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Aquaculture viability

A technical report to the Australian Government from the CSIRO Northern Australia Water Resource Assessment, part of the National Water Infrastructure Development Fund: Water Resource Assessments

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CSIRO Northern Australia Water Resource Assessment acknowledgements

This report was prepared for the Department of Infrastructure, Regional Development and Cities. The Northern Australia Water Resource Assessment is an initiative of the Australian Government's White Paper on Developing Northern Australia and the Agricultural Competitiveness White Paper, the government's plan for stronger farmers and a stronger economy. Aspects of the Assessment have been undertaken in conjunction with the Northern Territory Government, the Western Australian Government, and the Queensland Government.

The Assessment was guided by three committees:

(i) The Assessment's Governance Committee: Consolidated Pastoral Company, CSIRO, DAWR, DIIS, DoIRDC, Northern Australia Development Office, Northern Land Council, Office of Northern Australia, Queensland DNRME, Regional Development Australia - Far North Queensland and Torres Strait, Regional Development Australian Northern Alliance, WA DWER

(ii) The Assessment's Darwin Catchments Steering Committee: CSIRO, Northern Australia Development Office, Northern Land Council, NT DENR, NT DPIR, NT Farmers Association, Power and Water Corporation, Regional Development Australia (NT), NT Cattlemen's Association

(iii) The Assessment's Mitchell Catchment Steering Committee: AgForce, Carpentaria Shire, Cook Shire Council, CSIRO, DoIRDC, Kowanyama Shire, Mareeba Shire, Mitchell Watershed Management Group, Northern Gulf Resource Management Group, NPF Industry Pty Ltd, Office of Northern Australia, Queensland DAFF, Queensland DSD, Queensland DEWS, Queensland DNRME, Queensland DES, Regional Development Australia - Far North Queensland and Torres Strait

Note: Following consultation with the Western Australian Government, separate steering committee arrangements were not adopted for the Fitzroy catchment, but operational activities were guided by a wide range of contributors.

This report was reviewed by Nigel Preston (Independent Consultant), Ian Watson (CSIRO) and Cuan Petheram (CSIRO)

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Photo: Tiger prawns. Source: CSIRO

Director’s foreword

Sustainable regional development is a priority for the Australian, Western Australian, Northern Territory and Queensland governments. In 2015 the Australian Government released the ‘Our North, Our Future: White Paper on Developing Northern Australia’ and the Agricultural Competitiveness White Paper, both of which highlighted the opportunity for northern Australia’s land and water resources to enable regional development.

Sustainable regional development requires knowledge of the scale, nature, location and distribution of the likely environmental, social and economic opportunities and risks of any proposed development. Especially where resource use is contested, this knowledge informs the consultation and planning that underpins the resource security required to unlock investment.

The Australian Government commissioned CSIRO to complete the Northern Australia Water Resource Assessment (the Assessment). In collaboration with the governments of Western Australia, Northern Territory and Queensland, they respectively identified three priority areas for investigation: the Fitzroy, Darwin and Mitchell catchments.

In response, CSIRO accessed expertise from across Australia to provide data and insight to support consideration of the use of land and water resources for development in each of these regions. While the Assessment focuses mainly on the potential for agriculture and aquaculture, the detailed information provided on land and water resources, their potential uses and the impacts of those uses are relevant to a wider range of development and other interests.

C. Chilcott

Chris Chilcott

Project Director

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Shortened forms

SHORT FORM	FULL FORM
ABFM	Australian Barramundi Farming manual
APFM	Australian Prawn Farming Manual
BoM	Bureau of Meteorology
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEM	Digital elevation model
DAF	Department of Agriculture and Fisheries, Queensland
FAO	Food and Agricultural Organisation of the United Nations
EIA	Environmental Impact Assessment
FCR	Feed conversion ratio
GBR	Great Barrier Reef
GCMA	Gold Coast Marine Aquaculture
GIS	Geographic information system
GM	Gross margin
HAT	Highest astronomical tide
IAA	Integrated agriculture-aquaculture
LSM	Land suitability mapping
NPV	Net present value
NSW	New South Wales
NT	Northern Territory
PL	Postlarvae
PL15	Postlarvae, 15 days after metamorphosis
QLD	Queensland
RAS	Recirculating aquaculture system
SA	South Australia
SJ3	Stage three juvenile
SST	Sea surface temperature
STRM	Shuttle Radar Topography Mission
TAS	Tasmania
UK	United Kingdom
US	United States
VIC	Victoria
WA	Western Australia
WSSV	White Spot Syndrome Virus
YTK	Yellowtail Kingfish

Units

UNITS	DESCRIPTION
cm	centimetres
°C	temperature on Celsius scale
GL	gigalitres, 1,000,000,000 litres
ha	hectares, 10,000m^2
kg	kilogram
kL	kilolitres, 1000 litres
L	litres
m	metres
mg	milligrams
ML	megalitres, 1,000,000
mm	millimetres
m^2	metres square
ppt	parts per thousand
t	tonnes

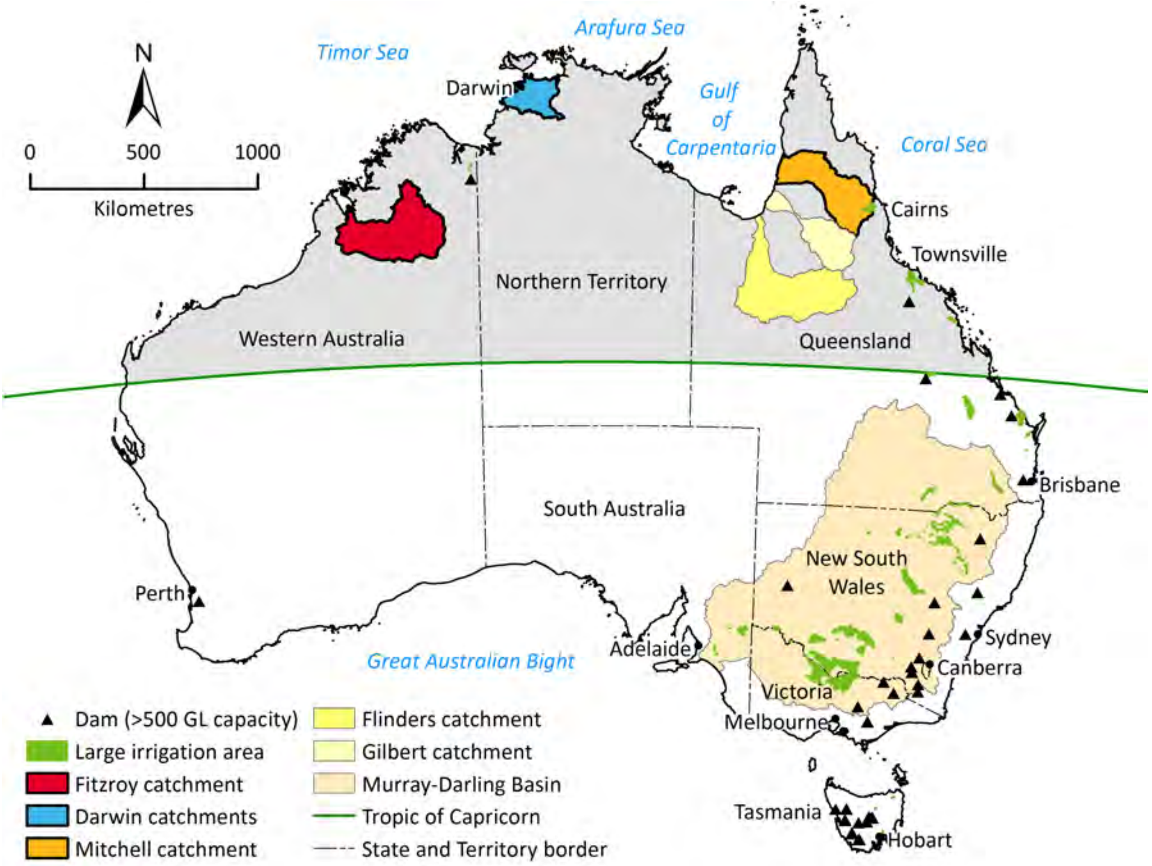
Preface

The Northern Australia Water Resource Assessment (the Assessment) provides a comprehensive and integrated evaluation of the feasibility, economic viability and sustainability of water and agricultural development in three priority regions shown in Preface Figure 1:

- Fitzroy catchment in Western Australia
- Darwin catchments (Adelaide, Finniss, Mary and Wildman) in the Northern Territory
- Mitchell catchment in Queensland.

For each of the three regions, the Assessment:

- evaluates the soil and water resources
- identifies and evaluates water capture and storage options
- identifies and tests the commercial viability of irrigated agricultural and aquaculture opportunities
- assesses potential environmental, social and economic impacts and risks of water resource and irrigation development.



Preface Figure 1 Map of Australia showing the three study areas comprising the Assessment area
Northern Australia defined as that part of Australia north of the Tropic of Capricorn. Murray–Darling Basin and major irrigation areas and large dams (>500 GL capacity) in Australia shown for context.

While agricultural and aquacultural developments are the primary focus of the Assessment, it also considers opportunities for and intersections between other types of water-dependent development. For example, the Assessment explores the nature, scale, location and impacts of developments relating to industrial and urban development and aquaculture, in relevant locations.

The Assessment was designed to inform consideration of development, not to enable any particular development to occur. As such, the Assessment informs – but does not seek to replace – existing planning, regulatory or approval processes. Importantly, the Assessment did not assume a given policy or regulatory environment. As policy and regulations can change, this enables the results to be applied to the widest range of uses for the longest possible time frame.

It was not the intention – and nor was it possible – for the Assessment to generate new information on all topics related to water and irrigation development in northern Australia. Topics not directly examined in the Assessment (e.g. impacts of irrigation development on terrestrial ecology) are discussed with reference to and in the context of the existing literature.

Assessment reporting structure

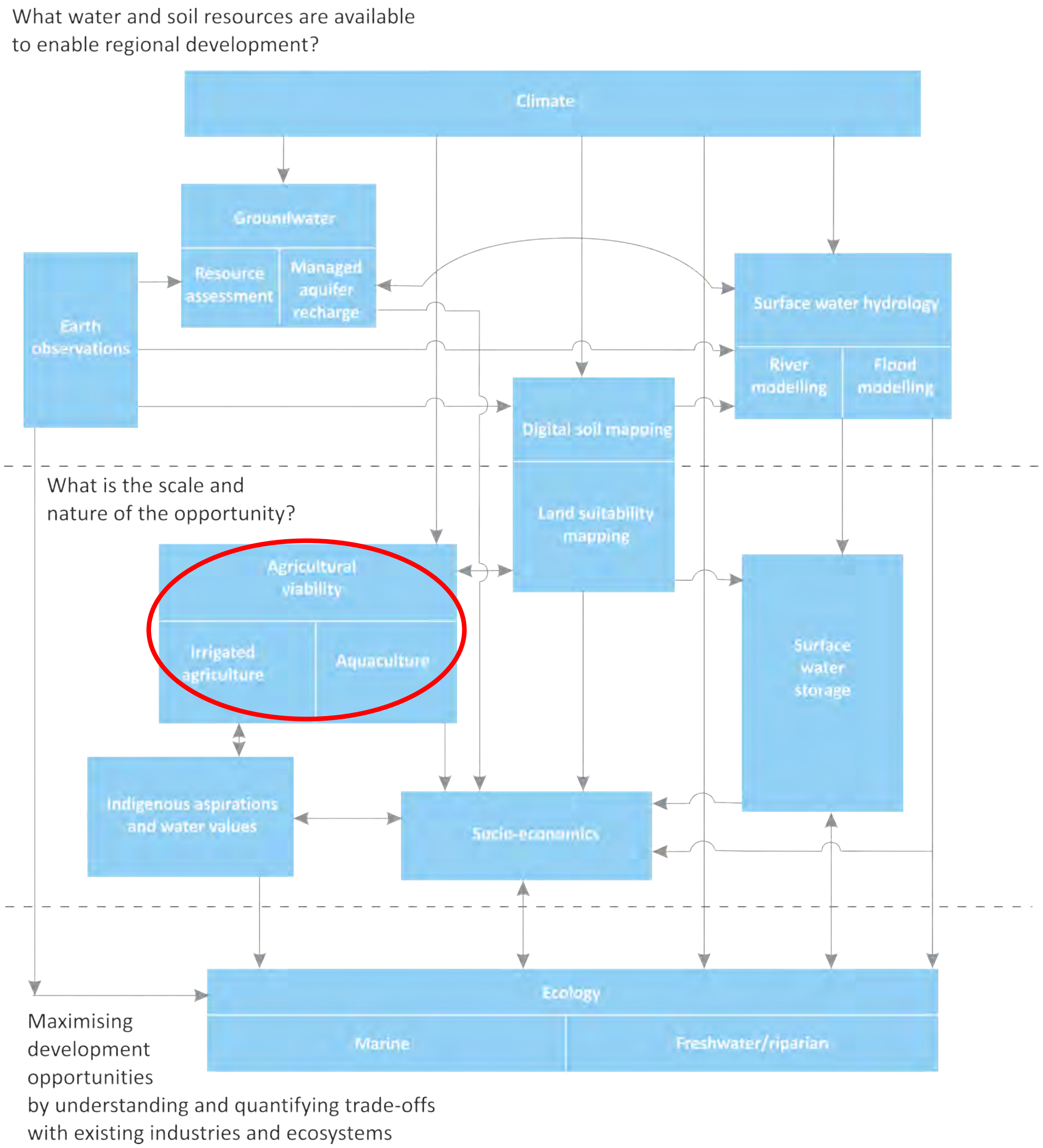
Development opportunities and their impacts are frequently highly interdependent and, consequently, so is the research undertaken through this Assessment. While each report may be read as a stand-alone document, the suite of reports most reliably informs discussion and decision concerning regional development when read as a whole.

The Assessment has produced a series of cascading reports and information products:

- Technical reports, which present scientific work at a level of detail sufficient for technical and scientific experts to reproduce the work. Each of the ten activities (outlined below) has one or more corresponding technical reports.
- Catchment reports for each catchment that synthesise key material from the technical reports, providing well-informed (but not necessarily scientifically trained) readers with the information required to make decisions about the opportunities, costs and benefits associated with irrigated agriculture and other development options.
- Summary reports for each catchment that provide a summary and narrative for a general public audience in plain English.
- Factsheets for each catchment that provide key findings for a general public audience in the shortest possible format.

The Assessment has also developed online information products to enable the reader to better access information that is not readily available in a static form. All of these reports, information tools and data products are available online at http://www.csiro.au/NAWRA. The website provides readers with a communications suite including factsheets, multimedia content, FAQs, reports and links to other related sites, particularly about other research in northern Australia.

Functionally, the Assessment adopted an activities-based approach (reflected in the content and structure of the outputs and products), comprising ten activity groups; each contributes its part to create a cohesive picture of regional development opportunities, costs and benefits. Preface Figure 2 illustrates the high-level links between the ten activities and the general flow of information in the Assessment.



Preface Figure 2 Schematic diagram illustrating high-level linkages between the ten activities (blue boxes)
Activity boxes that contain multiple compartments indicate key sub-activities. This report is a technical report. The red oval indicates the primary activity (or activities) that contributed to this report.

Executive summary

This report reviews current aquaculture production and practices in Australia, with an emphasis on species and land-based aquaculture systems appropriate for future development in northern Australia. The available land area suitable for land-based aquaculture enterprises in the three study areas is assessed based on key land suitability criteria using Land Suitability Mapping (LSM). A broad-scale assessment of the quality and volumes of water required for potential future aquaculture industries is also provided. Key risks for developing aquaculture enterprises in northern Australia and the potential for integration of aquaculture with other agricultural activities are discussed. In the final section of the report, an economic framework which can be used to assess the financial viability of aquaculture enterprises in northern Australia is provided.

Australia has many natural advantages in terms of the development of agricultural and aquaculture industries, such as political stability, proximity to major Asian markets, and considerable land and water resources. Northern Australia in particular has advantages in terms of aquaculture development, due to the untapped potential of available land and water resources, and a prevailing climate characterised by high air temperatures, which is ideal for culturing most tropical aquatic species.

Previous studies have reported the significant opportunity for marine land-based aquaculture along Australia's northern coastline (CSIRO, 2014; McLeod et al., 2002). However, this report is the first to estimate and assess the suitability of land in northern Australia for freshwater aquaculture, and to provide a more detailed assessment of marine aquaculture for the Fitzroy, Darwin and Mitchell catchments in particular. A desktop evaluation of the current Australian aquaculture industry is included as context for assessing opportunities in northern Australia.

Current aquaculture production and practices in Australia are reviewed for a range of culture species and industries, with emphasis on potential land-based systems and tropical species appropriate for culture in northern Australia. The opportunity for aquaculture development in northern Australia is outlined, noting the slow pace of development compared with southern Australia over past decades.

Two candidate species for land-based aquaculture in northern Australia are identified in the report; the black tiger prawn *(Penaeus monodon)* and the barramundi (*Lates calcarifer*). Fundamental aspects of the biology and culture of these two species, and a third candidate species suitable for freshwater pond culture (the red claw crayfish, *Cherax quadricarinatus*), are outlined. All three species have well-established culture practices and markets, and each are suited to land-based culture in the marine and brackish or freshwater environments of northern Australia.

Land and water suitability for aquaculture development was assessed in the three study areas based on a wider range of criteria specific to the aquaculture requirements of the three candidate species. LSM identified significant areas of land for potential aquaculture development within each of the Fitzroy, Darwin and Mitchell catchments. When overlaid with water suitability modelling, land areas of more than 500,000 ha and 700,000 ha were identified as suitable for marine farming in earthen and lined ponds respectively. Of these areas, 9,500 ha and 225,000 ha were identified as Class 1 land (i.e. suitable with negligible limitations) for marine farming in earthen and lined pond respectively. For freshwater farming, vast areas of land were identified as suitable in all three study areas for both earthen (3,000,000 ha) and lined ponds (13,000,000 ha). For a sense of comparison in terms of the opportunity presented in northern Australia, the current Australian prawn farming industry utilises approximately 900 ha. The report thus finds the scale of potential land available in the Assessment area presents a significant opportunity to expand Australian aquaculture enterprises.

The report also finds scope for integrating aquaculture with other agricultural industries in northern Australia and a range of potential opportunities are noted. These include opportunities to use raw agricultural plant products directly as feed sources, or when processed as feed ingredients in formulated pelletised diets for prawns and barramundi (depending on development of a feed mill in northern Australia) and the use of large quantities of agricultural plant materials in 'bio floc' aquaculture systems or as a primary carbon source in 'Novacq™' production.

Despite these opportunities, challenges to the development of aquaculture in northern Australia are posed by competition from Asian imported products and regulatory barriers. Other key risks outlined in the report include potential chemical toxicants present in the waters or sediments of potential sites, and pathogen and disease risks that may present.

A framework for assessing the financial viability of aquaculture enterprises in northern Australia was developed based on indicative costs for a range of aquaculture enterprises that differ in species farmed, scale and intensity of production. Operating costs are high, and annual expenditure on inputs can exceed the initial cost of development. Variable costs dominate the total costs of aquaculture production, and even small changes in quantities and prices of inputs and produce can have a relatively large impact on net profit margins. These values could differ substantially between different locations and experience of operator, and even small differences from the indicative costs or prices provided could significantly impact profitability.

Based on the natural advantages that northern Australia possesses, and through the large land areas identified as suitable for aquaculture in the three study areas assessed using LSM, this report finds considerable opportunity for future aquaculture development in northern Australia. While there are challenges to the development and operation of aquaculture enterprises, the potential to exploit these natural advantages and develop modern and sustainable aquaculture industries presents a compelling opportunity.

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Part I

Introduction and overview

1 Introduction

1.1 Global aquaculture overview

Aquaculture is the controlled farming of fish, molluscs, crustaceans and plants in an aquatic environment. Culture type is broadly divided by water salinity, latitude, environmental location and culture habitat. Aquaculture is one of the fastest growing food sectors in the world (Bank, 2013). In 2014, 580 species were under culture worldwide, including 362 fish, 104 molluscs, 62 crustaceans and 50 other species (frogs, reptiles, invertebrates and aquatic plants) (FAO, 2016).

Freshwater fish production from earthen ponds is the largest contributor to global aquaculture production by volume. In 2014, close to 60% of the total global aquaculture production of 74 million t was freshwater fish (FAO, 2016). Marine aquaculture species are generally highest in value, representing 36% of global production and 43% of total value. In 2013, salmonids were the highest value commodity, with 17% share by value, followed by prawns with 15% (FAO, 2016).

In 2014, the aquaculture sector surpassed fisheries as the main contributor of edible seafood (FAO, 2016). The majority of aquaculture production is for human consumption, although some species are specifically produced for jewellery and clothing or processed into by-products such as fertilisers and adhesives. In 2014, total global production of edible seafood from aquaculture equalled 74 million t, with almost 90% produced in Asia. In the Asia region, China is by far the largest producer with 45 million t of output per year. Over 90% of the 18 million people employed in fish farming are based in Asia (FAO, 2016).

1.2 Aquaculture by category

1.2.1 WATER SALINITY

Aquaculture production is classified into two main categories; marine or freshwater. Farming of animals in marine (salty) water can occur in the sea and on the land. Farming in freshwater occurs only on the land. A third category is brackish, which occurs in water which has less salt than marine water, but more than freshwater.

1.2.2 LATITUDE

Aquaculture species are broadly classified by latitude. Tropical or warm water aquaculture occurs in the tropical zone, between the Tropic of Cancer (23°26’13.2N) and the Tropic of Capricorn (23°26’13.2NS). Temperate or cool water aquaculture occurs in the temperate zone, between the Arctic circle and the Tropic of Cancer (23°26’13.2N) and the Antarctic circle and the Tropic of Capricorn (23°26’13.2NS).

1.2.3 ENVIRONMENTAL LOCATION

The environmental location of aquaculture production is either sea or land based. Sea-based operations are located in natural marine waters (e.g. ocean, bay or estuary) whereas land-based operations are located on land, in man-made or natural marine or freshwater environments.

1.2.4 CULTURE HABITAT

Culture habitat is designed to suit animal behaviour and the requirement to contain and protect the stock. In general, free swimming species (e.g. fish) are suited for culture in cages, ponds and tank systems. Crustaceans (bottom dwelling) are best suited to culture in ponds. Molluscs and aquatic plants are best suited for fixed and suspended systems such as rafts, racks and longlines.

1.3 Production intensity

In aquaculture, production intensity is determined by animal stocking density. A high-stocking density increases the potential yield and profitability, but typically also the risk level associated with production. In general, production systems are classified as extensive, semi-intensive or intensive.

Extensive production is the simplest system and commonly involves production where no supplemental feeds are provided to the culture environment. Production of ‘non-fed’ aquatic organisms (e.g. aquatic plants, bivalves, and some fish and crustacean species when reared in extensive systems) make up around half of the total volume of global aquaculture production. These species utilise the natural productivity available in the culture area for growth. Aquatic plants (mainly marine tropical seaweed) are cultured in around 50 countries and in 2014 production was over 27 million t (FAO, 2016).

The other half of global aquaculture production is derived from ‘fed’ species. Semi-intensive systems involve stocking seed from a hatchery, routine provision of feed and monitoring and management of water quality. Productivity is species dependent and ranges from 1000 to 5000 kg/ha per crop. Intensive systems involve a high-stocking density, provision of a specifically formulated feed and strict monitoring and management of water quality. Productivity depends on species and can range from 5000 to 20,000 kg/ha or even higher per crop. In 2014, global fed species aquaculture production was equivalent to 74 million t (FAO 2016).

1.4 Production trends and markets

In 2014, the value of the global aquaculture industry was US$160 billion, comprising US$99 billion from fish, US$16 billion from molluscs and $US7 billion from crustaceans. To meet increasing global demand for fish, the aquaculture industry is expected to increase by 17% by 2025, with fish to remain as the primary driver of production (FAO, 2016). The production of fed species is the fastest growing sector and is predicted to be the dominant sector in the future.

Fish is one of the most traded food commodities worldwide. In 2014, the sale of edible fish as live, fresh or chilled product had declined to be half of total sales. In contrast, the supply and worldwide distribution of frozen low-value white fish aquaculture products, such as Asian catfish, carp and tilapia has increased dramatically. The market for salmonids (particularly salmon) has grown strongly in recent decades to become the largest single commodity by value in 2013 (FAO, 2016). Atlantic salmon is considered a high-value product, with the demand for a range of processed products increasing. The prawn market is the second largest commodity by value (FAO, 2016). The white fish market, traditionally dominated by temperate wild caught fish, is now experiencing strong competition from lower value white fish.

1.5 Major challenges to aquaculture development

Expansion of the aquaculture industry over the last 40 years has been rapid. In 1974 aquaculture accounted for less than 10% of fish for human consumption, however by 2015 this had increased to be around 50% of total edible seafood (FAO, 2016). This rapid expansion has placed pressure on and increased competition for finite natural resources, particularly on fishery and land resources. Management of existing and development of new resources is essential for a sustainable future.

1.5.1 FISH MEAL

Fish meal and fish oil derived from wild caught fish are highly nutritious ingredients for farmed fish feeds. A significant proportion of global fishery catch is processed into fish meal and fish oil, the majority of which ends up in aquaculture feeds. As global aquaculture production of fed species increases so will the demand for feed. In general, fish require a minimum equivalent amount of feed (feed conversion ratio or FCR) to produce fish biomass. Based on this requirement, at least 37 million tonnes of feed is required annually, however due to losses and inefficiencies actual feed usage is much higher. In 2009, the aquaculture industry consumed around 4500 t (>70% of total available stock) of global fish meal and fish oil (Tacon and Metian, 2008). In 2014, 16 million tonnes of marine fisheries capture was used to produce fish meal and fish oil. The finite supply and high price of fish meal and fish oil is a key constraint of aquaculture growth.

Increased demand for aquaculture products will intensify the pressure on fisheries resources, particularly for fish meal and fish oil. Due to a decline in *anchovetta* catch, fish meal production has almost halved since 1994, when the catch was 30 million t (FAO, 2016). Traditionally, fish meal and fish oil are produced by milling and drying whole fish. Continual decline and fluctuation in catch has necessitated that up to 30% of current production is from the processing of fish by-products. As the price (US$1747 per t in 2013) and demand for fish meal has increased, so has the trend to reduce the level of fish meal/oil in feeds and find alternative ingredients (FAO, 2016).

1.5.2 TERRESTRIAL CROPS

Terrestrial plant crops, such as soybean, are increasingly being used for partial replacement of fish meal and fish oil as ingredients in aquaculture feeds. Increased use of terrestrial crops has reduced the reliance on fishery products, but is increasing the pressure on available freshwater resources for crop production. Aquaculture’s current demand for terrestrial plants is low (~4%), and any increase in demand will compete directly with demand from livestock and humans. In this way, major growth in aquaculture production will put pressure on world food supplies. According to (Troell et al., 2014) major aquaculture expansion has the potential to make global food security less resilient. This risk can be minimised by maintaining diversity in the species under culture (currently >500 species) and diverse use of crops, livestock and fisheries products and their by-products as ingredients in aquaculture feeds (Troell et al., 2014).

1.5.3 AVAILABLE SITES

Around the world and particularly in Asia, there is strong and increasing competition between aquaculture, urban development, tourism and agricultural farming for coastal land. This had led to various governments developing assessment methods which identify suitable land for a specific aquaculture species (usually for prawns in coastal areas). In Australia, land-based aquaculture has a small footprint (<3,000 ha (Savage, 2016))compared to crop agriculture, which required around 22 million ha of land for production in 2016–17 (Agbenyegah et al., 2017). There is enormous potential for expansion of aquaculture production in Australia. Preliminary broad-scale analysis by (McLeod et al., 2002) indicated that 1.2 million ha of Australia's northern coastline is suitable for marine pond-based aquaculture. Although the land may be suitable for pond aquaculture, the zoning of adjacent waterways, such as the Great Barrier Reef Marine Park, and other marine reserves, as well as associated environmental management regulations, has made it difficult to gain approval to develop aquaculture enterprises in some areas.

1.5.4 DISEASE

Like many other farming systems, diseases, either due to pathogens endemic to farming regions or introduced through translocations of animals from other regions, have had, and continue to have, major impacts on global aquaculture production. The resulting economic loss to the global industry is estimated to be US$6 billion per year (World Bank, 2014). Aquatic diseases caused by a range of pathogenic agents such as viruses, bacteria, fungi and parasites have varying impacts across species, geographies, rearing systems and life stages. Significant resources are being invested to mitigate disease risks through the use of different rearing systems and preventative biosecurity measures, however the opportunity and capacity to implement such improved approaches varies significantly across geographies and industries (World Bank, 2014). Compared with many other countries, Australia has many advantages in terms of the opportunity to mitigate disease risks through sound regulatory processes controlling translocation, technological knowledge and capability, and the greater geographic spread between farming operations in many regions.

1.6 Key linkages with other activities of the Northern Australia Water Resource Assessment

This report drew on information and models generated by other activities in the Assessment, in particular the companion technical reports on:

- climate (Charles et al., 2016)
- digital soil mapping (Thomas et al., 2018a)
- land suitability (Thomas et al., 2018b)
- agricultural viability (Ash et al., 2018a; Ash et al., 2018b; Ash et al., 2018c)
- socio-economics (Stokes et al., 2017).

2 Aquaculture viability in northern Australia

2.1 Aquaculture opportunity

This report assesses the opportunity for tropical marine and freshwater aquaculture in land-based systems in northern Australia.

Australia is one of the most politically stable countries in the world, located in the Asia-Pacific region, on similar time zones and logistically close to major Asian markets. Northern Australia is characterised by high maximum air temperatures commonly above 30 °C (BOM, 2015), which is an ideal climate for culturing most tropical aquatic species, including barramundi and prawns. There is significant untapped potential for expansion of land based aquaculture in northern Australia. The current Australian aquaculture industry has a footprint of <3000 hectares. As noted above, preliminary broad-scale analysis by (McLeod et al., 2002) indicated that 1.2 million ha of Australia's northern coastline is suitable for marine pond-based aquaculture. A previous CSIRO study has identified around 500,000 ha of suitable land available in each of the study areas for the development of large-scale marine pond aquaculture, with an estimated value of $1 billion (CSIRO, 2014). This report is the first to assess the suitability of land in northern Australia for freshwater aquaculture and provides a more detailed assessment of marine aquaculture for the Fitzroy, Darwin and Mitchell catchments.

2.2 Scope of report

The aquaculture viability report provides a desktop evaluation of the Australian aquaculture industry and describes methods to generate soil attribute maps, which are then applied in the land suitability analysis. A broad-scale assessment of the quality and volumes of water required for potential future aquaculture industries is also provided The work reported here represents one of the ten multidisciplinary activities of the Northern Australian Water Resource Assessment (the Assessment) encompassing the Fitzroy catchment in Western Australia (WA), the Darwin catchments (comprising the Finniss, Adelaide, Mary and Wildman catchments) in the Northern Territory (NT), and the Mitchell catchment in Queensland (QLD). The location of these catchments in northern Australia is shown in Figure 2-1 and covers a combined area of approximately 197,000 km^2.

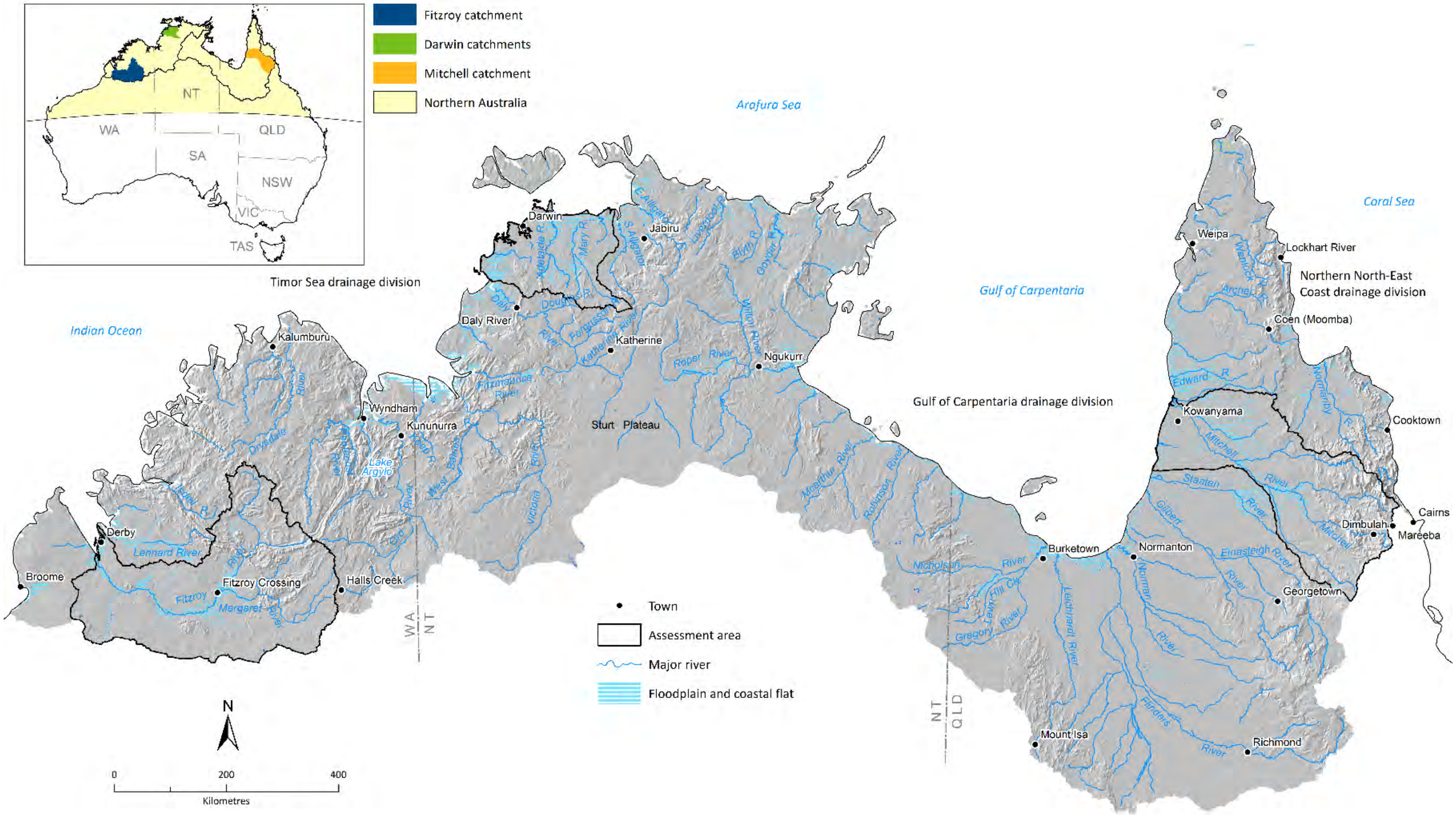

Figure 2-1 Northern Australian coastal drainage and relief patterns

The Fitzroy, Darwin and Mitchell catchments and significant settlements are shown. The inset highlights these catchments and areas north of 20^{o} north.

