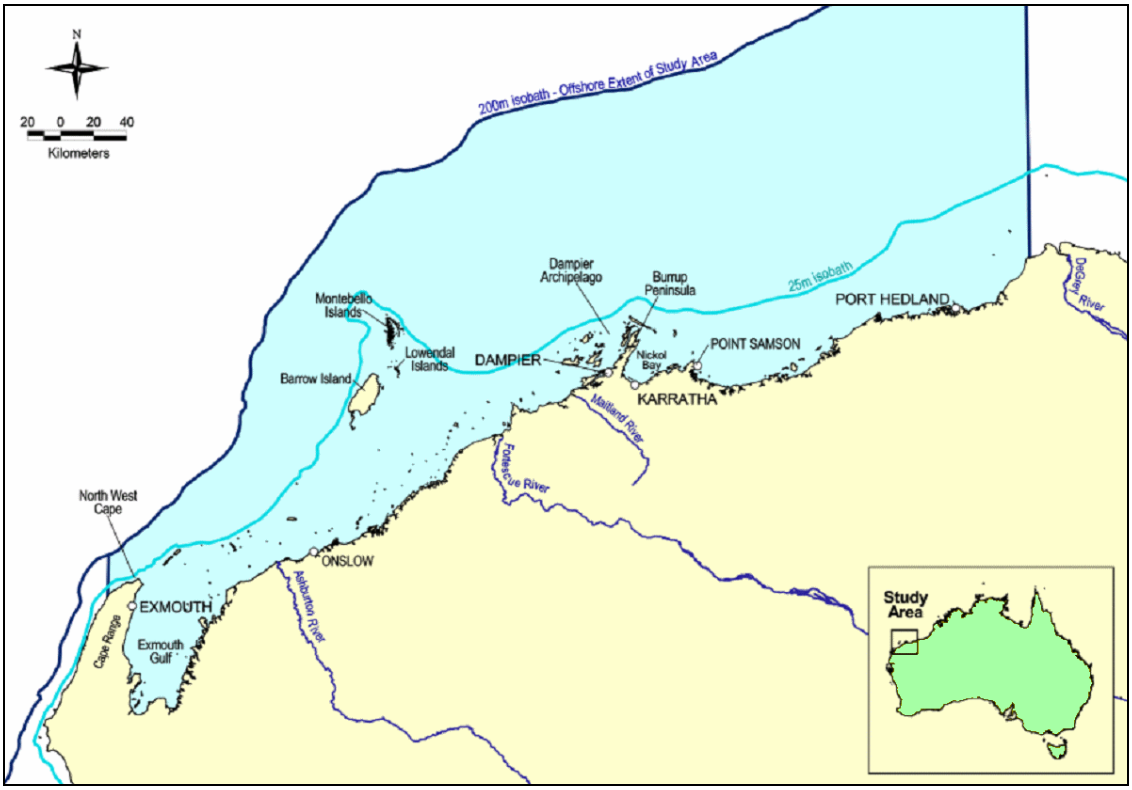


Figure 1.1.1: Site map indicating the core study area for NWSJEMS extending from North West Cape in the west almost to De Grey in the east and offshore to the 200 m isobath.

The North West Shelf is also characterised by many natural features considered to be of high ecological value (figure 1.1.2). These include coastal and shallow water habitats such as mangrove forests, seagrass beds and coral reefs, and shelf habitats built around complex sponge communities. These habitats support a diverse fish community, as well as listed species such as dugongs, turtles and whale-sharks.

Prior to NWSJEMS, many of the potential impacts of industrial development on the natural ecosystem had received little attention, with existing information being scattered and difficult to access and integrate. The rapid rate of growth has also led to complex, and somewhat fragmented, management and regulatory structures. However, the Western Australian Government recognised that a collaborative and informed approach is essential in balancing and managing the many uses of the North West Shelf ecosystem. As a result, NWSJEMS was established to support ecologically sustainable development of the North West Shelf region.

Figure 1.1.2: Natural assets of the North West Shelf.

1.2 Study objectives

The objective of NWSJEMS was to develop and demonstrate practical and science-based methods that support, under existing statutory arrangements, integrated regional planning and multiple-use management of the North West Shelf marine ecosystems. The two key activities supporting this objective were to:

1. compile, extend and integrate the scientific information and understanding of the marine and coastal ecosystems of the North West Shelf; and
2. develop and demonstrate practical, science-based methods that directly support integrated marine planning and management for ecologically sustainable development of the North West Shelf.

Achieving this ambitious objective required the development of a broad range of sophisticated new data management tools that would support the collation, retrieval, integration and display of key information. It also required modelling tools that would support data extrapolation, scenario exploration and allow evaluation of management strategies in terms of policy or management objectives.

1.3 Study results and outcomes

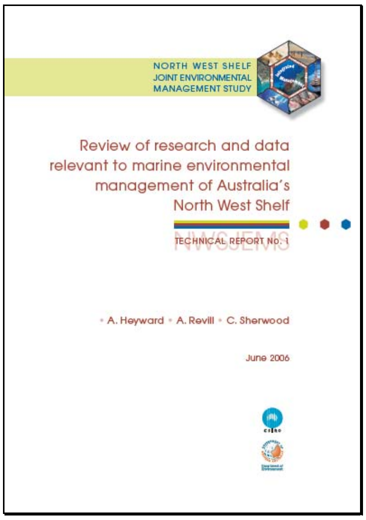
The results of NWSJEMS have been documented in a series of 18 technical reports covering reviews of pre-existing information, accessing information, modelling physical and biological processes, characterising human activities and impacts, and evaluation of management strategies (figure 1.3.1). All reports are available at: http://www.marine.csiro.au/nwsjems

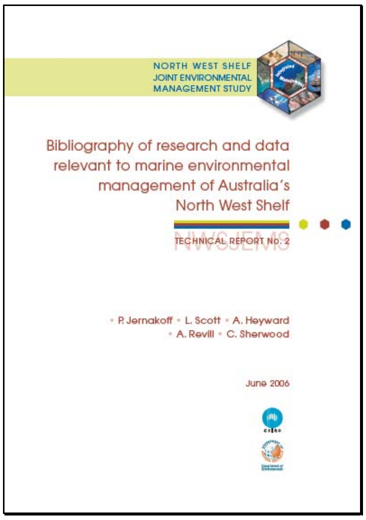
This final report attempts to give a broad overview of the products and enhanced scientific understanding generated by NWSJEMS.

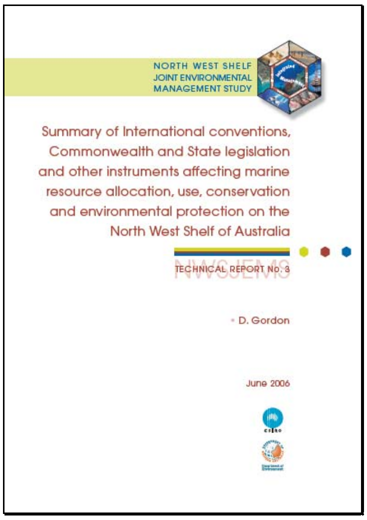
While many of the outcomes of NWSJEMS will only become evident over time, the study has already had very significant impacts on research directions that extend well beyond the North West Shelf environment. Many of the tools and methodologies have been extended and adopted in other applications (figure 1.3.2). Experience gained through the sequential development of alternative model representations has led to significant advances in ecosystem model structure and implementation, both within Australia and overseas. The next generation of management strategy evaluation models now being developed for regional applications, such as Ningaloo Reef, will be the first such agent-based models to include an extensive dynamic foodweb. The modelling advances made during NWSJEMS have also strongly influenced the development of a range of other ecosystem models currently being applied in New South Wales, Victoria, the Antarctic, the west coast of the USA, and Mexico.

While the datasets and tools developed by the study are starting to be used both within Western Australian management agencies and by industries operating on the North West Shelf, the broader implications for sectoral management approaches on the North West Shelf will only emerge over the longer term. Another avenue through which this may occur is the Commonwealth’s bioregional planning process in the North West Marine Region, where NWSJEMS represents a large proportion of the total available information and system understanding.

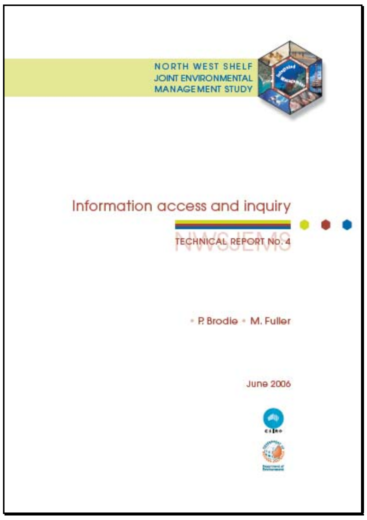
Collations of pre-existing information

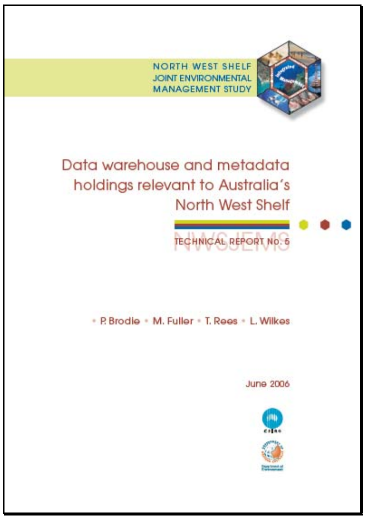


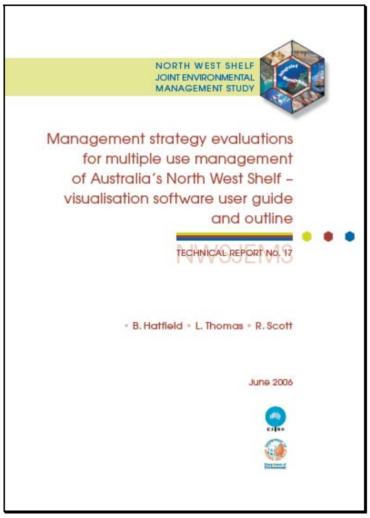




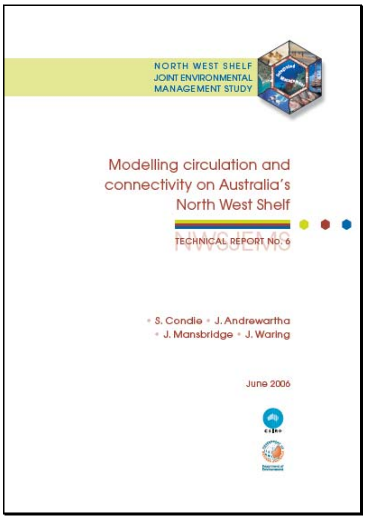
Accessing information from the study

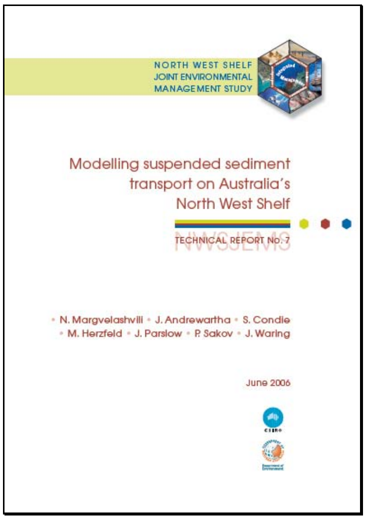






Physical and biogeochemical processes





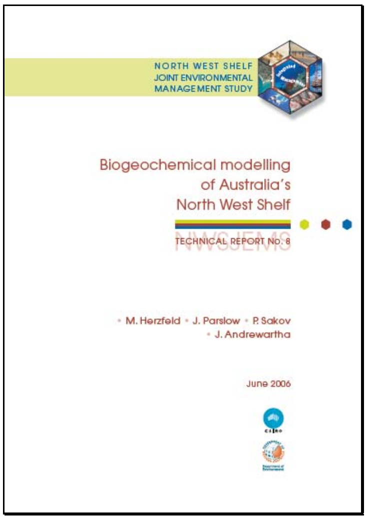
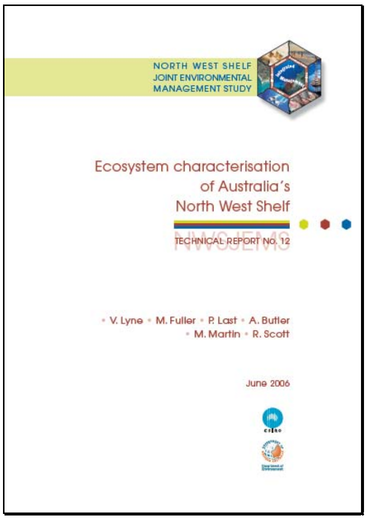
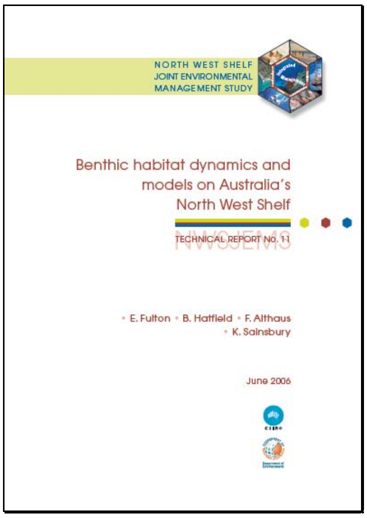
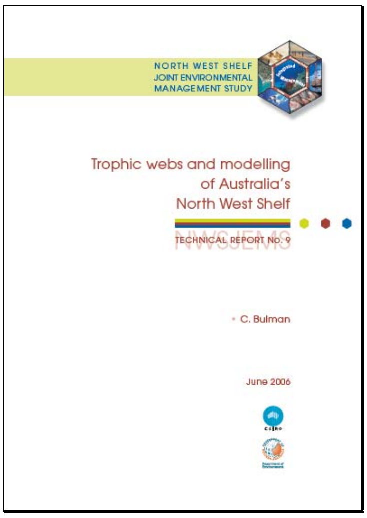


Figure 1.3.1: NWSJEMS technical reports available at http://www.marine.csiro.au/nwsjems.