The three objectives covered in this report are to:

1. Provide a review of current aquaculture production and practice in Australia.
2. Devise a water and land suitability analysis framework for selected crops.
3. Assess the land suitability outputs that are generated.

This report focuses on marine and fresh water fish, molluscs and crustacean species which are suitable for land-based culture, have a level of domestication, and are produced primarily as edible seafood. The minimum acceptable level of domestication or captive rearing is the use of wild caught parents to produce hatchery reared seed. Species which rely on the capture of wild seed for production have been excluded from consideration; the one exception being oyster, where some production comes from 'wild-spat' which originate from larvae occurring naturally in the local waterways. Other exclusions include aquatic plants, ornamental fish, amphibians, reptiles and mammals.

2.3 Assessment area

This section describes the physiography and post-European settlement patterns for the Fitzroy, Darwin and Mitchell catchments (the 'Assessment area'). The section also reviews the current state of the aquaculture industry in northern Australia and significant aquaculture assessment surveys that have been completed in the study areas.

2.4 Fitzroy catchment

2.4.1 OVERVIEW OF STUDY AREA

The Fitzroy catchment study area (see Figure 2-2 and Figure 2-3) is defined by the Fitzroy Australian Water Resource Council River Basin. The Fitzroy catchment originates in the King Leopold Ranges and drains into King Sound south of Derby, encompassing an area of 94,000 km2. The Fitzroy catchment is comprised of two main population centres, Derby, population 3261 (Australian Bureau of Statistics, 2013b) and Fitzroy Crossing, population 1144 (Australian Bureau of Statistics, 2013d). There are also 57 smaller Indigenous communities for a total catchment population of about 7000 people.

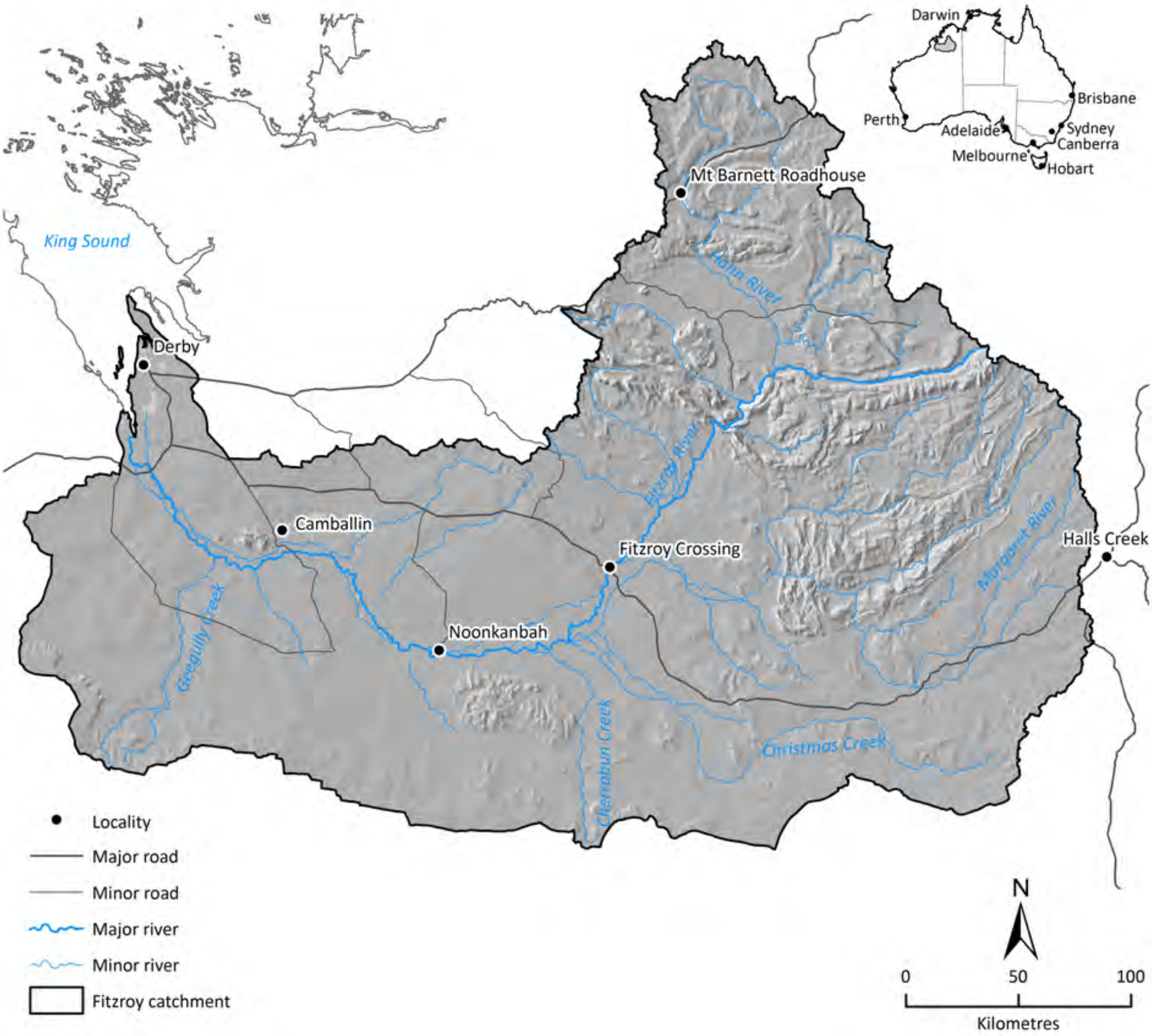

Figure 2-2 Fitzroy catchment, showing surrounding towns, the Fitzroy River and tributaries with relief patterns accentuated

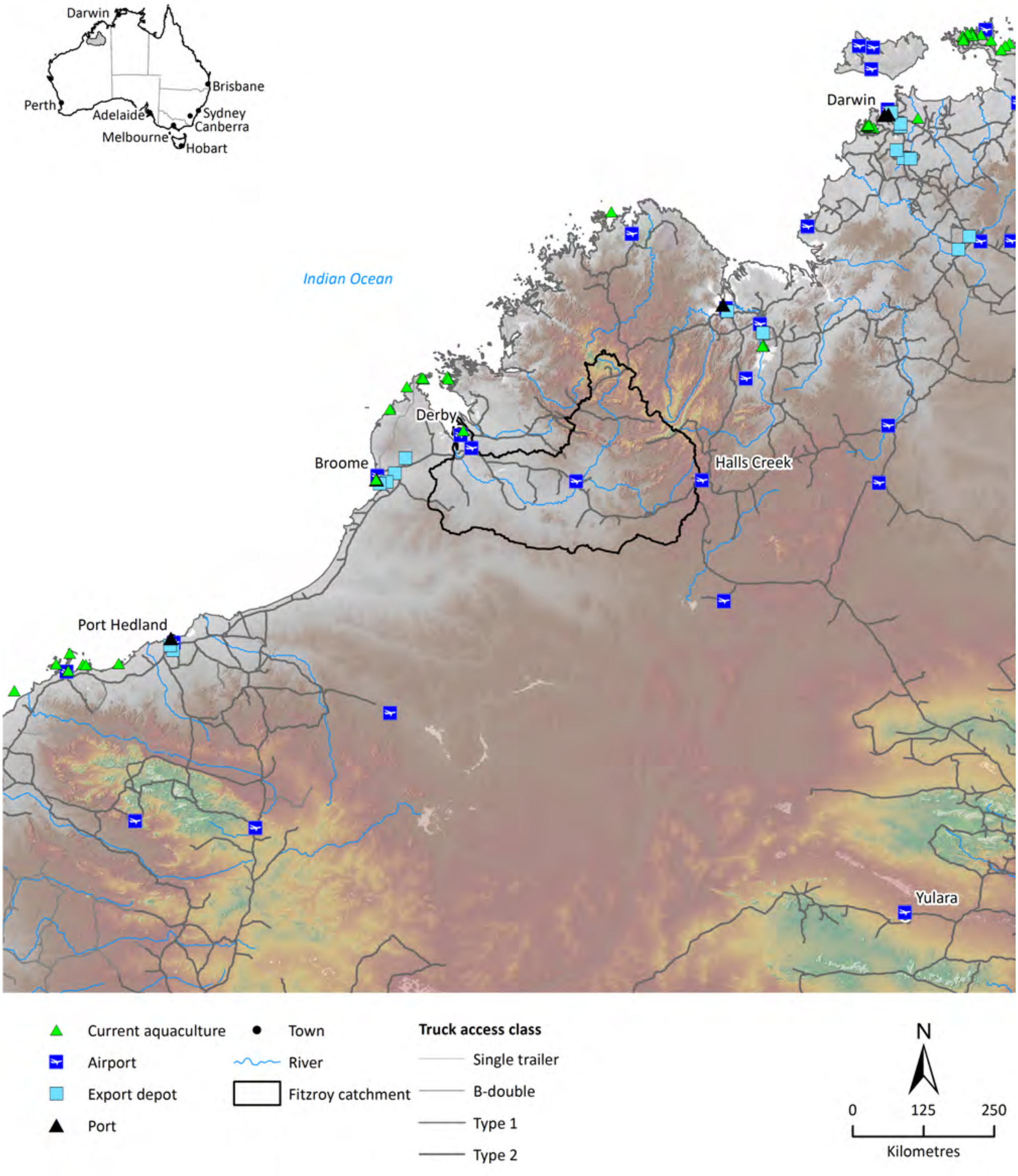

Figure 2-3 Fitzroy catchment, showing location of current aquaculture operations, airports, ports and truck access

The main land use activity in the study area is pastoralism (95%), characterised by large grazing leases of cattle on native pastures, shrubs, and introduced forages and legumes. Nature conservation and Indigenous Protected Areas cover the remaining area.

Northern Australia has diverse and highly valued natural ecosystems, which provide commercial, recreational and cultural value, as well as maintaining ecological functions and habitats for plants and animals (Abel and Rolfe, 2009). The ecology of aquatic ecosystems is fundamentally linked to the seasonality of the wet–dry tropical climate that regulates the flow regime, as well as the landscape it drains (Warfe et al., 2011). The natural flow regime and connectivity between aquatic ecosystems are critical for sustaining freshwater and marine biodiversity, and natural ecological processes.

2.4.2 CLIMATE

The Fitzroy catchment lies near the typical southernmost extent of the deep westerly wind regime associated with the Australian summer monsoon, and its climate is characterised by a highly distinctive wet- and dry-season. The largest proportion of rainfall in coastal areas of the Fitzroy catchment comes from active monsoon periods, while further inland and up the catchment a greater contribution of rainfall results from monsoon bursts and daily thunderstorm activity.

The mean annual rainfall, averaged over the 125-year historical period (1890 to 2015) over the Fitzroy catchment was 552mm, with close to 93% of rain falling during the wet-season (November to April) (Charles et al., 2016). Rainfall is highest in the north of the catchment as these locations are more frequently affected by monsoonal westerly winds and the Kimberley heat trough.

Minimum temperatures are consistently higher in coastal areas. Areal potential evaporation in the Fitzroy catchment exceeds 2000 mm in most years (Charles et al., 2016). It exhibits a strong seasonal pattern, ranging from 200 mm per month during the build-up (October to December) and the wet-season, to about 100 mm per month during the middle of the dry-season (June). The high potential evaporation rates and relatively low rainfall result in a large annual rainfall deficit across most of the catchment. Consequently, a large proportion of the catchment is semi-arid.

Sea surface temperatures (SST) in marine waters offshore to the Fitzroy catchment are ideal for the culture of the majority of tropical aquatic species from October to May (Charles et al., 2016) (Figure 2-4). The warming trend of SST in northern Australia has the potential to prolong the grow-out season for some aquatic species.

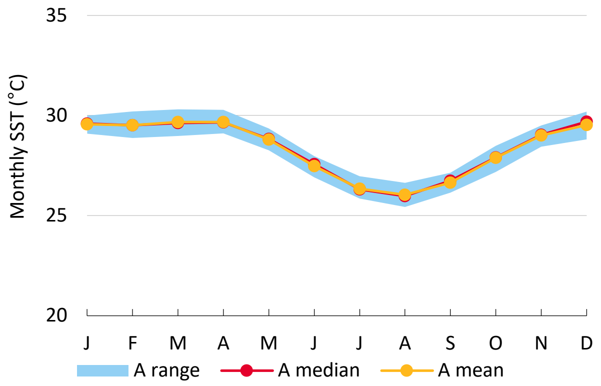

Figure 2-4 Historical monthly SST offshore to the Fitzroy catchment
123°, 16°S; A range is the 10th to 90th percentile monthly SST for 1970 to 2015 period.

2.4.3 CURRENT AQUACULTURE INDUSTRY

There is little land-based aquaculture in the Fitzroy catchment. However, Australia’s largest barramundi farm is located in Cone Bay, in marine waters adjacent to the Fitzroy catchment. Fish are cultured in large sea cages with the farm having a lease of 1340 ha in sheltered waters and a licence to produce 15,000 t per year. A 2013 report by the West Australian Government on inland aquaculture in WA reviewed eight candidate species for land-based culture. However, with the exception of barramundi, the majority of the species were considered better suited to culture in the cooler southern inland regions (Government of Western Australia, 2013). A 2014 report by the CSIRO identified 516,000 ha of coastal land potentially suitable for tropical land-based aquaculture in WA. Barramundi and tiger prawns were identified as established species suitable for culture in this region (CSIRO, 2014).

A large prawn farming business has been proposed in WA and the NT. The Australia agri-food company, Seafarms Group, is planning a multi-million dollar farming enterprise with major pond grow-out production based in the Victoria River District of the NT, 106 kilometres west of Kununurra, WA. The proposal is to develop the world's largest integrated aquaculture enterprise, which at full scale is projected to have the capacity to produce over 100,000 t of black tiger prawns per year (InvestNT, 2017; WA Gov, 2017)

2.5 Darwin catchments

2.5.1 OVERVIEW OF STUDY AREA

The Darwin catchments study area is defined by the Finniss, Adelaide, Mary and Wildman Australian Water Resource Council river basins (Figure 2-5 and Figure 2-6). Collectively, they encompass an area of about 30,000 km^2. The city of Darwin is located within the Finniss River basin and is the capital of the NT. The greater Darwin region (including the local government areas of Darwin, Palmerston and Litchfield and the city of Darwin) has a population of 136,828 (ABS, 2016), while the NT has a population of 228,833.

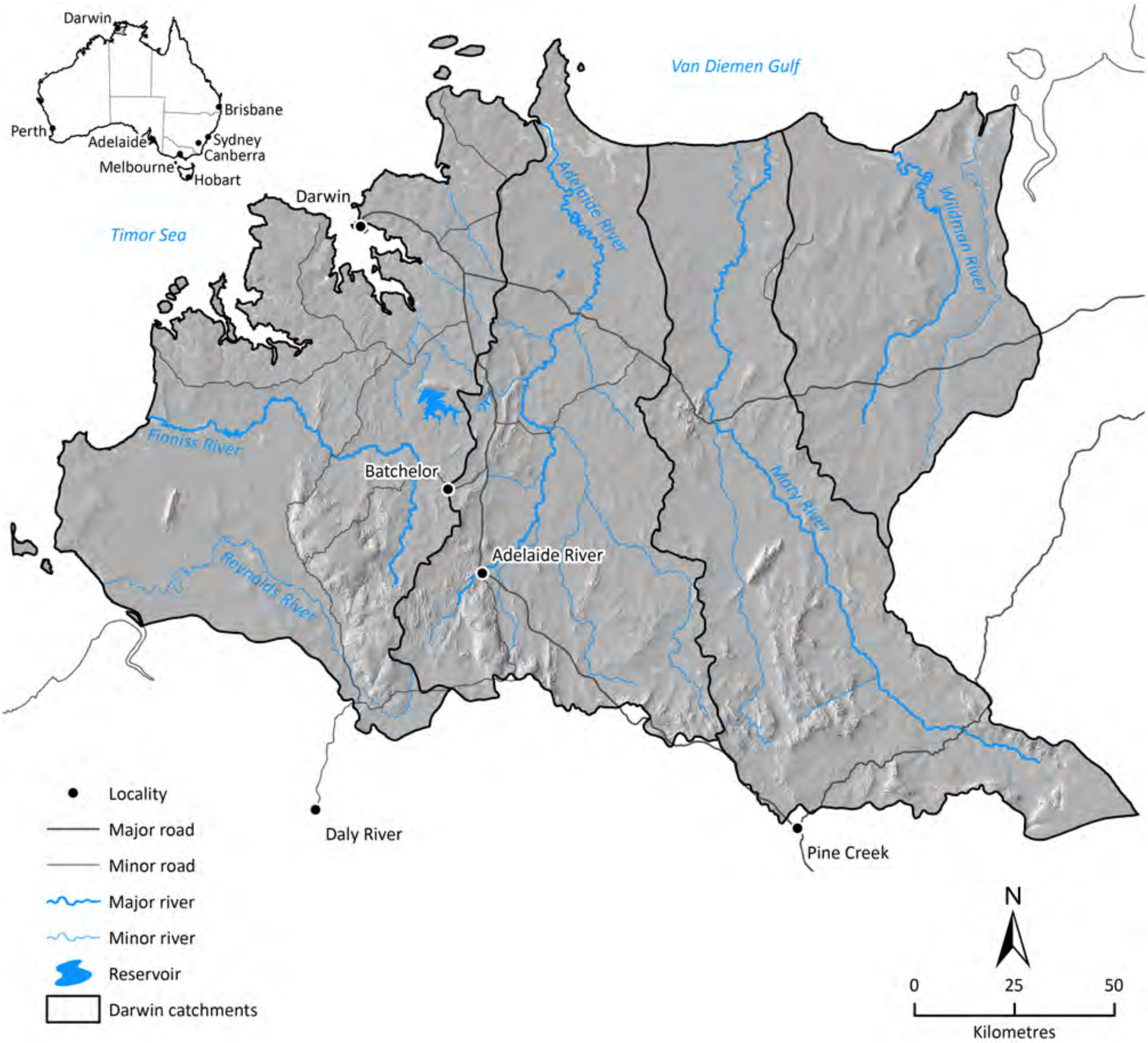

Figure 2-5 Darwin catchments, showing surrounding towns, rivers and tributaries with relief patterns accentuated

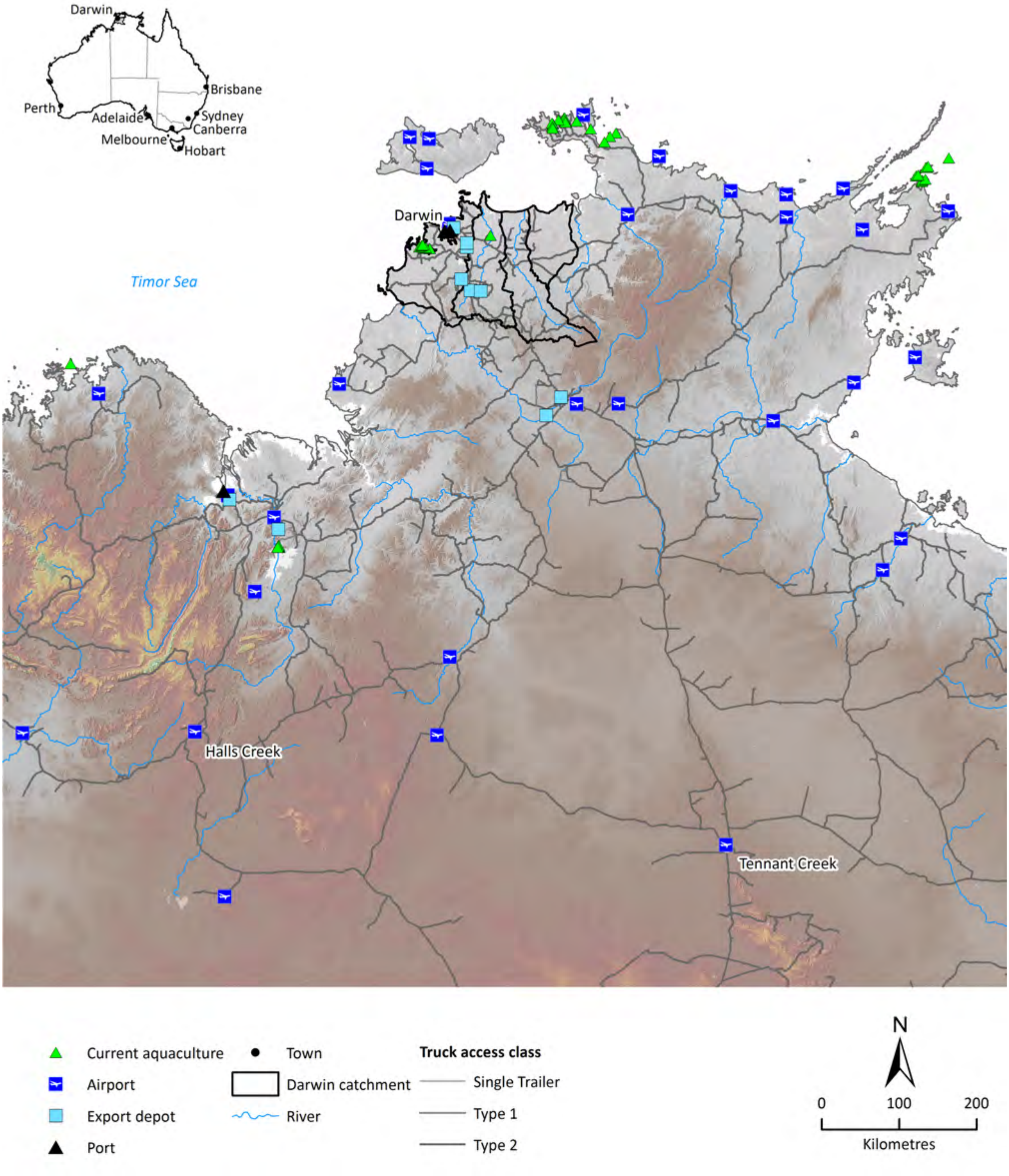

Figure 2-6 Darwin catchments, showing location of current aquaculture operations, airports, ports and truck access.

The main land use activity in the study area is conservation (53% or 15,800 km^2), with extensive grazing comprising 30.7% or 9130 km^2, farming 6.6% or 1950 km^2 (dryland cropping and horticulture, forestry and modified pastures) and irrigated agriculture 0.3% or 81.3 km^2 (irrigated pastures, crops and horticulture). The Finniss and Adelaide rivers are critical for Darwin's domestic water supply, with the area of land designated urban and peri-urban at 2.3% or 675 km^2 of the total study area.

Northern Australia has diverse and highly valued natural ecosystems, which provide commercial, recreational and cultural value, as well as maintaining ecological functions and habitats for plants and animals (Abel and Rolfe, 2009). The ecology of aquatic ecosystems is fundamentally linked to the seasonality of the wet–dry tropical climate that regulates the flow regime, as well as the landscape it drains (Warfe et al., 2011). The natural flow regime and connectivity between aquatic ecosystems are critical for sustaining freshwater and marine biodiversity, and natural ecological processes.

2.5.2 CLIMATE

The Darwin catchments are characterised by a distinctive wet- and dry-season due to their location in the Australian summer monsoon region. The mean annual rainfall, averaged over the 125-year historical period (1890 to 2015) over the Darwin catchments was 1423 mm, with close to 95% of rain falling during the wet-season (November to April) (Charles et al., 2016). Of this a considerable proportion is due to tropical cyclones or tropical lows, which cross the catchments every couple of years. During the build-up period (September to October) the bulk of rain falls within 100 km of the west coast of the NT, including the Finniss and Adelaide river catchments, while the Mary and Wildman river catchments generally receive less rainfall over this period. From November onwards, rainfall distribution is much more uniform across the four catchments. Areal potential evaporation in the Darwin catchments exceeds 1800 mm in most years (Charles et al., 2016). It exhibits a strong seasonal pattern, ranging from 200 mm in October to about 125 mm in June. The Darwin catchments are relatively flat, and consequently there is no topographic influence on climate parameters such as rainfall and temperature.

SST in marine waters offshore to the Darwin catchment are ideal for the culture of the majority of tropical aquatic species from October to May (Charles et al., 2016) (Figure 2-7). The warming trend of SST in northern Australia has the potential to prolong the grow-out season for some aquatic species.

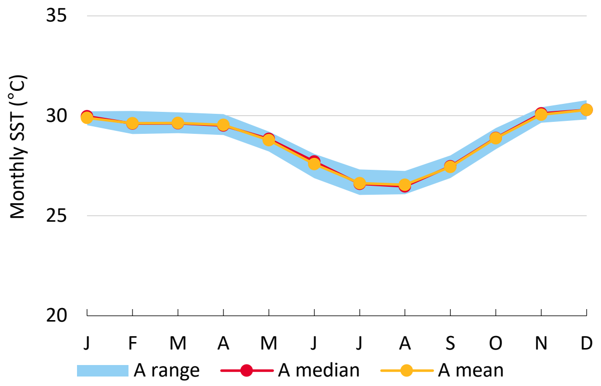

Figure 2-7 Historical monthly SST offshore to Darwin catchments
130°E, 12°S; A range is the 10th to 90th percentile monthly SST for 1970 to 2015 period.

2.5.3 CURRENT AQUACULTURE INDUSTRY

Fisheries (including wild catch and aquaculture) are major contributors to the agriculture sector in the NT ($79.2 M in 2014-15). The Humpty Doo Barramundi fish farm produces over 1000 t of barramundi per year, exporting fish both interstate and overseas (Humpty doo barramundi, 2014).

The fish are farmed in ponds, with marine water pumped from the Adelaide River. The NT Department of Primary Industry and Resources Aquaculture Research Centre in Darwin are currently conducting research on the farming of marine species (black-lipped oysters, giant clams and sea cucumbers), with the engagement of Indigenous communities as a key component. A 2015 CSIRO report identified 528,000 ha of coastal land potentially suitable for tropical land-based aquaculture in the NT. Barramundi and Tiger prawns were identified as established species suitable for culture in this region (Preston et al., 2015).

2.6 Mitchell catchment

2.6.1 OVERVIEW OF STUDY AREA

The Mitchell catchment study area (Figure 2-8 and Figure 2-9) is defined by the Mitchell Australian Water Resource Council River Basin. It encompasses an area of 72,000 km^2 and contains part of the Mareeba–Dimbulah irrigation area, which extends into the upper headwaters of the Walsh River. The study area consists of the local government areas of Kowanyama, with the Mareeba, Carpentaria and Cook shires making up the majority of the catchment. The population in the catchment is sparse (less than 6000), and there are no major urban population centres. The largest settlements are the towns of Dimbulah, population 1414 (Australian Bureau of Statistics, 2013c), Kowanyama, population 1031 (Australian Bureau of Statistics, 2013e) and Chillagoe, population 192 (Australian Bureau of Statistics, 2013a).

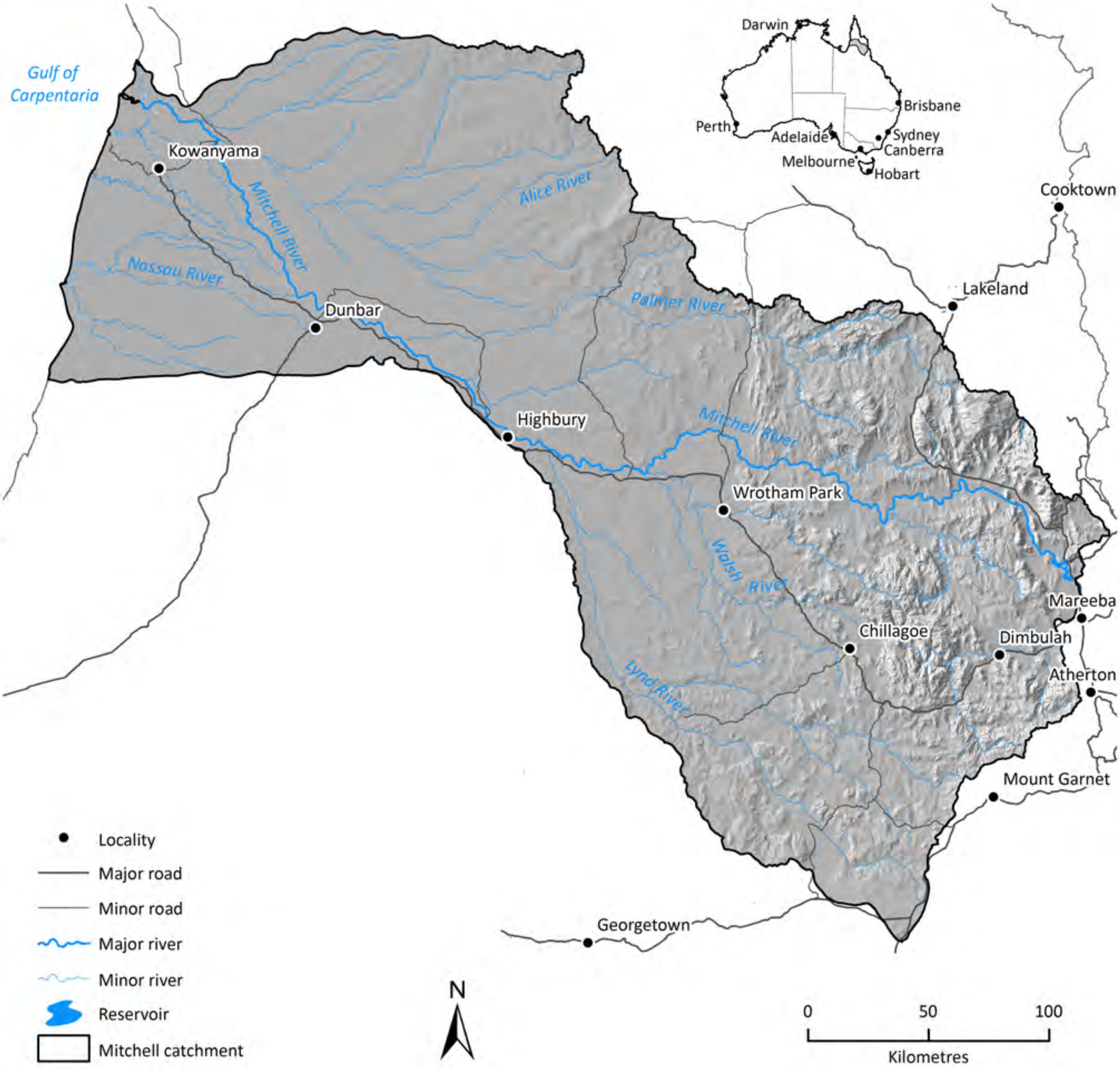

Figure 2-8 Mitchell catchment, showing surrounding towns, the river and tributaries with relief patterns accentuated

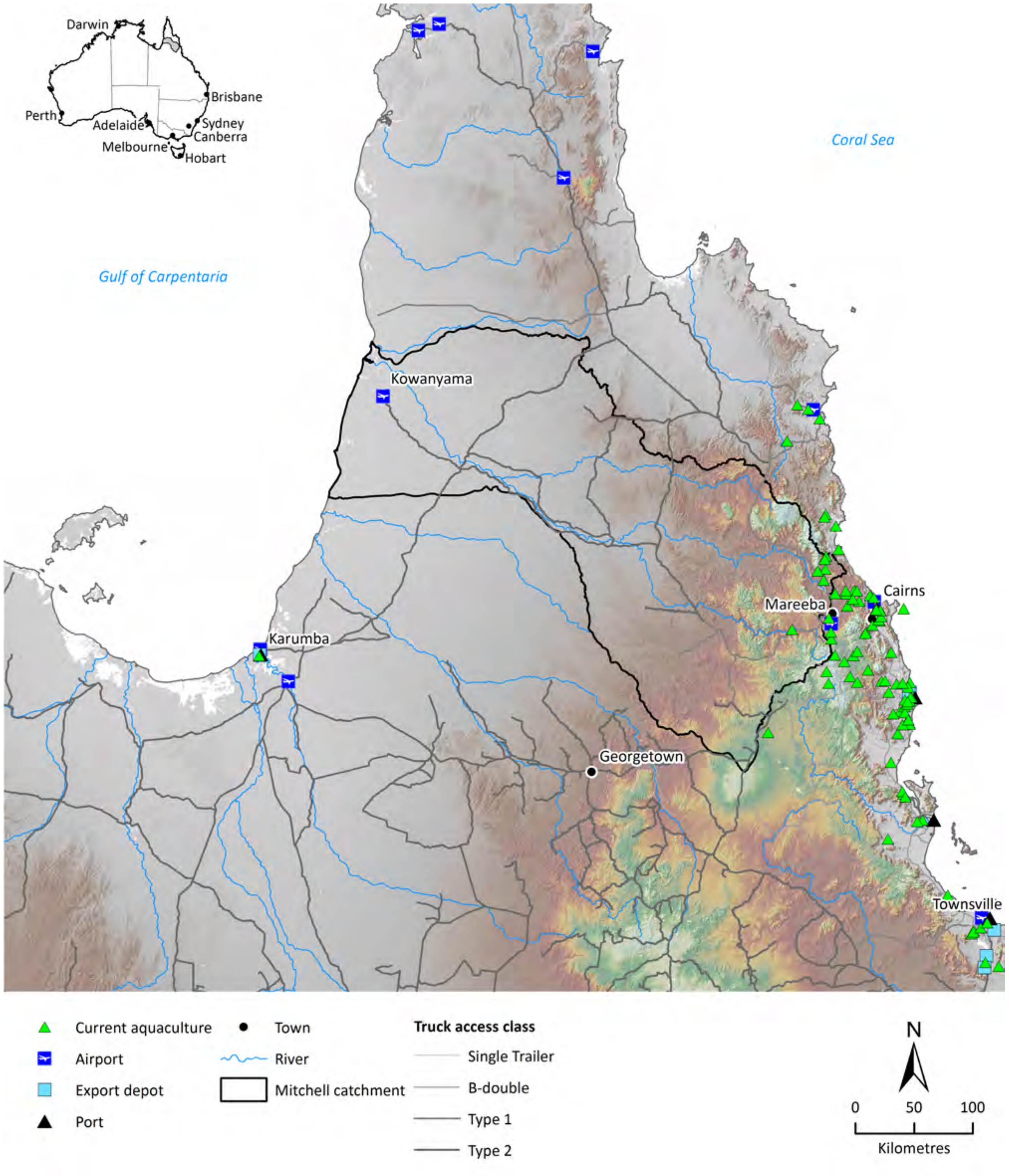

Figure 2-9 Mitchell catchment, showing location of current aquaculture operations, airports, ports and truck access

The main land use activity in the study area is pastoralism (95.1%), characterised by large grazing leases where cattle graze native pastures and shrubs, with little clearing of trees to support sown and improved pastures or crops. Conservation reserves comprise the second largest land use, but only constitute 2.9% of the catchment. In the Mareeba–Dimbulah irrigation area within the upper catchment, there is some irrigated agriculture, horticulture and small-scale cattle fattening projects, comprising 0.3% of the catchment.

The value of agricultural production from irrigated agriculture (including parts of the Mareeba irrigation area outside of the catchment) was AUD$552 million in 2015, of which 80% was derived from horticulture and forestry, with bananas (AUD$91 million), mangoes (AUD$83 million) and avocadoes (AUD$51 million) being the largest contributors. Fisheries are also an important contributor to local economic activity. The main fishery in the Gulf of Carpentaria is the Northern Prawn Fishery, the most valuable single gear fishery managed by the Commonwealth (AUD$115.2 million in 2013–14 (Savage, 2016)).

Northern Australia has diverse and highly valued natural ecosystems, which provide commercial, recreational and cultural value, as well as maintaining ecological functions and habitats for plants and animals (Abel and Rolfe, 2009). The ecology of aquatic ecosystems is fundamentally linked to the seasonality of the wet–dry tropical climate that regulates the flow regime, as well as the landscape it drains (Warfe et al., 2011). The natural flow regime and connectivity between aquatic ecosystems are critical for sustaining freshwater and marine biodiversity, and natural ecological processes.

2.6.2 CLIMATE

The Mitchell catchment is characterised by a distinctive wet and dry-season due to its location in the Australian summer monsoon region. The mean annual rainfall for the Mitchell catchment, averaged over the 125-year historical period (1890 to 2015), was 996 mm, with close to 97% of rain falling during the wet-season (November to April) (Charles et al., 2016). Of this a considerable proportion is due to tropical cyclones or tropical lows, which cross the catchment every couple of years.

The bulk of wet-season rainfall comes from active monsoon bursts, which bring significant shower and thunderstorm activity into the catchment from the west. Other major rainfall contributions come from thunderstorm activity during the transition months of October, November and April (often associated with Gulf Lines), and during monsoon break periods. It is worth noting that some parts of the far upper Mitchell catchment receive rainfall throughout the dry-season months (approximately 20 to 50 mm per month).

Areal potential evaporation in the lower and upper Mitchell catchment is about 1900 and 1800 mm respectively in most years (Charles et al., 2016). It exhibits a strong seasonal pattern, ranging from 200 mm per month during the build-up (October to December) and the wet-season, to about 100 mm per month during the middle of the dry-season (June).

SST in marine waters offshore to the Mitchell catchment are ideal for the culture of the majority of tropical aquatic species from October to May (Charles et al., 2016) (Figure 2-10). The warming trend of SST in northern Australia has the potential to prolong the grow-out season for some aquatic species.

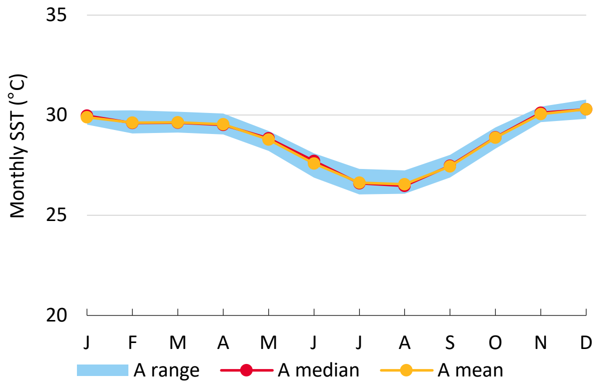

Figure 2-10 Historical monthly SST offshore to the Mitchell catchments
141°E, 15°S; A range is the 10th to 90th percentile monthly SST for 1970 to 2015 period.

2.6.3 CURRENT AQUACULTURE INDUSTRY

There is little land-based aquaculture in the Mitchell catchment. There are a two small red claw (freshwater crayfish) farms located near Mareeba in the eastern region of the catchment. A QLD government facility located at Walkamin (near Mareeba) has dedicated pond and tank systems for freshwater aquaculture and fisheries research. While the facility is currently not in operation, it has a history of barramundi and red claw research. A 2015 CSIRO report identified 594,000 ha of coastal land potentially suitable for tropical land based aquaculture in Queensland. Barramundi and tiger prawns were identified as established species suitable for culture in this region (Preston et al., 2015).

3 Australian aquaculture overview

3.1 Introduction

Australian aquaculture production primarily comprises fish, crustacean and molluscs, with the majority of production occurring in temperate regions. The combined value of tropical aquaculture production from WA, Qld and the NT accounts for less than 25% of the total value of Australian production (Savage and Hobsbawn, 2015).

The main temperate aquaculture species are Atlantic salmon (*Salmo salar*), pacific oysters (*Crassostera gigas*) and Sydney rock oysters (*Saccostrea glomerata*). Other cooler water species include blue mussels (*Mytilus edulis*), yellowtail kingfish (*Seriola lalandi*), greenlip abalone (*Haliotis laevigata*), blacklip abalone (*Haliotis rubra*), freshwater trout (*Oncorhynchus mykiss* and *Salvelinus fontinalis*) and marron (*Cherax tenuimanus*).

The main species farmed in the warmer water regions of northern Australia are black tiger prawns (*Penaeus monodon*), banana prawns (*Fenneropenaeus merguiensis*), barramundi (*Lates calcarifer*) and red claw (Cherax quadricarintus). Other small volume species include marron (*Cherax tenuimanus*), cobia (*Rachycentron canadum*), silver perch (*Bidyanus bidyanus*), Murray cod (*Maccullochella peelii peelii*), jade perch (*Scortum barcoo*) and oysters.

Over 95% of Australian production is from marine species. Barramundi, a euryhaline fish tolerant of marine and freshwater, is the only tropical species farmed in freshwater in significant quantities (>3000 t) in Australia (Savage, 2016). The next highest volume freshwater species is silver perch with production of 314 t and value of around AUD$4 million in 2014-2015. The vast majority of fed species (80%) are marine fish cultured in sea cages. The remaining 20% of fed species are fish and crustaceans cultured in land-based systems primarily from coastal ponds. Culture of non-fed molluscs in suspended systems such as rafts, racks and longlines account for about 13% of total production.

3.1.1 AUSTRALIAN INDUSTRY PRODUCTION AND VALUE

Australia is a very small contributor to global seafood production (<0.2%). Australian seafood production totalled 235,000 t in 2014–15, with aquaculture contributing 42% of the total (FAO, 2016). Over the last 20 years Australian aquaculture production has increased by an average of 11% annually (Skirtun et al., 2013) to a production value of AUD$1.2 billion in 2014-2015.

3.1.2 TEMPERATE INDUSTRY PRODUCTION AND VALUE

The salmonid sector (mainly Atlantic salmon) has seen the most rapid growth, with production reaching 48,614 t with a value of AUD$631 million in 2014-2015. Atlantic salmon farming is now Australia’s most valuable seafood sector, accounting for 55% of the total value of Australian aquaculture production (Savage and Hobsbawn, 2015). All salmon farming is based in Tasmania with grow-out production occurring in near-shore sea cages. Production of edible mollusc species has been relatively stable over the last decade, with oysters (edible) and abalone the main sectors.

In 2014-2015, oyster production declined by 6% to 10,870 t with a value of AUD$92 million. This decline was largely due to a serious disease episode. During the same period, abalone production increased by 3% to 849 t and a value of AUD$29 million.

3.1.3 TROPICAL INDUSTRY PRODUCTION AND VALUE

Prawns and barramundi are the largest sector by volume with production reaching 5282 t and 3772 t, respectively in 2014–2015 (Savage, 2016). Prawns are the highest value sector, with the industry worth AUD$86 million in 2014–2015 (Savage, 2016). The vast majority of prawn and barramundi farming occurs along the east coast of Queensland, in coastal land-based ponds. Freshwater crustacean production in 2014–2015 consisting of marron, red claw and yabbies was 143 t with a value of AUD$3.8 million. Production of freshwater fish silver perch in 2014–2015 was 314 t with a value of AUD$3.9 million (Savage, 2016).

3.2 Production and market trends

Since 2004–2005 annual aquaculture production in Australia has increased by 5% each year to about 100,000 t in 2014–2015 (Savage, 2016). The majority of production, value and growth (74%) has come from the salmon sector. During this period the value of the Tasmanian salmon industry increased from AUD$192 million to AUD$631 million (Savage, 2016). Other industries have also grown in value during this period, including prawns (AUD$20 million increase), barramundi (AUD$20 million increase) and abalone (AUD$12 million increase) (Savage, 2016). Production of most other species have either plateaued or declined in the last decade.

Australian seafood has a global reputation for being high quality. Over half (52%) of Australian seafood (wild caught and farmed) is exported. The main export markets for Australian seafood are China, Japan, Hong Kong and Vietnam. Over two-thirds of exported products are premium wild caught products, including lobster destined for China and Hong Kong, which had an export value of AUD$691 million in 2014–2015 (Savage, 2016). In contrast, the vast majority of aquaculture production is consumed domestically. However, export of farmed salmon (particularly to China) almost doubled in value to $48 million in 2014–2015. Australia remains a net importer of seafood. Total import of fisheries and aquaculture product in 2014–2014 was valued at AUD$2 billion (Savage, 2016). In contrast to Australia's high-value exports, the bulk of the imported product is lower value fish and prawns, such as canned tuna and frozen fish.

3.3 Major challenges to the Australian industry

3.3.1 MARKET COMPETITION

The cost of production in Australia means that tropical species (particularly white fish and prawns) are currently not price competitive with the same or similar product when farmed in Asia. International markets for tropical Australian species are typically for live crustaceans (e.g. lobsters and crayfish) and tropical reef fish species (e.g. coral trout). These species are either not currently farmed or only in small volumes. Species with seasonal supply cannot meet the volume requirements to access premium markets. The outlook is more positive for temperate species.

Atlantic salmon has clear market differentiation (pink flesh) from tropical species and sufficient scale to access high-end markets.

The majority of seafood consumed in Australia is imported and the proportion is rising. 67% of seafood was imported in 2014-2015 (Savage, 2016). The most common imports are canned fish and frozen fish and prawns, the majority coming from China and Thailand.

Import of cheap prawns and white fish from South-East Asia directly competes with Australian farmed produce. This is particularly relevant to tropical species such as prawns and barramundi which are farmed in South-East Asia and Australia. In addition, there is wild caught barramundi and prawns from north Australian fisheries which compete with the local farmed product. A challenge for Australian producers is that there is little to visibly differentiate between the many species of imported 'white' prawns and white fish and the Australian product. Australian farmed Atlantic salmon is less affected by cheap imports, as the species has no local fishery, is not suitable for farming in South-East Asia, and is easily distinguished from imported low-value white fish.

3.3.2 INDUSTRY REGULATION

The aquaculture industry is managed by numerous agencies at the local, state and federal levels of government. To date, significant development of marine aquaculture in northern Australia has in part been constrained by complex legislation and the absence of aquaculture-specific policy. A parliamentary inquiry into the development of northern Australia identified the regulatory environment as a serious impediment to major expansion of the prawn farming industry (Parliament of Australia, 2014).

In general, large areas of low-value land located away from populated coastal areas are likely to be suitable for freshwater ponds. In contrast, marine ponds require higher value coastal land, often located in close proximity to towns or regional centres. Compared to marine pond aquaculture, freshwater pond aquaculture is ranked as a low environmental risk option for development. There is no difference in the probability of marine or fresh pond water escaping containment and seeping in to the groundwater or surrounding environment. However, marine water discharged into groundwater or freshwater bodies has greater potential to cause negative environmental and ecological impacts.

The approval process for an aquaculture licence is simple to obtain for freshwater pond-based farming. This is reflected in the number of licence approvals. For example, in QLD in 2014-2015 there were 158 development approvals for freshwater red claw production compared to 58 approvals for marine prawn production. The disconnection between the number of licence approvals and value of the respective industries ($1 million for red claw and $86 million for prawns) is due to the greater difficulty in obtaining an aquaculture licence for marine pond-based farming (Savage, 2016).

The approval process will vary depending on the state or territory and jurisdiction of water source. Specific details on the approvals required for a land-based aquaculture operation can be found at the website of the relevant authority. Two reviews undertaken in 2013 and 2014 by the Centre for International Economics (CIE) provide a good overview of the regulatory framework for aquaculture in Queensland (CIE, 2013; 2014). The 2014 CIE review provides a comparative assessment of Queensland with three southern jurisdictions, which highlights the degree of difference in regulatory approaches across jurisdictions (CIE, 2014).

3.4 Temperate species

Temperate aquaculture in Australia is largely comprised of fish and mollusc culture. Temperate fish production is dominated by the farming of one introduced salmonid species, the Atlantic salmon (*Salmo salar*), in Tasmania. The initial phases of Atlantic salmon production occur on land in freshwater facilities, with the later phases occurring in sea cages. Oyster aquaculture constitutes the largest sector of mollusc aquaculture. Five species of oysters are farmed in the southern states with pacific oysters and Sydney rock oysters providing most of the farmed production. Oysters are initially produced as larval ‘spat’ in indoor hatcheries, or settle into production systems as ‘wild’ spat, before being grown-out in different types of systems in either intertidal or subtidal zones. Abalone aquaculture is another significant sector of mollusc aquaculture. Two main species are farmed; the blacklip and the greenlip, as well as a hybrid of the two species. Production occurs at sea on artificial reefs or cages suspended above the seafloor, and in land-based farms.

3.4.1 ATLANTIC SALMON

Atlantic salmon (*Salmo salar)* is of the family Salmonidae. Originally endemic to the North Atlantic rivers and seas, the species has been introduced for aquaculture to the major salmon farming areas of the world. The species is the dominant salmonid farmed globally, with leading producers being Norway and Chile, followed by other areas of Europe and North America. Current worldwide production of farmed salmonids is around 2 million t per year, with this species constituting more than 90% of the farmed salmon market (Marine Harvest, 2017).

Salmon farming commenced in Tasmania in the mid-1980s. Fertilised eggs were purchased from a hatchery in the New South Wales high country that imported original stock from Nova Scotia, Canada in the 1960s. A sea farm was established at Dover in the south of Tasmania and a hatchery was developed at Wayatinah in the central highlands. The first commercial harvest in the summer of 1986–1987 was 53 t. The Tasmanian industry now produces almost 50,000 t per year. The industry has become the leading farming industry in Tasmania, provides significant economic benefits, and when coupled with the smaller trout industry, has created over 2,000 direct jobs and over 6,000 indirect jobs (TSGA, 2017).

The major global markets for farmed Atlantic salmon are the European Union and North America. The major products remain fresh (whole, steaked, filleted), frozen, and smoked (mainly for the European market) (Marine Harvest, 2017). The Tasmanian industry produces all forms of products and sells into both domestic and international markets.

Historically, in the Australian aquaculture production system, the maturing adult fish (called broodstock) were moved from sea cages on marine farms to hatcheries in early autumn in preparation for spawning. In order to better manage biosecurity, broodstock are now typically maintained in freshwater throughout their lives (i.e. they are essentially landlocked). Meanwhile, production stocks are reared in both freshwater and seawater.

The salmon industry has been successful and the fastest growing livestock production sector in Australia for many reasons. The popular flavour, differentiation from low-value white fish, and perceived health benefits has resulted in a strong (and global) market for this fish product. The amenability of the species to culture and established production systems positioned the species well for aquaculture. The cage systems used for the main marine phase of rearing allowed for high productivity. The amenability to large-scale culture underpinned the successful industrialisation of farming, which have made this species appealing for investment as compared to other aquaculture species (Marine Harvest, 2017). Tasmania benefited from expertise which had existed in other global farming regions, particularly in the UK, Norway and North America, which aided rapid development of the industry (TSGA, 2017).

The Tasmanian industry has consolidated over time, with fewer, larger companies now dominating the industry. The development of the government-industry cooperative hatchery enterprise to provide fertilised eggs and smolts to be sold at the cost of production to industry partners, plays a major role in operating the industry breeding program. Due to the importance of salmon farming to the state, there has been considerable government support in terms of regulatory measures to allow the industry to grow. However, the industry faces many typical aquaculture challenges such as the cost-effective provision of feeds and management of disease, as well as issues particular to their industry, such as preventing seals predating on salmon within the marine cages. In recent times the industry has faced even greater challenges due to the size and projected scale of growth of production, which relate to environmental sustainability and social licence (Australia Institute, 2016). One solution that has been proposed to allay these concerns is to farm ‘offshore’ in ‘fortress pens’ or ‘well-boats’, which will remove production from more environmentally and socially contentious nearshore environments, but which will come at greater financial risk and cost (Huon, 2017).

3.4.2 OTHER TEMPERATE SPECIES

Australian temperate aquaculture is dominated by the Atlantic salmon industry, with the oyster and abalone industries being the next most important species on a production and value basis in southern Australia. Freshwater barramundi is a modest sized temperate industry, with most other industries being small, cottage or niche level, or emerging. In terms of relative scale and value, the oyster industries produces about 11,000 t of shell-on product per year, valued at about AUD$92 million. The abalone industry produces about 850 t for both live and canned markets with a total value of about AUD$29 million. The other temperature aquaculture industries combined produce about 4,000 t of product with a value of AUD$15 million (Savage, 2016).

The oyster industry includes both endemic and introduced oyster species. The Sydney rock oyster and the flat oyster are indigenous species, while the pacific oyster is native to Japan and was brought to Australia in several introductions since the 1940s (NSW Oyster, 2017). The Sydney rock oyster is more tolerant of warmer waters, with culture predominantly coming from along the New South Wales (NSW) coast, but also in areas of QLD and WA. The pacific oyster dominates production in South Australia (SA) and Tasmania (TAS) where waters are cooler, but is also produced around Port Stephens in NSW. Oysters are grown in different farming systems, which can be broadly segregated into ‘rack and rail’ and ‘long-line’ systems (MDCA, 2017).

The abalone industry farms two main indigenous species; the blacklip and the greenlip, as well as a hybrid of these two species (Hamilton et al., 2009). Most farming occurs in Victoria (VIC), SA and TAS, but some production also occurs in NSW and WA. Some production occurs on artificial reefs or cages in the natural environment, but most culture occurs in land-based tanks systems which afford much greater control over culture (MESA, 2017). Indoor seawater systems are either round tank systems fitted with hides, or more commonly shallow raceways with flowing seawater which are called ‘slab’ systems.

A range of other fish, crustacean and mollusc species are also farmed in temperate areas of Australia. The yellowtail kingfish is a marine fish species which has recently been cultured in the marine environment, with the first commercial quantities produced in SA in 2004 (Seafood Frontier, 2017). Farming operations have since expanded to other states, particularly NSW. The initial stages of production take place in land-based hatcheries, after which the fish are transferred to sea cages for rearing to market size (Oceanwatch, 2017). Mulloway is another marine fish species which was originally farmed in SA, but has now expanded into NSW. The earliest stages of production takes place in land-based hatcheries, after which the fish are transferred to either sea cages or land based ponds for grow-out to market size (Oceanwatch, 2017).

Several fish species are also farmed in freshwater systems in the temperate regions of Australia. Two trout species are cultured across the southern states. Rainbow trout are farmed primarily as an aquaculture (food) species, whereas brown trout are typically produced for stocking recreational fishing environments. Trout production occurs on land in freshwater pond or raceway systems (VFA, 2015). The tropical barramundi is also farmed in the southern states, primarily in VIC and SA, in heated freshwater recirculating aquaculture systems (RAS) (Mainstream, 2017). Murray cod is a native species for which culture is still in its infancy. This species is cultured extensively in farms dams for recreational fishing re-stocking purposes, but also in RAS, or a combination of RAS and pond systems, by a small number of operators for aquaculture purposes (NSW DPI, 2016b). The native silver and golden perch are also produced for both recreational fishing stocking and aquaculture purposes, with silver perch the predominant species produced for food and most production occuring in NSW. Beyond the hatchery phases, commercial aquaculture of silver perch typically occurs in earthen ponds, but they can also be produced in cages, raceways or in tanks (NSW DPI, 2016a) .

The blue mussel is the only mussel species farmed in Australia. This mollusc species is new to farming in Australia, with culture in estuaries in NSW, VIC, SA, and TAS. The species are farmed using two main productions systems, ‘rafts’ and ‘longlines’(NSW DPI, 2016a). The only temperate water marine crustacean currently considered for aquaculture is the southern rock lobster, however development of this industry is only at a research phase (IMAS, 2017).

Two main species of freshwater crustaceans are currently farmed at a small scale. Yabbies are mostly farmed as a hobby species extensively in dams throughout all southern mainland states, however there are some small commercial aquaculture operations across all states (NSW DPI, 2016a). Marron is farmed in ponds across the southern mainland states, particularly SA, with WA having a modest size industry involving many small farmers (ACWA, 2017).

3.5 Established tropical species

Australian tropical aquaculture is dominated by marine crustacean and fish culture. Tropical crustacean aquaculture primarily involves the farming of marine prawns. Black tiger (*Penaeus monodon*) and banana prawns (*Fenneropenaeus merguiensis*) are the main species currently produced. All marine prawn production occurs in land-based ponds, the majority in north QLD followed by south QLD, and northern NSW. In 2014-2015, prawn aquaculture production constituted around 8% of total aquaculture production in Australia, totalling 5,282 t (Savage, 2016). There are plans for a global-scale integrated prawn farming enterprise operating from sites in the NT and WA, with stage one production targeting 14,000 t of black tiger prawns per year, increasing to 100,000 t when in full operation (InvestNT, 2017). The only tropical freshwater crustacean under significant production is the fresh water crayfish, red claw. In 2015-2016, red claw aquaculture contributed 51 t of production. All production occurs in land-based ponds, the majority in QLD.

Tropical fish aquaculture is dominated by the farming of barramundi. According to 2014-2015 ABARES data, 78% of the 3772 t of annual production is from QLD, mainly from land-based ponds. A further 20% is produced in sea cages in WA (Savage and Hobsbawn, 2015). Production from the NT is not included in the ABARES data, but is estimated to be in the order of 1000 t per year. As noted previously, small volumes of barramundi production also come from the temperate states, including NSW (62 t), VIC and SA, with fish grown in RAS. Cobia is an emerging tropical fish species with all production (100 t) occurring in land-based ponds in north Queensland.

3.5.1 PRAWNS

The global prawn aquaculture industry consists of many marine prawn species of the family Penaeidae which are farmed throughout tropical and subtropical regions. Asian countries dominate the market, producing about 67% of global production, with Latin American countries producing about 30% of production. The white shrimp (*Litopenaeus vannamei)* is the most dominant species farmed, with the black tiger (*Penaeus monodon)* a distant second, as shown in Figure 3-1. The global industry has experienced booms, declines and stagnations from year to year over the recent decade, largely driven by disease issues impacting on major production regions, most recently in South-East Asia and China. In 2015-2016 global production was estimated at around 2 million t (primarily white shrimp and black tiger) (FAO, 2016). The major global markets for farmed prawns are North America, the European Union, Japan, and China. Market demand is primarily for raw and cooked frozen products, with a recent trend toward ‘ready-to-eat’ and ‘easy-to-cook’ convenience products.

Figure 3-1 Black tiger prawn
Source: CSIRO

Prawn farming commenced in Australia in the 1980s with the first farms established in south and north QLD. Multiple indigenous Australian prawn species have been, and are currently farmed, including the black tiger, banana and kuruma prawns. Notably, the exotic Pacific white shrimp (*L. vannamei)* is not, and cannot be, farmed in Australia, due to Australian Quarantine & Inspection (AQIS) regulations. Prawn farming requires pond water temperatures routinely above 25^{o} C during the production season (QDPIF, 2006). Consequently, more than 95% of existing farm production comes from tropical and sub-tropical regions on the east coast of QLD, with smaller production from northern NSW, NT and WA. The total land area currently used for production is in excess of 900 ha, with clusters of QLD farms around Mackay, Bundaberg, Townsville, Cairns and just south of Brisbane. Prawn farming is Queensland's largest aquaculture sector, providing the equivalent of 300 full-time jobs mostly in rural communities. Production figures for the 2015-2016 year indicated around 4,500 t were produced, which equates to an annual value of approximately AUD$86 million (Savage, 2016). Australian prawn production is predominantly for the domestic market, with 67% of the market for cooked 'fresh or frozen' product and 33% for green 'fresh or frozen' product.

Australian prawn farming is dominated by the black tiger prawn. Black tiger prawns are found naturally at low abundances across the waters of the Indo-West Pacific, with wild Australian populations making up the southernmost extent of the species. Within Australia, the species is most common in the tropical north, but does occur in lower latitudes. In waters off the east coast of Australia postlarvae can be found year-round but are at highest abundance in early summer following the major breeding period of mature adults in spring (Gribble et al., 2003). When breeding, adult females can spawn multiple times, releasing hundreds of thousands of eggs each time into the seawater environment. The first larval stage nauplii hatching from these eggs survive for two days on their yolk reserves, before going through many subsequent larval metamorphoses until becoming postlarvae, which have the morphology of small prawns. The larvae migrate from the oceanic waters and settle as postlarvae in brackish water nursery grounds, such as mangrove estuaries and swamps. Sub-adults inhabit the shallow waters of foreshore, living among the sparse seagrass beds, and typically move into deeper waters on approaching adult age for breeding (Dall et al., 1990; Vance et al., 2002).

In Australian aquaculture production systems, the adult prawns (called broodstock) are introduced to the maturation facility within indoor hatcheries for ‘conditioning’ and then spawning. Most black tiger prawn hatcheries use wild caught broodstock, which are acquired during specialist fishing trips from prawn trawlers and transported to the commercial hatcheries. On arriving to the hatchery, the broodstock are ‘conditioned’ with high quality feed and over a period of weeks, ripe females are selected daily and transferred into ‘spawning tanks’ for spawning. The period of conditioning and spawning typically takes three to six weeks, depending on the quality and numbers of broodstock acquired, the size of the hatchery, and the number of postlarvae needed to supply the farm. Eggs collected daily from spawnings are transferred to hatching tanks within which the first larval stage nauplii will hatch. These hatched nauplii are left for a day in the hatching tanks before being transferred to the larval rearing section of the hatchery for on-rearing. The nauplii metamorphose through different larval stages before reaching a postlarval age suitable for stocking in commercial earthen ponds; this age being 15 days following metamorphosis to postlarvae, which is an age called ‘postlarvae 15’ or PL15. During larval-rearing, the larvae and postlarvae are fed a mixture of different live and artificial feeds, the composition changing with each stage. The duration from egg to PL15 in a typical hatchery ranges from 23 to 25 days (FAO, 2007). The hatchery period from collection of wild broodstock to producing the quantity of PL15 needed to stock all ponds typically takes two to three months.

Beyond the hatchery phase, the PL15s are typically grown to market size in land-based pond systems. A typical pond in the Australian industry would be rectangular in shape; about 1 ha in area and about 1.5 metre in depth, although there are considerable variations between and within farms, often to make use of available land (Figure 3-2). The ponds are either wholly earthen; lined on the banks with black plastic and earthen bottoms; or fully lined, although this is not common in the Australian industry. In Australia, pond grow-out of black tiger prawns typically operates at stocking densities considered as ‘semi-intensive’ or ‘intensive’ (‘intensive’ is used for the remainder of this report), which typically means that ponds are stocked between 25-50 individuals m^{-2}. These pond systems are fitted with multiple aeration units, such as paddlewheels and aspirators which serve to both aerate and circulate the water, the former for purposes of consolidating the waste into a central sludge pile which allows a greater area of the pond bottom to be optimal for the prawns while also making the sludge easier to remove at the end of the crop (QDPIF, 2006). As an example, for intensive farming, ponds may be fitted with about eight aeration units early in the crop, which might consist of six paddlewheels and two aspirators set up in an optimised configuration to achieve good water circulation, whereas the number required might double by the end of the crop when prawn biomass is greatest (Mann, 2012).

Figure 3-2 Aerial view tiger prawn farm
Source: GCMA

At the start of each prawn crop, prior to stocking with postlarvae, the ponds need to be prepared and filled with water. Between harvests, the pond bottoms are dried and unwanted sludge from the previous crops are removed, and if needed, additional substrate is added. Prior to filling the ponds, lime is often added to buffer pH, particularly in areas where there are acid sulfate soils. The ponds are then filled with filtered seawater and left for about one week prior to postlarval stocking. Algal blooms in the water are encouraged through addition of organic fertiliser. These blooms are essential for both shading of the prawns and to discourage benthic algal growth, but also for the nutritional value they provide for the planktonic community within the ponds (QDPIF, 2006).

For stocking ponds for each crop, PL15s (Figure 3-3) produced at nearby hatcheries are commonly transported from the hatchery tanks to the ponds in aerated transporter bins. Water conditions in the transporters can be easily matched to the pond conditions to reduce time for pond acclimation. PL15s needing to be transported greater distances from the hatcheries to the ponds are typically packed into polystyrene boxes with highly oxygenated seawater, or stocked into specialist transporters fitted with aeration/oxygenation systems appropriate for holding postlarvae for many hours during transit. On arrival at the pond, the PL15s need to be acclimated to pond conditions such as temperature and salinity (QDPIF, 2006).

Figure 3-3 Post larval tiger prawns (PL15)
Source: GCMA

In the first month after stocking, the PL15s grow rapidly into small prawns, primarily relying on the natural productivity (zooplankton, copepods, and algae) supported by the algal bloom for their nutrition. Very small quantities of commercial feed are also added multiple times daily to assist with the weaning process and provide an energy source for the pond bloom. During this period no water exchange is required.

Approximately one month after the prawns are stocked, pellet feed becomes the primary nutrition source; this occurring when the daily feed requirement of the prawn population exceeds what is available from the natural productivity provided by the pond bloom. The major component of pelleted feeds are meals of terrestrial plant origin, and meals of captured marine fish and crustaceans (e.g. krill) origin; the latter typically the more expensive and valued of the basal components. A range of other components, which have ‘immuno-stimulatory’ and ‘bioactive’ properties, are also commonly within the pelleted feeds at lower quantities. The quality of pelleted prawn diets is often broadly ascribed to protein content, with most Australian farmers using diets of high quality, consisting of 30 to 40% protein (FAO, 2007). Prawns are fed a pellet feed three to five times per day, with the first at sunrise and the last at sunset or into the night. The pellets are presented in a form that is water stable and of a size suitable for the particular growth stage of the prawn. Feed is a major cost of prawn production; around 1.5 kg of feed is required to produce 1 kg of prawns. Based on such a feed conversion ratio (FCR) of 1.5, a 100 ha intensive operation averaging a pond yield of 8 t/ha would produce 800 t of prawns and require 1200 t of feed per crop (FAO, 2007).

Effective prawn farm management involves maintaining water quality conditions within ranges optimal for prawn growth and survival, and this becomes progressively complex as prawn biomass and the quantity of feed added to the system increase. As the crop proceeds, both the prawn biomass increases, as does the biological oxygen demand required by the microbial population within the pond in breaking down organic materials. With these increasing demands, the requirement for water exchange and mechanical oxygen (Figure 3-3) addition from paddlewheels increases. Towards the end of the production season the prawn biomass peaks, and increasing numbers of aeration units are required in each pond to maintain optimal oxygen. Water exchange involves either the introduction of new water or recycling of existing water from the bioremediation pond back to the production pond. In some cases, freshwater, if available, can be added to manage high water salinity from evaporative losses. In most cases, water salinity is not managed, excepting through seawater exchange, and will increase naturally with evaporation and decrease with rainfall and flooding. Strict regulation of the quality and volume of water which can be discharged means efficient use of water is standard industry practice.

Figure 3-4 Paddlewheel in prawn pond
Source: GCMA

Effluent water released to the environment from a prawn pond will often contain nutrients, algae and sediment particles at higher levels than occur naturally in ocean waters. To mitigate these impacts on the environment, most Australian prawn farms allocate up to 30% of their productive land for water treatment by pre-release containment in settlement systems. Such treatment reduces suspended solids and dissolved nutrients in the effluent before release to the environment (QDPIF, 2006). Many Australian farms also recirculate water, which minimise fluctuations in water quality and reduces risks of introducing pathogens resident in the natural environment.

Prawn typically reach optimal marketable size within six months of pond culture, with a common target prawn harvest size of 30 g. Different approaches are used when harvesting the ponds across companies and ponds. Often the crop is partially harvested using traps or wing nets set at night when the prawns are active. The traps operate to catch the larger prawns (Figure 3-5) inside the nets, while allowing the smaller prawns to escape. This skimming process enables selective removal of only those prawns which have surpassed minimal commercial size. Ponds are also drain harvested, which involves draining the entire pond and capturing all prawns at the outlet in a single collection event (QDPIF, 2006). After harvest, prawns are typically processed immediately, with larger farms having their own production facilities that enable grading, cooking, packaging and freezing activities (Figure 3-6, Figure 3-7 and Figure 3-8).