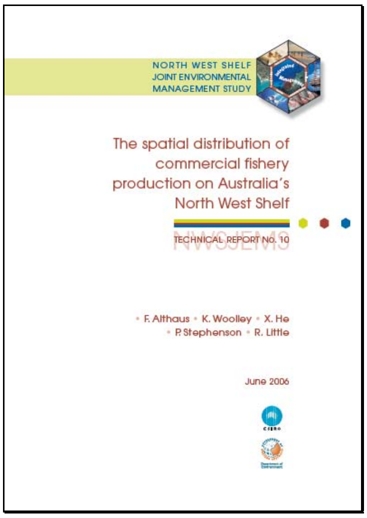
Habitats and foodwebs

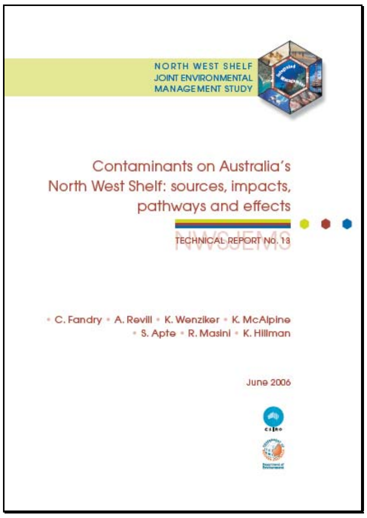


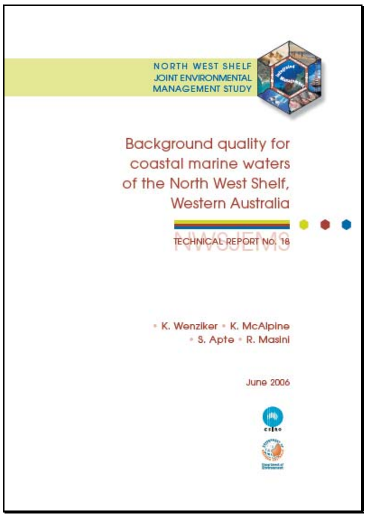




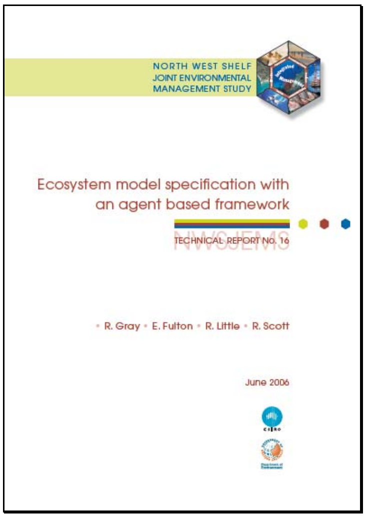
Human impacts

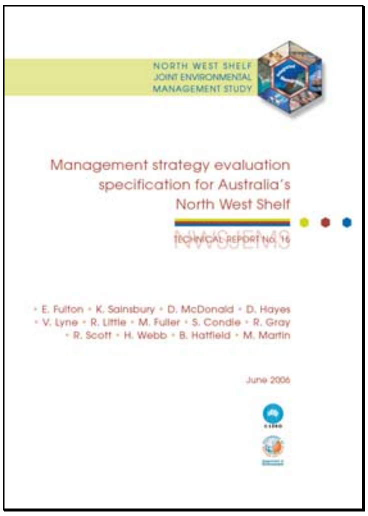






Management strategies





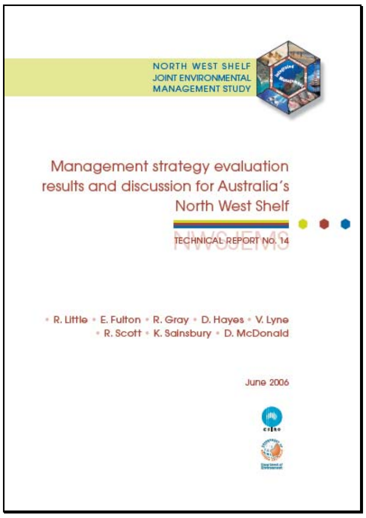
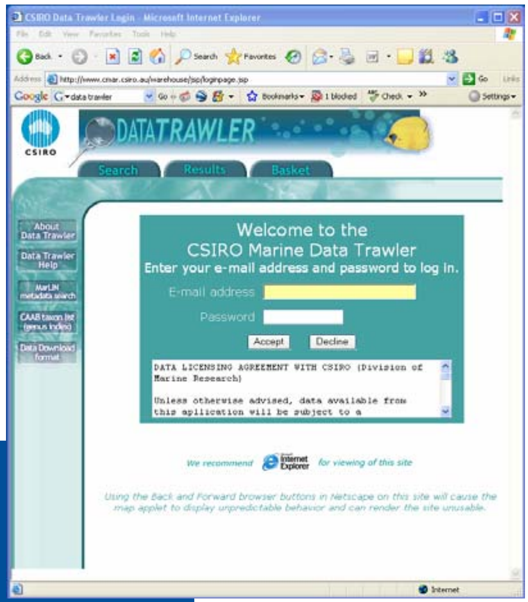
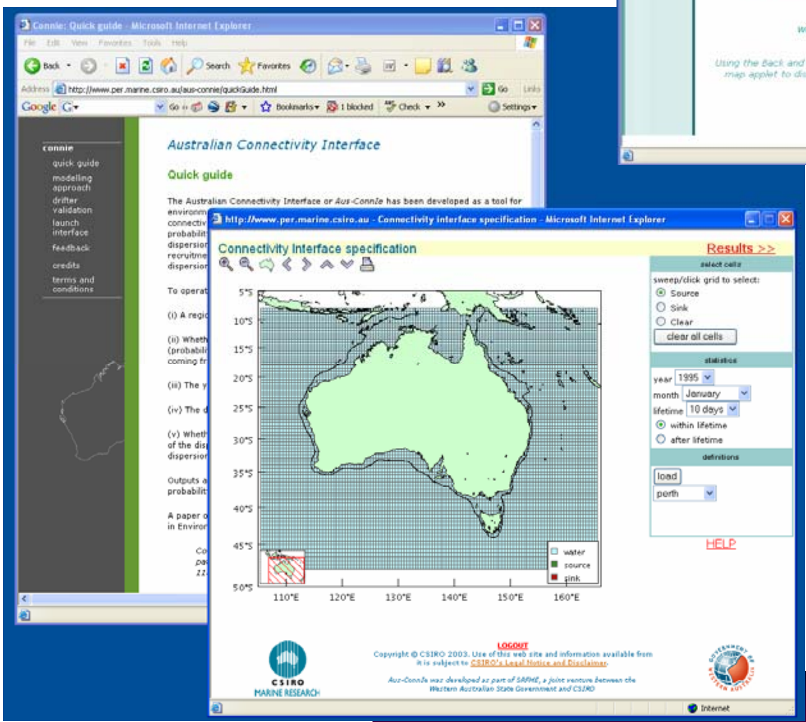


Figure 1.3.1: (continued).

The web-based tool *Data Trawler* developed by NWSJEMS is now the standard tool for online identification and retrieval of marine data held by CSIRO.





The connectivity interface (*ConnIe*) developed by NWSJEMS as a web-tool for scientists and managers to investigate spatial connectivity on the North West Shelf has subsequently been extended into a nation-wide resource.

Techniques developed by NWSJEMS to regionalise the North West Shelf based on ecological considerations have subsequently been adopted for the National Marine Bioregionalisation of Australia.

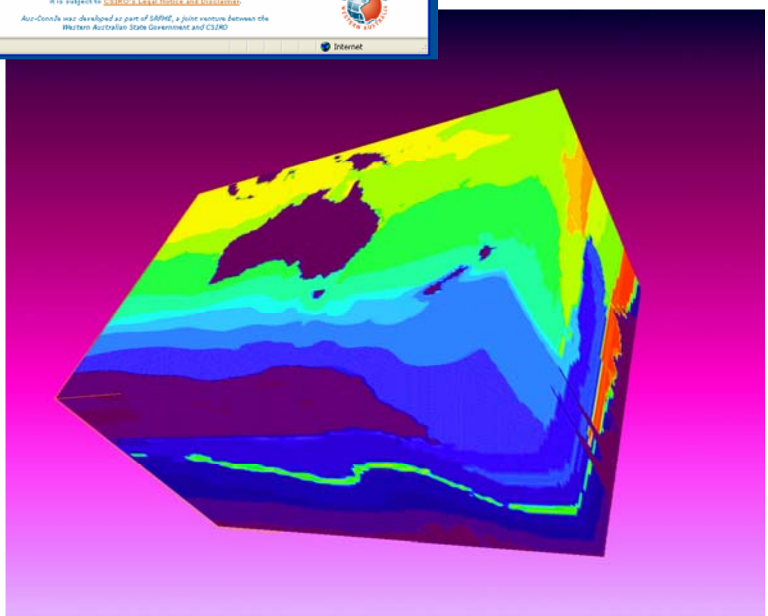


Figure 1.3.2: Examples of the broader impacts and benefits flowing from NWSJEMS.

2. CHARACTERISTICS OF THE NORTH WEST SHELF ECOSYSTEM

2.1 Water column characteristics

The water properties on the North West Shelf are influenced by large scale currents flowing through the region, including the Indonesian Throughflow and the Leeuwin Current (figure 2.1.1). These influences are strongest in autumn when reinforced by the trade winds, but then diminish during the monsoon. This strong seasonality is not mirrored in the nutrient or phytoplankton distributions because the large scale currents lower the pycnocline in the winter (when stratification is weak and up slope intrusions would ordinarily be greatest), thus inhibiting exchange of nutrient rich deep water with the surface (figure 2.1.1).

The North West Shelf circulation is strongly influenced by semi-diurnal tides, and their amplitude is determined by the spring-neap cycle. On the inner shelf sediment resuspension is largely controlled by tidal currents, so that water column turbidity also rises and falls with the spring-neap cycle. These aspects will be discussed more fully in section 3 in the context of circulation and biogeochemical modelling results.

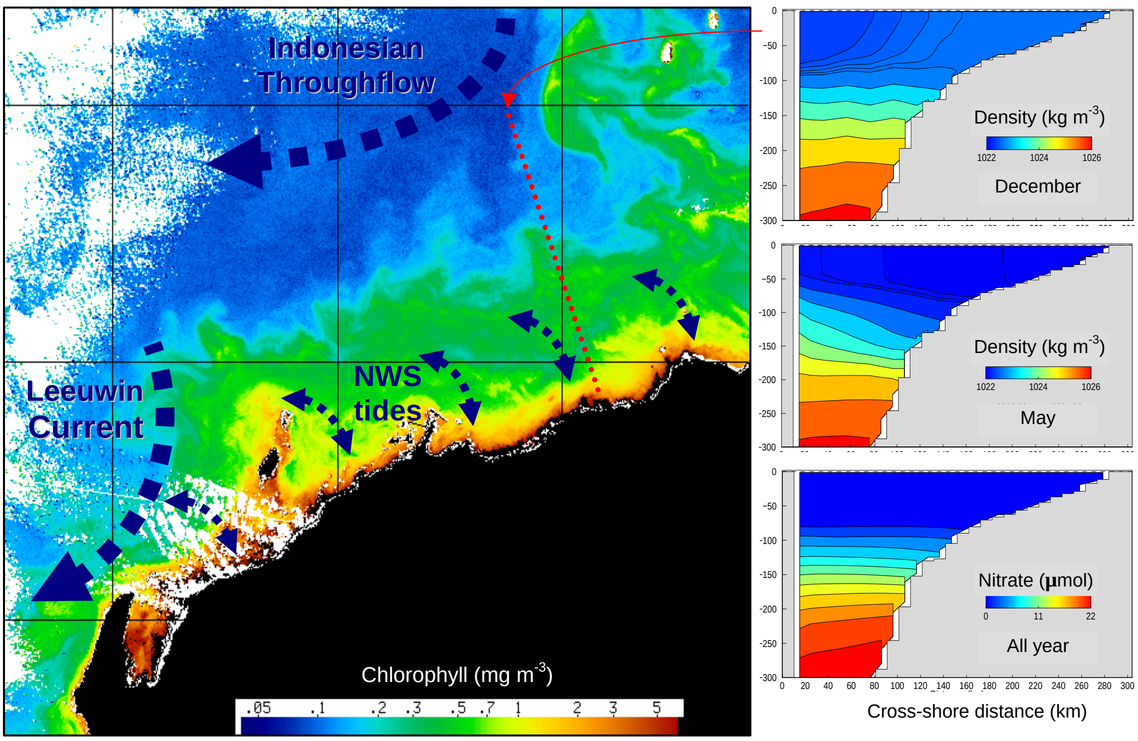


Figure 2.1.1: Dominant currents in the region overlain on Chlorophyll-*a* estimated from *SeaWiFS* satellite data recorded on 30 April 2000 (left). Vertical sections of density during the summer monsoon (top right) and autumn trade winds (centre right), and nitrate representative of the entire year (bottom right) all taken from the *CSIRO Atlas of Region Seas*.

2.2 Benthic habitats

Many species and communities on the North West Shelf depend strongly on key habitats, such as mangroves, seagrasses, macro-algae and sponges, for food and protection from predation. Consideration of habitat dynamics has therefore become an integral part of marine conservation and resource management of the region.

Many key habitats of the North West Shelf are exposed to frequent, and in some cases severe, disturbance. This can arise naturally in the form of tropical cyclones, or through human uses such as development of coastal infrastructure or trawling in coastal and shelf waters. Habitats thus serve as the nexus linking species with natural disturbance and human uses.

Nearshore and offshore community types on the North West Shelf can be distinguished based on physical influences. The coastline predominantly consists of systems of barrier islands and associated protected lagoons that support mangrove communities. The inner shelf consists of gently inclined Pleistocene limestone extending a few kilometres offshore and interspersed by limestone reefs and small islands that support coral communities. Bottom sediments also differentiate habitats, with the nearshore zone characterised by muddy substrates derived from land run-off, transitioning to sandy substrate on the tidally dominated mid-shelf, and then to finer sands and muds of biogenic origin in deeper water.

NWSJEMS collated many disparate sources of information on habitats within the study region including published documents, digital and paper maps, imagery, statistical analyses, and expert information (figure 2.2.1). This information was integrated into a hierarchical habitat classification framework that provided a spatially nested structuring of habitat units (figure 2.2.2).

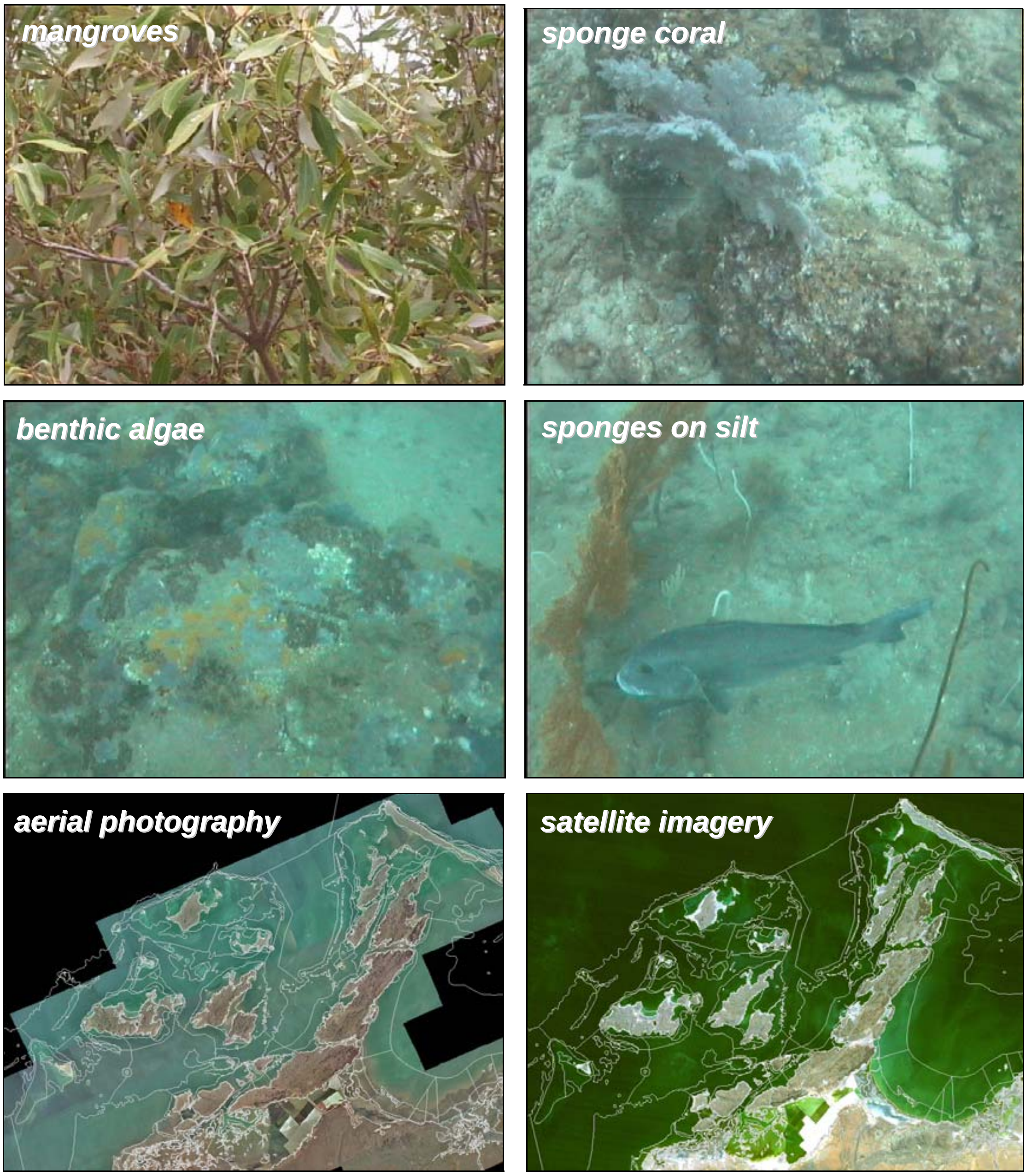


Figure 2.2.1: Examples of habitat related data collated for NWSJEMS. The four video images (upper) were recorded as part of the fieldwork component of the study.