Assessments of the economics of prawn farming for intensive pond farming enterprises in Queensland have estimated feed constitutes 26% of costs, labour 21%, processing associated costs 15%, capital 11%, larvae 9%, electricity and water supply 9%, and other costs 9% (CIE, 2013). Recent attention has focused on electrical energy usage, due to industry concerns over rising costs. The majority of electrical costs in intensive operations are associated with the pond grow-out operations, primarily the powering the aeration systems which can operate continually throughout large parts of the season, but also the various water pumping requirements (Miller, 2011). Energy requirements per enterprise increase where additional components, such as processing and hatchery, are added to the grow-out component. Typically, energy requirements *per pond* are comparable irrespective of farm size, resulting in overall enterprise energy usage being largely dependent on the numbers of ponds used in grow-out operations (Miller, 2011). For some larger farms, grow-out production can be staggered, and shifts used for processing, to lessen power requirements and energy costs through spreading energy demand (Miller, 2011). While energy for grow-out and for freezing requirements of the processors is typically supplied through the electrical grid, requirements for heating, such as for processing, are typically supplied through diesel and/or LPG (Miller, 2011). Recent reports have examined options for on-site, renewable energy generation, along with broader opportunities for energy cost savings, as a means to curb impacts of rising enterprise energy costs and increase overall profitability of farming (Miller, 2011).

Figure 3-5 Prawn harvest
Source: GCMA

Figure 3-6 Grading prawns by size
Source: GCMA

Figure 3-7 Cooked prawns in ice slurry
Source: GCMA

Figure 3-8 Prawns in freezer
Source: GCMA

Unlike the salmon industry, the Australian prawn industry has grown more slowly. Growth has largely come from increased productivity per unit area through improved diets, farming methods and in some instances, genetics. More recently, there has been some consolidation of the industry which has seen expansions of some of the larger existing operator farms, but this has been balanced by some smaller farms ceasing operations. The prawn industry has many challenges, which have been highlighted at certain times but are ongoing, including rising power costs, scarcity of qualified expertise, and disease impacts, most notably the production and regulatory-response impacts of the White Spot Syndrome Virus (WSSV) disease in farms in south-east QLD in the 2016-2017 farming season. Moreover, the ongoing reliance of wild broodstock, which comes at significant cost and risk in terms of pathogen introduction, and which has resulted from the lack of domesticated and selectively bred stock, has both constrained pond productivity and also at times seen ponds unstocked due to lack of postlarval supply. A major impediment to the industry over the past decade has been the difficult regulatory environment for obtaining new licences and expansions. This is largely due to the restrictions posed by the location of the Great Barrier Reef Marine Park in the receiving waters off the Queensland coast, which requires strict conditions and standards for operating, but also involves multiple and disconnected layers of government approval (Preston et al., 2015).

3.5.2 BARRAMUNDI

Barramundi (*Lates calcarifer*) are one of Australia's most recognisable and highly prized sporting and eating fish (Figure 3-9). Its iconic status coupled with excellent palatability has created significant recreational and commercial fishing industries in northern Australia as well as making it the most highly produced and valuable tropical fish species in Australian aquaculture (Savage, 2016).

Figure 3-9 Barramundi
Source: CSIRO

Barramundi inhabit the tropical north of Australia from the Exmouth Gulf in WA through to the Noosa River on Queensland's east coast. While the term 'barramundi' or 'barra' is used to describe the species in Australian waters, it is also commonly known as the 'Asian sea bass' or 'giant sea perch' throughout its natural areas of distribution in the Persian Gulf, the Western Indo-Pacific region and Southern China (Schipp et al., 2007).

Barramundi have a complex life cycle which includes freshwater and marine phases (Schipp et al., 2007). Beginning life as males, they have the ability to change sex as mature adults. After spawning and once hatched, larval fish will inhabit coastal marine areas for the first year of life before moving to freshwater habitats. Around three years of age, mature males migrate to coastal estuaries to spawn between the months of September and March. Most barramundi mature as males at around 50 cm in length. Sex change occurs at around 80 cm, providing they inhabit marine waters and have spawned at least once as a functional male(Moore, 1979). Outside of Australia, barramundi is farmed on a large scale in Taiwan, China and throughout Southeast Asia. Recent farming operations have also been established in the USA and Israel (Schipp et al., 2007). Australia produces around 4000 t per year, which although significant in terms of domestic tropical aquaculture, represents only a small percentage of global barramundi production.

Barramundi culture commenced in Australia in the mid-1980s with the first farm established in north Queensland. Today, farming occurs in all mainland states as well as the NT (Schipp et al., 2007). Production in Australia is primarily from land-based ponds in QLD and the NT, and in sea cages in northern WA. Smaller volumes are produced in southern Australia, with production in NSW, VIC and SA involving climate controlled environments using RAS to maintain optimal conditions for growth.

The conditioning and spawning of broodstock and the rearing of larval fish through to fingerlings takes place in land-based hatcheries. Barramundi are a highly fecund species, with females able to produce millions of eggs per spawning (Davis, 1984). However, subsequent mortality rates during the earliest larval and rearing phases can be very high. In the hatchery, at around 20-25 mm in length, the fingerlings are weaned off a live diet (rotifers and *Artemia*) to a commercial pellet. Due to the cost and infrastructure required many producers elect to purchase fingerlings from independent hatcheries, moving fish straight into their nursery cycle. Regular size grading is essential during the nursery stage due to aggressive and cannibalistic behaviour (Schipp et al., 2007). Size grading helps to prevent mortalities and damage due to predation on smaller fish, and assists with consistent growth. The process can be done by hand, using small floating box graders or grading machines. There is generally no need for grading during grow-out (>120g).

Barramundi have many attributes that make them an excellent aquaculture candidate: fast growth (1 kg plus in 12 months); year round fingerling availability; well-established production methods; hardiness i.e. they have a tolerance to low oxygen levels, high stocking densities and handling as well as a wide range of temperatures (Schipp et al., 2007). Possibly the most attractive attribute is that barramundi are euryhaline, and so able to thrive and be cultured in fresh and marine water. A pellet feed is produced by the two largest Australian aquafeed manufacturers (located in Brisbane and Hobart), providing a specific diet which promotes efficient growth and feed conversion. The industry is heavily reliant on these mills to provide regular supply of high quality feed.

Stocking rates of barramundi vary significantly depending on culture method. RAS systems can hold biomass up to 100 kg per 1000 L while typical pond biomass will be around <3 kg per 1000 L. The main factors which determine productivity are the provision of optimal water temperature, dissolved oxygen, effective waste removal, expertise of farm staff and the overall health of the stock.

Feed is a major cost of barramundi production. As a carnivorous species, high dietary protein levels, with fishmeal as a primary ingredient, is required for optimal growth (Glencross, 2006). Significant increases to global fishmeal prices over recent years have resulted in higher feed costs for farmers. Barramundi typically require between 1.2 and 1.5 kg of pelleted feed for each kilogram of body weight produced.

Under optimal conditions barramundi can grow to over 1 kg in 12 months and to 3 kg within two years (Schipp et al., 2007). Warm water temperatures in northern Australia enable fish to be stocked in ponds year round. Farms in the cooler southern regions of Australia rely on climate controlled environments with higher costs of production and so tend to focus on producing plate-sized fish (400-700 g) with a faster turnover. Depending on the intended market, harvested product is processed whole or as fillets and delivered fresh (refrigerated; ice slurry) or frozen. Smaller niche markets for live barramundi are available for Asian restaurants in some capital cities. Freshwater barramundi can have an earthy flavour which is not favoured by Australian consumers.

Proper final preparation such as purging (holding in clean saltwater without feed) prior to final harvest can assist in removing these flavours.

The Australian Barramundi Farmers Association estimates that with the recent expansion of the two largest farms in Australia (NT and WA), as well as increased production throughout the industry, output is expected to grow to 10,000 t in 2018 and 25,000 t in 2025. The major competition with the Australian product is the import of frozen barramundi and low-value white fish from Southeast Asia. It is estimated that between 13,000 t and 15,000 t of barramundi is imported into Australia each year. Consumers have very little to visibly distinguish local barramundi from lower cost white fish imports, often choosing on price alone. There is increasing pressure on government from Australian seafood producers to introduce ‘country of origin labelling’ for seafood sold in domestic markets. This would improve transparency for consumers and provide a marketing advantage for Australian product.

Barramundi are susceptible to a variety of bacterial, fungal and parasitic organisms, and are at highest risk of disease when exposed to sub-optimal water quality conditions (e.g. low oxygen, temperature extremes). The major biosecurity concern for Australian farmers is an outbreak of exotic disease such as scale-drop syndrome and pot-belly disease which is endemic to Asia. Relevant expertise and the limited availability of diagnostic services is also another major hurdle in accurately identifying and treating potential disease outbreaks.

As with all farming enterprises, rising power, feed and labour costs are placing increasing pressure on financial viability. Expansion and growth, particularly in QLD has also been limited with strict restrictions and regulatory requirements involved in waters adjacent to the Great Barrier Reef. Improvements to feeds, including cheaper fishmeal alternatives, a greater share of the local market and increased genetic selection for growth and disease resistance will help ensure the future viability of barramundi aquaculture in Australia.

Assessments of the economics of barramundi farming for pond farming enterprises in Queensland in 2008 have estimated feed constitutes 42% of costs, labour 20%, processing associated costs 1%, capital 18%, larvae 4%, electricity and water supply 5%, and other costs 10% (QDPIF, 2008).

3.5.3 RED CLAW

There are over 100 species of freshwater crayfish in Australia. The main species of commercial interest in northern Australia is red claw (*Cherax quadricarinatus*). The name ‘red claw’ is derived from the distinctive red markings present on the claws of the male crayfish. Red claw are a warm water species, which inhabit still or slow moving water bodies (Jones, 1998). The natural distribution of red claw ranges from the tropical catchments of QLD and the NT to southern New Guinea (Austin and Knott, 1996). Production stretches from south-east to far north Queensland. Red claw are best suited for culture in tropical regions of northern Australia (Jones, 1990).

The red claw life cycle is simple. In tropical regions, mature females can be egg bearing year-round. A ten week incubation follows mating, after which the eggs hatch to produce small crayfish. After three months, the juveniles weigh around 15 g and around 100 g after 12 months. Red claw can live for up to five years and reach a maximum size of 600 g (Jones, 1990).

Red claw have many traits which make them attractive for aquaculture production. A simple life cycle is beneficial, in that complex hatchery technology is not required (Jones et al., 1998). The crayfish can survive in high temperature and oxygen depleted water (<2mg/L) and remain out of the water for extended durations. Low oxygen is a major stressor to most aquatic species. The ability of red claw to tolerate low oxygen levels is beneficial in terms of handling, grading and transport (Masser and Rouse, 1997). Red claw have a broad thermal tolerance, with optimal growth achievable between 23 to 31°C. Water temperature and feed availability are the variables which most affect crayfish growth. Red claw are a robust species which is most susceptible to disease (including viruses, fungi, protozoa, bacteria) when conditions in the production pond are sub-optimal (Jones, 1995). There have been no major disease outbreaks in Australia, which has been partly attributed to extensive farming practice and large geographic separation between farms (Jones and Ruscoe, 1996).

Queensland has a small red claw industry with a total production of 51 t per year, which equated to a value of AUD$1.3 million in 2015-16 (DAF, 2017). The annual value of the industry has seen little fluctuation between 2008 and 2015. In general, farms have a small footprint (<5 ha) and are run as extensive operations, with production from 1 to 3 t/ha per year.

The industry started in the 1980s based on technology transferred from the marron crayfish industry in WA (Jones, 1990). Red claw breed freely in production ponds. A common industry practice is to manage mixed generations of red claw in the one pond. The crayfish are harvested at regular intervals, with re-stocking occurring from natural reproduction. This is an extensive husbandry practice, not considered to be economically viable when conducted at a small scale (<4 ha) (Hinton and Jones, 1997).

Production ponds are earthen lined, rectangular in design and average 1 ha, and are sloping in depth from 1.2 m to 1.8 m. Sheeting is used on the pond edge to keep the red claw in the pond (migration tendency) and netting surrounds the pond to protect stock from predators (Jones et al., 2000). Red claw are suited to earthen pond culture; unlike many crayfish species they do not dig deep burrows.

At the start of each crop, prior to stocking with red claw, the ponds need to be prepared and filled with water. Between harvests, the pond bottoms are dried and unwanted sludge from the previous crops are removed, and if needed, additional substrate and shelters are added. Lime is often added prior to filling the ponds to buffer pH, particularly in areas where there are acid sulfate soils. The ponds are then filled with freshwater and left for about two weeks prior to stocking. Algal blooms in the water are encouraged through addition of organic fertiliser. These blooms are essential for both shading of the red claw and to discourage benthic algal growth, but also for the nutritional value they provide for the planktonic community within the ponds (Jones et al., 2000)

A prepared pond is stocked with around 250 females and 100 males which have reached sexual maturity. Natural mating results in the production of around 20,000 advanced juveniles. Red claw are omnivorous, foraging on natural productivity such as microbial biomass associated with decaying plant and animals. Early stage crayfish almost solely rely on natural pond productivity (phytoplankton and zooplankton) for nutrition. As the crayfish progress through the juvenile stages, the greater part of the diet changes from planktonic to organic particulates (detritus) found on the pond bottom. Very small quantities of a commercial feed are also added on a daily basis to assist with the weaning process and provide an energy source for the pond bloom. During this period no or minimal water exchange is required. The provision of adequate shelters (net bundles) is essential at this stage to improve survival (Jones, 2007).

Approximately four months after stocking, the juveniles are harvested by flow trap and graded by size and sex for stocking in a production ponds. Red claw naturally migrate upstream with water flow, manipulation of this response is used to harvest cray fish from ponds using flow traps (Jones, 2007). A flow trap consists of a ramp which exits the pond into an elevated tank. Pond water is pumped up the ramp in to the tank, while the pond is slowly drained. The crayfish move up the ramp and in to the tank, which contains water and aeration. This method is effective in harvesting large quantities of red claw and is also used at various stages of production to grade animals for stocking and at final harvest.

Juveniles are stocked in production ponds from 5 to 10/m^2, with shelters important during the grow-out stage, with 250/ha recommended. During the grow-out phase pellet feed becomes an important nutrition source, along with the natural productivity provided by the pond. The major components of pelleted feeds are meals of terrestrial plant origin. The quality of pelleted red claw diets is often broadly ascribed to protein content, with most Australian farmers using diets consisting of 25-30% protein. Red claw are fed once daily, however the pellet feed is not particularly water stable and a limited range of sizes are available (Jones, 2007).

Effective farm management involves maintaining water quality conditions within ranges optimal for crayfish growth and survival, and this becomes progressively complex as crayfish biomass and the quantity of feed added to the system increase. As the crop proceeds, both the crayfish biomass increases, as does the biological oxygen demand required by the microbial population within the pond in breaking down organic materials. With these increasing demands, the requirement for water exchange and mechanical oxygen addition from paddlewheels increases. Towards the end of the production season the crayfish biomass peaks, and increasing numbers of aeration units may be required in each pond to maintain optimal oxygen levels in the pond. Water exchange involves either the introduction of new water or recycling of existing water from the bioremediation pond back to the production pond. Strict regulation on the quality and volume of water which can be discharged means efficient use of water is standard industry practice.

Red claw are harvested within six months of stocking to avoid reproduction in the production pond. At this stage the crayfish will range between 30 to 80 g. Stock are graded by size and sex into groups for market, breeding or further grow-out (Jones, 2007).

After harvest, red claw are transported to a processing shed where they are stocked in tanks until being packed live for market (Jones et al., 2000). There is high global demand for freshwater crayfish. The small volume of product means that the majority of Australian product is traded domestically. In 2014-15 the average price of red claw was AUD$23/kg. This compares favourably with prawns (AUD$16/kg) and barramundi (AUD$9/kg). The premium price is achieved as the majority of production is traded as a live product. Under effective management, crayfish can be harvested from ponds on a weekly basis. The relative small supply of available product has led to red claw being traded in diverse domestic markets, such as restaurants, seafood markets and pet shops. There is a large international market for crayfish, but a large and consistent supply is required to access these markets (Jones et al., 2000).

Current commercial feeds are low cost and provide a nutrition source for natural pond productivity as much as the crayfish. The small size of the industry means that feed is produced in a terrestrial animal (e.g. poultry) mill, rather than a dedicated aquaculture mill. This use of terrestrial animal mills has resulted in the production of feed with low water stability and limited ability to manipulate pellet size. Recent research on feed development has focused on improving feed stability and feed formulation (Pirozzi et al., 2016).The development of an optimal high performance feed is widely believed to be essential to increase industry production and expansion (Zeng et al., 2014).

Red claw breed freely in production ponds. This is beneficial in that complex hatchery technology is not required. However, low fecundity, and the associated inability to source high numbers of quality seed, is also an impediment to intensive expansion of the industry. Fecundity of red claw compared to marine prawns is low, 1000 to 200,000 eggs respectively. Unlike the prawn industry, where there is clear demarcation between the hatchery and grow-out operation, there is no dedicated hatchery operation to allow focused improvements in fecundity and seedstock production. Overcoming the bottleneck of seedstock production requires a dedicated hatchery facility either on-site or operated independently. In recent years there has been a focus on developing independent hatchery technology which has resulted in the establishment of two small hatcheries. A new hatchery technology known as SJ3 (Stage Three Juvenile) farming has been developed (Stevenson et al., 2013). SJ3 crayfish are at a life stage where they can survive independently without the mother. Ultimately, this new technology will allow a farm to consistently purchase SJ3 stock directly from a hatchery, as occurs in the marine prawn industry, and has the potential to revolutionise the red claw industry

In QLD in 2014-15 there were 158 farms with current development approvals, with only 26 of the approvals in operation. In 2015-16, there were 25 farms producing red claw (DAF, 2017). Freshwater farming is classified as environmentally low-risk. In general, it is not difficult to obtain approval for small-scale freshwater aquaculture farming in Australia. The number of suitable locations for freshwater crayfish farming is likely to be large. According to Johnston and Jones (2001), for a farm to be viable, pond footprint must be a minimum of 4 ha. However, the average size of a red claw farm is 2 ha. The primary reason that many farms are small is because a production footprint of less than five hectares does not require an EIS to gain approval. This has led to the development of an industry which consists of numerous hobby-sized operations.

Red claw aquaculture in Australia is a small and stable industry. A simple life cycle and the established practice of mixed generation culture means they are a suitable candidate for extensive farming in northern Australia.

3.5.4 COBIA

Cobia or the black kingfish (*Rachycentron canadum*) is a large benthopelagic fish species distributed throughout the world’s tropical and subtropical waters (Shaffer and Nakamura, 1989). The species has an elongated body; a broad flattened head; a darkish brown dorsal, and whitish ventra, colouration (Figure 3-10). Younger fish have a white stripe running along their mid-section, which fades as the fish ages. Cobia are opportunistic carnivores (Salini et al., 1994), which can grow very rapidly, and reach a weight of 60kg and 2m length (Franks and Warren, 1999).

Figure 3-10 Cobia
Source: CSIRO

Several characteristics make cobia an exceptional candidate for aquaculture, including fast growth rates that can exceed 5 kg per year, amenability to commercial aquafeeds, excellent palatability and wide tolerance of temperature and salinity (Holt et al., 2007). Commercial culture of the species began in Taiwan in the late 1990s and has spread to other regions in the Asia-Pacific and the Americas (Benetti et al., 2008; Nhu et al., 2011). Annual production has remained steady since 2010 at 40,000-50,000 t per year, with China accounting for approximately 90% of global production (FAO, 2016).

The development of cobia farming in Australia commenced through research initiatives in 2007, which focused on introducing cobia as an alternative and off-season crop for prawn farms in Queensland (Dutney and Palmer, 2008). Juvenile production infrastructure and techniques, customised from experience with other fish species, were developed by the Queensland Department of Agriculture (QDAF), and the first juvenile cobia were supplied from QDAF to commercial prawn farms in Queensland in the following years to assess commercial viability of farming cobia in prawn ponds.

Despite the potential of cobia farming, the development of an Australian industry has been limited, due in part to low or inconsistent supply of seed stock. Research undertaken by QDAF focused on broodstock husbandry and hatchery methods have made breakthroughs in spawning technology and continues to improve reliability of fingerling production (Dutney, 2016) This has been coupled with QDAF research supporting advances in farm husbandry methods, health management and product development. The progress to date has seen the establishment of a successful fledgling industry of about 100 t annually, which is being produced by a single operation in north Queensland.

3.6 Potential tropical species

3.6.1 CRUSTACEANS

In addition to shrimp, several other crustaceans are cultured, with crab species contributing most to global production. The culture of various crab species, such as mud crabs and blue swimmer crabs, has been practiced for many years in Asia, and this region of the world still dominates global farmed crab production, with approximately 950,000 t produced annually in 2015, with more than 70% coming from China. The omnivorous Chinese mitten crab accounts for two-thirds of production, whereas the remainder is largely estuarine and more carnivorous portunid crabs, such as mud and blue swimmer crabs. Interest in crab culture in Australia has primarily focused on portunid crabs, and particularly mud and blue swimmer crabs.

The *Scylla* species of marine portunid crabs, commonly referred to in Australia as mud crabs, are distributed throughout the tropical Indo-Pacific region and in some areas of the eastern Pacific. These species commonly live in mangrove areas of estuaries. The crabs are omnivorous scavengers, and feed on other invertebrates, dead fish and aquatic plants, but are also cannibalistic. Adult males develop large claws and can grow up to 3 kg (Paterson and Mann, 2011). The blue swimmer crab (*Portunus pelagicus*) is another portunid widely distributed throughout the Indo-Pacific and generally occurs in intertidal estuaries, preferring areas near reefs, mangroves, seagrass and algal beds. Blue swimmer crabs are carnivorous, feeding on a wide range of slow moving benthic invertebrates, and are cannibalistic. The males are easily identifiable by their bright blue and purple colouring, and long, prominent claws (Paterson and Mann, 2011; Romano and Zeng, 2008; Smallridge, 2002).

Crab culture has traditionally focused on capture and fattening of juvenile crabs from the wild, rather than grow-out from egg to market size. Although significant progress has been made developing the hatchery and grow-out techniques and feeds able to underpin true commercial aquaculture, capture and fattening farming is still common practice. While mitten crabs dominate global farmed production, the portunid crabs are species of high value and demand in many global markets. In addition, mud crabs have the commercial advantage of being able to be transported and marketed live, which adds to its status and price in the market. The commercial production of soft-shell blue swimmer crabs in Australia, which are crabs harvested soon after losing their shell, provides another valuable marketing advantage (Hungria et al., 2017; Paterson and Mann, 2011).

Portunid crabs grow rapidly in commercial culture, particularly when reared at low densities (i.e. under one crab m^{-2}), with mud crabs able to reach commercial size of 200 to 500 g in four to nine months, and blue swimmer crabs able to reach commercial size of 150 mm carapace length in five months (Paterson and Mann, 2011; Romano and Zeng, 2008; Smallridge, 2002). Currently, portunid aquaculture is practiced only in the USA and Asia, and the process is at an early stage of technological development for most species (Hungria et al., 2017). Initiatives to commercially culture portunids in Australia have not progressed beyond a pilot-scale, with modest volumes of soft-shell blue swimmer crabs exported frozen (Hungria et al., 2017). Although large-scale production of larvae and juveniles in captivity is technically possible, mortality rates are still high, largely due to dietary problems and high rates of cannibalism. The low stocking densities required for crab culture constrain profitability for large-scale culture (Paterson and Mann, 2011; Romano and Zeng, 2008; Smallridge, 2002). In places like Australia, the absence of a significant commercial portunid fishery, and the high cost of producing a soft-shell product, both pose significant competitive hurdles for crab aquaculture.

Significant efforts have also been made to develop aquaculture industries for other tropical crustacean species, such as the bay lobster or Moreton Bay bug (*Thenus* spp.) and the tropical rock lobster (*Panulirus ornatus*) (AIMS, 2016). Development of the bay lobster industry is currently confined to a single initiative in northern NSW (ABL, 2017) whereas tropical rock lobster aquaculture in Australia is still at a development phase. Recently the CRC for developing Northern Australia has announced a 3 year AUD$2.5 million project to develop cherabin (*Macrobrachium rosenbergii*) aquaculture. Cherabin is a freshwater crayfish endemic to north Australia. The project will apply international research to establish a hatchery in Broome and grow-out operations in Kununurra, WA (CRCNA, 2018).

3.6.2 FISH

The aquaculture potential for high-value tropical reef fish species such as grouper (*Epinephelus* spp.), coral trout (*Plectropomus* spp.) and barramundi cod (*Cromileptes altivelis*) have been advocated but not realised for several decades. The high prices paid for live coral trout in markets such as Hong Kong (up to AUD$60 per kg) (Little et al., 2015) provide a lucrative target for farms looking to capitalise on significant export demand.

Culture methods are generally interchangeable with barramundi (i.e. land-based hatcheries utilising tanks for larval rearing and nursery stages followed by transfer to marine ponds or sea cages for grow-out). In general, the complexity and lack of economic viability of production has seen few emerging tropical species progress beyond the research stage and even less beyond the pilot-scale. Standard constraints to development include reliance on wild brood stock, low survival in the hatchery, inconsistency of seed supply, sub-optimal feed, and limited established grow-out practice. Significant government research into broodstock husbandry, hatchery methods and health management as well as funding for private enterprises will be needed to develop a tropical species industry in northern Australia. Development of the grouper industry is currently confined to small initiatives in northern (BlueHarvest; Harvest) and southern (Ecomarine) QLD.

3.7 Indigenous aquaculture

There is physical evidence that Indigenous Australians have practiced aquaculture equivalent practices of selective capture and fish holding for over 30,000 years (NSW DPI, 2016a). These man-made structures were often located in the slow flowing areas of river systems to exploit the natural shape of waterways and utilise stones and sticks to construct traps and pond-like enclosures. The heritage listed Brewarrina (Ngunnhu) fish traps, a series of stone weirs and ponds constructed across a half kilometre stretch of the Barwon River (NSW), are thought to be among the oldest man-made structures in the world (NSW GOV, 2017).

4 Farming systems and operations

Aquaculture farming systems range from huge sea cages and large earthen ponds to compact-land based tank systems.

4.1 Sea cages

Cage farming primarily involves the farming of fish stocked in a water permeable cage structure in a natural water body, most commonly a protected bay or lake. Land-based farming involves the pumping of water (marine or fresh) from a natural water body to a man-made containment structure. Cage farming is the most efficient method of fish production as appropriate site selection will ensure a constant supply of high quality water essential for optimal culture conditions. Cage systems rely on water currents such as tides to disperse and dilute nutrients and wastes associated with production. The effectiveness of this process will depend on the location of the cage, tidal variation, the condition of mesh, cage size, stocking density and the proximity of neighbouring cages.

Sea cages are designed to be predator proof and cope with local conditions, including waves, currents and storms. Location should enable routine access for maintenance and for feeding and harvesting of fish. Sea cage enterprises range from subsistence family operations using small floating hand-sewn nets to large companies with expansive circular sea cages which can hold hundreds of tonnes of fish. In intensive sea cage operations the production species is typically a high-value marine carnivorous fish. In Australia, the dominant species farmed in sea cages is Atlantic salmon (*Salmo salar)* in Tasmania. In northern Australia, barramundi (*Lates calcarifer*) is farmed in sea cages in Cone Bay, WA, immediately to the seaward of the Fitzroy catchment.

This report focuses on the opportunity for land-based aquaculture in northern Australia. The use of cages or racks in ocean, bays or estuaries are not discussed in any further detail.

4.2 Land-based systems

4.2.1 PONDS

The primary culture unit for land-based farming is purpose-built ponds. Pond structures typically include an intake channel, production pond, discharge channel and a bioremediation pond. In most cases the ponds and channels are earthen based, but may be partly or fully plastic-lined. The objective of the pond is to be a containment structure, an impermeable layer between the pond water and the local surface and groundwater. In 2007, the Queensland Government released a set of guidelines for constructing and maintaining aquaculture production systems *(*DAF, 2007*).* The objectives of the guidelines were to provide a consistent approach to the construction and maintenance of aquaculture ponds. The guide provides a comprehensive risk assessment of pond containment structures with regard to topography, geology, soils, groundwater and acid sulfate soils.

4.2.2 EARTHEN POND

Soils for earthen ponds should have a low permeability and high structural stability. During production the environment in an established earthen pond is relatively stable, with the organic material from production and that pre-existing in the soil well mixed. The production process results in the accumulation of organic materials on the pond base, which may require seasonal removal. The majority of production ponds in Australia are earthen. In Australia, around 10% of prawn production ponds have an earthen base with lined walls. Lined walls reduce erosion and enable a steep gradient, which improves water circulation and provides an environment less conducive to problematic benthic algal species.

4.2.3 LINED PONDS

Ponds should be lined if the soils are permeable and haulage of suitable soils is not an economical option. Synthetic liners have a higher capital cost, but provide an impermeable layer between the pond and the local surface and groundwater. They are often used in high intensity operations which require high levels of aeration and current; conditions which would lead to significant erosion in earthen ponds. Lined ponds require only minimal maintenance during the dry-out period between crops.

4.2.4 TANK SYSTEMS

Recirculating aquaculture systems (RAS) are intensive modular tank-based systems. Site selection is less important as these systems are located indoors and are designed to control and optimise environmental conditions such as water temperature, oxygen and nutrient levels. Compared to other aquaculture production systems, RAS are compact, have a high level of automation and are expensive to set up and operate. Other operations, such as ponds and sea cages may utilise RAS for those stages of the culture production cycle requiring some form of control, such as broodstock conditioning, larval rearing and nursery phases.

Tanks used in RAS can come in a variety of shapes and sizes. Tank selection is specific to the species being cultured, the building footprint and the equipment required to remove waste and treat culture water. Other key considerations include the ability to provide a uniform culture environment and the ease of management for maintaining, handling and harvesting stock. The size and type of tanks used vary throughout the production cycle. Larval tanks are small and round with even circulation and bases designed to assist with waste settlement and removal. As the species under culture continues to grow, the tank size and shape will become more important. For example, a circular or oval tank is more appropriate for actively swimming species, such as Atlantic salmon, than a rectangle tank. Conversely, a circular tank will take up more usable space in a facility that has a culture species that is indifferent to shape (e.g. barramundi).

Tank-based rearing systems will have a species specific maximum carrying capacity, with excessive stocking densities likely to stress the animals, place additional demands on aeration and waste removal, as well as increase the risk of disease. When the size of the tank is over specified it will utilise excessive space, be difficult to manage, require greater pumping and water volumes and often create areas of poor flow where waste material may aggregate.

All tanks have the same basic design. These include inlets and outlets to efficiently move water and remove waste as well as aeration lines in the form of air stones or diffusers. The need for back-up power generators and alarm systems is critical as power or equipment failures are likely to stop water flow or aeration into the system, potentially leading to the loss of stock.

The key component of RAS is the filtration system. Culture water must be continuously fed from the tank outlet to filtration equipment for cleaning and treatment before returning to the holding tank. Filtration is both mechanical and biological. Mechanical filtration uses an inert screen or medium to remove organic particles such as uneaten feed and faecal particles. Water will then move to the biological filter. The main role of the biological filter is to remove dissolved nitrogenous waste (particularly ammonia) excreted by culture stock. Biological filters use a high surface area medium as a substrate to support bacterial growth. These microbial populations convert ammonia to less toxic nitrate by a process known as nitrification. The final process can involve the addition of oxygen, temperature modification (heating or cooling) and sterilisation (UV; ozone) to optimise water parameters before returning to the culture tank.

RAS operations are complex and require specialised staff across a range of disciplines. Expertise in process control and electronics are important for efficient operation, while experience in water chemistry, animal biology and health are essential for production. In Australia, barramundi is the main species produced in freshwater RAS, predominantly in temperate states. These systems are an excellent option for small-scale production where operation is required close to market, land is limited and climate (temperature) conditions are otherwise sub-optimal for culture of the target species.

4.3 Pond operation

The standard production pond in Australia is purpose-built, rectangular in shape, occupies 1 ha of footprint and is 1.5 m deep. The majority of ponds are earthen, although ponds may also have lined walls or be fully lined. Standard containment structures on a farm include a supply channel, production pond, discharge channel and a bioremediation pond (Figure 4-1).

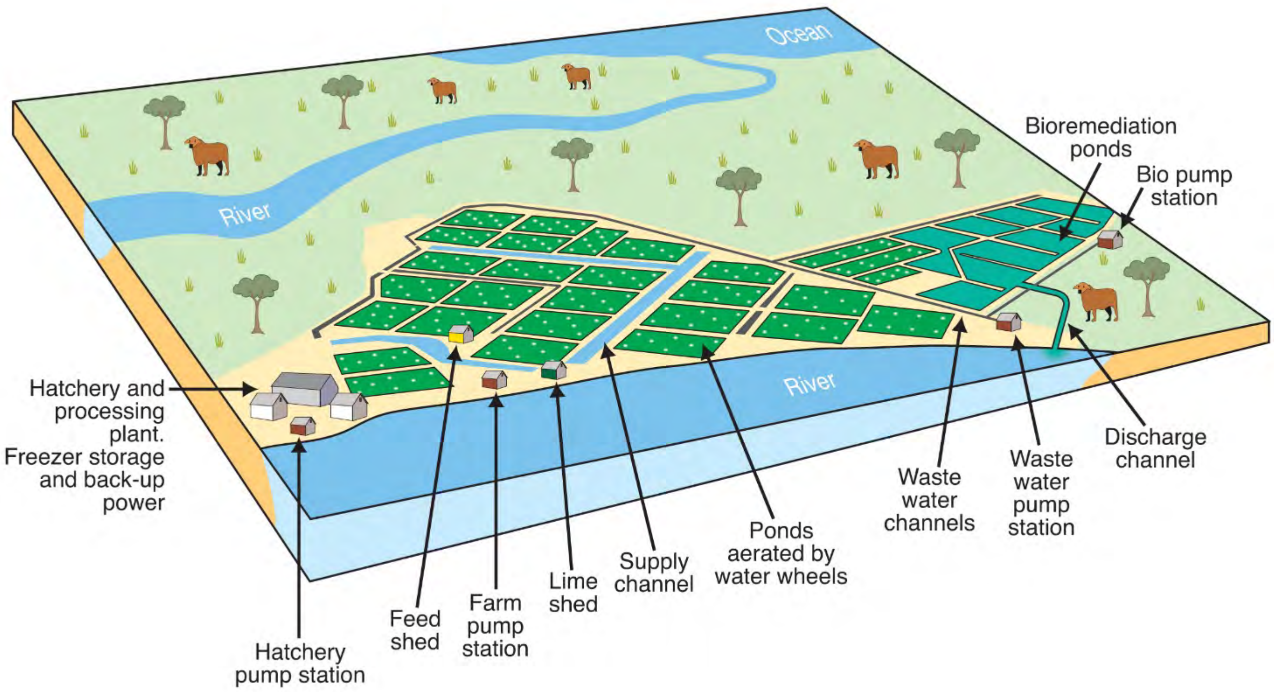

Figure 4-1 Schematic of marine aquaculture farm

Optimal sites for farms are flat and have significant elevation to enable ponds to be completely drained between seasons. The elevation of the land on which the ponds and channels are constructed has a large bearing on production efficiency (Figure 4-2). It is most critical that the all ponds and channels can be fully drained during the off (dry-out) season to enable machinery access to sterilise and undertake pond maintenance. Optimal land for ponds are flat and have an elevation of 5 to 10 m above the AHD due to the impact of floods, cyclone surges etc.