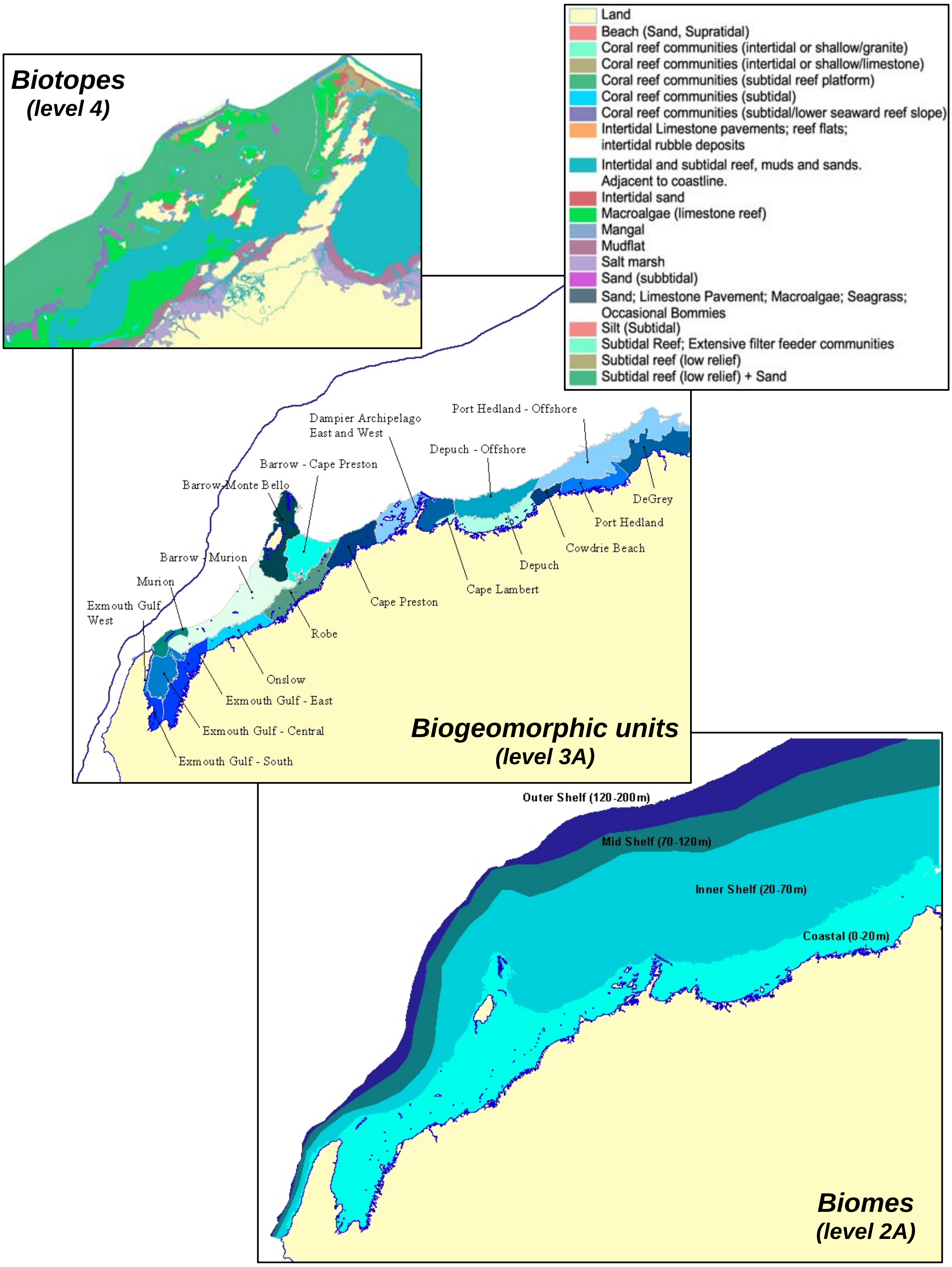


Figure 2.2.2: Levels of habitat mapping for the North West Shelf based on the hierarchical framework. The entire North West Shelf is a province (level 1). Provinces reflect the paleo-evolutionary structuring of the region; biomes reflect the large-scale environmental gradients (depth at level 2A); biogeomorphic units reflect major geomorphic structures or fields (e.g. bays, deltas, island groups); and biotopes reflect more specific habitat types (e.g. intertidal sands, mudflats, coral reefs). Because data is often not available at finer scales, the spatial coverage of the mapping tends to shrink at higher levels in the hierarchy.

2.3 Human activities

The North West Shelf supports extensive industrial activity including commercial fisheries, oil and gas exploration and production, major port operations, salt production, and other forms of coastal development and infrastructure building (figure 2.3.1).

Figure 2.3.1: Infrastructure development on the North West Shelf supporting major industries such as oil and gas production, processing and export of iron ore, and salt production.

A number of foreign and domestic fisheries have operated on the North West Shelf within the last 50 years (table 2.3.1, figure 2.3.2) with fleets currently operating out of Onslow, Dampier, Point Samson and Port Hedland. All of the existing fisheries operate under management restrictions including limited licenses, gear restrictions, and spatial and seasonal closures. Interactions with threatened species (sea snakes, sea turtles) and a large number of fish and invertebrate by-catch species have also led to the recent introduction of bycatch reduction devices in the prawn fleet, along with additional protection of designated nursery areas.

Table 2.3.1: Commercial fisheries operating on the North West Shelf.

Period	Fishery	Target species	Depths	Area
1959 to 1963	Japanese stern trawl	*Lethrinus*	30 to 120 m	116°E to 117°30'E
1972 to 1990	Taiwanese pair trawl	*Nemipterus*, *Saurida*, *Lutjanus*, *Lethrinus*	30 to 120 m	
1979 to 1989	South Korean and Chinese stern trawl			
1984 to present	Domestic trap	*Lethrinus*, *Lutjanus*, *Epinephelus*	20 to 80 m	
1987 to present	Domestic stern trawl	*Nemipterus*, *Saurida*, *Lutjanus*, *Epinephelus*, *Lethrinus*	30 to 120 m	east of 116°45'E
1963 to present	Prawn trawl	Tiger, king, endeavour, banana		Nickol Bay, Onslow, Exmouth Gulf

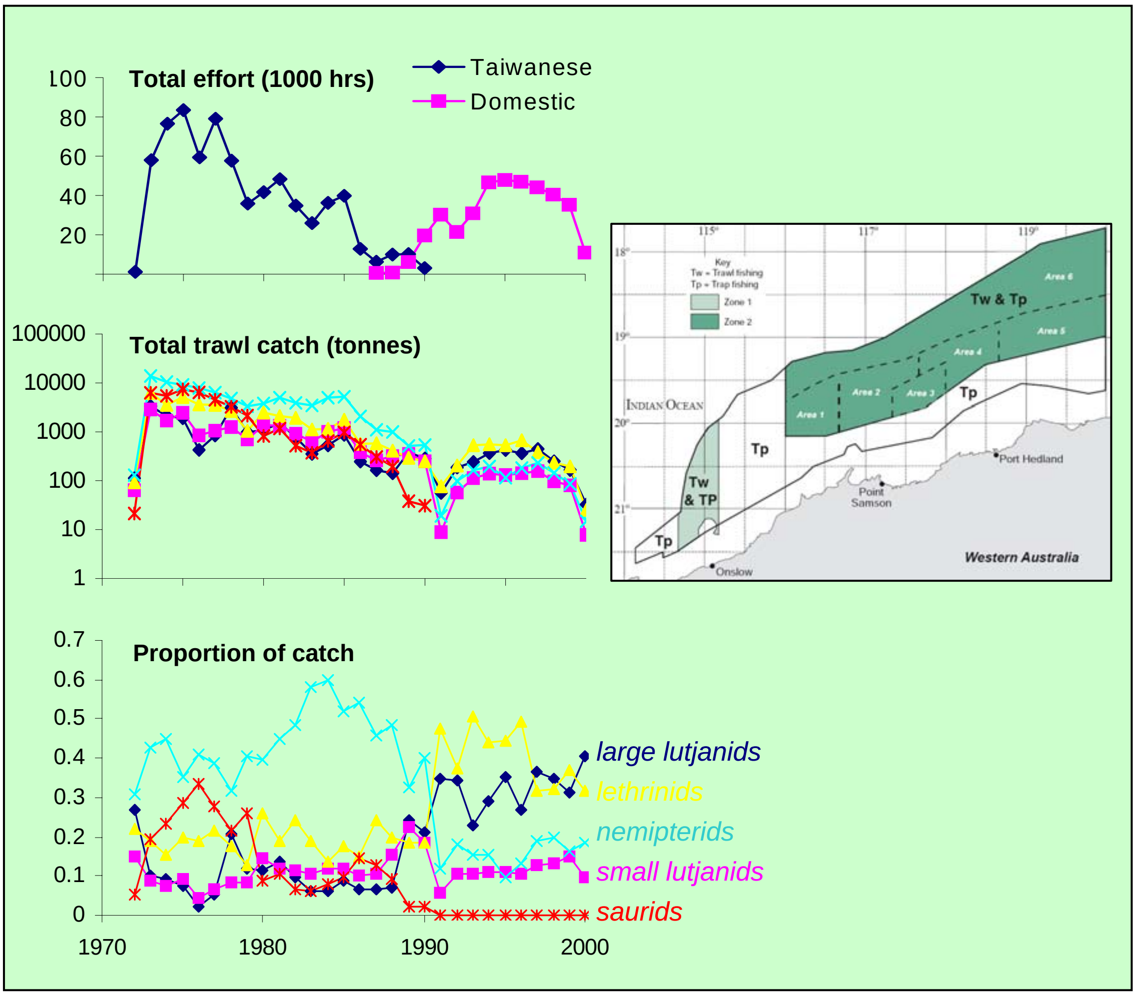


Figure 2.3.2: Data from the Taiwanese (1973 to 1990) and domestic (1987 to 2000) trawl fisheries operating on the NWS. The inset map, taken from the Pilbara Demersal Finfish Fisheries Status Report (http://www.fish.wa.gov.au/docs/sof/2004/), shows the zoning now used to manage the trawl and trap fisheries (Zone 1 has been closed to trawling since 1998).

Industrial activities on the North West Shelf, such as oil and gas production, salt production, waste water treatment, power generation and shipping, are responsible for a range of point and diffuse source contaminant inputs (figure 2.3.3). Effective environmental management relies on an understanding of the sources, types and quantities of wastes discharged and their environmental consequences.

A database of annual loadings of point source contaminants discharged into North West Shelf waters was compiled for the period 1985 to 2001 and their chemical transformations, pathways and potential biological impacts were reviewed. The contaminants included toxicants such as heavy metals (barium, cadmium, chromium, copper, lead, mercury and zinc), petroleum compounds (produced formation water and oil), nutrients (nitrogen), and organometalloids (tributyltin or TBT).

Water quality analyses were also undertaken as part of NWSJEMS, confirming that contaminant levels in coastal waters were generally well below ANZECC and ARMCANZ guidelines. While all the available data suggested that any acute effects on the North West Shelf are likely to be highly localised, chronic and cumulative effects are still poorly understood and were identified as a major source of uncertainty in development of impact models.

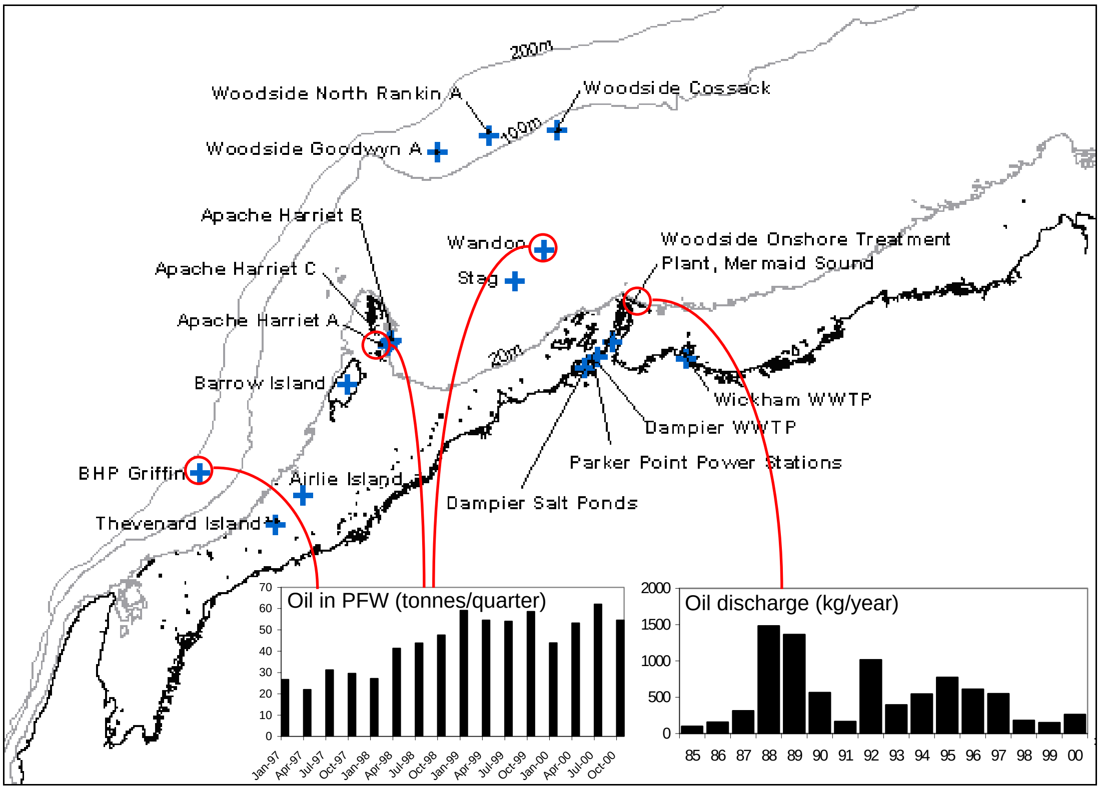


Figure 2.3.3: Main contaminant discharge locations within study area and example time-series of oil discharge rates linking to the most significant discharge sites. In 2000, 12 million tonnes of produced formation water (PFW) containing 214 tonnes of oil was discharged from nine offshore petroleum facilities. This equates to 6.5% of the estimated 3300 tonnes of oil naturally seeping into North West Shelf waters.

3. ECOLOGICAL PROCESSES ON THE NORTH WEST SHELF

3.1 Ocean currents and connectivity

Ocean circulation on the North West Shelf influences nearly all aspects of the ecosystem, including sediment transport and turbidity patterns, primary production in the water column and bottom sediments, and recruitment patterns for organisms with pelagic phases in their life cycles. Currents are also of direct interest to most industries operating on the North West Shelf, particularly those associated with fisheries, shipping, and offshore structures and operations.

NWSJEMS was the first attempt to describe the water circulation and transport patterns across the region on time scales from hours to years, and space scales from 10 km over the entire shelf to one kilometre in a selected focus area around the Dampier Archipelago. It also provided a framework for embedded models describing processes such as sediment transport, nutrient cycling, and primary and secondary production (section 3.2).

A series of nested circulation models were developed (figure 3.1.1) with forcing by realistic winds, tides, and large-scale regional circulation. The simulations covered a period of more than six years, allowing the tidal, seasonal, and interannual characteristics to be investigated, as well as the response to episodic events such as tropical cyclones.

Model results showed that the instantaneous current patterns are strongly dominated by tides and its spring neap cycle. However, longer-term transports over the inner and mid shelf were mainly controlled by wind-driven flow, which followed the seasonal switch from summer monsoon winds to southeasterly trades in winter. Over the outer shelf and slope the large-scale regional circulation also had a major influence.

Connectivity patterns throughout the shelf were also characterised by forcing a particle transport model with the modelled circulation (figure 3.1.2). Results have been summarised in statistical form and can be accessed through a web tool developed as part of the study and referred to as the Connectivity Interface or *ConnIe* (http://www.per.marine.csiro.au/connie). This tool is finding applications in areas such as larval dispersion and recruitment studies, and the development of scenarios and risk assessments for contaminant dispersion and invasive species.

3.2 Sediment transport

The distributions and movements of sediments on the North West Shelf have a major influence on the ecosystem, primarily through their effect on primary production and benthic habitat distributions. They are also highly relevant to human activities, particularly construction and maintenance of offshore structures, dredging, and other developments that modify habitats.

NWSJEMS provides a general characterisation of the distributions of suspended and bottom sediments based on available data. These data confirm the existence of a high turbidity zone extending from the coastline to around the 20 m isobath. Bottom sediments also show a marked cross shelf zonation, with gravel and sand dominating the inner shelf, and finer sand, silts and clays dominating the less energetic outer shelf.