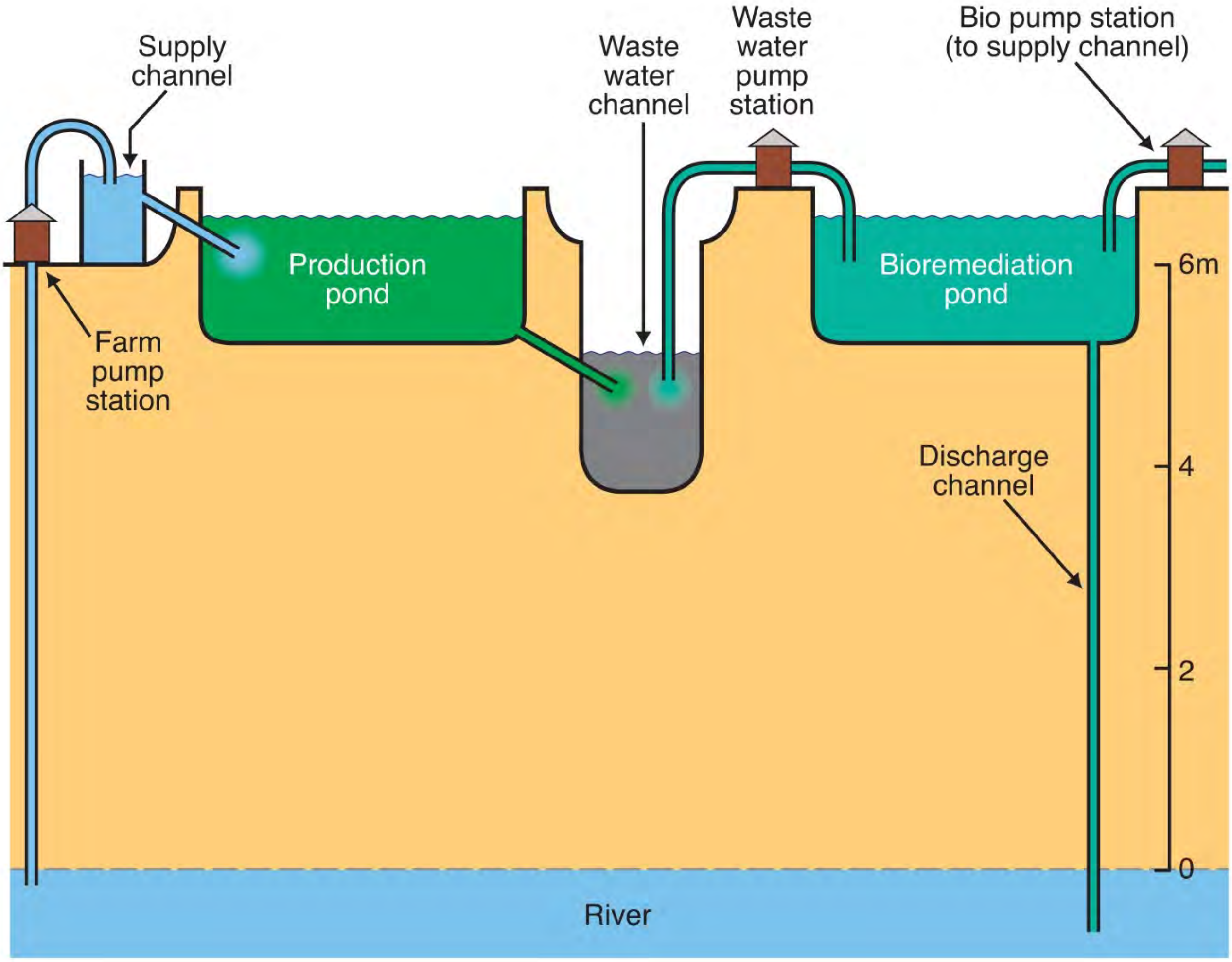

Figure 4-2 Cross-section of a marine aquaculture farm detailing optimal land elevation and water flow

Pump stations are used to distribute water around the farm. Marine water is pumped from a primary pump station located near the water source (usually a river) to a raised supply channel engineered to gravity-deliver water to the ponds. Depending on the specific location of the primary pump station, operation may be possible at all times or restricted to periods when suitable quality water is available (e.g. high tide). During production and at final harvest water is discharged from production ponds via gravity into a waste water channel. A secondary pump station is then used to pump the water from the waste water channel to the bioremediation pond. The role of the bioremediation process is to reduce suspended solids and nutrients (nitrogen and phosphorus) in the water to meet discharge water quality standards set by regulators. Water treated by the bioremediation pond is either recirculated to the production pond via a third pump station and the supply channel or discharged by gravity to the river. The specifications of each pump station are in keeping with the volume of water required to fill the ponds and to service water exchange requirements. Farm layout should be designed to minimise the chance of reintroducing discharged water to the ponds via the primary pump station. The location of the primary pump station and the discharge channel should be separated by as large a physical distance as practical. In general, best practice involves access of source water at high tide and discharge of water at low tide.

Farms use aerators (typically electric paddlewheels and aspirators) to help maintain optimal water quality in the pond. The aerators provide oxygen and create a current which concentrates waste material in the centre of the pond. The farm should have access to mains electricity (including three phase). A survey by (Paterson and Miller, 2013) found that a medium sized 50 ha prawn farm in Australia uses around four gigawatt hours annually. The majority of the power requirement is to run pond aeration. Back-up power, usually via a diesel generator, is required to run all the aerators on the farm during power failure. Large farms may require multiple generators.

Feed and the labour required to distribute feed is a major cost of aquaculture. In tank-based RAS systems the feed is hand delivered by staff. In pond-based systems, modified vehicles are used for feed distribution. The vehicles are used to transport petrol-powered blowers, which distribute feed from a hopper into the pond. Automated pond feeding systems are now also used for high density prawn operations overseas.

A range of vehicles are used to support land pond-based aquaculture production. Small operations are likely to use multipurpose vehicles and sub-contract specialist support as required. Large operations are likely to own a range of fit for purpose vehicles. A utility or 4WD motorbike is used for general access, to monitor water quality conditions and to access the pump stations. Tractors are used for pond preparation and general maintenance of the farm. Forklifts are required to unload and load supplies such as feed and harvest bins. Earthmoving equipment such as a back hoe and excavator are used for construction and maintenance of ponds and channels.

A range of multipurpose sheds and shelters are required on a farm. Feed is one of the major costs of aquaculture production. During the production season a farm will require around 1.5 times the quantity of total production (e.g. 100 t production equates to 150 t feed). A feed shed should have the capacity to store up to three months of feed in a weather and rodent proof environment. Sheds appropriate for the segregation and safe storage of chemicals, fertiliser and fuel are also required. Large carport-style sheds are commonly used for the storage of vehicles such as tractors and forklifts. A well-equipped workshop suitable for the maintenance and repair of farm equipment and vehicles is standard. The construction, maintenance and repair of electric paddlewheels are regular tasks undertaken by farm staff.

4.4 Key water quality parameters for tropical aquaculture

The type (or stage) of water used in pond-based aquaculture can be categorised as source, culture or discharge. Source water (marine or fresh) is used to fill and exchange ponds, and should be abundant in quantity and stable in its physiochemical parameters. The availability of optimal (species specific) quality source water is essential for cost-effective aquaculture production. The water contained in a pond is the culture water and its physiochemical parameters are dynamic and vary with conditions (such as evaporation and precipitation) and inputs (e.g. animal density, feed and fertilisers). Discharge waters are effluent and after bioremediation should have similar physiochemical parameters to the source water.

4.4.1 SOURCE WATER

Water salinity and temperature are the key parameters which determine species selection and production potential for any given location. Most species can survive a broad range of temperatures. However, optimal production only occurs within a much narrower temperature range, and farming profitability is driven by the optimality of water temperature. Suboptimal water temperature (even within tolerable limits) will prolong the production season (slow growth) and increase the risk of disease. The tolerable and optimal water quality parameters for barramundi, black tiger prawns and red claw crayfish are listed in Table 4-1.

Table 4-1 Key tolerable and optimal water quality parameters for black tiger prawns, barramundi and red claw

	BLACK TIGER PRAWNS		BARRAMUNDI		RED CLAW	
Parameter	Tolerable	Optimal	Tolerable	Optimal	Tolerable	Optimal
Temperature (C°)	15 to 35	26 to 32	16 to 35	28 to 32	12 to 33	26 to 29
Salinity (ppt)	5 to 40	10 to 25	0 to 40	0 to 35	0 to 3	0
pH	–	7.0 to 9.0	–	7.5 to 8.5	–	7.0 to 8.5
Dissolved oxygen (mg/L)	–	>4	–	>4	–	>5

Source: parameters based on information from Australian Prawn Farming Manual (QDPIF, 2006)

4.4.2 WATER SALINITY

Water salinity is a measure of the total dissolved salts present in a water body. It is usually expressed as parts per thousand (ppt). Culture species are often described according to their adaptation to salinity in their culture environment. These measurements allow us to categorise culture species as fresh water, euryhaline and marine (Table 4-2).

Table 4-2 Species category by water salinity tolerance

PARAMETER	FRESHWATER	EURYHALINE	MARINE
Salinity (ppt)	0 to 5	0 to 40	15 to 40

Salinity will influence the balance of internal salts and water within aquatic organisms. The maintenance of this balance is known as osmoregulation. A freshwater fish may be able to tolerate high salinities for a short period of time but the increased stress and demand placed on their osmotic system will result in poor condition and possible death. Conversely marine species in low or water with no salinity are unable to balance internal water and salt concentrations. Euryhaline species such as barramundi can perform equally well in both freshwater and marine environments.

4.4.3 WATER TEMPERATURE

Fish and crustaceans have no internal means of regulating body temperature, relying on their environment to maintain bodily function. Water temperature is the key climate factor affecting growth and metabolism of tropical aquatic species. Each species has a specific thermal tolerance for growth and survival, with optimal growth achieved within a narrow temperature range within the tolerance limits (Jobling, 1997).

The influence of temperature on the metabolic rate of the species will be a key driver of activity levels, immune system functionality, feed consumption, nutrient utilisation and growth. If the water is too cold metabolism will slow until feeding ceases and the animal eventually dies. Immune response will also be compromised to a point where mild disease organisms can devastate an otherwise healthy population. Conversely, if water temperature increases beyond an animal's thermal limits, the associated stress and imbalance created will cause mortalities.

4.4.4 PH

pH is a measure of the acidity or alkalinity of an environment. The scale of measurement is between one (strongly acidic) and 14 (strongly alkaline) with balance reached at seven or 'neutral'. Most aquatic organisms prefer neutral to slightly alkaline conditions.

Within culture systems the pH can vary significantly. In RAS, the respiration processes of aquatic organisms form acidic compounds which move the water pH to decreasingly lower levels (i.e. <7). Without careful management and adjustment this can damage the sensitive gills, eyes and skin tissue of stock. In ponds, dense algal blooms may cause pH to change dramatically over the course of a day. pH will be the lowest at dawn due to respiration processes overnight while algal photosynthesis during the day will gradually increase pH towards alkaline levels. In prawn farming, suboptimal pH at pond start-up will also reduce plankton growth, which provides not only a feed source for the small postlarvae, but also has a critical role in maintaining water quality and shading out problematic benthic algae.

Farmers will often utilise buffering chemicals such as sodium bicarbonate and lime to mitigate low pH levels. pH can also significantly influence other water quality parameters. For example, ammonia will become more toxic as pH levels rise, meaning a sudden increase in a culture system with high ammonia levels will stress and potentially lead to stock loss.

4.5 Culture water

Culture water quality will vary throughout the season with increasing stock biomass and inputs. Oxygen is removed from the system by respiration of stock, algae and input of feed. Oxygen is added to the system mechanically from paddlewheels and aspirators and naturally through wind, water exchange and during the algal oxygen production phase. Nutrient levels will also vary within the farming season, increasing with stock biomass (e.g. feed and excretions). Suitable nutrient levels are maintained by management of stock biomass, feed input addition and water exchange.

4.5.1 DISSOLVED OXYGEN

The presence of adequate dissolved oxygen within a culture system is a critical requirement for all aquatic species. It is normally measured as mg/L (milligrams per litre) or as % saturation where the amount of oxygen that can be held in the water gradually reduces with increasing water temperature. For example, 100% saturation indicates the maximal amount of oxygen that can be held at that specific water temperature under normal conditions.

As with temperature, each species has different requirements for oxygen. Insufficient levels within farming systems over time will increase stress responses, reduce growth, increase the likelihood of disease and cause death.

Pond management of oxygen is critical. Oxygen demand rises through the season as biomass and feed inputs increase. In addition, algal bloom within ponds will influence major changes in oxygen levels throughout a daily cycle. This needs to be monitored closely as photosynthesis will occur during the day to provide oxygen to the system but remove oxygen overnight via respiration. The results of insufficient oxygen provision under these conditions can be catastrophic.

4.5.2 NUTRIENTS

The effect of dissolved nutrients such as nitrogen and phosphorus as well as solid materials (clay particles; faecal waste) are all additional factors requiring management in aquaculture systems. The ability to operate a farm will be determined by legislative requirements setting the maximal allowable levels that these parameters can be present in discharge waters.

In a pond, biological productivity is limited by the amount of nitrogen and phosphorus present in the water and soil. Inputs such as feed and fertiliser as well as the ammonia excreted from culture species means these factors need to be balanced to ensure adequate growth conditions for associated blooms to occur without exceeding the capabilities of bioremediations systems and discharge limits. Alternatively, the presence of nitrogenous waste products such as ammonia will become highly toxic to aquatic life if not managed correctly.

Suspended solids (turbidity) in the form of organic material (algae; plankton) or clay particles can become problematic to aquatic species and culture environments. In a pond, suspended solids are a direct measure of the amount of light that is able to penetrate the water column. Farmers will normally measure turbidity by dropping a probe or a black and white disc (secchi) into the pond to estimate the depth where the item of measurement is no longer visible. The implications for culture stock can be varied. High levels of suspended solids in RAS systems indicate inefficient water turnover and filtration. Irritation of gill membranes and bacterial infections caused by excess nutrients can also be problematic. In a pond or cage environment highly turbid waters can significantly reduce oxygen availability.

4.6 Discharge water

Management of water quality in ponds is a key component of aquaculture production. A consequence of water quality management is the requirement to discharge effluent water in to the surrounding environment. In general, discharge water from freshwater aquaculture can be easily managed and provides a water resource suitable for general or agriculture specific irrigation. Marine discharge water is comparatively difficult to manage, with limited reuse applications. The key difference in discharge management is that marine (salty) water must be discharged at the source, whereas location for freshwater discharge is less restrictive and potential applications numerous (e.g. irrigation).

A large multi-disciplinary study on intensive Australian prawn farming which assessed the impact of effluent on downstream environments (CSIRO, 2013) found that Australian farms operate under world best practice in regards to the management of discharge water. The study found that discharge water had no adverse ecological impact on receiving water and that nutrients could not be detected 2km downstream from the discharge point.

While Australian prawn farms are reported as being among the most environmentally sustainable in the world (CSIRO, 2013), location of the industry adjacent to the World listed GBR and related strict policy on discharge has been a major constraint to expansion of the industry. Strict discharge regulation which require zero net addition of nutrients in waters adjacent to the GBR has all but halted expansion in the last decade. An example of the regulatory complexity in this region is the 14 year period taken to obtain to gain approval to develop a site in the Burdekin shire in North Queensland (APFA, 2016). Over the last decade increases in production have been due to improvements in production efficiency rather than any expansion of industry footprint.

In a report to the QLD government (Department of Agriculture and Queensland, 2013) it was suggested that less populated areas in North Australia (e.g. Gulf of Carpentaria) which have less conflict for the marine resource may have potential as areas for aquaculture development. The complex regulatory environment in QLD was a factor in the decision by project Sea Dragon to investigate Greenfield development in WA and NT as an alternative location for what would be Australia's largest prawn farm (Seafarms, 2016).

Today most farms (particularly marine) use bioremediation ponds to ensure that water discharged off-farm into the environment contains low amounts of nutrients and other contaminants. The prawn farming industry in QLD have adopted a code of practice to ensure that discharge waters do not result in irreversible or long term impacts to the receiving environment (Donovan, 2011).The requirement is that discharge waters have similar physiochemical parameters to the source water. In QLD, water discharge policy minimum standards for prawn farming include minimum standards for physico-chemical indicators (e.g. oxygen and pH) and nutrients (e.g. Nitrogen, phosphorus and suspended solids) and total volume (EHP, 2013).

4.7 Predicted water use for established aquaculture species

4.7.1 BLACK TIGER PRAWN

To fill a standard production pond (1 ha), 15 ML of water is required. Based on a grow-out period of 150 days and an average daily water exchange of 5%, each pond would require 127 ML of marine water per crop. During periods of low precipitation and high evaporation up to 0.1ML of freshwater could be added on a daily basis as a means to manage water salinity. However, it is important to note that not all of the water used is necessarily new (source) water, as a significant volume can be recycled after treatment in bioremediation ponds. The volume of water required to be discharged or possibly diverted to a secondary application (e.g. agriculture) is equivalent to the total pond water use for the season, minus total evaporative losses and the volume of recycled water used during production.

Based on a value of 127 ML of marine water required per crop, a standard prawn crop of 8t/ha equates to a marine water requirement of 15.9 kL/kg or 15.9 ML/t of harvested prawn product. The approach to management on the farm will dictate both the volume of freshwater that may be required per crop, but also whether reductions in the total marine water requirement can be made based on the extent of water recycling used throughout the crop.

4.7.2 BARRAMUNDI

To fill a standard production pond (1 ha), 15 ML of water (usually marine water) is required. Based on a grow-out period of two years and an average daily water exchange of 5%, each pond would require 562 ML per crop. It is important to note that not all of the water used is new (source) water, as a significant volume could be recycled after treatment in the bioremediation ponds. The volume of water required to be discharged or possibly diverted to a secondary application (e.g. agriculture) is equivalent to the total pond water use for the season, minus total evaporative losses and the volume of recycled water used during production.

Based on a value of 562 ML of marine water required per crop, a standard barramundi crop of 30t/ha has a water requirement of 18.7 kL/kg or 18.7 ML/t of harvested fish product. The approach to management on the farm will dictate both the volume of freshwater versus marine water that will be required per crop, but also whether reductions in the total water requirement can be made based on the extent of water recycling used throughout the crop.

4.7.3 RED CLAW

To fill a standard production pond (1 ha), 15 ML of freshwater is required. Based on a grow-out period of 300 days and an average water exchange of 1%, each pond would require 48 ML per crop. While bioremediation and water recycling is an option, with such low requirements for water exchange it may be that farms operate without significant reliance on recycling of bioremediated freshwater into their ponds. The volume of water required to be discharged or possibly diverted to a secondary application (e.g. agriculture) is equivalent to the total pond water use for the season, minus total evaporative losses and the volume of recycled water used during production.

Based on a value of 48 ML of freshwater required per crop, a standard red claw crop of 3t/ha equates to a water requirement of 16 kL/kg or 16 ML/t of harvested crayfish.

Part II Water and land suitability for aquaculture

5 Water and land suitability for aquaculture

5.1 Introduction

The use of geographic information system (GIS) mapping is an established tool for land-based aquaculture site selection. The technology is a rapid and economical method for broad-scale land suitability assessment. Multi-criteria assessment, which involves the integration of soil maps and biophysical characteristics with GIS maps, is an increasingly common tool for land-based aquaculture site selection. Spatial analysis of proposed sites is able to incorporate environmental, biophysical and socio-economic data to allow informed decision making (Kapetsky and Travaglia, 1995).

Prior to the development of GIS technology there was limited knowledge on the location and size of land suitable for pond-based aquaculture development. Specific sites were selected by field investigations, with limited consideration of planning, sustainability and potential land and water conflicts. By the late 1980s the use of GIS technology emerged as a novel and efficient tool to assist in the identification and governance of aquaculture suitable land. GIS methods are easily adapted to suit the size of the Assessment area, with the criteria being broad and general at the national level and becoming more specific when assessed by state or region. The more limitations evaluated in the assessment, the more specific the analysis. Broad analysis may indicate land suitable for the construction of ponds, while more detailed analysis can determine land suitability for specific species. In general, as the criteria for evaluation become more specific (by species) the land area assessed to be appropriate will decrease in size. The scale of the study will affect the resolution (level of detail). Studies completed assessing continental Africa and Madagascar (Kapetsky, 1994) were conducted at low resolution, while assessment of Sinaloa state in Mexico (AguilarManjarrez and Ross, 1994) and the Lingayen Gulf in the Philippines (Paw et al., 1994) had a medium or high level of resolution, respectively. The resolution of a study will affect the degree and nature of information available for practical decision making.

The 2015 study and report, *Sustainable Development of Northern Australia: Aquaculture futures for coastal Northern Australia* (Preston et al., 2015), is the most recent relevant GIS-based assessment. . The focus of the study was the identification of possible sites for large-scale intensive farming of high-value marine species. GIS methods developed by (McLeod et al., 2002) were applied to identify optimal biogeographic locations for land-based fish and crustacean aquaculture in coastal northern Australia. The first step involved a coarse preselection using low resolution data, which are typically cheap, extensive and easily available. The second step involved fine-scale analysis with high-resolution data. A set of refined physical parameters defined by (McLeod et al., 2002) was used to select potential sites (Table 5-1). For every land parcel, each parameter was assigned an output (score), and the overall rating of the block was a function of the sum of the parameter outputs. Preliminary site selection focused on distance to coast and general land topography, ignoring soil type and composition.

Table 5-1 Key relevant constraints and the applied rules and ratings

Constraint rating is a measure of suitability as follows: 4 = not limited; 3 = slightly limited; 2 = severely limited; and 1 = not suitable. Overall suitability was based on a combined limitation rating.

CONSTRAINT	RULE	RATING
Distance-to-water	Distance-to-water <500m	4
	500m Distance-to-water <1000m	3
	1000 m distance-to water <2000m	1
	2000 m <distance-to water	0
Elevation	5 m <elevation <15m	4
	0 m <elevation <5 m or 15 m elevation <20m	3
	20 m <elevation <25 m	1
	25 m <elevation or elevation <0 m	0
Slope	Slope <2%	4
	2% <slope <4%	3
	4% <slope <5%	1
	5% <slope	0

Source: McLeod et al., 2002.

The report concluded that there is significant untapped potential for expansion of land-based aquaculture in northern Australia. Preliminary broad-scale analysis by (McLeod et al., 2002) indicated that 1.2 million ha of Australia’s northern coastline is potentially suitable for marine pond-based aquaculture. The report estimated the value of large-scale marine pond aquaculture in northern Australia could be as much as AUD$1 billion, with around 500,000 ha of suitable land available in each northern state or territory (Preston et al., 2015).

5.2 Methods

5.2.1 WATER SUITABILITY ASSESSMENT

Aquaculture pond data and meteorological information (SILO climate data (Jeffery et al., 2001)), from two sites in eastern Australia (Bribie Island and Mossman, QLD), were used to calibrate a simulation model for key pond parameters (water temperature, salinity, evaporation and precipitation rates) at the two sites. Using meteorological data for selected stations in the Assessment area, the pond water temperature and salinity were simulated using calibrated models for specific, artificial pond filling scenarios (entire water exchange at a specific date, constant water level) using sea water. The model outputs show the changes in pond salinity under those scenarios driven by evaporation and precipitation, as well as pond water temperature. While the models do not account for the effect of variation in temperature or salinity of the source water on pond water parameters, the model outputs do indicate how meteorological patterns of each study area will likely influence pond salinity and water temperature.

5.2.2 LAND SUITABILITY ASSESSMENT

For this land assessment of the Fitzroy, Darwin and Mitchell catchments, a set of limitations were adapted from (McLeod et al., 2002) to determine land suitability for development of marine or freshwater ponds (Table 5-2). Each category was assessed for production in earthen and plastic-lined ponds (Table 5-3).The suitability of areas for aquaculture development was assessed from the perspective of soil and land characteristics, and proximity to sea water for marine species. The soil and land limitations considered included clay content, sodicity and rockiness; and mainly refer to geotechnical considerations (e.g. construction and stability of pond walls). Other limitations, including slope, and the likely presence of gilgai microrelief and acid sulfate soils, infer more difficult, expensive and therefore less suitable development environments, and a greater degree of land preparation effort.

Suitability was assessed for earthen and lined ponds. For earthen ponds, key considerations included soil properties, preventing pond leakage and soil acidity (pH); the latter taking into account negative growth responses of species from unfavourable pH values (i.e. biological limitation) as well as engineering, as pH may affect the structural integrity of earthen walls. The aquaculture suitability rules, including the limitation classes and suitability subclasses for each species by pond configuration, is provided in Apx Table A-1. The characteristics of tides and their suitability for marine aquaculture have not been applied in this analysis therefore the full inland distance of tidal waters has not been explored.

Table 5-2 Rationale for limitation assessment for aquaculture land and water suitability analysis

LIMITATION	BRIEF RATIONALE
Water temperature	Water temperature is a key factor for species selection for a given region. While most species have a broad thermal tolerance, optimal production occurs across a narrow range. Pond water temperature varies seasonally.
Water salinity	Water salinity is a key factor for species selection. For the majority of species, optimal production occurs across a relatively narrow range, usually either marine or freshwater. However, euryhaline species are efficiently produced under marine and freshwater conditions.
Distance to marine water source	Pond distance from a marine water source has a large bearing on the required capital investment and ongoing crop production efficiency.
Elevation	Land elevation has significant bearing on ability to drain production and bioremediation ponds, which impacts on ongoing production efficiency.
Slope	Land slope has significant bearing on required capital investment to construct ponds and channels.
Soil clay content (%)	The objective of the pond containment structure is to provide an impermeable layer between the pond water and the local surface and groundwater. Soil clay content (%) is a good indicator of the potential to produce an impermeable soil layer.
Soil pH	Soil acidity or alkalinity may lead to certain toxicities.
Acid sulfate soils	Acid sulfate soils are more expensive to develop, manage and can be detrimental to animal health and reduce crop production efficiency.
Soil depth	Soil depth has significant bearing on required capital investment to construct ponds.
Permeability	A measurement of the ease that the pond water can travel through the pond base and wall.
Rockiness	Rockiness has significant bearing on required capital investment to construct ponds.
Gilgai	Gilgai presence has significant bearing on required capital investment to construct ponds.

Table 5-3 Candidate and pond type

CANDIDATE	POND TYPE
Marine	Earthen
	Plastic-lined
Freshwater	Earthen
	Plastic-lined

The limitation constraint rating for candidate and pond type can be found in Appendix A. A 5-Class land suitability ranking was used based on guidelines developed by the Food and Agriculture Organisation (FAO, 1976; 1985) and presented in Table 5-4. The ranking applies a suitability term (suitable → currently unsuitable → unsuitable) and a limitations term (negligible → minor → moderate → severe → extreme). Each drop in suitability implies that more management input (and cost) is required to achieve incremental increases in crop production. The limitation term is a proxy for the level of management required to overcome the current level of limitation. By convention the most limiting factor is identified in Class 2 (and greater) to indicate the management intervention required to elevate the class.

Table 5-4 Land suitability classes

CLASS	SUITABILITY	LIMITATIONS	DESCRIPTION
1	Highly suitable land	Negligible	Highly productive land requiring only simple management practices to maintain economic production.
2	Suitable land	Minor	Land with limitations that either constrain production or require more than the simple management practices of Class 1 land to maintain economic production.
3	Moderately suitable land	Considerable	Land with limitations that either further constrain production or require more than those management practices of Class 2 land to maintain economic production.
4	Currently unsuitable land	Severe	Currently unsuitable land due to severe limitations that preclude successful sustained use of the land for the specified land use. In some circumstances, the limitations may be surmountable with changes to knowledge, economics or technology.
5	Unsuitable land	Extreme	The limitations are so severe that the specified land use is precluded. The benefits would not justify the inputs required to maintain production and prevent land degradation in the long term.

Source: Based on FAO (1976, 1985) and adapted from DSITI and DNRM (2013) and van Gool et al. (2005).

5.3 Water and Land suitability overview

The broad suitability of water for aquaculture across each of the three study areas shows similar patterns that are governed by evaporation and precipitation (for marine species) and ocean and air temperatures for all species. Suitability of water salinity for marine species is affected by seasonal variation of evaporation and precipitation. Water temperature is optimal for the majority of the year for most tropical species.

The suitability of land for aquaculture across each of the study areas also shows similar broad patterns that are strongly governed by access to sea water (for marine species), soil type - especially as this relates to permeability, terrain (slope) and rockiness – depending on the suite of limitations active in the land suitability framework. Areas suitable for fresh water lined ponds are most extensive throughout all three study areas, noting that no assessment of proximity to or availability of fresh water was included in the discussions that follow. Areas of shallow rocky soils, landscapes where slopes exceed 5% and those areas with high acid sulfate soil potential are generally precluded from aquaculture development. Earthen ponds are restricted to areas of deeper clay (>0.5 m depth; a depth determined in consultation with expert advice from Aquaculture Activity) and heavier loam soils where soil compaction and stability properties are suitable for pond construction. Areas with moderate to rapid soil permeability, such as deep sands are not suitable, as loss of pond water and potential contamination of groundwater are major constraints. Marine species, including prawns, are constrained by distance from the coast or influence of marine tides, making large inland areas of the Mitchell and Fitzroy catchments unsuitable. Suitability for marine species is therefore much more restricted than the freshwater species. The following sections include discussions on the aquaculture water and land suitability patterns for marine and freshwater species in earthen and lined ponds for each of the study areas. The suitability for barramundi and other euryhaline species (i.e. species able to tolerate a wide range of salinities) correlate to both marine and freshwater suitability patterns.

5.4 Results

5.4.1 FITZROY CATCHMENT

Water suitability

Sea surface temperatures (SST) from oceanic waters offshore (Figure 5-2) to the Fitzroy catchment are ideal for the culture of a majority of tropical aquatic species from October to March (Charles et al., 2016). The comparatively shallow nearshore and estuarine waters in the Fitzroy catchment are likely to be to significantly higher in temperature than adjacent oceanic waters. If the warming trend of SST in northern Australia continues (*see companion technical report on climate, Charles et al., (2016)*) this may have the potential to prolong the grow-out season for some aquatic species.

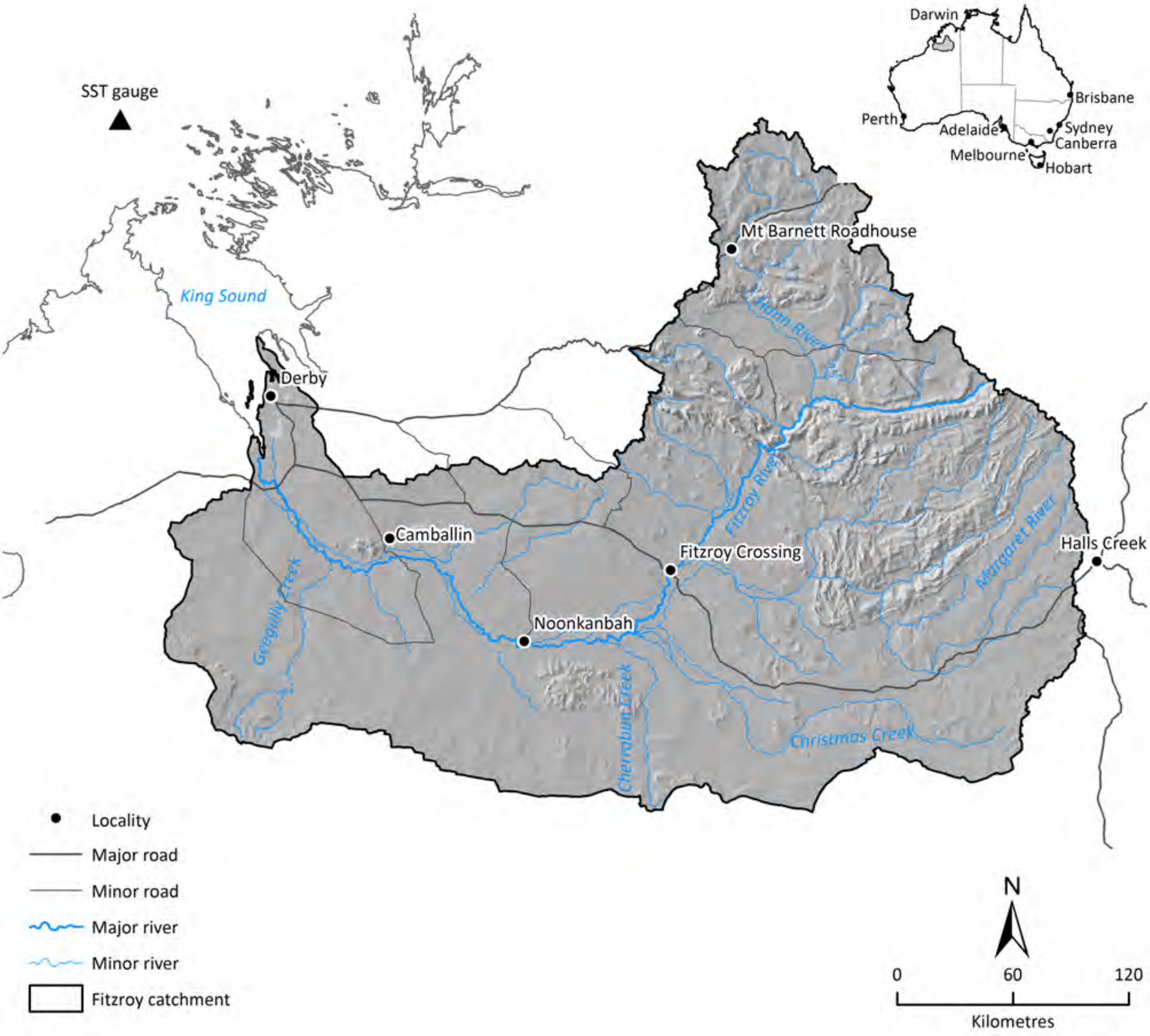

Figure 5-1 Location of SST gauge, Fitzroy catchment

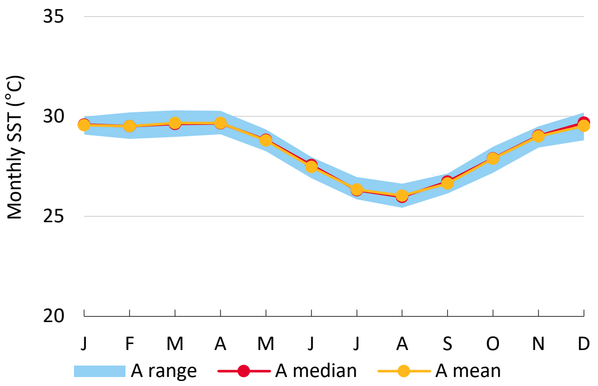

Figure 5-2 Historical monthly SST offshore, Fitzroy catchment

A range is the 10th to 90th percentile monthly SST for 1970 to 2015 period. Source: Charles et al. (2016).

Marine ponds

The first pane of (Figure 5-3) shows simulated model outputs of pond water salinity based on parameters of pond water temperature, evaporation and precipitation (shown in the bottom two panes) derived from meteorological data, and based on the initial filling of ponds with 36 ppt water on the first day of a given month of the year. For example, a pond filled on the 1st October 2015 exhibits salinity levels that are largely buffered by rainfall during the wet-season. Lower precipitation rates during the same period in 2016 shows salinity levels quickly increasing above those of the previous year and then continuing to rise throughout the dry-season.

Elevated pond water salinities during the dry-season due to evaporation and low precipitation rates may be difficult to manage, as the addition of large amounts of freshwater to lower pond salinities may be impractical or too costly. For example, a standard marine pond (1 ha) receiving no precipitation and 10 mm evaporation per day, would require daily addition of 100,000 L (0.1 ML) of freshwater to maintain optimal salinities. A 100 ha farm would require 10 ML of freshwater per day or 1.5 GL for a 150 day season. A site offering a brackish water source (i.e. 10 to 20 ppt) may be better suited to farming marine or euryhaline species in the Fitzroy catchment. High evaporation and low precipitation periods would be considerably easier to manage by filling ponds at the lowest optimal salinity of the target species and regulating water exchanges at suitable intervals.

Pond water temperatures are optimised for most tropical aquaculture species between September and April. Water temperatures during the mid-year dry-season while tolerable, fall below the optimal growth threshold for tropical culture species.

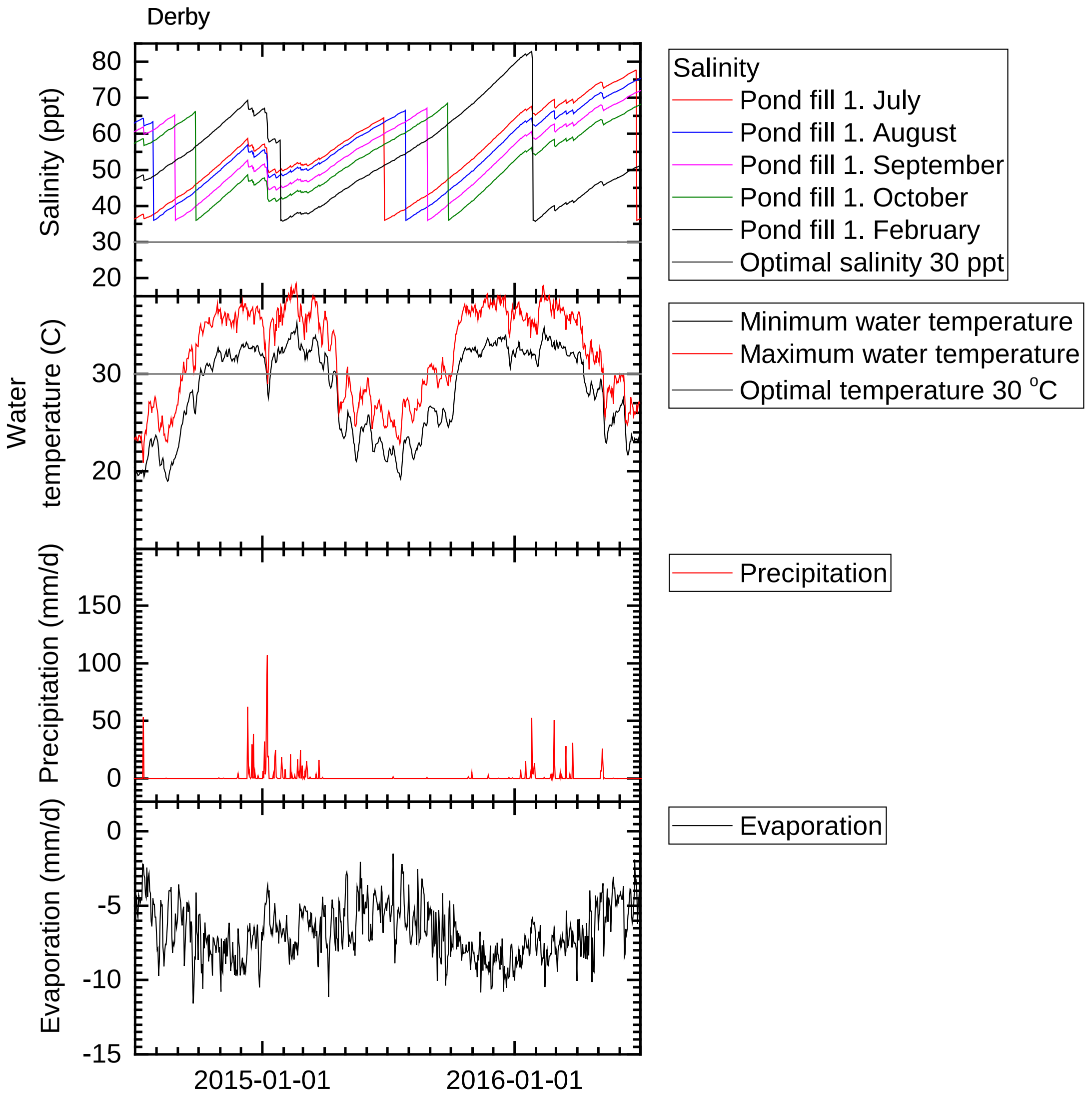

Figure 5-3 Simulated salinity, water temperature, evaporation and precipitation rates based on SILO climate data at Derby, WA
(Jeffery et al., 2001).

Freshwater ponds

Freshwater ponds have no salt content and therefore water exchange has no effect on culture water salinity. However, there is a requirement to maintain pond volume. For example, a standard pond (1 ha) receiving no precipitation and 10 mm evaporation per day, would require daily addition of 100,000 L (0.1 ML) of freshwater to maintain pond volume. A 100 ha farm would require 10 ML of freshwater a day or 3 GL for a 300 day season.

Land suitability

Marine earthen ponds

Around 35,000 ha of land was found to be suitable for marine earthen ponds. Around 500 ha was suitable with negligible limitations, 4000 ha with minor limitations and 31,000 with moderate limitations (Table 5-5). As shown in Figure 5-4 and Figure 5-5 this area is restricted to the coastal margin and associated with seasonally or permanently wet soils and along the margins of the main river channel on cracking clays.

Table 5-5 Land suitability analysis results for Fitzroy catchment (ha)

CLASS	SUITABILITY	LIMITATIONS	FRESH EARTHEN	FRESH LINED	MARINE EARTHEN	MARINE LINED
1	Highly suitable	Negligible	2099	3,015,865	500	1343
2	Suitable	Minor	11,378	2,122,882	4248	36,273
3	Moderately Suitable	Considerable	647,050	799,792	30,987	18,181
4	Currently unsuitable	Severe	3,783,215	567,400	18,549	1324
5	Unsuitable	Extreme	4,936,204	2,874,008	9,327,485	9,324,647

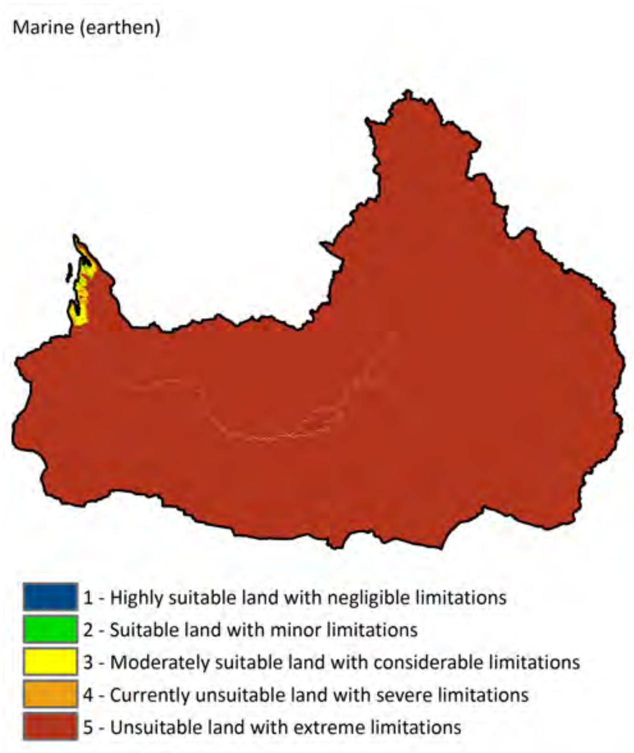

Figure 5-4 Land suitability map for marine earthen ponds in Fitzroy catchment

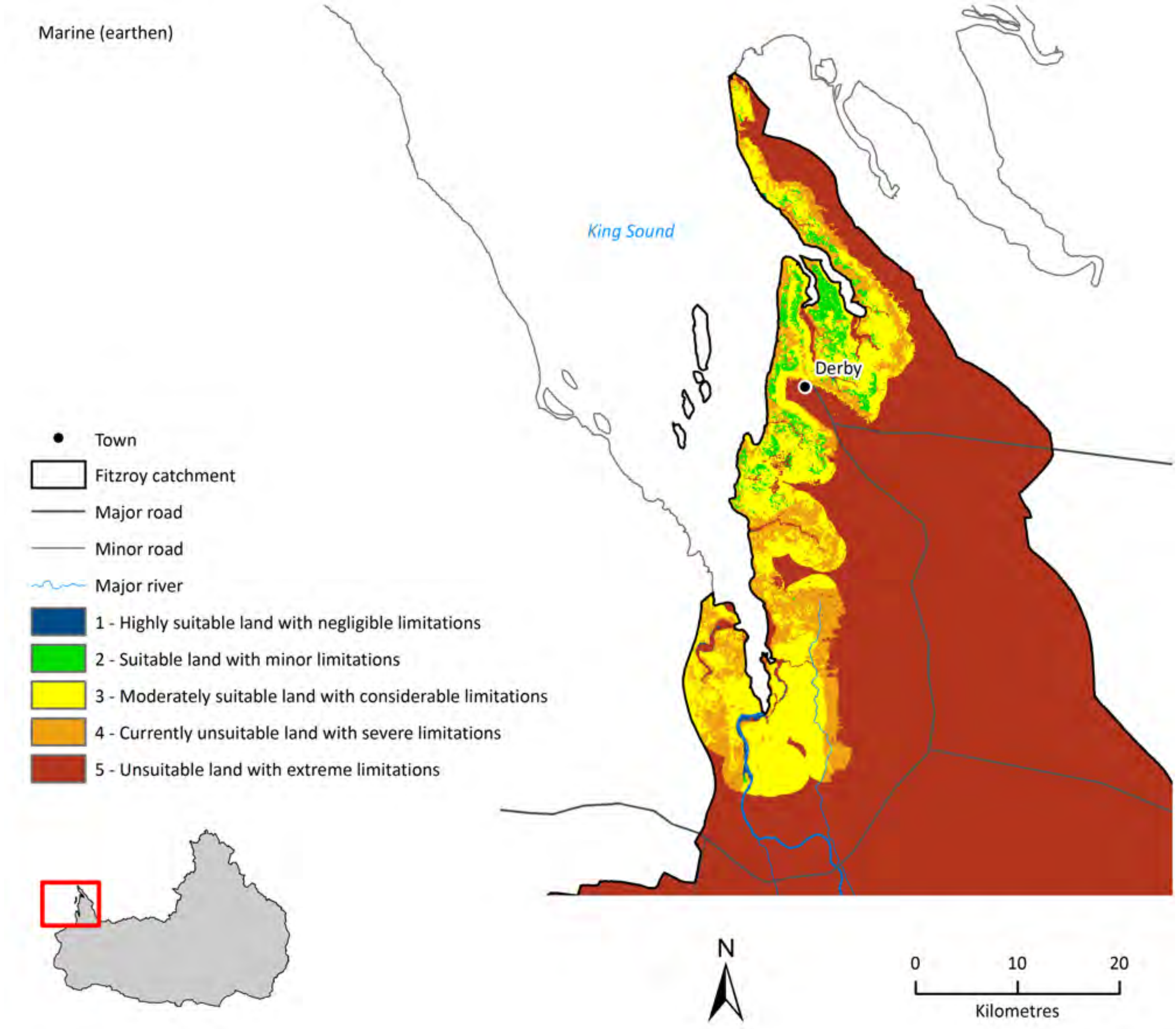

Figure 5-5 Land suitability map for marine earthen ponds in coastal area of Fitzroy catchment

Marine lined ponds

Around 55, 000 ha (<1% of catchment) of land was found to be suitable for marine lined ponds. Around 1000 ha was suitable with negligible limitations, 36,000 ha with minor limitations and 18,000 ha with moderate limitations (Table 5-5). As shown in Figure 5-6 and Figure 5-7 this area is restricted to the coastal margins of the catchment and coincides mainly with seasonally or permanently wet soils and also the cracking clays along the margins of the river.

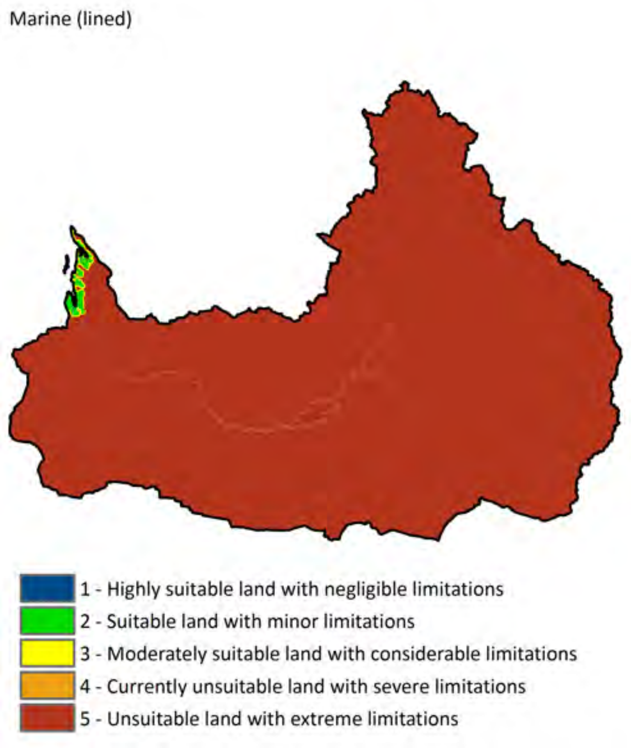

Figure 5-6 Land suitability map for marine lined ponds in Fitzroy catchment

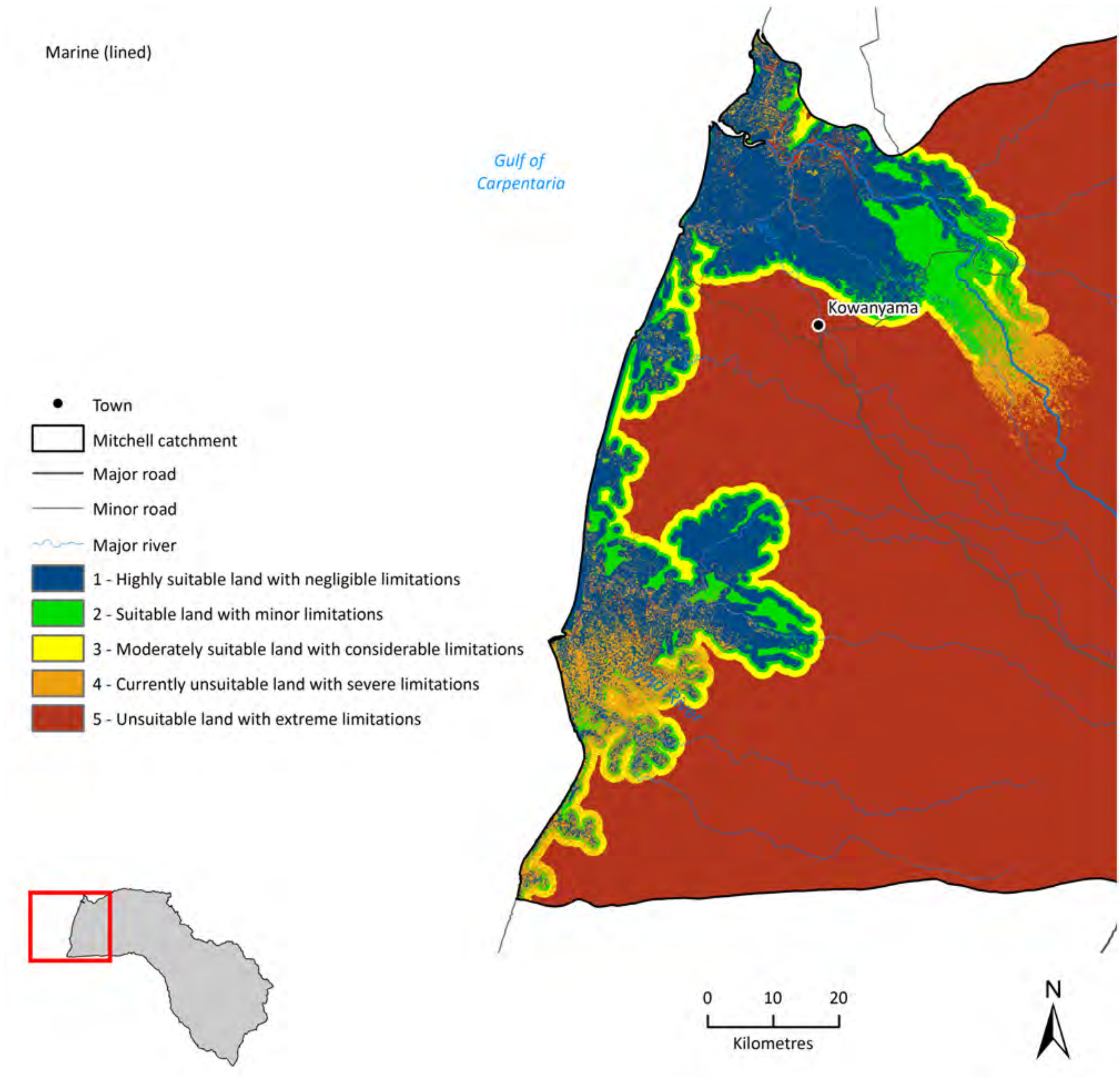

Figure 5-7 Land suitability map for marine lined ponds in coastal areas of Fitzroy catchment

Freshwater earthen ponds

Around 660,000 ha of land was found to be suitable for freshwater earthen ponds. Around 2000 ha was suitable with negligible limitations, 11,000 ha with minor limitations and 647,000 ha with moderate limitations (Table 5-5). As shown in Figure 5-8 and these areas are close to the coastline where seasonally or permanently wet soils dominate. Moderately suitable Class 3 areas cover 7% of the catchment, coinciding with cracking clay soils along the main river margins in the central areas. Non-suitable areas (Class 4 and 5) coincide with red sandy soils and the shallow and/or rocky soils that are on sloping soils.

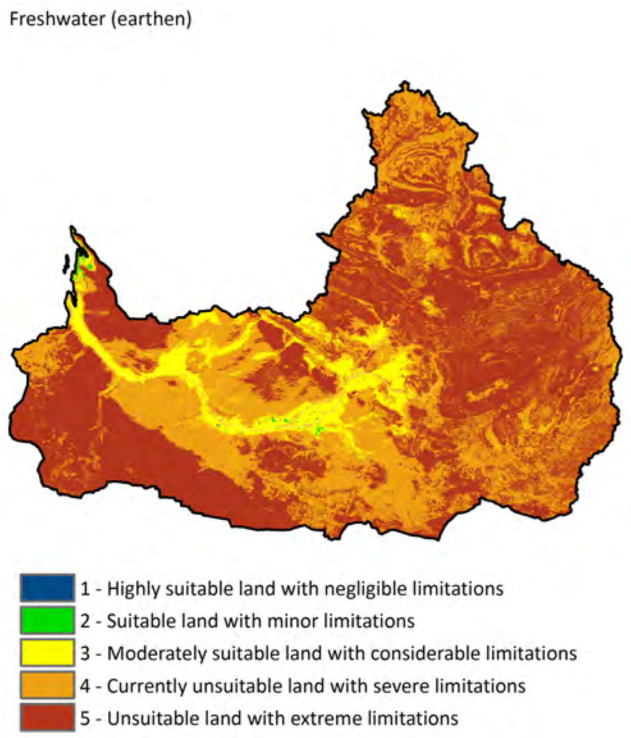

Figure 5-8 Land suitability map for freshwater earthen ponds in Fitzroy catchment

Freshwater lined ponds

Around 6 million ha of land (63.2%) in the catchment is suitable for the development of freshwater lined ponds. Around 3 million ha was suitable with negligible limitations, 2 million ha with minor limitations and 800,000 ha with moderate limitations (Table 5-5). An additional 5.3 million ha were suitable if the freshwater ponds were lined. As shown in Figure 5-9 these areas dominate the central and eastern areas of the catchment including red sandy soils, cracking clay soils, red loamy soils and brown, yellow and grey loamy soils (i.e. low gradient, deeper and non-rocky soils).

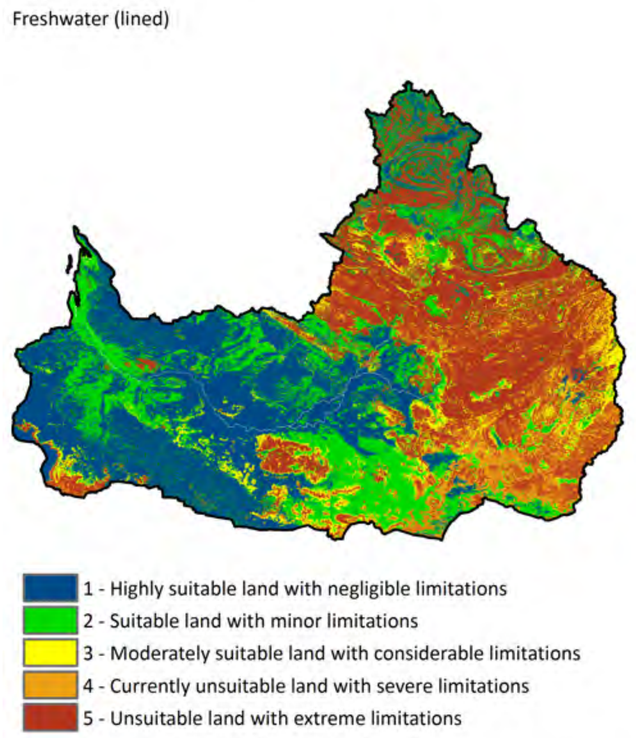

Figure 5-9 Land suitability map for freshwater lined ponds in Fitzroy catchment

5.4.2 DARWIN CATCHMENTS

Water suitability

SST from oceanic waters offshore (Figure 5-11) to the Darwin catchments are ideal for the culture of a majority of tropical aquatic species from October to March (Charles et al., 2016). The comparatively shallow nearshore and estuarine waters in the Darwin catchments are likely to be significantly higher in temperature than adjacent oceanic waters. If the warming trend of SST in northern Australia continues (*see companion technical report on climate, Charles et al., (2016)*), this may have the potential to prolong the grow-out season for some aquatic species.

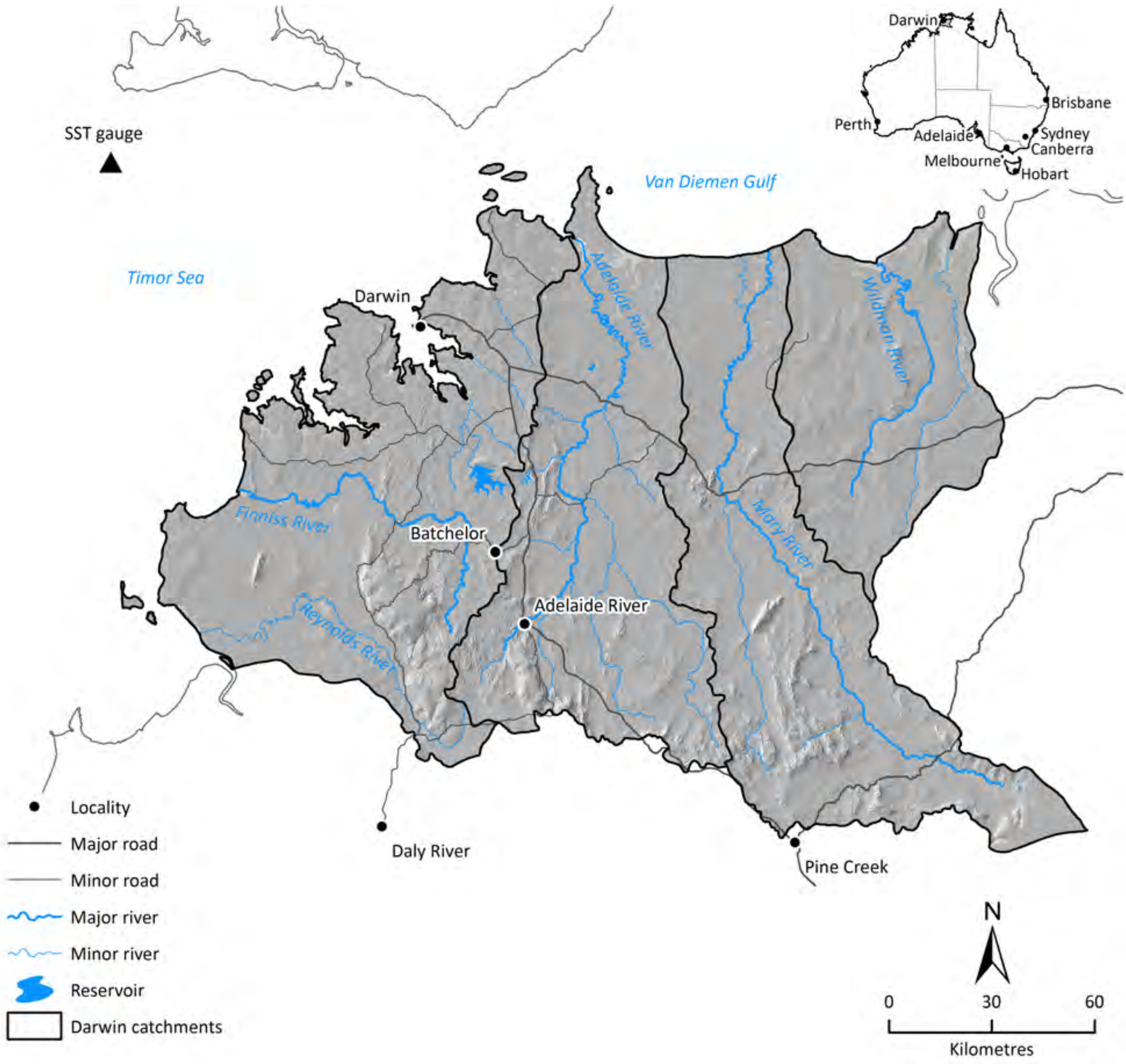

Figure 5-10 Location of sea surface SST gauge, Darwin catchments

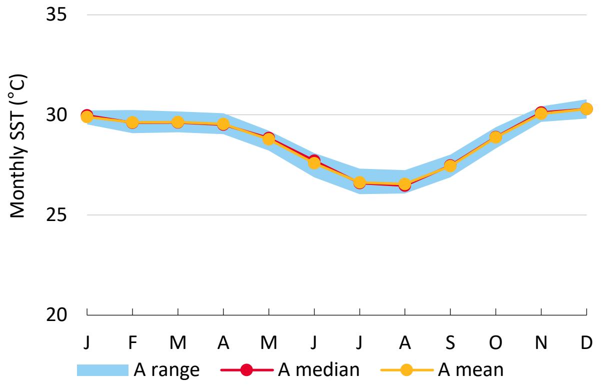

Figure 5-11 Historical monthly SST offshore Darwin catchments

(A range is the 10th to 90th percentile monthly SST for 1970 to 2015 period). Source: Charles et al. (2016).

Marine ponds

The first pane of Figure 5-12 shows simulated model outputs of pond water salinity based on parameters of pond water temperature, evaporation and precipitation (shown in the bottom two panes) derived from meteorological data, and based on the initial filling of ponds with 36 ppt water on the 1st day of a given month of the year. For example, a pond filled on 1 October exhibits salinity levels that are largely buffered by rainfall during the wet-season. Pond salinity progressively increases from April to September due to continuing evaporation and low rainfall.

Elevated salinities during the dry-season due to evaporation and low precipitation rates may be difficult to manage, as the addition of large amounts of freshwater to lower pond salinities may be impractical or too costly. For example, a standard marine pond (1 ha) receiving no precipitation and 10 mm evaporation per day, would require daily addition of 100,000 L (0.1 ML) of freshwater to maintain optimal salinities. A 100 ha farm would require 10 ML of freshwater per day or 1.5 GL for a 150 day season. Evaporative influences and low precipitation periods would be considerably easier to manage by filling ponds at the lowest optimal salinity of the target specie and regulating water exchanges at suitable intervals.

Pond water temperatures are optimised for most tropical aquaculture species between September and April. Minimum pond water temperatures during the mid-year dry-season fall below the optimal growth threshold for tropical culture species.

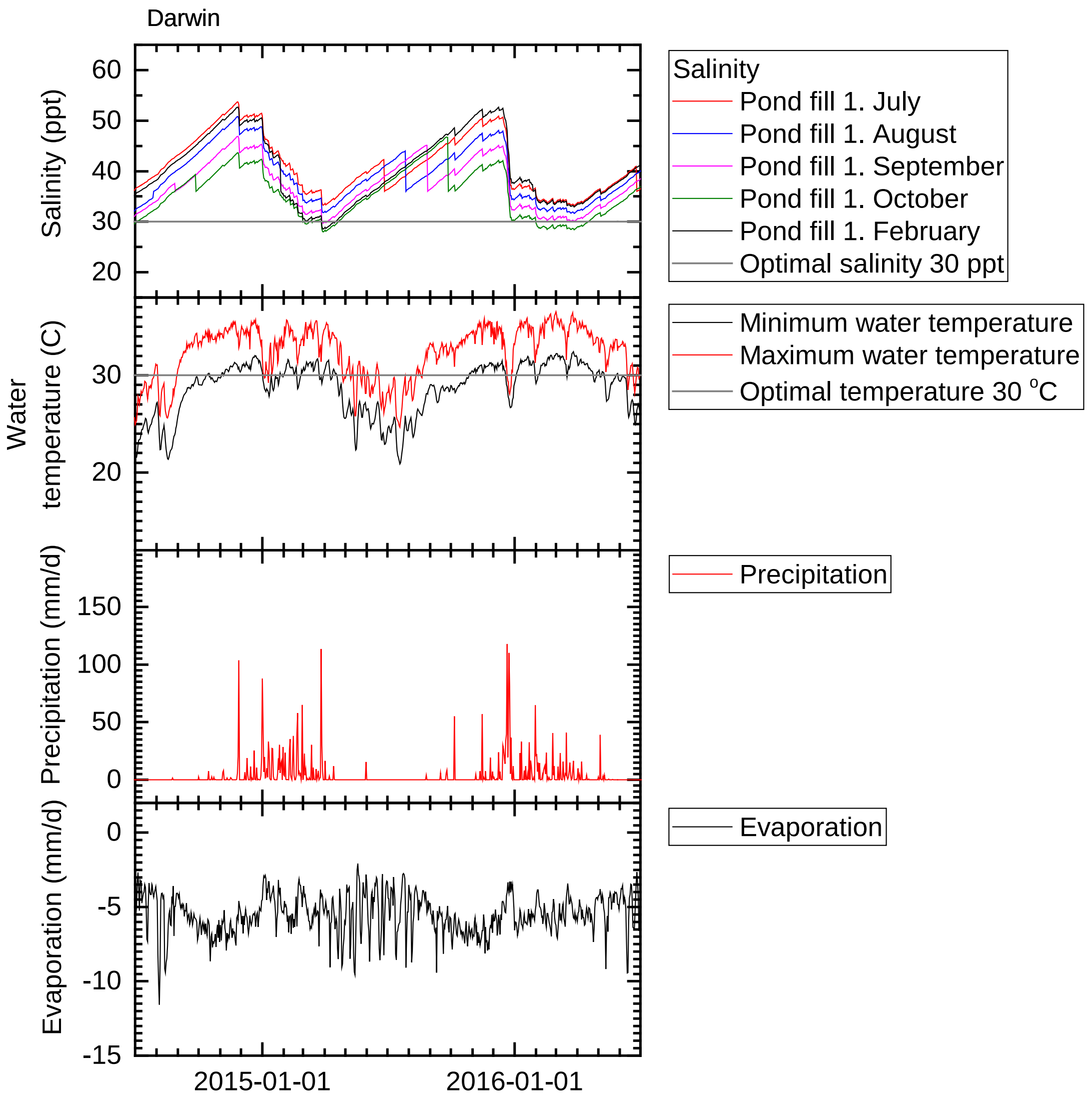

Figure 5-12 Simulated salinity, water temperature, evaporation and precipitation rates from SILO data at Darwin, NT

Freshwater ponds

Freshwater ponds have no salt content and therefore water exchange has no effect on culture water salinity. However, there is a requirement to maintain pond volume. For example, a standard pond (1 ha) receiving no precipitation and 10 mm evaporation per day, would require daily addition of 100,000 L (0.1 ML) of freshwater to maintain pond volume. A 100 ha farm would require 10 ML of freshwater a day or 3 GL for a 300 day season.