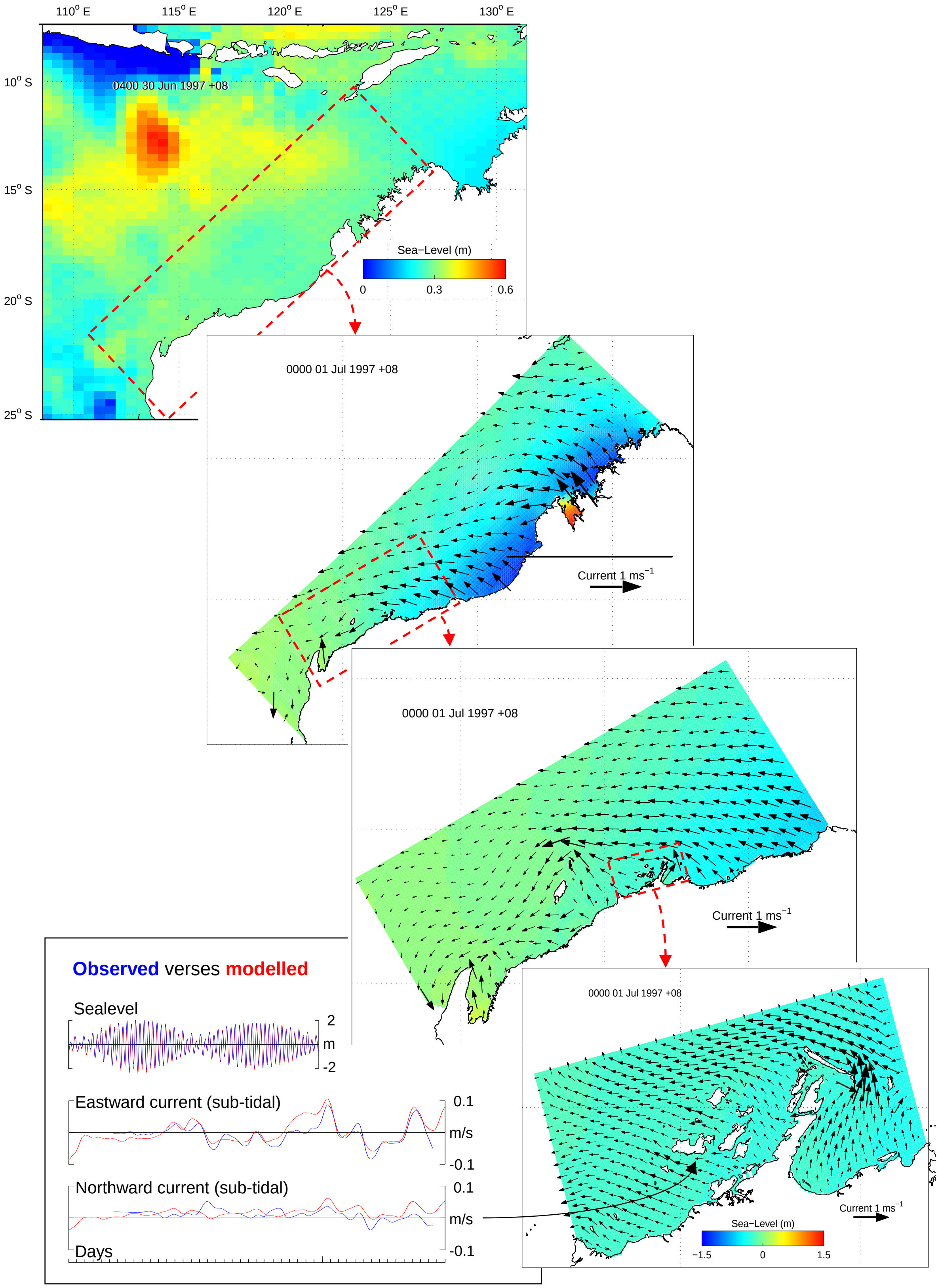
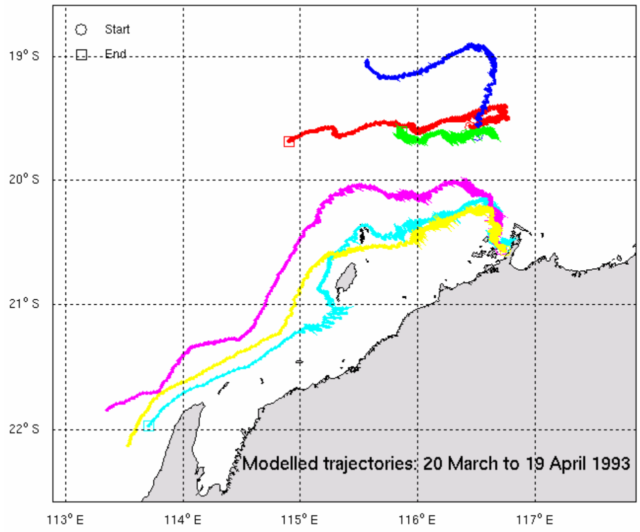


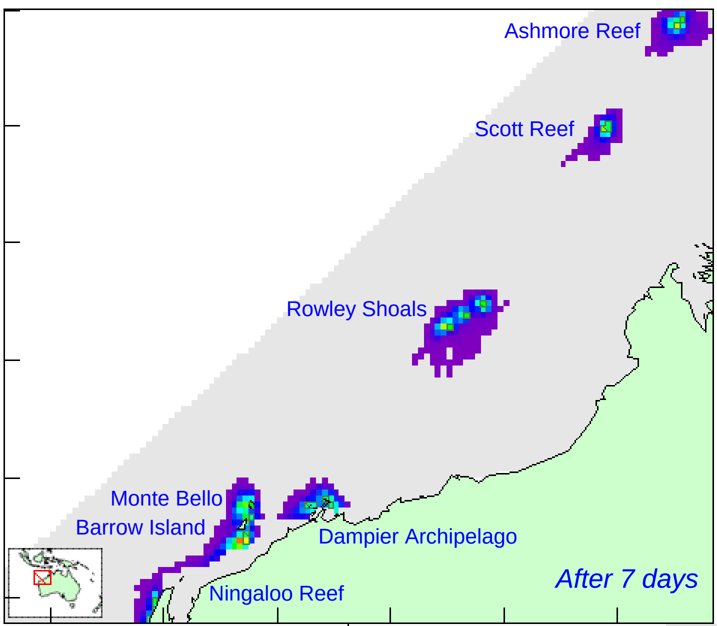
Figure 3.1.1: Example outputs from the circulation models nested from global scale down to local scale around the Dampier Archipelago. Sea level is indicated by colour and surface current strength and direction by arrows. Examples of comparisons with observed time-series are also shown (bottom left).

http://www.per.marine.csiro.au/connie

Individual trajectories of particles released within two small areas simultaneously and tracked for 30 days. The trajectories diverge quite rapidly, suggesting the need for a statistical description as provided by the study in the web tool *ConnIe*.



Connectivity distributions from coral reef sources during the coral spawning period. After seven days (left) there was significant transport from Monte Bello and Barrow Island to Ningaloo Reef.
After 28 days (below) there was also some exchange from Ashmore to Scott Reef.



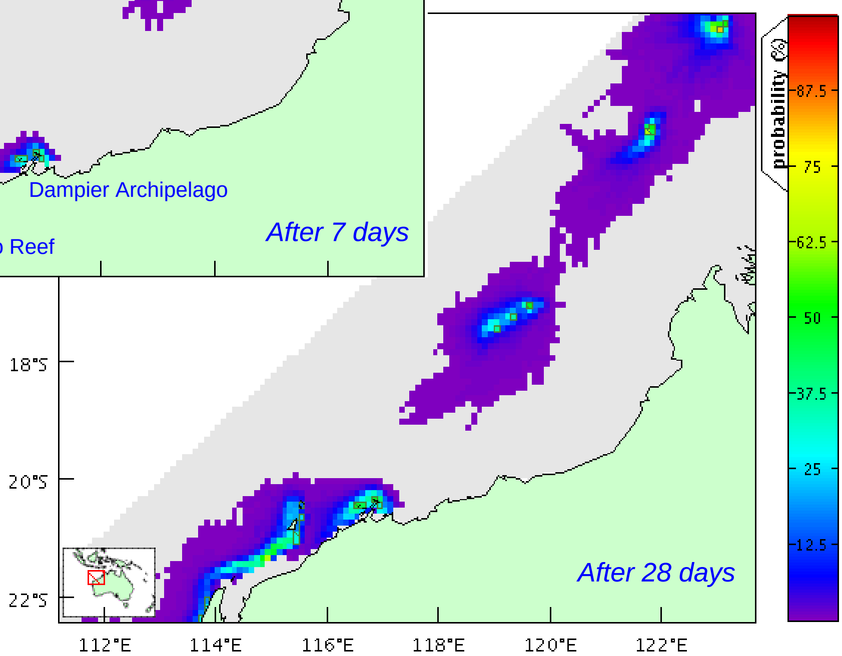


Figure 3.1.2: Example particle trajectories derived using the circulation model (upper) and connectivity statistics, based on thousands of such trajectories, generated using the ConnIe web interface (lower).

The sediment transport model was imbedded within the circulation model and used to estimate resuspension, deposition, and suspended transport patterns over the NWS. The simulations successfully reproduced the observed cross shelf zonation, with gravel and sand dominating the inner shelf, and finer sand, silts and clays dominating the less energetic outer shelf (figure 3.2.1). The model also predicted a persistent strip of elevated suspended sediment concentrations along the inner shelf, peaking during spring tide (figures 3.2.1 and 3.2.2).

Long-termed average sediment fluxes were directed southwest along the shelf and off the shelf. While there were significant uncertainties associated with these fluxes, the results suggested that sediment losses from the shelf exceeded the mean annual river loads by at least a factor of three over the simulation period.

The model also predicted major sediment transport events during tropical cyclones, with off-shelf loads during Tropical Cyclone Bobby, in 1995, exceeding annual loads during non-cyclone years by more than an order of magnitude (figure 3.2.3). These simulations also demonstrated how cyclone-induced ocean eddies could capture large quantities of suspended sediments and carry them offshore to be deposited as a deep ocean mound.

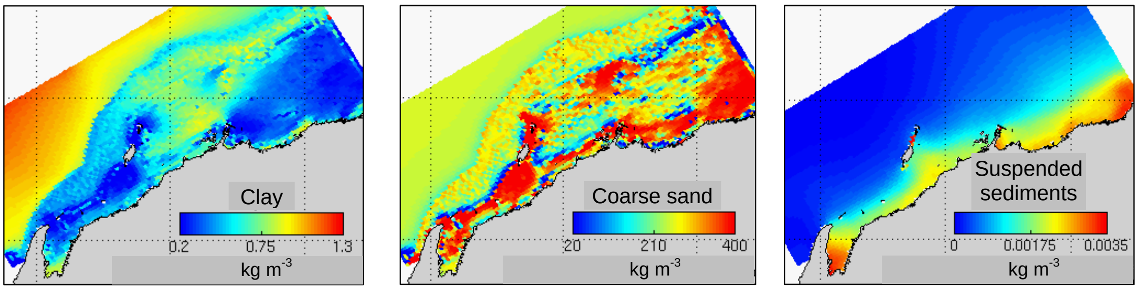


Figure 3.2.1: Bottom distributions of fine and coarse sediments (left and centre) and total suspended sediment concentration near the surface (right).

3.3 Primary production

Nutrient cycling and primary production on the North West Shelf was examined using a biogeochemical model embedded within the circulation model described above. Model fluxes suggested that nutrients are primarily carried into the system by horizontal currents before diffusing upward into the photic layer.

Primary production predominantly occurred within a subsurface chlorophyll maximum below the mixed layer at depths of around 70 m. This feature was maintained by a balance between uptake of dissolved nitrate by phytoplankton and nitrate export in particulate form. Its depth corresponded to the combination of light and nitrate that maximised phytoplankton growth. However, grazing by zooplankton increased with depth and tended to drive the subsurface chlorophyll maximum towards the surface.

Variability of the subsurface chlorophyll maximum occurred primarily in response to the spring neap tidal cycle. Surface chlorophyll concentrations were highest in an offshore band, particularly during spring tides when mixing provided a ready supply of nutrients but light levels on the inner shelf were strongly limited by resuspended sediments (figure 3.2.2). This feature moved further offshore during the dry season as stronger winds and increased evaporative cooling extended vertical mixing offshore.

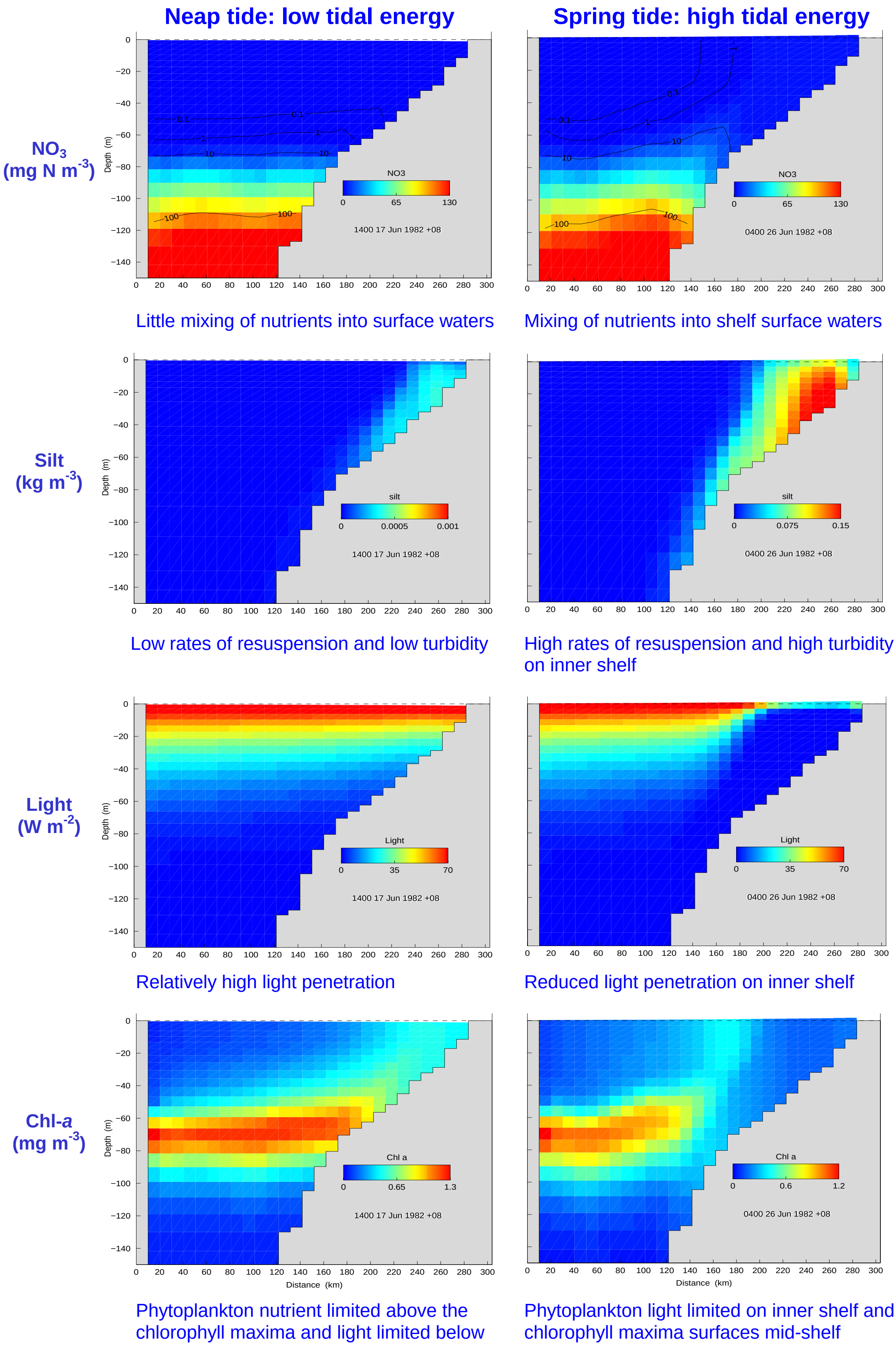


Figure 3.2.2: Contrasting conditions under neap tide (left) and spring tide (right) including their influence on primary productivity (as viewed through a vertical slice extending offshore from Port Hedland and to a depth of 150 m).