Land suitability

Marine earthen ponds

Around 260,000 ha of coastal land was found to be suitable for marine earthen ponds. Around 3000 ha was suitable with negligible limitations, 69,000 ha with minor limitations and 187,000 ha with moderate limitations (Table 5-6). As shown in Figure 5-13 and Figure 5-14, suitable areas are restricted to seasonally and permanently wet soils in the marine and coastal low-lying plains. This area is dominated by Class 3 land, which along with areas of Class 2 land, extend a significant distance inland along the Adelaide River, while there is a smaller component in the lowest reaches of the Wildman River.

Table 5-6 Land suitability analysis results for Darwin catchments (ha)

CLASS	SUITABILITY	LIMITATIONS	FRESH EARTHEN	FRESH LINED	MARINE EARTHEN	MARINE LINED
1	Highly suitable	Negligible	1495	1,193,157	3394	86,584
2	Suitable	Minor	105,590	982,910	68,802	185,980
3	Moderately suitable	Considerable	561,206	222,821	187,056	148,249
4	Currently unsuitable	Severe	1,862,675	240,561	204,192	47,937
5	Unsuitable	Extreme	430,866	322,385	2,498,383	2,493,083

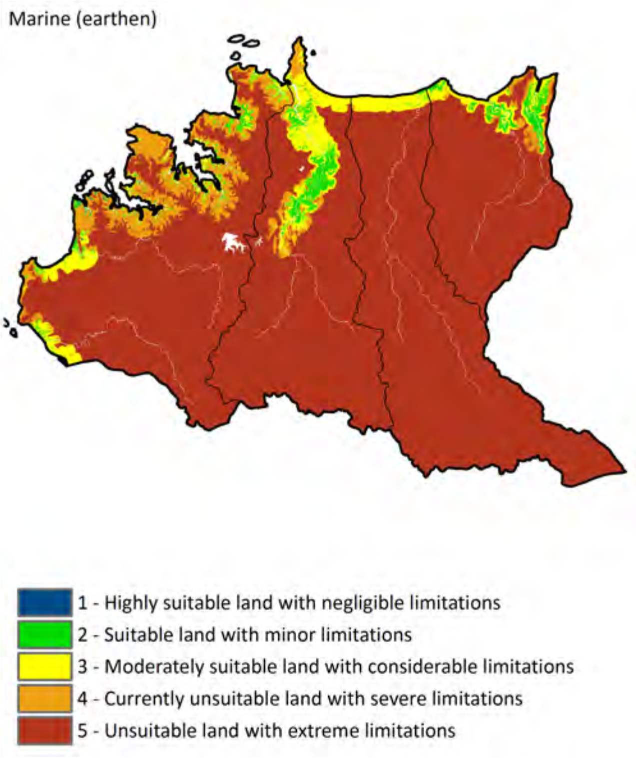

Figure 5-13 Land suitability map for marine earthen ponds in Darwin catchments

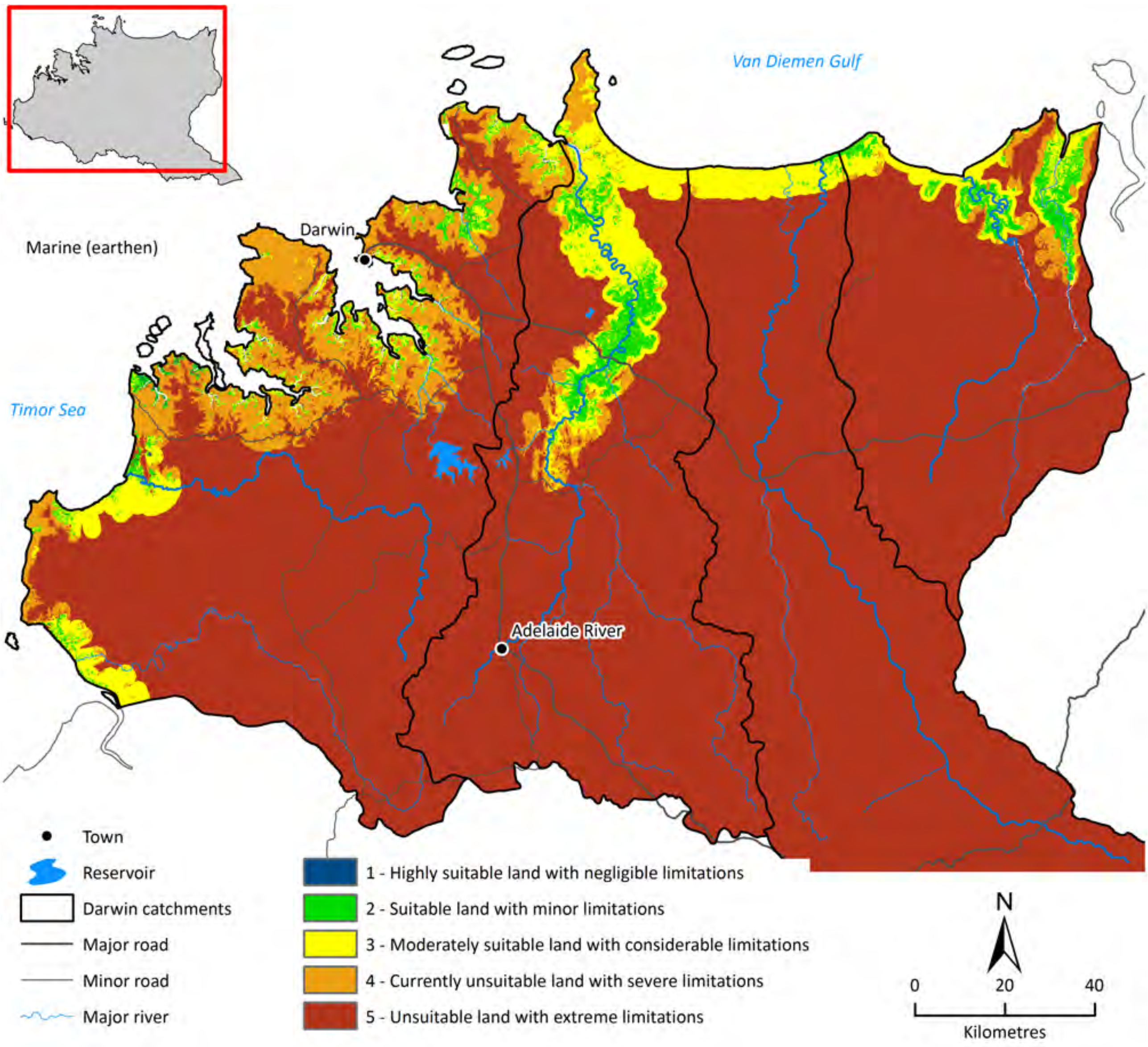

Figure 5-14 Land suitability map for marine earthen ponds in coastal area of Darwin catchments

Marine lined ponds

Around 420,000 ha of coastal land was found to be suitable for marine lined ponds. Around 86,000 ha was suitable with negligible limitations, 185,000 ha with minor limitations and 148,000 with moderate limitations (Table 5-6). As shown in Figure 5-15 and Figure 5-16, the area suitable for marine lined ponds extends a significant distance inland along the Adelaide River where the marine tidal influence is strong, and along much of the coastal fringe. The dominant soils for suitable areas are seasonally or permanently wet soils and to a lesser extent, red loamy soils where gradient slope permits.

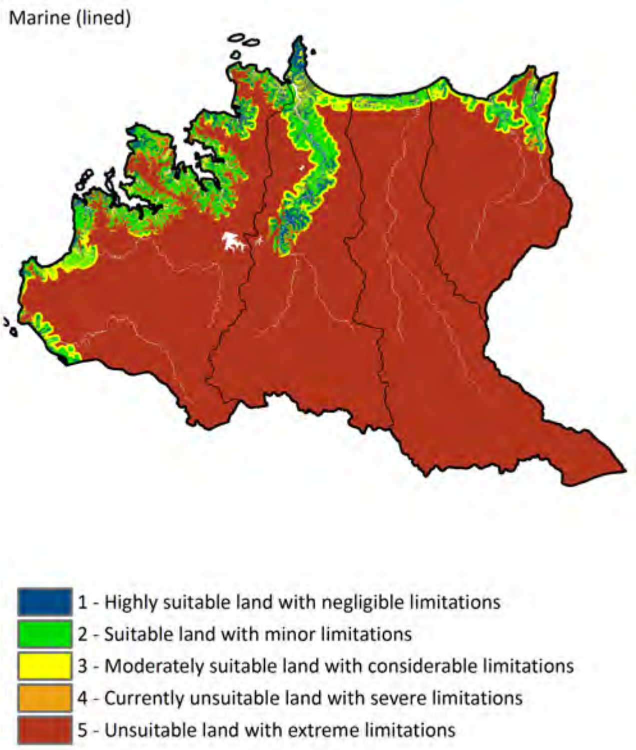

Figure 5-15 Land suitability map for marine lined ponds in Darwin catchments

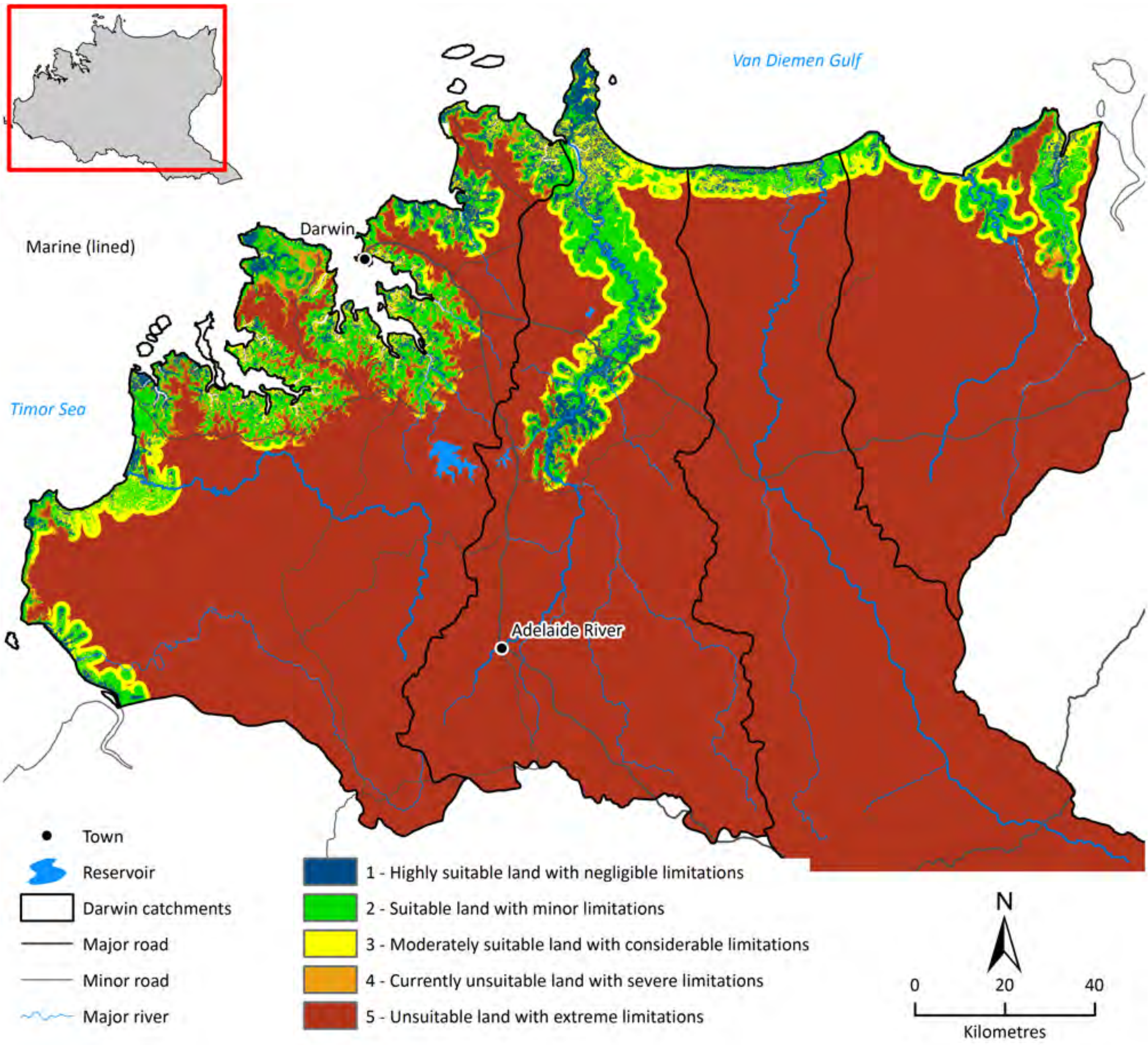

Figure 5-16 Land suitability map for marine lined ponds in coastal area of Darwin catchments

Freshwater earthen ponds

Around 670,000 ha of land was found to be suitable for freshwater earthen ponds (Table 5-6). Around 1500 ha was suitable with negligible limitations, 105,000 ha with minor limitations and 560,000 ha with moderate limitations (Table 5-6). As shown in Figure 5-17, these areas are mainly associated with flatter terrain of seasonally or permanently wet soils and found in the lower catchments particularly in the Wildman and Adelaide river catchments.

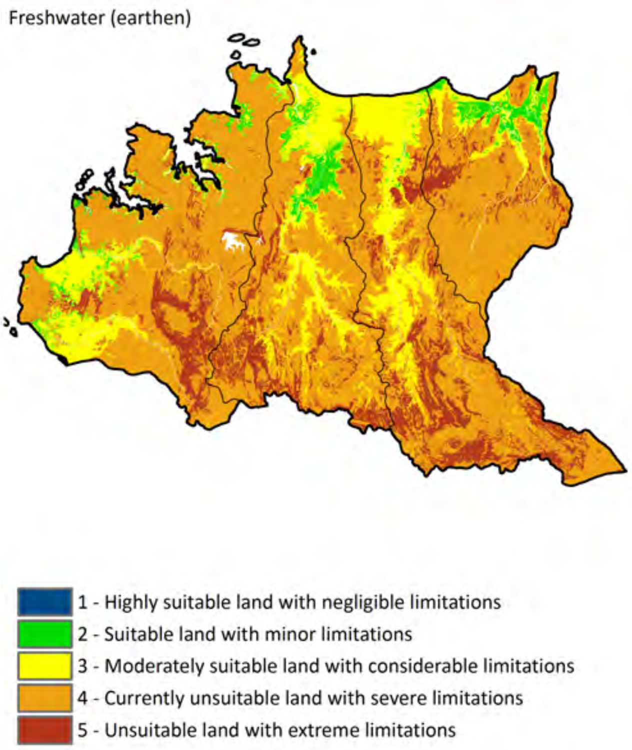

Figure 5-17 Land suitability map for freshwater earthen ponds in Darwin catchments

Freshwater lined ponds

Around 2.4 million ha of land in the catchments is suitable for the development of freshwater lined ponds (Table 5-6). Around 1.2 million ha was suitable with negligible limitations, 980,000 ha with minor limitations and 222,000 ha with moderate limitations (Table 5-6). As shown in Figure 5-18, these areas dominate low gradient areas of the lower catchments, although a significant proportion of suitable areas are also to be found in the low gradient areas of the upper catchments. Areas moderately suitable to unsuitable (Classes 3 to 5), therefore, coincide strongly with the shallow and/or rocky soils in the catchments.

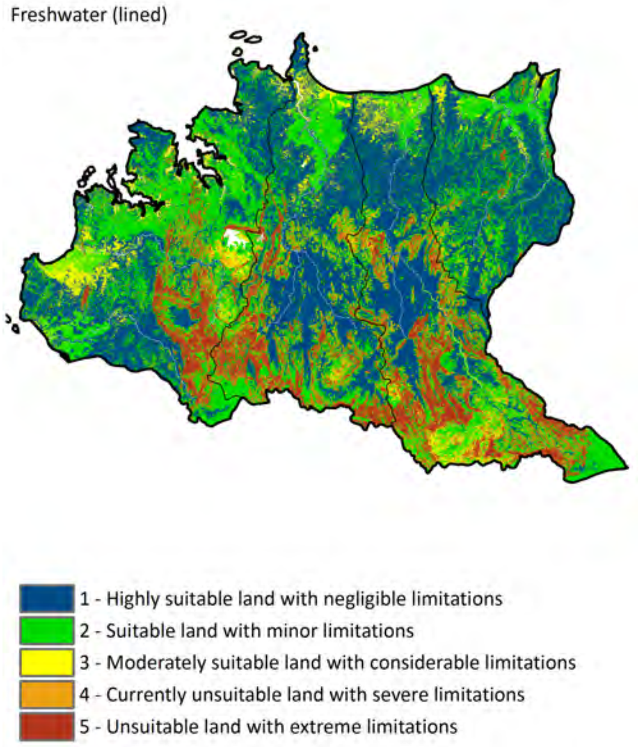

Figure 5-18 Land suitability map for freshwater lined ponds in Darwin catchments

5.4.3 MITCHELL CATCHMENT

Water suitability

SST from oceanic waters offshore Figure 5-20 to the Mitchell catchment are ideal for the culture of a majority of tropical aquatic species from October to March (Charles et al., 2016). The comparatively shallow nearshore and estuarine waters in the Mitchell catchment are likely to be significantly higher in temperature than adjacent oceanic waters. If the warming trend of SST in northern Australia continues (*see companion technical report on climate, Charles et al., (2016)*) this may have the potential to prolong the grow-out season for some aquatic species.

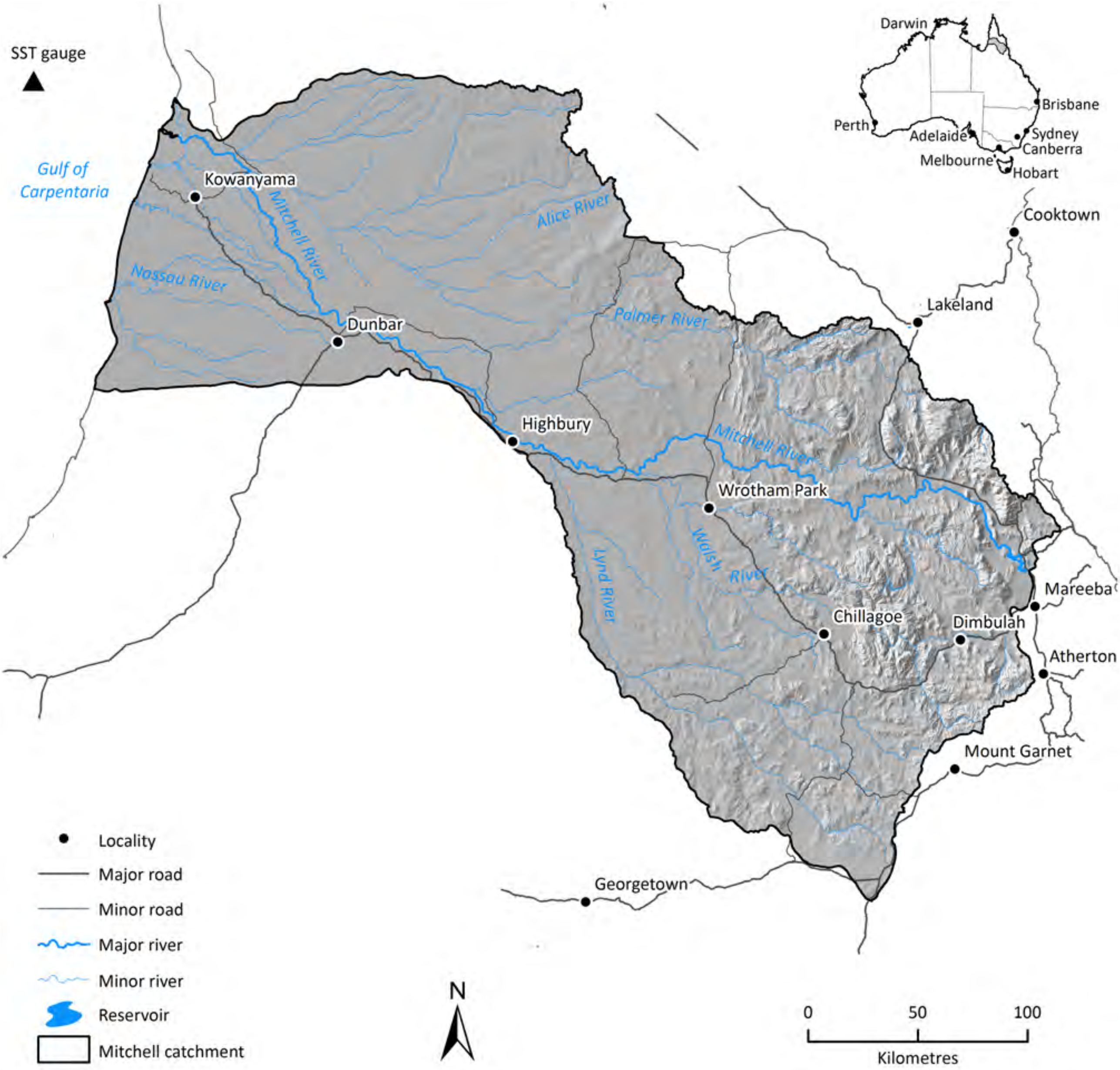

Figure 5-19 Location of SST gauge, Mitchell catchment

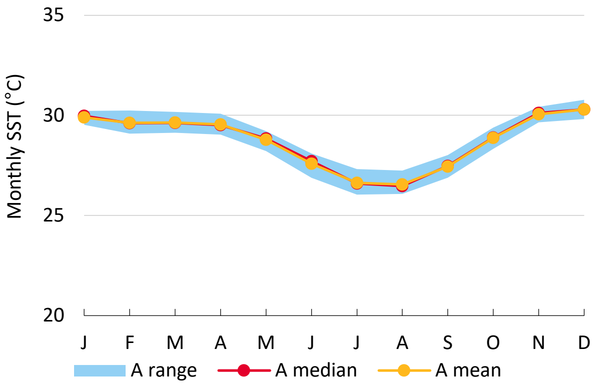

Figure 5-20 istorical monthly SST offshore for the Mitchell catchment

A range is the 10th to 90th Percentile monthly SST for 1970 to 2015 period. Source: Charles et al., 2016.

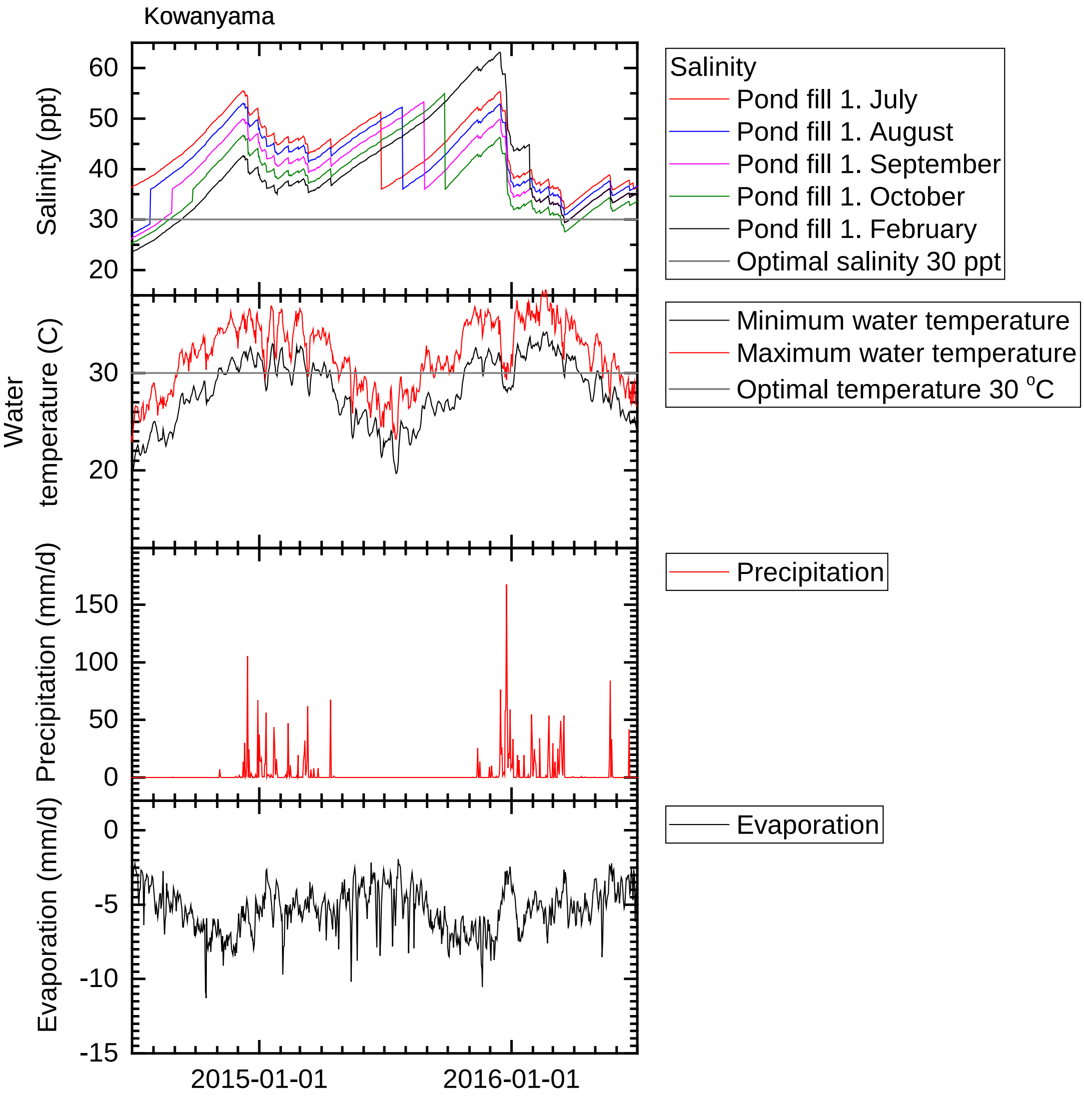

Figure 5-21 Simulated salinity, water temperature, evaporation and precipitation rates from SILO data at Kowanyama, QLD

Marine ponds

The first pane of Figure 5-21 shows simulated model outputs of pond water salinity based on parameters of pond water temperature, evaporation and precipitation (shown in the two bottom panes) derived from meteorological data, and based on the initial filling of ponds with 36 ppt water on the 1st day of a given month of the year. For example, pond filling on the 1st October charts levels that are significantly buffered by rainfall during the wet-season. Low precipitation to December 2014 shows salinity rapidly increasing above those of a similar period in 2015 and then continuing throughout the dry-season (i.e. from April 2015).

Elevated salinities during the dry-season due to evaporation and low precipitation rates may be difficult to manage, as the addition of large amounts of freshwater to lower pond salinities may be impractical or too costly. For example a standard marine pond (1 ha) receiving no precipitation and 10 mm evaporation per day, would require daily addition of 100,000 L (0.1 ML) of freshwater to maintain optimal salinities. A 100 ha farm would require 10 ML of freshwater a day or 1.5 GL for a 150 day season. Evaporative effects and low precipitation periods would be considerably easier to manage by filling ponds at the lowest optimal salinity of the target species and regulating water exchanges at suitable intervals.

Pond water temperatures are optimised for most tropical aquaculture species between September and April. Minimum pond water temperatures during the mid-year dry-season are shown to fall below the optimal growth threshold for tropical culture species.

Freshwater ponds

Freshwater ponds have no salt content and therefore water exchange has no effect on culture water salinity. However, there is a requirement to maintain pond volume. For example, a standard pond (1 ha) receiving no precipitation and 10 mm evaporation per day, would require daily addition of 100,000 L (0.1 ML) of freshwater to maintain pond volume. A 100 ha farm would require 10 ML of freshwater a day or 3 GL for a 300 day season.

Land suitability

Marine earthen pond

Around 216,000 ha of coastal land was found to be suitable for marine earthen ponds. Around 6000 ha was suitable with negligible limitations, 54,000 ha with minor limitations and 156,000 ha with moderate limitations (Table 5-7). As shown in Figure 5-22 and Figure 5-23, these areas are restricted to seasonally or permanently wet soils along and close to the coastline, and in sand or loam over sodic clay subsoils in the lowest reaches of the river and channels.

Table 5-7 Land suitability analysis results for Mitchell catchment (ha)

CLASS	SUITABILITY	LIMITATIONS	FRESH EARTHEN	FRESH LINED	MARINE EARTHEN	MARINE LINED
1	Highly suitable	Negligible	0	2,655,141	5,877	138,456
2	Suitable	Minor	55,581	1,638,217	54,612	61,950
3	Moderately suitable	Considerable	1,867,440	316,519	155,741	34,978
4	Currently unsuitable	Severe	2,486,694	776,573	58,525	56,465
5	Unsuitable	Extreme	2,736,564	1,759,829	6,858,159	6,858,159

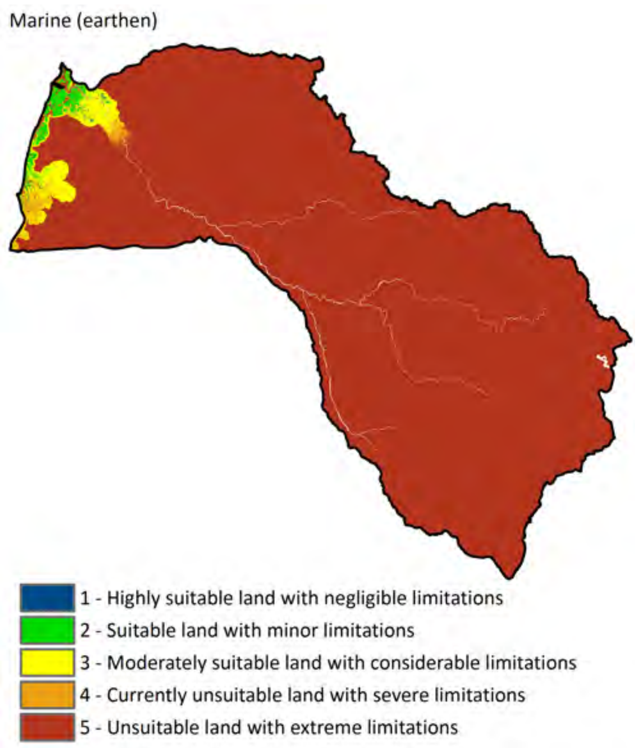

Figure 5-22 Land suitability map for marine earthen ponds in Mitchell catchment

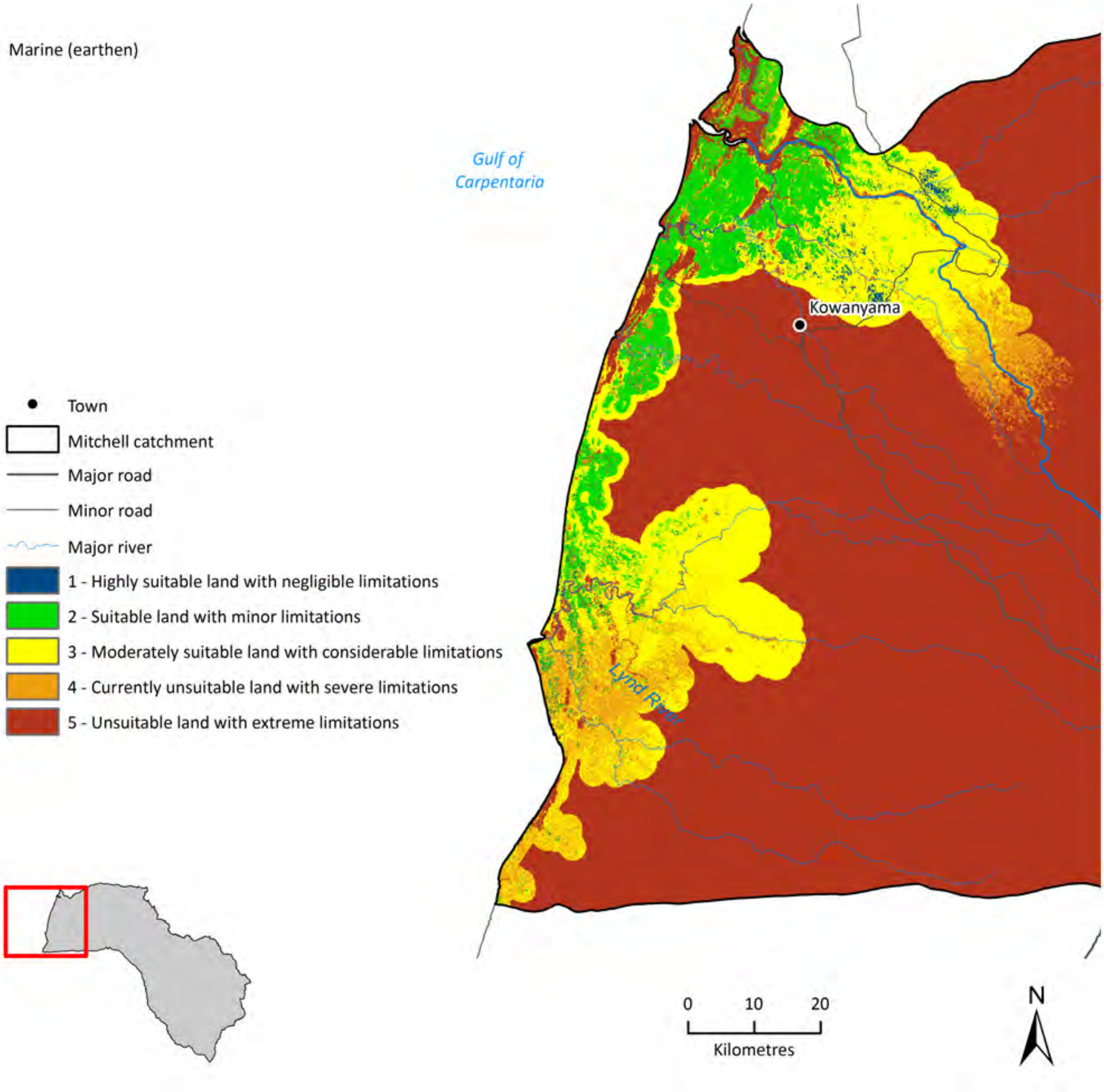

Figure 5-23 Land suitability map for marine earthen ponds in coastal area of Mitchell catchment

Marine lined ponds

Around 235,000 ha of coastal land was found to be suitable for marine lined ponds. Around 138,000 ha was suitable with negligible limitations, 61,000 ha with minor limitations and 34,000 ha with moderate limitations (Table 5-7). As shown in Figure 5-24 and Figure 5-25, these areas coincide strongest with seasonally or permanently wet soils and sand or loam over sodic clay subsoils and combined represent 3% of the catchment.