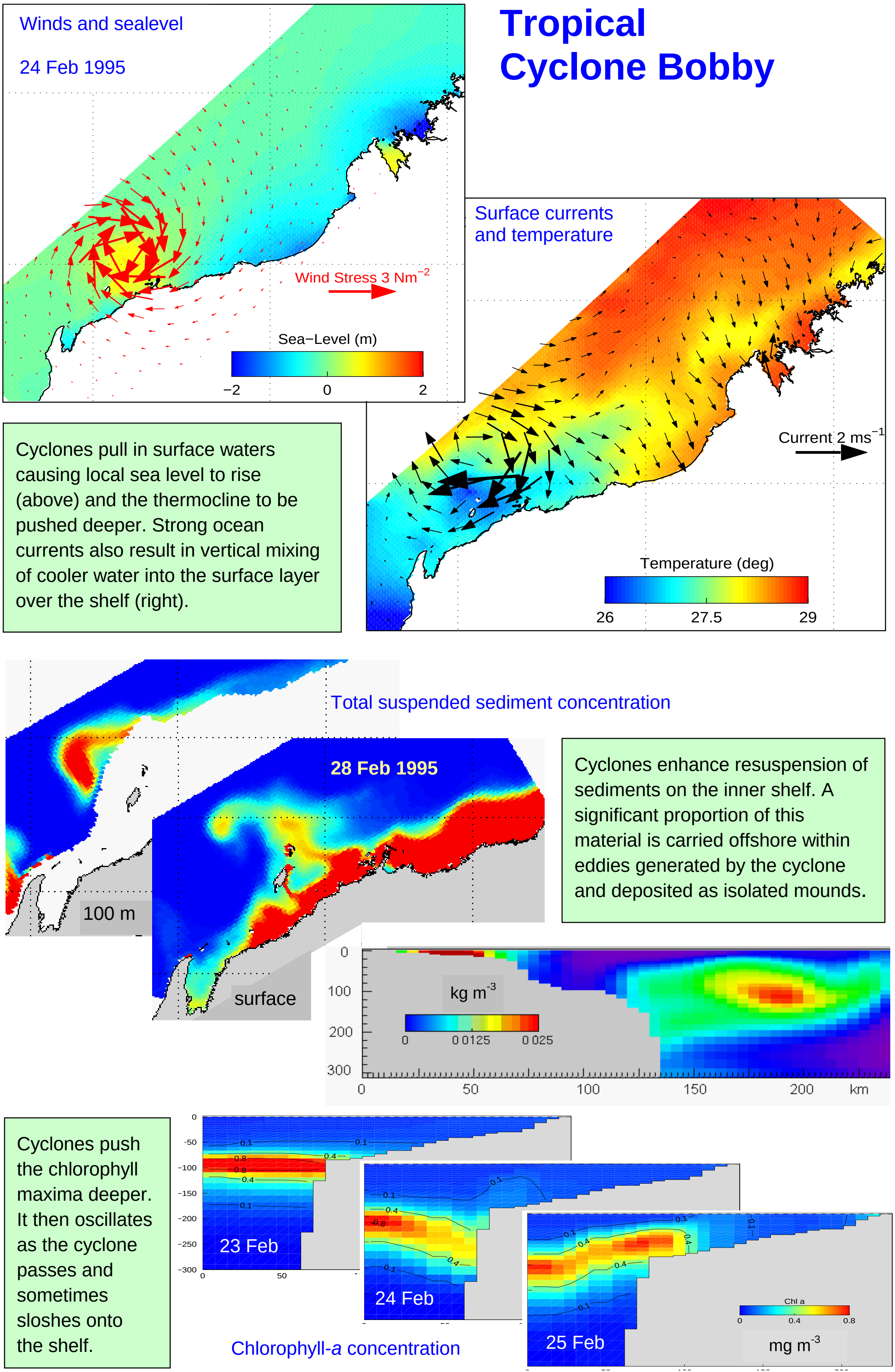


Figure 3.2.3: Modelled responses of the North West Shelf system to Tropical Cyclone Bobby (February 1995) represented in terms of oceanographic conditions (upper), suspended sediment (centre) and chlorophyll (lower).

3.4 Food web interactions

Understanding trophic interactions between key species (or groups of species) and their prey is important in determining long-term potential fishery production and broader impacts on the ecosystem. A food web was constructed for the North West Shelf on the basis of available dietary and biomass data (figure 3.4.1) and then incorporated into a trophodynamics model based on the *Ecopath-Ecosim-Ecospace* modelling system which has been applied to many other fisheries. The food web had shallow (20 to 120 m) and deep (120 to 200 m) components to reflect both the major differences on community structure in these different depth ranges and the ontogenetic migrations from the shallow to the deep communities by some species (figure 3.4.1).

The pelagic sub-system was found to be quite dominant in terms of biomass and has extensive links to the demersal system that was heavily exploited by the foreign trawl fishery. While the complexity and highly connected nature of the North West Shelf food web would typically suggest a mature system, the high ratio of primary production to total biomass (and respiration) is more typical of immature systems. This apparent ambiguity is consistent with a system that has lost maturity, in this case through fisheries exploitation. For example, lizard fish have increased as trawling has expanded their preferred habitat through removal of benthos.

Despite many data constraints and modelling assumptions, the spatial model adequately predicted most trends in fish biomasses. Scenario results suggest that effects of spatial management on the North West Shelf are far outweighed by the effects of managing the effort applied in the fishery (figure 3.4.2). Continuation of current effort levels for another 30 years resulted in major declines in some groups (e.g. carangids). However, reducing fishing rates in the second half of the 30 year simulation had beneficial effects for nearly all species, either reducing declines or enhancing increases. For example, Red Emperor declined significantly from 1987 to 2001, before starting on a slow recovery trajectory.

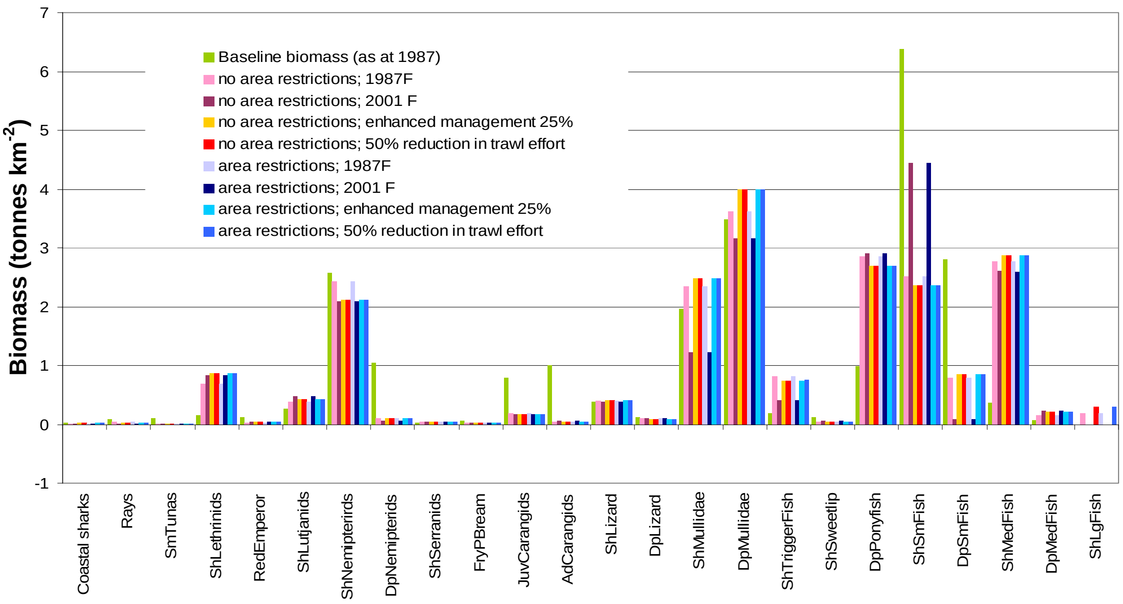


Figure 3.4.2: Predicted biomass of major fish groups after 30 year simulations under various scenarios. Green columns are 1987 baseline biomasses. (F = fishing level, Sm = small, Med = medium, Lg = large, Juv = juvenile, Ad = adult, Sh = shallow, Dp = deep).

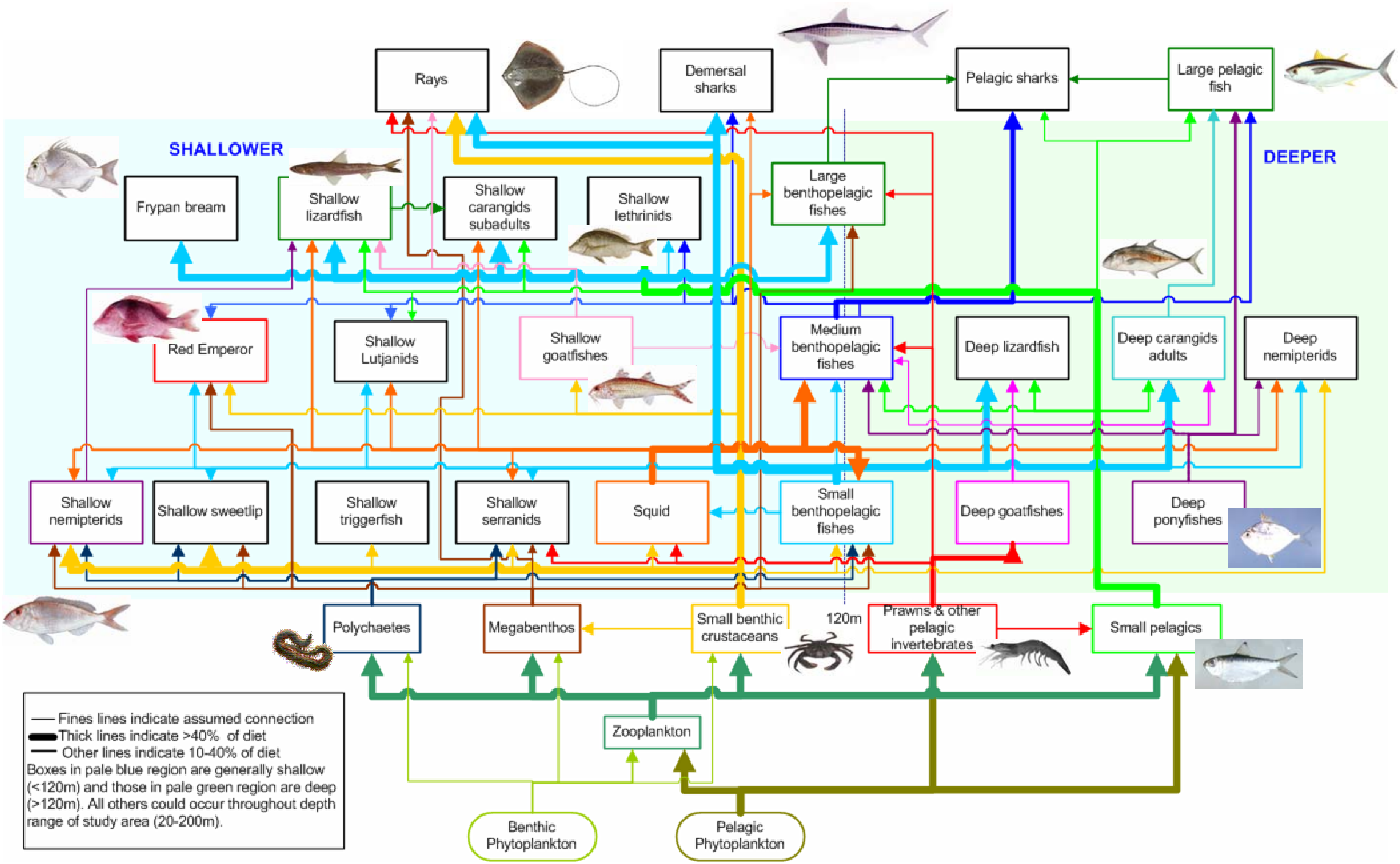


Figure 3.4.1: Food web of the North West Shelf with shallow water groups to the left and deeper water groups to the right.

3.5 Habitat changes

The biogeochemical models described in section 3.3 provide an indication of where nutrient and light conditions are suitable for the growth of habitat forming groups such as seagrasses and macroalgae (figure 3.5.1). However, such models do not currently take into account other key dependencies, such as the distribution of suitable substrate (e.g. sandy substrate for seagrasses and hard substrate for macroalgae), historical distributions of influences such as fish trawling, or the processes by which these organisms recruit into new areas.

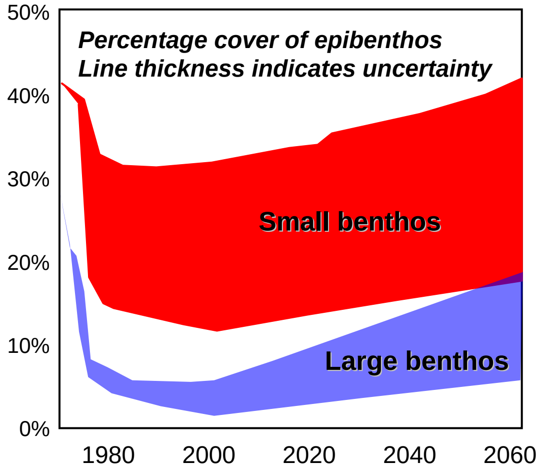
Developing dynamic habitat models requires observations over time. In the case of sponges (and other epibenthos), a large photographic dataset of North West Shelf benthic habitats recorded between 1983 and 1997 by CSIRO was used to calculate fractional coverage of small (< 0.25 m) and large (> 0.25 m) organisms on the seabed at depths between 20 and 200 m. There was substantially less data available for mangroves, seagrasses and macroalgae, so these models were parameterised from the literature and expert knowledge.

For each of the habitat types, a multivariate analysis was used to help identify factors to include in the habitat dynamics model. A dynamic age-structured metapopulation model was then developed, which included dependencies on depth, substrate dependent recruitment, growth, natural mortality, and removal rates by fishing and tropical cyclones.

The dynamics predicted for seagrass and macroalgae on the North West Shelf showed that they are strongly influenced by depth, substrate, cyclones and fishing, while mangroves are much less sensitive to these factors. Predicted distributions of seagrass and mangroves fall within the viable nutrient and light environments estimated from the biogeochemical model (figure 3.5.1). However, it is also clear that these environments extend far beyond the geographical coverage of the existing data (compare the first two rows of maps in figure 3.5.1).

Results from the model of sponges (and other epibenthos) reproduced the observed patterns of strongly depth related recruitment (figure 3.5.1). They also showed that trawling (by both foreign and domestic fleets) was probably a significant factor in shaping the current distribution of benthic habitats on the North West Shelf.

The model's ability to predict recovery rates that match the empirical data was limited by the resolution of both the model and historical fishing data (right). However, it is clear that depletion rates are rapid (with most damage occurring within the first five years of an activity such as fishing) and recovery times can be slow (potentially more than 20 years). These findings support a precautionary approach in exposing areas to impacts and suggest that spatial management aimed at habitat recovery may require a long commitment to produce tangible results.



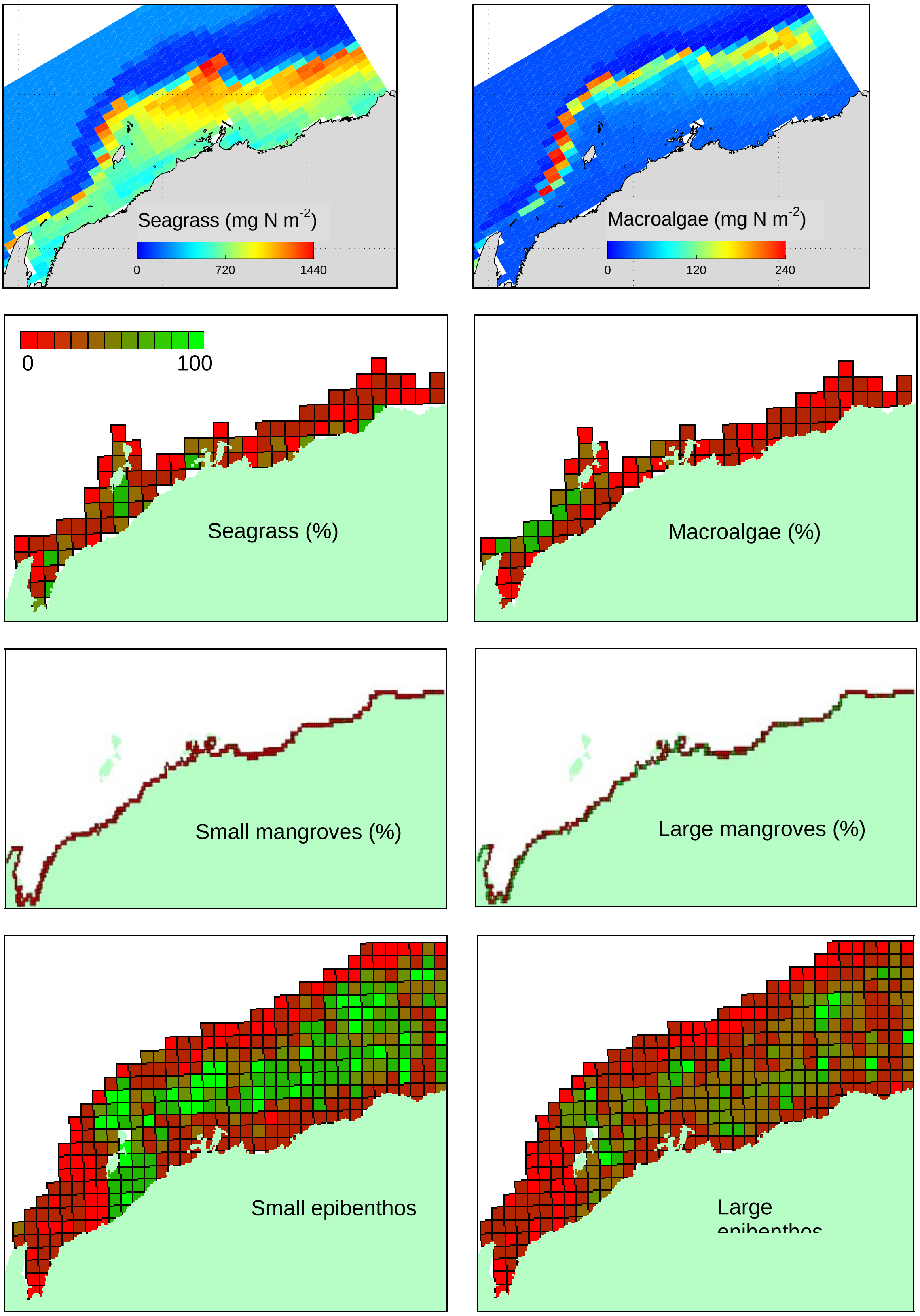


Figure 3.5.1: Viable nutrient and light environments for seagrass and macroalgae estimated by the biogeochemical model (top) and distributions of seagrass, macroalgae, small mangroves (< 1 m), large mangroves (> 1 m), small epibenthos (< 0.25 m) and large epibenthos (> 0.25 m) predicted by the habitat model (without fishing).

4. MANAGING HUMAN ACTIVITIES ON THE NORTH WEST SHELF

4.1 The management strategy evaluation approach

Management Strategy Evaluation (MSE) is a simulation based framework that can be used to test and compare the outcomes of alternative management strategies against defined targets. These targets are usually based on the objectives of management and other stakeholders. MSE simulations explicitly represent the following components (figure 4.1.1):

- the ecosystem;
- the socio-economic system as represented by the various sector activities;
- monitoring and assessment of both of the ecosystem and socio-economic system; and
- the management decision process.

Our understanding of each of these components is limited. The MSE approach therefore endeavours to consider recognised uncertainties in identifying strategies that can robustly deliver to management objectives.

While the track record of MSE in single sector management is now quite extensive, NWSJEMS represented the first attempt to apply the approach across multiple sectors. The key sectors represented in the MSE modelling were:

- the oil and gas industry including exploration, extraction, processing, and transportation;
- coastal development including power generation, port facilities, iron ore production and transport, and salt production;
- fisheries including commercial prawn trawling, fish trawling and trapping, and recreational fishing; and
- conservation related activities including zoning and other measures to protect key species and habitats.

Considering all of these sectors within a single simulation framework allowed for investigation of both cumulative impacts and the potential benefits of coordinated monitoring and management across sectors.

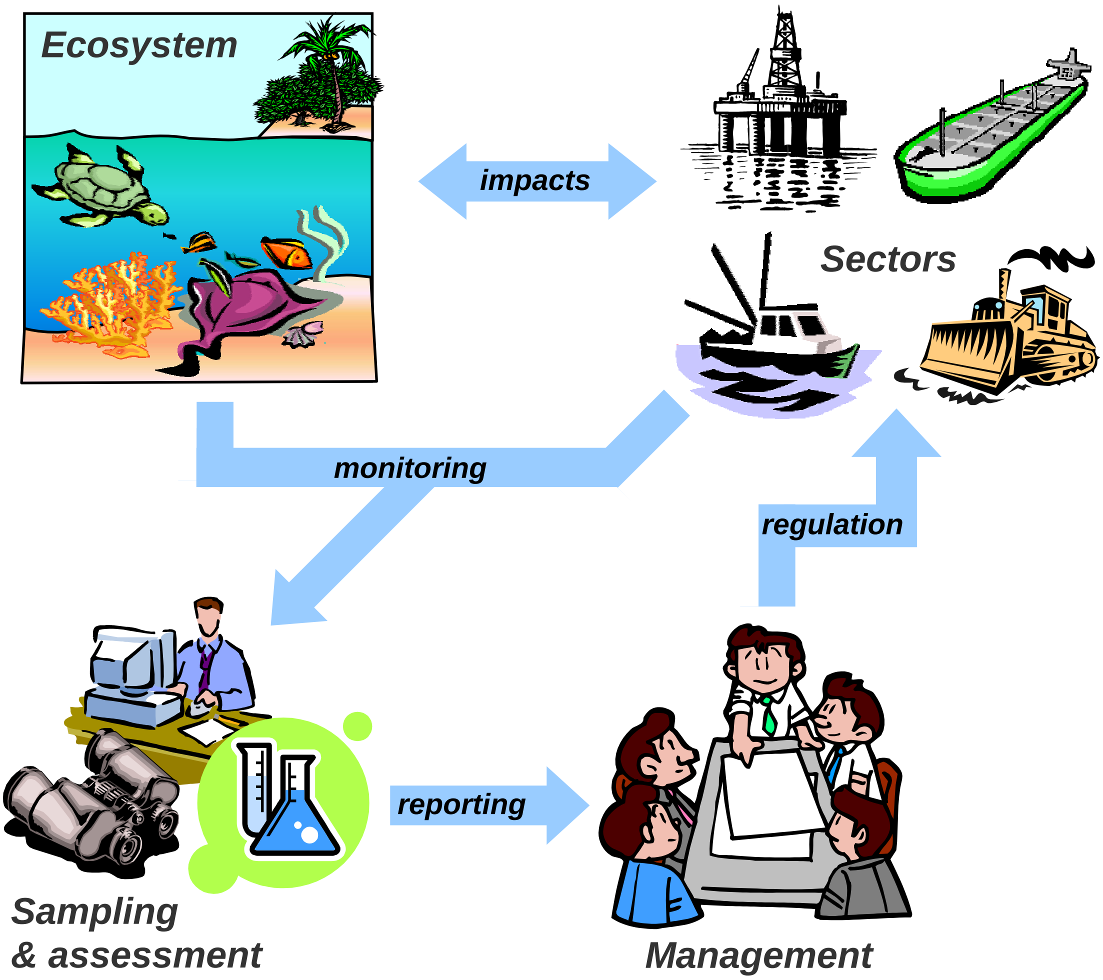


Figure 4.1.1: Components included in the MSE model. Traditional ecological models include selected parts of the ecosystem and, in some cases, key human impacts. Additionally, the MSE model includes explicit representation of monitoring activities, the management decision process and its regulatory outcomes.

4.2 The three dimensions of the MSE analysis

The North West Shelf MSE model was specified in terms of:

- three sets of model structures and model parameters for the North West Shelf system spanning key uncertainties;
- three future human development scenarios; and
- three alternative regional management strategies for achieving management objectives.

These model specifications, development scenarios and management strategies constituted the three dimensions of the MSE analysis, together making a total of 27 combinations (figure 4.2.1). In addition, the models included many stochastic elements (based on random number draws) and each of the 27 combinations was run many times (typically 10 to 30) to capture the underlying randomness in the system dynamics.

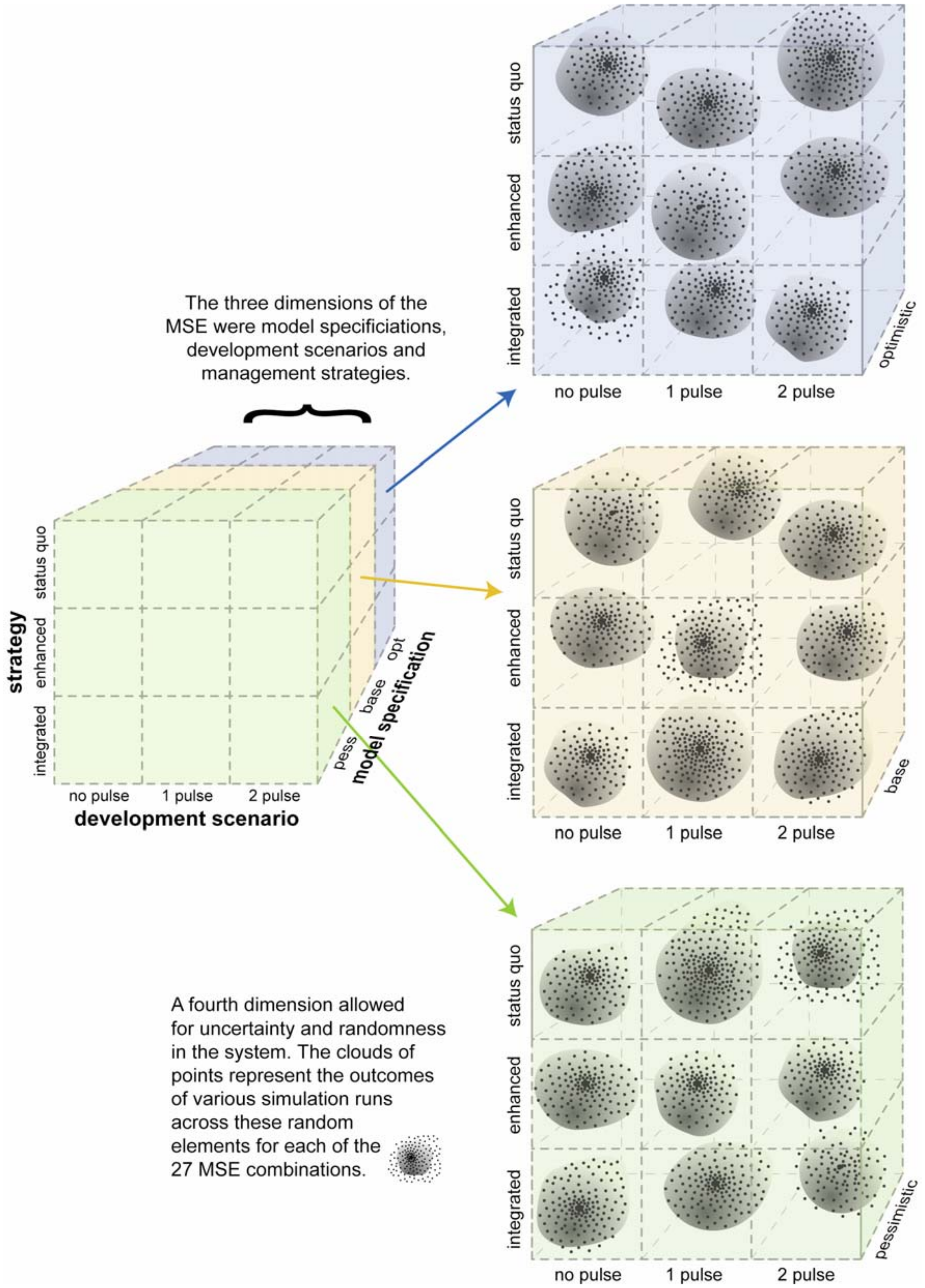


Figure 4.2.1: Schematic diagram of the three dimensions of the MSE analysis also showing the stochastic nature of the solution space as a fourth dimension.

The three *model specifications* defined both model structures and model parameter values within both agent-based sub-models and more traditional differential equation-based sub-models. These sub-models represented key physical components (bathymetry, water properties, substrate types), biological components (mangroves, seagrass and epibenthic habitats; listed species such as turtles and sharks; and commercial fish and crustaceans), and human components (fisheries, contaminant inputs and coastal habitat destruction). They also represented the physical and biological processes that connect these components (physical dispersion, reproduction, mortality, habitat dependency, fisheries extraction, and uptake of contaminants). In many instances the design of these sub-models relied heavily on the ecological models and outputs described in section 3.

Combinations of model structure and parameter values were considered that could reasonably match the available historical data (within the 80% confidence intervals). Within these constraints, combinations were selected corresponding to:

1. the most *optimistic* interpretation of the system's productivity and resilience to human impacts (i.e. productive fish resources with fast habitat recovery and low uptake of contaminants);
2. the most *pessimistic* interpretations of these same characteristics; and
3. a *base* interpretation that was intermediate between the optimistic and pessimistic and closest to reasonable expectation.

The three *development scenarios* were specified to account for uncertainty in the future level of industrial activity in the North West Shelf region and were designed to represent:

1. recent (i.e. 2002) levels of infrastructure, residential and industrial development and environmental protection (i.e. no pulse);
2. the planned development over the following five years with no further development beyond 2007 (i.e. 1-pulse); and
3. as in (2) with a second similar cycle of development from 2008 to 2012 (i.e. 2-pulse).

Each scenario included developments in each of the four industry sectors: oil and gas, coastal development, fishing and conservation.

The three *management strategies* chosen for evaluation focused on the same four sectors and were closely aligned to existing sector-by-sector legislative requirements. They broadly represented:

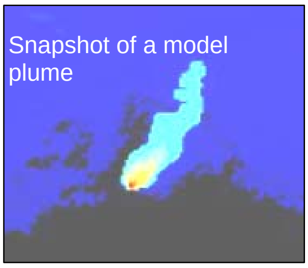
1. a *status quo* strategy consisting of the combination of sectoral management strategies in place in 2002;
2. an *enhanced strategy* that modified existing sectoral strategies so as to allow some management objectives to be met more effectively and to bring individual sectors up to "state-of-the-art" management for that sector; and
3. an *integrated strategy* made up of a set of coordinated sectoral strategies, with shared monitoring and the potential for multi-sectoral management responses.

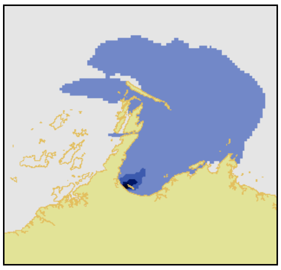
This option was most closely aligned with the aspirations of ecosystem-based-management, where cross sector considerations are explicitly considered.

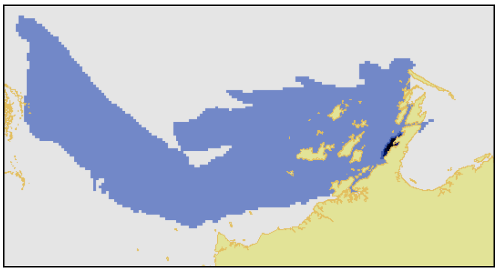
4.3 Results from the MSE analysis

Within the limited range of model specifications, development scenarios and management strategies considered, the MSE modelling results suggest that much of the marine and coastal environment of the North West Shelf has retained its ecological integrity. Under suitable management strategies, there also appears to be good prospects of recovery from existing impacts, even under increased economic development.

The model results at the regional scale were remarkably insensitive to the development scenarios. This is because most impacts were highly localised. For example, the model results suggested that while the footprint of detectable contaminants from coastal sources was fairly extensive, toxic levels were much more restricted (figure 4.3.1).







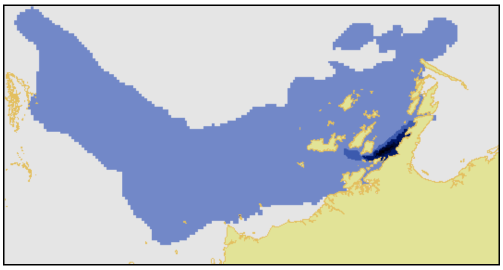


Figure 4.3.1: Snapshot of model plume from Nickol Bay (left) and maximum extent of the plumes from the outfalls at Nickol Bay (centre), Mermaid Sound (top right), and Hammersley (bottom right), based on model results. The darker shadings indicate the more localised area that may have exceeded ANZECC guidelines in some model scenarios.

There was significant dependence on the model specifications (figure 4.3.2). For example, the exposure of banana prawns to contaminants was sensitive to the movements of schools in response to rainfall events and the distribution of benthic habitat. Hence uncertainties in model structure and parameter values dominated the variation seen in both their stocks and associated catches. In contrast, species such as mangroves (not shown) were largely insensitive to model specifications

Management strategies had a significant influence on a wide range of environmental and socio-economic outcomes (figures 4.3.3 and 4.3.4). The *status quo* and *enhanced management strategies* generally invoked similar responses, with the latter yielding some advantages in terms of lower habitat fragmentation and higher commercial and recreational fish catches. However, both of these strategies were significantly outperformed by the *integrated management strategy*, where shared monitoring and the option for multi-sector responses resulted in consistently better outcomes. Specifically, the integrated strategy provided:

- higher biodiversity;

- higher abundances of some high conservation value species;
- significantly increased stocks and catch rates of high-value fish species;
- increased recreational fish catch;
- a net reduction in commercial fishing effort;
- a reduction in contaminant impacts; and
- a reduction in the risk of ship collisions and catastrophic spills.

These benefits were achieved at the cost of a significant reduction in commercial fishery gross margins (figure 4.3.4).

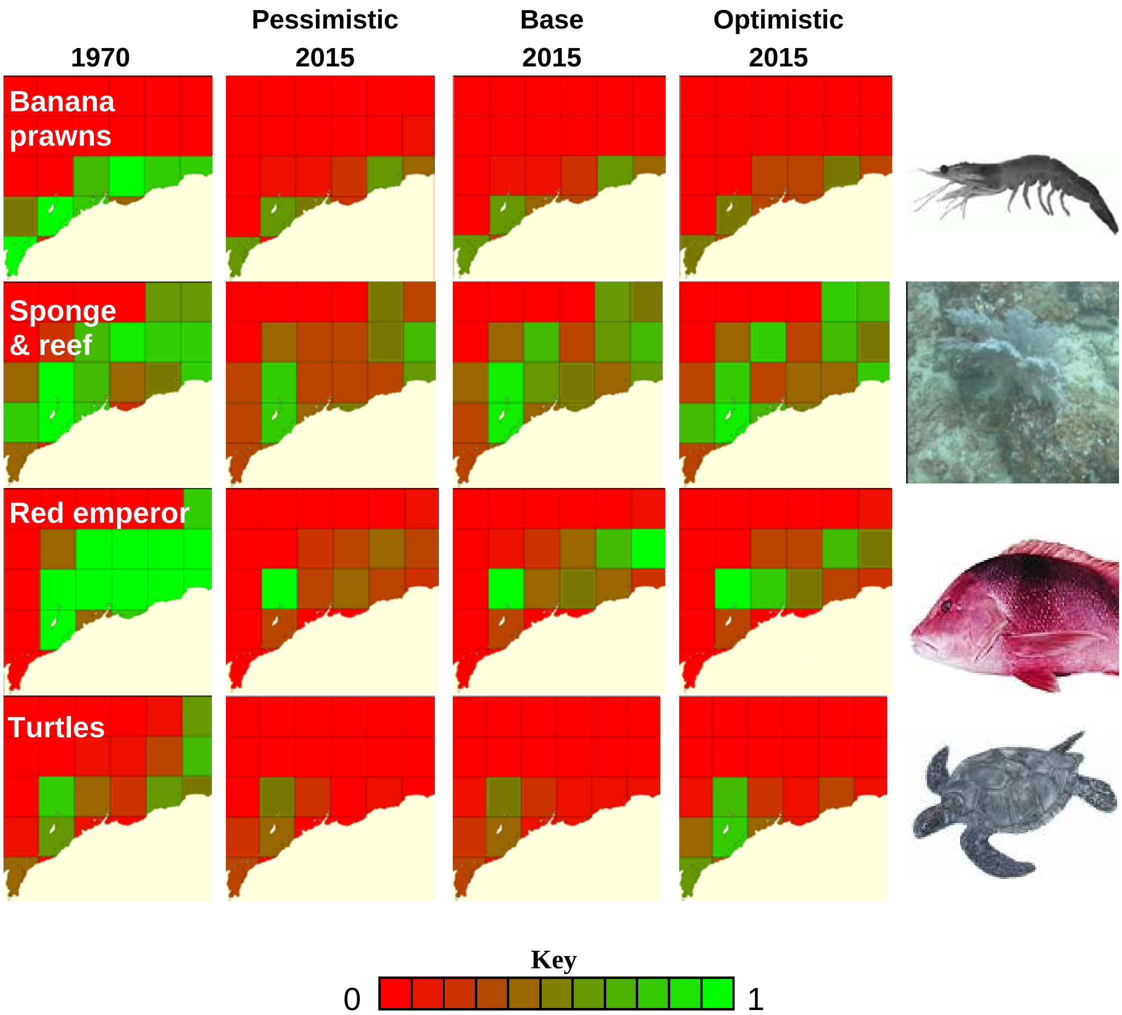


Figure 4.3.2: Coarse scale distributions of relative biomasses corresponding to the three model specifications for banana prawns (1st row); sponge and reef epibenthos (2nd row); red emperor or *Lutjanus sebae* (3rd row), and turtles (4th row). Distributions tended to be less patchy under optimistic specifications due mainly to higher productivity or recovery rates. Results were largely insensitive to the development scenarios due mainly to the limited spatial extent of most impacts.

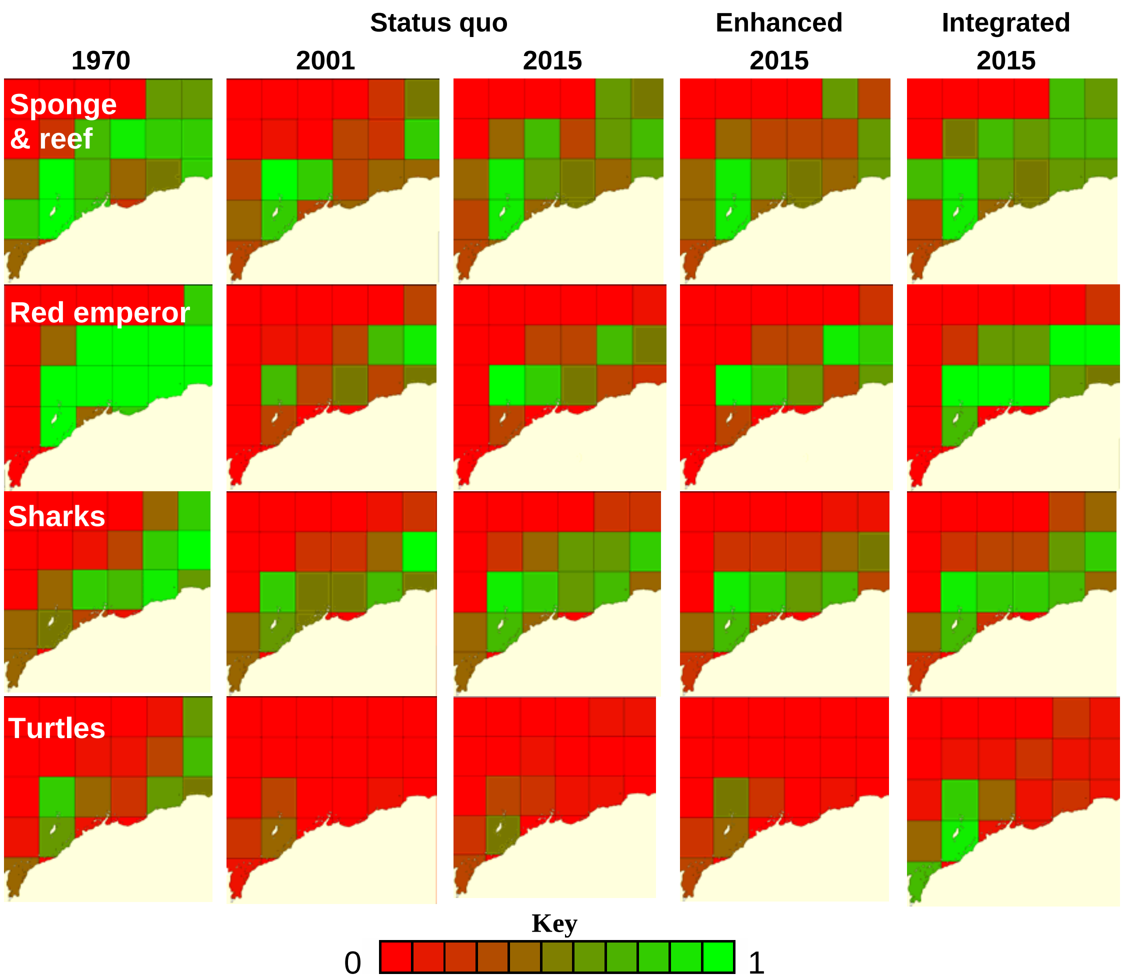
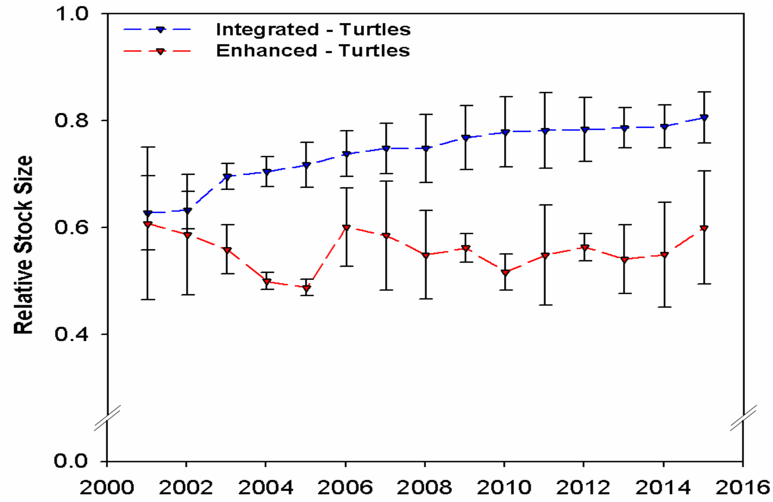
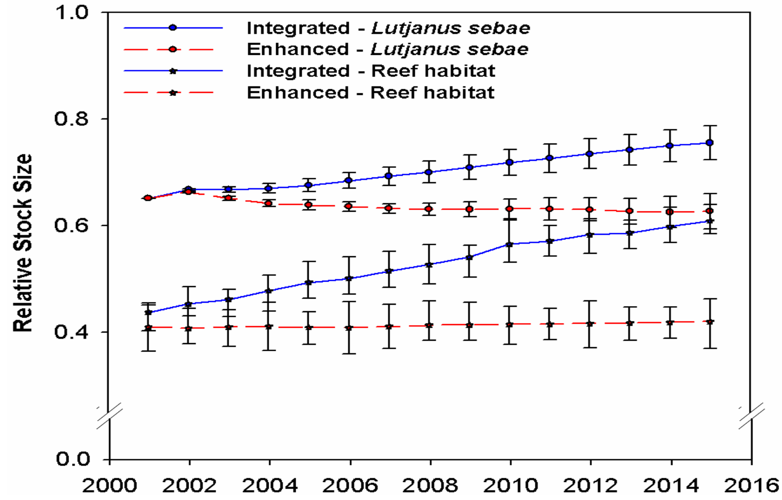


Figure 4.3.3: Coarse scale distributions of relative biomasses through time of sponge and reef epibenthos (intermediate model specifications – 1st row); red emperor snapper or *Lutjanus sebae* (optimistic model specifications – 2nd row); sharks (optimistic model specifications – 3rd row); turtles (pessimistic model specifications – 4th row). Results were largely insensitive to the development scenarios mainly because of the limited spatial extent of most impacts.

The integrated strategy resulted in significant recovery of turtle populations mainly through the reductions in bycatch mortality achieved by substantially reducing effort in the trawl fishery.



Reduced effort in the trawl fishery under the integrated management strategy also allowed the gradual recovery of red emperor and reef habitats.



Reduced effort in the trawl fishery under the integrated management strategy substantially reduced economic returns to the fishery in the short to medium term.

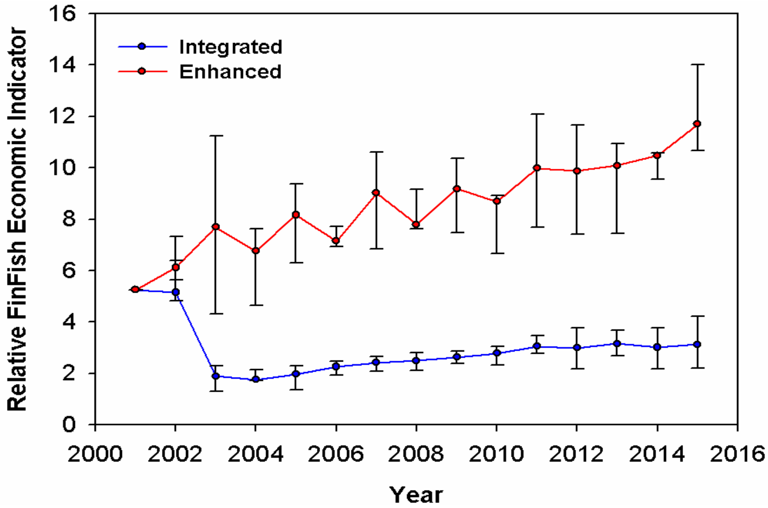


Figure 4.3.4: Time-series of ecological and economic indicators contrasting the enhanced and integrated management strategies (under intermediate model specifications). Under optimistic model specifications (not shown) recovery of turtle populations could be achieved with significantly less impact on the fishery, suggesting that improved understanding of turtle population dynamics should be a priority in achieving both conservation and fisheries objectives.

5. MAKING STUDY OUTCOMES AVAILABLE

5.1 Metadata

Following a comprehensive review of data sets and other information relevant to the marine ecosystems, infrastructure and industries of the North West Shelf, the *MarLIN* metadata system hosted by CSIRO was used to document all data sets identified as potentially useful to NWSJEMS (figure 5.1.1).

http://www.marine.csiro.au/marlin/

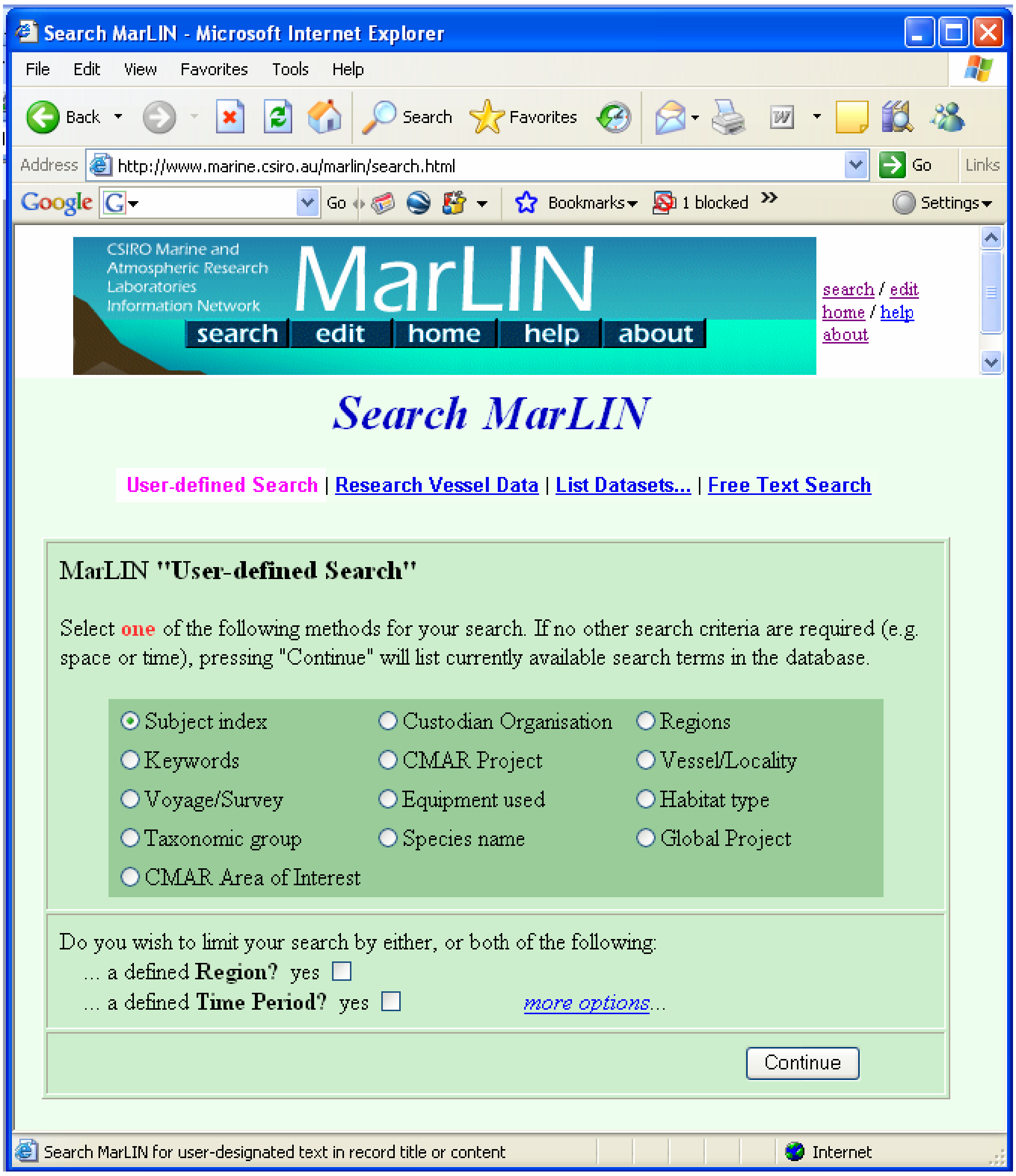


Figure 5.1.1: The search page of the online metadata system *MarLIN*. NWSJEMS datasets can be found by searching under *"CMAR Project"* and selecting *"North West Shelf - Joint Environmental Management Study - 02-03"* or *"North West Shelf - Project # - [project name]"*.

5.2 Data storage and access

NWSJEMS engineered a spatially enabled relational database as a repository for the wide range of physical and biological data types used in the study. With the exception of a number of very large model output datasets, data collated or generated by the study was stored in this repository known as the *Data Warehouse*.

A web tool, known as the *Data Trawler*, was developed to allow access to information stored within the *Data Warehouse*. *Data Trawler* was designed for discovering datasets through a parameter search, investigating the search results, previewing the datasets, and downloading data sets allocated to a “shopping basket” (figure 5.2.1).

http://www.marine.csiro.au/warehouse/jsp/loginpage.jsp

Figure 5.2.1: Pages of the online *Data Trawler* used for dataset discovering, investigation, preview and download. An example of the email sent following a successful download is shown on the bottom right.

5.3 Specialist web tools

Several visualisation tools were developed for analysing and exploring the inputs and results of NWSJEMS. *ConnIe* has already been described briefly in figure 3.1.2. A second tool referred to as the *NWS Technical User Interface* was used by programmers running the MSE models to assist with the complex task of model calibration and validation.

A third tool, *ViewNWS*, is available as an integrated software and data package on CD for scientists and managers wishing to explore the MSE model results in terms of environmental, social and economic indicators (figures 5.3.1 and 5.3.2). *ViewNWS* displays include maps, digital images and time series of both real observational records and model outputs. It allows a complete view of the system dynamics to be developed under various management or monitoring strategies, model specifications and human use or environmental change scenarios. The application was specified to be readily configurable to other terrestrial, coastal and marine systems in preparation for future applications.

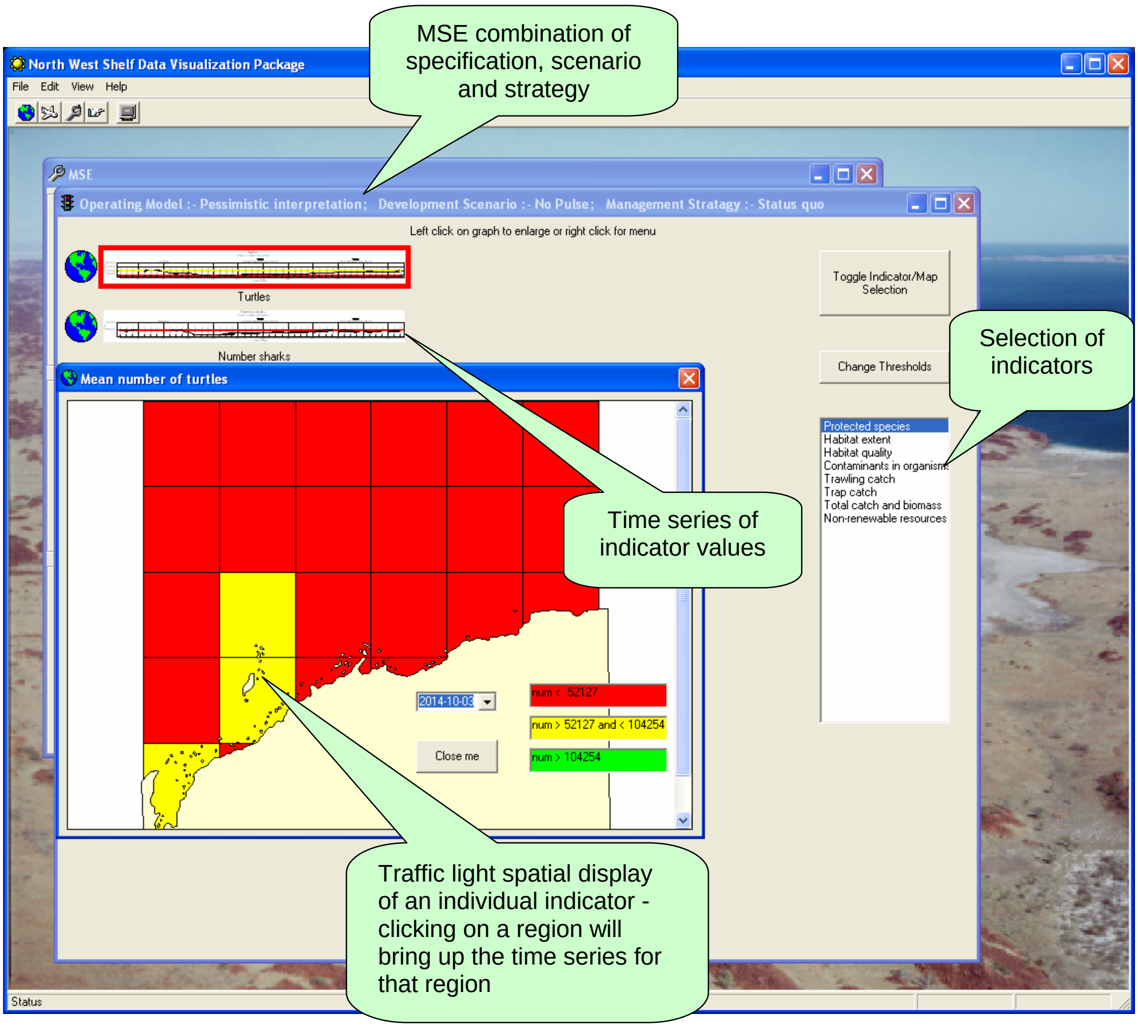
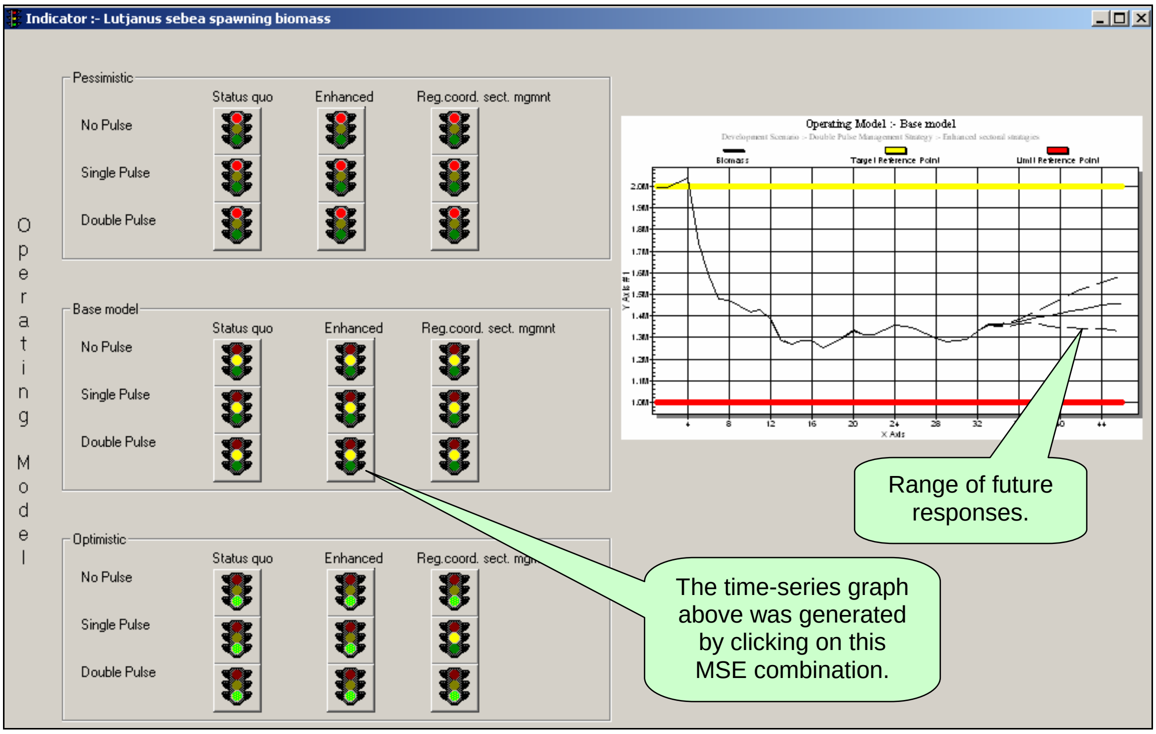


Figure 5.3.1: An example of the displays available in *ViewNWS* for exploring the MSE model results.



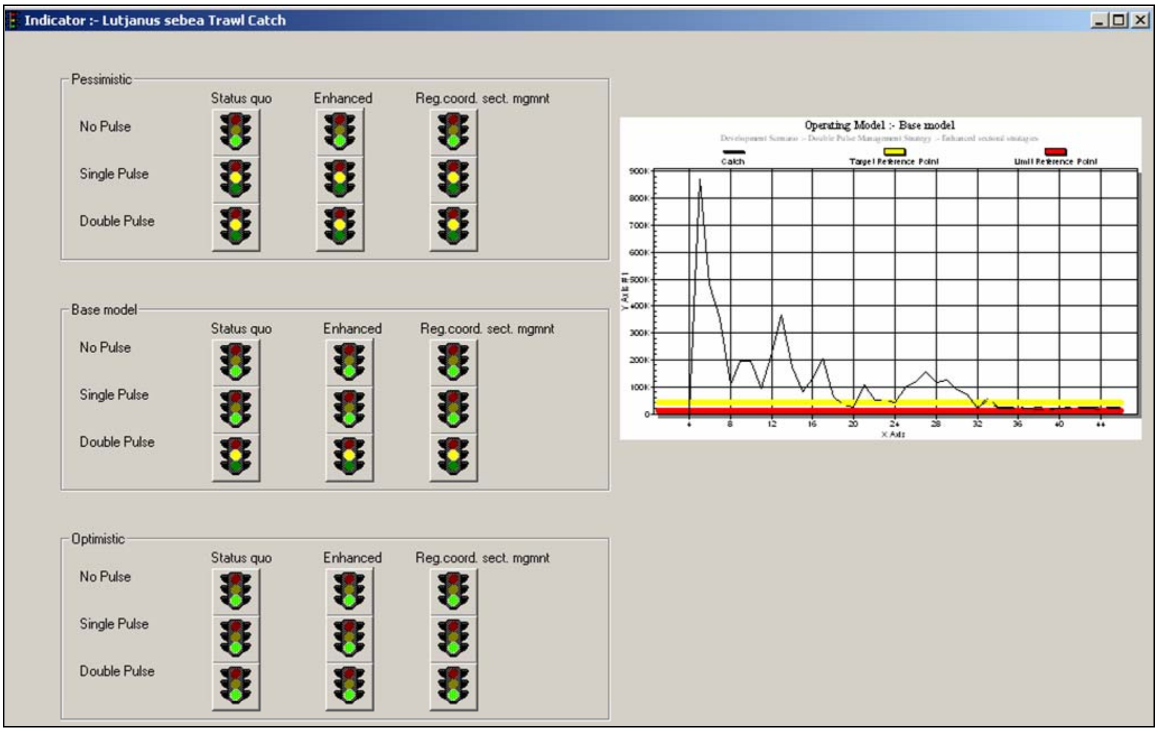


Figure 5.3.2: The indicator screen of *ViewNWS* summarises the results for each indicator across the three dimensions of the MSE. A green light shows that the indicator value is above the target reference point, an amber light that it is between the target and limit reference points, and a red light that it is below the limit reference point. While the traffic lights refer only to conditions at the end of the model run, complete time-series under any of the 27 MSE combinations can also be displayed (right). The examples shown here correspond to red emperor spawning biomass (upper) and red emperor trawl catch (lower).

6. CONCLUSION

NWSJEMS was established with challenging and ground breaking objectives. It was motivated by the desire for science to support a more integrated management approach to the sustainable development of marine industries and other human activities on the North West Shelf. The challenges to this approach included collating and interpreting previously scattered information about all aspects of the coastal and marine ecosystem and associated human uses; building the tools to effectively access this information; developing explanatory and predictive models and scenarios for the natural system and human impacts on it; and developing methods to predict the range of outcomes expected under different development scenarios and management regimes.

The study was very successful in most of these areas and in a number of areas is already starting to provide substantial benefits to the study participants. It has transformed our knowledge and understanding of the North West Shelf system. Starting from a range of valuable (but disparate) historical datasets, NWSJEMS has made the North West Shelf one of the best studied marine regions in Australia. Certainly no other region has the range of modelling, data access and analysis tools currently available for the North West Shelf.

The application of the MSE approach to multiple sectors proved to be a particularly challenging component of the study. The results successfully demonstrated the approach and pointed to significant advantages in a more coordinated strategy to monitoring and management across sectors (without necessarily moving beyond existing statutory and jurisdictional arrangements). However, NWSJEMS represents only the initial steps towards practical implementation and adoption of multiple-use MSE within a real planning and management setting. Ongoing research is focusing on improving the software framework for MSE modelling, including supporting more efficient implementation procedures.

The study provides a range of new challenges and opportunities for the future. Development on the North West Shelf is continuing to accelerate under the current resources boom, including expansion along the neighbouring Kimberly coast. The tools developed by NWSJEMS are likely to find a broader range of applications as new infrastructure is planned and the potential for conflicts between uses of the marine environment becomes more evident.

ACKNOWLEDGMENTS

This report was compiled by Scott Condie using material from the NWSJEMS Technical Report Series.

The following people and agencies have contributed significantly to the Study through the provision of technical expertise and advice, and historical data and information. The Study partners gratefully acknowledge their contribution.

Western Australian State agencies
Department of Environment and Conservation (Department of Conservation and Land Management and Department of Environment)
Department of Fisheries
Department of Industry and Resources (Department of Mineral and Petroleum Resources)
Department of Land Information
Department for Planning and Infrastructure (Department of Transport)
Pilbara Tourism Association
Shire of Roebourne
Town of Port Hedland
Tourism Western Australia
Western Australian Land Information System
Western Australian Museum

Commonwealth agencies
Australian Institute of Marine Science
Geoscience Australia (formerly Australian Geological Survey Organisation)

Consultants
Cognito Consulting
David Gordon International Risk Consultants
METOCEAN Engineers (formerly Weather News International, Perth)
Oceanica (formerly DA Lord and Associates)

Industries
Australian Petroleum Production Exploration Association (APPEA)
Apache Energy
BHP Petroleum
Chevron Australia
Dampier Salt
Hamersley Iron
Mermaid Marine
Woodside Energy

Individuals
Clay Bryce
Graham Cobby
Nick D’Adamo
Mike Forde
David Gordon
Andrew Heyward

Barry Hutchins
Bryan Jenkins
Di Jones
Ian LeProvost
Ray Masini
Mike Moran
Steve Newman
Eric Paling
Kelly Pendoley
Bob Prinz
Chris Simpson
Shirley Slack-Smith
Di Walker

Editorial and publishing
Louise Bell – Graphics/cover design
Lea Crosswell – Webpage design
Rob McKenzie – Editor
Diana Reale – Webpage design
Linda Thomas – Editorial consultant/layout and design
Helen Webb – Editorial consultant/Project Manager

Front cover photos courtesy of:
Centre – Coral reef ecosystem, WA Museum, Clay Bryce
Aquaculture pearls, Department of Fisheries WA
Recreational fishing, Department of Fisheries WA, Jirri Lockman
Offshore petroleum platform, Woodside Energy Ltd
Commercial Fishing, Department of Fisheries WA
Tourism, CSIRO
Coastal development aerial photos, Hamersley Iron Pty Ltd