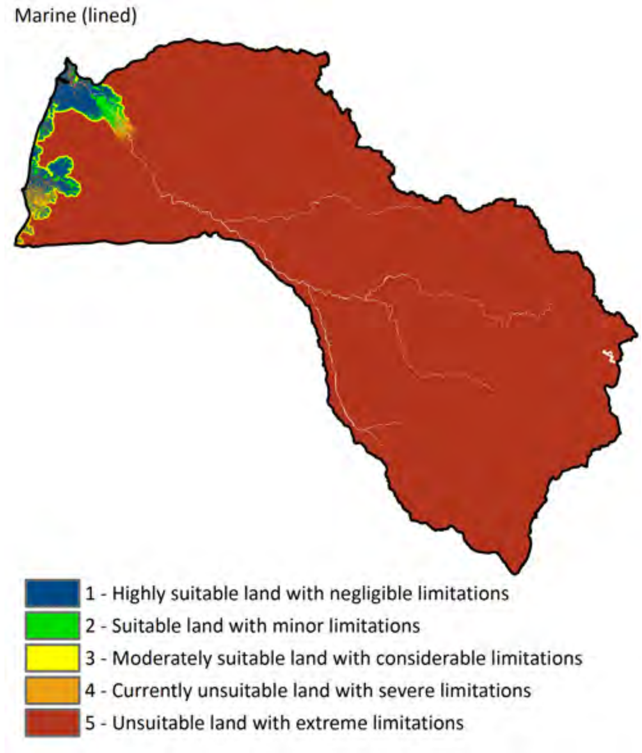

Figure 5-24 Land suitability map for marine lined ponds in Mitchell catchment

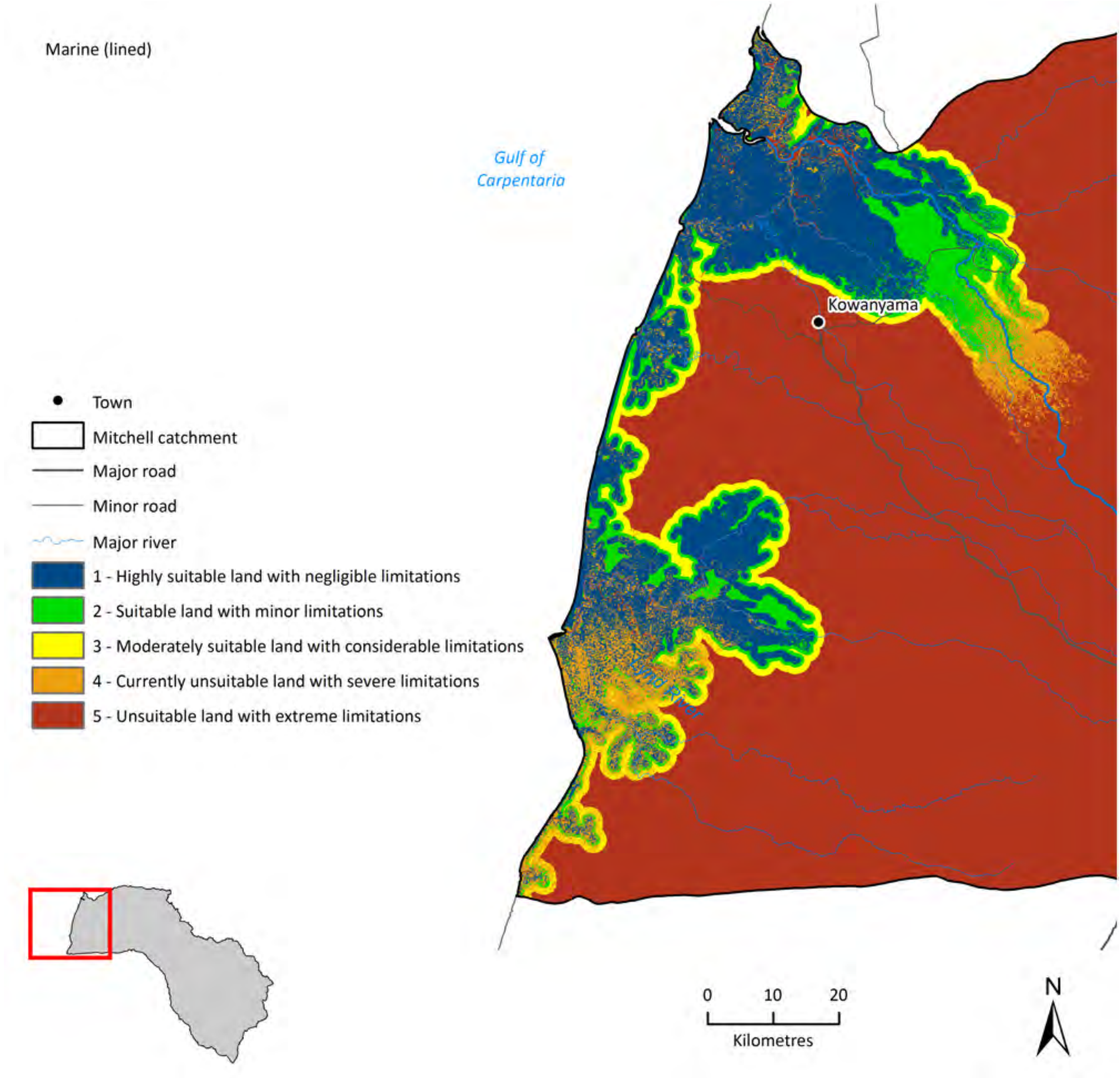

Figure 5-25 Land suitability map for marine earthen ponds in coastal area of Mitchell catchment

Freshwater earthen ponds

Around 27% (1.9 M ha) of land was found to be suitable for freshwater earthen ponds. Around 55,000 ha with minor limitations and 1.8 million ha with moderate limitations (Table 5-7). As shown in Figure 5-26, this area of suitable land is found on the northern coastal margin of the catchment where seasonally or permanently wet soils and brown, yellow and grey sandy soils dominate, as well as along the margins of the main river channels dominated by seasonally or permanently wet soils and sand or loam over sodic clay subsoils and cracking clay soils in the lowlands.

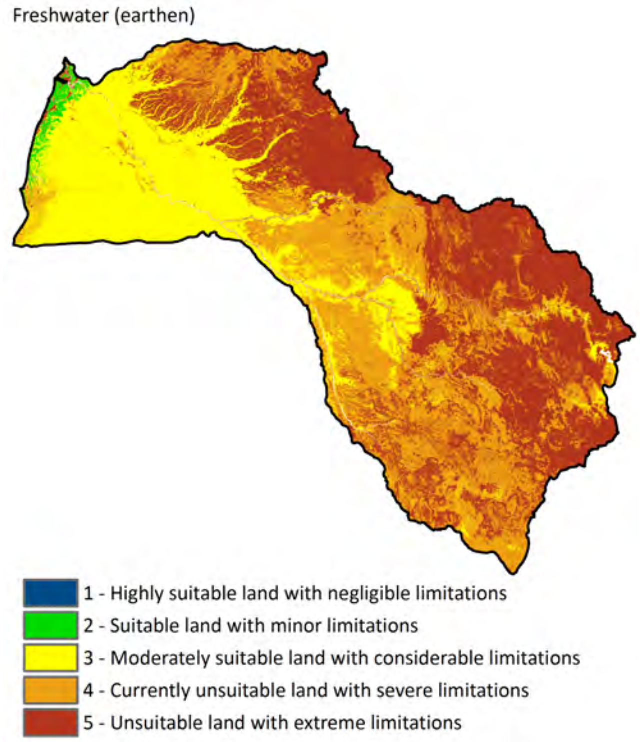

Figure 5-26 Land suitability map for freshwater earthen ponds in Mitchell catchment

Freshwater lined ponds

Around 4.6 million ha of land was found to be suitable for freshwater lined ponds. Around 2.6 million ha was suitable with negligible limitations, 1.6 million ha with minor limitations and 300,000 with moderate limitations. As shown in Figure 5-27, almost all of the lowlands are suitable (Class 1 and 2) whereas in the uplands, Class 3 dominates the suitable land classes. These areas are associated with shallow and/or rocky and friable non-cracking clay or clay loam soils.

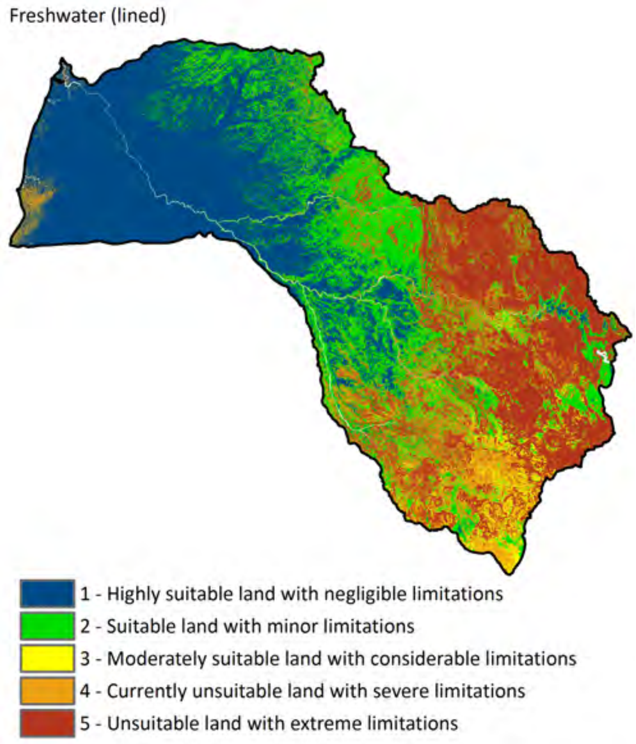

Figure 5-27 Land suitability map for freshwater lined ponds in Mitchell catchment

6 Opportunity to integrate aquaculture and agriculture industry

There has been a long history of integrated agriculture-aquaculture (IAA). IAA involves the transfer of a waste output or resource from one system to another system, resulting in greater efficiency in output (Edwards, 1998). In its simplest form the practice involves combined production of fish and crops (Prein, 2002). Today, the practice is most commonly used by small-scale freshwater aquaculture enterprises in Southeast Asia and developing countries, which benefit from the financial security of a diverse income stream. In Australia the use of IAA is not common, with an industry focus on intensive single species culture. However, there are potential opportunities in northern Australia to use IAA practices to maximise the use of nutrient-rich waste water, water storage, feed and feed ingredients and bio floc systems and feed ingredient production (such as Novacq™).

6.1 Aquaculture waste water for irrigation systems

Fresh and marine pond-based operations provide up to 15 ML per ha per year of nutrient-rich waste water for potential diversion to irrigation. In general, only waste water from freshwater aquaculture operations are suitable for irrigation of agricultural crops. The main nutrients of value in the discharge water are nitrogen and phosphorus. Aquaponics, which is the combination of aquaculture and hydroponics, is a dual crop technology that was developed in the 1970s to utilise RAS waste water to produce crops in a soil-free environment. In general, systems are compact and climate controlled and suitable for urban environments. There are some commercial aquaponics systems which integrate raceway tanks (fish) and glasshouses (crop). However, in general the technology remains the domain of hobby farmers. An international survey (Love et al., 2015) reported the average system size is around 10 t with tilapia spp. (freshwater fish) and basil (*Osmium basilicum*) the most common species under dual culture. In Australia at least one RAS barramundi farm (Tailor made fish farms, 2018) uses waste water to produce green leafy plants such as lettuce, bok choy, silver beets and herbs.

Due to the salty water used in marine aquaculture operations, the waste water is not suitable for irrigation of most plant crops. However, in recent years a technology has been developed which utilises the discharge water from prawn farms for the production of high-value seaweed (MBD, 2017). The seaweed is efficient at stripping nitrogen which enables the treated waste water to be recycled to the prawn ponds or discharged within allowable nutrient limits.

6.2 Aquaculture in water storage tanks

An integrated aquaculture-agriculture model for water use has previously been proposed for irrigated farming systems in Australia (Gooley et al., 2000). The concept involves the stocking of fish in cages in water storage dams which provide final irrigation to an agricultural crop. This is seen as an efficient use of water, as in this model the aquaculture component is a nonconsumptive user of the water, which enhances the nutrient load of the water, possibly off-setting some of the farm fertiliser costs (RIRDC, 2003). A project in Victoria involving four aquaculture demonstration sites concluded that Murray cod, trout and salmon can be produced in water storage dams, with the remaining water suitable for irrigation (Gooley, 2014). However, this farming method is yet to be taken up by the industry at any scale. Red claw is a good candidate as the crayfish readily consume raw agricultural plants and are suitable for production in irrigation storage water, on the provision that the pond or tanks are not completely emptied (Saoud et al., 2013).

6.3 Feed ingredient and feed

6.3.1 FEED INGREDIENTS

There is wide scope for the use of raw agricultural plant products in the production of red claw. Red claw farmers commonly feed raw agricultural plant meals as a nutrition supplement to a pellet feed (e.g. maize). There is also opportunity for the direct use of raw and processed agricultural feed ingredients into prawn and barramundi pond systems. This currently involves the addition of plant products (e.g molasses) into the pond to promote the development of algal blooms or addition as a carbon source in bio floc systems.

6.3.2 FEED

Aquaculture feeds for the majority of aquaculture species are a complete feed, specifically formulated for that species. In Australia, there are two major companies which produce aquaculture feeds and their locations are Brisbane and Hobart. The production of a water-stable feed, and the ability to manipulate pellet buoyancy, are key characteristics. In comparison to terrestrial stock feeds, aquaculture feeds are expensive (high protein) with specialised equipment required for production.

There are opportunities to use agricultural products (plant and animal) as ingredients in feeds for prawn and barramundi. However, this would require a specialised feed mill to be located in northern Australia to avoid the high cost of transport of raw ingredients to mills located in southern capital cities. In general, feed mills prefer to use product which is somewhat refined (e.g. dry and milled) for inclusion in the feed. However, some mills are integrated, with ownership of primary production or processing plants (e.g. poultry) which allows access to large volumes of by-products which can be rendered into high protein meals

Unlike most aquaculture species, the commercial feed for red claw can be produced in a less specialised terrestrial animal mill. Therefore, there is an opportunity for the establishment of a multi-purpose mill (aquaculture and livestock) in northern Australia, with close proximity a major benefit in term of transport costs.

6.4 Bio floc systems

The input of raw or processed plant materials are used to manage bio floc pond systems in pond-based aquaculture. The use of bio floc systems (a diverse bacterial population) in pond aquaculture is becoming increasing popular, particularly in prawn farming (Avnimelech, 2009). In prawn bio floc systems, the saleable product is the prawns, with the bio floc technology a sustainable and cost-effective water management strategy. Effective management of a bio floc system enables limited or zero water exchange, stable water conditions and the provision of a secondary nutrition source (bacteria and algae). In general terms, the technology involves close monitoring of water quality conditions and the addition of carbon to the pond to change the dynamics of the pond community from algal to bacterial. Constant aeration and supplemental carbon such as molasses from sugarcane is added throughout the production cycle to maintain a stable bio floc population.

Bio floc systems in intensive prawn farming provide a supplementary nutrition source (bacteria and algae) and have the potential to significantly reduce the quantity of feed required and the associated high transport costs of these inputs. The benefits are potentially greater for extensive prawn farming, where bio floc systems have the potential to completely negate the requirement to use commercial feeds as a nutrition source. There is potential for the industry to utilise hundreds of tonnes of agricultural plant materials to manage bio floc systems in northern Australia.

6.5 Novacq™

Novacq™ is a dry feed ingredient developed by CSIRO based on bio floc technology. Novacq™ has been shown to increase prawn growth rates by 20 to 30% when included in a standard feed. The ingredient is produced in isolation in conventional marine aquaculture ponds via the bio-conversion of low-value plant waste from agriculture. The bio-conversion process involves addition of agricultural sources such as bagasse (from sugarcane) into a marine pond containing specific concentrations of a range of nutrients. Unlike most tropical aquaculture species, Novacq™ has a broad tolerance to temperature, salinity and dissolved oxygen. In addition, the production phase of Novacq™ is not labour-intensive and short in duration (<2 months). Ridley Agri products hold the sole licence to produce and distribute Novacq™ in Australia. There is excellent potential for Novacq™ to be produced in northern Australia. In excess of 1000 t of agricultural products (e.g. sugarcane) would be required to produce sufficient Novacq™ to supply the Australian prawn farming industry.

7 Aquaculture risk assessment

As with any other agriculture sector, Aquaculture is exposed to a range of risks. In Australia, the primary considerations of any risk analysis of aquaculture include resource protection (in terms of human, animal and plant health; aquaculture farm environs; wild fisheries and the general environment); consumer preference for high quality and safe products; production profitability; legislative considerations; and other considerations relating to business investment. Any industry risk analysis needs to be done on a case-by-case and site-by-site basis, as many of the key risks are typically unique to the specifics of any proposed development.

7.1 Pesticides and insecticides

Hundreds of different chemicals, including oils, metals, pharmaceuticals, fertilisers and pesticides (e.g. insecticides, herbicides, fungicides) are used in different agricultural, horticultural and mining sectors, and in industrial and domestic settings, throughout Australia. The release of these chemical contaminants beyond the area of target application can lead to the contamination of soils, sediments and waters in nearby environments. In aquatic environments, including aquaculture environments, fertilisers have the potential to cause nonpoint source pollution. This eutrophication is caused by nutrients which trigger excessive growth of plant and algal species which then form hypoxic (low oxygen) ‘dead-zones’ and potentially elevated levels of toxic un-ionised ammonia (Kremser and Schnug, 2002). This can have a significant impact on the health and growth of animals in aquaculture operations, as well as in the broader environment. For example, health indicators are lower in barramundi collected from agriculturally impacted rivers in Queensland relative to those collected at more pristine sites. Certainly of concern to aquaculture in northern Australia are the risks posed to crustaceans (e.g. prawns and crabs) by some of the insecticides in current use. These insecticides can be classified based on their specific chemical properties and modes of action. The different classes of insecticides have broad and overlapping applications across these different settings.

The first class are organophosphate insecticides of which toxicity is not specific to target insects, raising concerns about the impacts on non-target organisms, such as crustaceans and fish (e.g. olfaction interruption in fish). Despite concerns about human health impacts and potential carcinogenic risks, organophosphates are still one of the most broadly used insecticides globally, and are still used in Australia for domestic pest control (Weston and Lydy, 2014; Zhao and Chen, 2016). These compounds are neurologically toxic and have been linked to declines in salmon returns (Laetz et al., 2009). Pyrethroid insecticides have low toxicity to birds and mammals, but higher toxicity to fish and arthropods. Phenylpyrazole insecticides are another class which also pose risks to non-target crustaceans (Stevens et al., 2011). Pyrethroid and Phenylpyrazole insecticides have previously been associated with aquatic toxicity around the world. Neonicotinid insecticides are a class being used in increasing amounts because they are very effective at eliminating insect pests, yet pose low risks to mammals and fish (Sánchez-Bayo and Hyne, 2014). Monitoring data from the Great Barrier Reef (GBR) catchments indicate that concentration of neonicotinid insecticides in marine water samples is rapidly increasing with widespread use. One significant concern for aquaculture is the risk that different insecticides, when exposed to non-target organisms, may interact to cause additive or greater than additive toxicity.

Existing monitoring data shows that pesticide concentrations are elevated in agricultural catchments. For instance, imidacloprid levels are high in streams adjacent to turf farms (Sánchez-Bayo and Hyne, 2014), and elevated diruon, atrazine and imdacloprid levels have been measured in GBR catchments with sugarcane, bananas, and other agricultural land uses (Devlin et al., 2015). Pesticide use is commonly higher in the tropics for a variety of environmental factors (Lewis et al., 2016), and dissipation rates are also typically faster in the tropics than in temperate environments (Lewis et al., 2016). Certainly there is potential for some pesticides to leach into the aquatic environment, and it is expected that leaching into aquatic systems is common after application following rainfall events and after irrigation. Some insecticides are stable in marine environments, and have low but consistent contamination. Water-soluble insecticides are typically transported in the waters, while less water-soluble pesticides are more persistent in sediments. How and where insecticides are sprayed has been shown to have a major impact on how well they are retained in their target areas.

Importantly, our knowledge of the toxicity of the different classes of pesticides, and risks of exposure in different farming regions of northern Australia, is only developing. An awareness and knowledge of the potential exposures, risks, and impacts that chemical contaminants may pose in a location is valuable when establishing and operating a commercial aquaculture enterprise, to ensure exposures are best mitigated. For the most vulnerable life cycle stages of production, such as the larval stages of rearing within the controlled hatchery environment, water treatment systems can be employed to mitigate risks of exposure to contaminants. However, for the broadacre pond systems, the best approach is to understand the risks of exposure in an area, and ideally to establish farms in areas of lower exposure.

7.2 Disease and biosecurity

As with all agricultural industries, there are a range of pathogens that pose risks to and may impact aquaculture. Fortunately, Australia is free of many of the aquatic pathogens that impact other aquaculture farming regions of the world. However, the impacts of endemic diseases, and the risks posed by the introduction of exotic diseases, require the Australian aquaculture industry to be ever-vigilant in monitoring for pathogens; to manage operations so as to ensure a healthy culture environment; and to strive for continual improvement in biosecurity systems to reduce risks, and mitigate the impacts, of disease.

The following section will discuss disease and biosecurity issues relating to the two main tropical farmed species, prawns and barramundi. However, there are significant, and often different, experiences and issues posed by pathogens and disease for all Australian aquaculture industries.

7.2.1 PATHOGENS

For prawns, the disease agents which have most impacted farming have been viruses. There are a very large number of different viruses that can infect prawns, which vary significantly in their ability to cause disease and impact production, and on the life stages they most impact. Fortunately, most of the highly pathogenic viruses are exotic to Australia. However, the recent discovery of the highly pathogenic White Spot Syndrome Virus (WSSV) in south-east Queensland farms has led to investigations to determine whether WSSV is in fact endemic, or the result of an aberrant localised introduction (QDAF, 2017). Several endemic viruses can also impact Australian prawn production, particularly when detrimental pond conditions, such as poor water quality, inflict environmental stress on the prawns and trigger disease episodes (QDPIF, 2006). Bacteria pathogens can also impact production, but are also often believed secondary to other stressors (QDPIF, 2006) . Recently, syndromes caused by toxicity associated with bacteria have had significant impacts on prawn production both in Australia (*Penaeus monodon* mortality syndrome (QDAF, 2016)) and even more so overseas (Acute Hepatopancreatic Necrosis Disease; (NACA, 2016)). Fungi and a range of other microbial and parasitic agents can also cause disease at various life stages and impact appearance of harvested prawn products, but have rarely impacted Australian farming in recent decades due to better health and pond management practices.

For barramundi, a range of viral, bacterial, fungal and parasitic pathogens can also impact hatcheries and grow-out. The predominant viral pathogens of concern for barramundi farming in Australia are the nodaviruses, which can cause major mortalities in larval and juvenile barramundi. Bacterial diseases, such as streptococcosis can also cause high mortalities in both fresh and marine farming systems. Vibriosis and other bacterial pathogens which infect the gut (causing 'bloat') and the gills also impact production in fresh and marine waters, but are typically secondary to other environmental and dietary stresses. Fungal disease-causing ulceration also periodically impact production in the freshwater and estuarine phases, and typically cause fish to become lethargic and prone to cannibalism. Parasitic protozoans residing in the skin and gills can increase in numbers at times and cause disease, and a blood protozoan has also been associated with major mortalities in sea caged barramundi. In addition to these non-infectious diseases, particular deformities can impact production and these are typically due to nutritional inadequacies in the diets provided.

7.2.2 DISEASE MANAGEMENT

Treatment actions once disease presents typically provide few options, particularly for viral pathogens, and are also costly to implement and rarely as effective as prevention. Consequently, for aquaculture, the most important component of disease management is prevention. Important components of prevention are hygiene and biosecurity in the earliest hatchery stages of production, as well as decontamination processes between crops to ensure the environment is clean before the next crop is commenced. Another very important aspect of disease management is to maintain a quality rearing environment, as both the introduction of pathogens, and more importantly the increase of pathogens in the environment and their manifestation to a disease episode, is typically triggered by increased stress on the animals caused by a poor rearing environment.

Due to the rudimentary immune system of crustaceans, there is limited ability to manage the most serious diseases once established, and so pathogen management has typically focused on exclusion through pathogen screening of broodstock, and postlarvae prior to stocking ponds. Some treatments for external bacterial and fungal pathogens are employed, particularly for broodstock and eggs and larvae within the hatchery (FAO, 2007). During the rearing of larvae, control of bacterial pathogens is typically focused on maintaining a good environment and through pre- and probiotics, with antibiotics used only in exceptional circumstances.

There are practical treatments that can be employed for bacterial, fungal and certain parasitic diseases experienced in barramundi culture, typically via oral or injected antibiotics for bacterial disease, and using altered salinity bathing for fungal and external protozoan pathogens. Access to antibiotics requires veterinary permission, and is becoming less common due both to overuse concerns, but also due to the limited effectiveness in treatment, as sick fish tend are not amenable to typical oral treatment. Chemical agents are used sparingly as a last resort and require strict control measures. The best solution for prevention and treatment is to improve water quality, reduce any stressors on the animals and reduce stocking densities where possible. But as for prawns, no current and practical means for treating viral diseases in the commercial culture environment currently exist.

7.2.3 BIOSECURITY

Biosecurity is the system of procedures or measures implemented to mitigate risk of pathogen introduction and spread, and disease. An important component of biosecurity in aquaculture is mitigating pathogen introduction. The provision of quality diets and environments also has a major role to play in mitigating disease.

The introduction of pathogens into a farming system comes from two main routes, the first being vertical transmission from parent to progeny, and the second being horizontal transmission from an infected environment, equipment, worker, or animal coming into contact with an uninfected animal during the rearing process. Horizontal transmission can occur through many vectors which harbour the pathogen, such as the rearing water, other animals, dead tissues that are consumed, or animal faeces which are consumed or touched. Understanding the primary mode of transmission for each pathogen is critical to understanding how to mitigate disease risks. Applying preventative biosecurity measures which mitigate risks of all routes of transmission for all likely problematic pathogens is a major key to managing disease. Importantly, the existence of pathogens in the farming system does not necessarily equate to disease, and so disease management in aquaculture needs to both exclude those pathogens you can and must, and manage those pathogens you cannot exclude and can live with.

A comprehensive knowledge of pathogen agents is essential for developing and implementing risk-based biosecurity measures to mitigate against disease impacts in aquaculture. Understanding of the diseases and disease agents that are likely present in various jurisdictions, or through the process of acquiring animal stocks, and which may impact adversely, is also important in developing a biosecurity plan. Government departments, such as the Department of Agriculture and Fisheries (DAF) in Queensland, have important roles in the ongoing surveillance of pathogens, in controlling translocation of stocks based on pathogen risks, and in undertaking investigations where potential disease episodes have been identified (Department of Agriculture and Queensland, 2013). Due to increasing awareness of pathogen risks and the need for biosecurity, and the increasing professionalism of farming operations, it is becoming more common for individual farms to undertake their own pathogen monitoring to minimise the disease risks to their operations. The key elements to effective biosecurity and disease management at the farm level are to access clean and healthy stocks; to provide a clean and healthy rearing environment (e.g.

good quality water); to provide an adequate quality and quantity of diet; and to control access to water, equipment and people that may introduce pathogens into the farming system.

7.2.4 RISK TO OTHER AQUACULTURE ENTERPRISES

A major risk posed by the development of new marine aquaculture enterprises to established aquaculture enterprises is associated with sharing of a water source (usually a river). The risk of contamination between enterprises is highest, when there is limited distance (<2 km) between the location of one farms discharge point and another farms supply point.

7.2.5 RISK TO WILD POPULATIONS

There is potential for disease transfer between aquaculture species (e.g. prawns and barramundi) and their respective wild populations. The main transfer routes are discharge waters containing disease or from infected animals (escapees) in discharge water or transferred by predatory vectors (e.g. seabirds). The potential impact of disease on wild populations will depend on pathogen volume, ability of pathogen to survive without a host, proximity of a significant susceptible host population and the health and tolerance of the host to the disease. In general, susceptible animals in the wild occur only in low density populations adjacent to land based aquaculture operations.

The effect that exotic or endemic disease outbreaks from aquaculture have on wild stocks is difficult to evaluate. In Australia, impacts of disease transferred from aquaculture to wild populations have not been widely reported and are difficult to detect. In overseas countries where WSSV is endemic there is little evidence that the disease has any effect on wild prawn populations. In Australia, the response to a suspected outbreak of exotic disease (e.g. WSSV) involves the farm notifying the relevant authorities, isolation of affected ponds and preventing water flow from the ponds to the surrounding environment. The authority (e.g. Biosecurity QLD) provides advice, which depending on the diagnosis may include destruction and disposal of stock and decontamination of site. In the case of the recent WSSV discovery in south-east Queensland, a surveillance program commenced (post decontamination) which requires 24 months of no detection of infection in the wild before farming can recommence (DAF, 2018). Since the introduction of the surveillance program in QLD only very small numbers of infected wild crustaceans have been detected, the vast majority sampled in the vicinity of the original discovery.

The discovery of exotic disease may have a larger impact on the fisher than the wild fishery. For example, in the case of WSSV in QLD, local commercial and recreation prawn fishers have been impacted by constraints imposed on the movement of uncooked prawns within a restriction zone which stretches from Caloundra to the NSW border (DAF, 2018). If an exotic disease (e.g. WSSV) was to be identified in aquaculture enterprises located in the Fitzroy catchment, commercial fishers operating in waters adjacent to the catchment would likely face similar restrictions in the movement of prawns.

Part III Economics

8 Economics of aquaculture enterprise

8.1 Introduction

This chapter provides a brief, generic analysis of what would be required for new aquaculture developments in the Fitzroy, Darwin and Mitchell catchments to be financially viable. First indicative costs are provided for a range of four possible aquaculture enterprises that differ in species farmed, scale and intensity of production. The cost structure of the enterprises was based on established tools provided by the Queensland Government for aquaculture enterprises to assess the finances of their existing or proposed businesses (https://publications.qld.gov.au/dataset/agbiz-tools-fisheries-aquaculture). Based on the ranges of these indicative capital and operating costs, gross revenue targets are then calculated that a business would need to attain to be commercially viable.

8.2 Enterprise-level costs for aquaculture development

Costs of establishing and running a new aquaculture business are divided here into the initial capital costs of development and ongoing operating costs. The four options were chosen to portray some of the variation in cost structures between potential development options, not as a like-for-like comparison between different types of aquaculture (Table 8-1).

Capital costs include all land development costs, construction, and plant and equipment, accounted for in the year production commences. The types of capital development costs are largely similar across the aquaculture options with costs of constructing ponds and buildings dominating the total initial capital investment. Indicative costs were derived from Guy et al. (2014), and consultation with experts familiar with the different types of aquaculture, including updating to 2017 dollar values (Table 8-1).

Operating costs cover both overheads, which do not change with output, and variable costs that increase as the yield of produce increases. Fixed overhead costs in aquaculture are a relatively small component of the total costs of production. Overheads consist of costs relating to licensing, approvals, and other administration (Table 8-1).

The remaining operating costs are variable (Table 8-1). Feed, labour and electricity typically dominate the variable costs. Aquaculture requires large volumes of feed inputs, and the efficiency with which this feed is converted to marketed produce is a key metric of business performance. Labour costs consist of salaries of permanent staff and casual staff who are employed to cover intensive harvesting and processing activities. Aerators require large amounts of energy, increasing as the biomass of produce in the ponds increase, which accounts for the large costs of electricity. Transport, although a smaller proportional cost, is important because this puts remote locations at a relative disadvantage to aquaculture businesses that are closer to feed suppliers and markets. In addition, transport costs may be higher at times if roads are cut (requiring much more expensive air freight or alternate, longer road routes) or if the closest markets become saturated. Packing is the smallest component of variable costs in the breakdown categories used here.

Revenue for aquaculture produce typically ranges between $10 and $20 per kg (on a harvested mass basis), but prices vary depending on the quality and size classes of harvested animals and how they are processed (e.g., live, fresh, frozen, or filleted) and farms are likely to deliver a mix of products targeted to what their particular markets demand. Note that the mass of sold product may be substantially lower than the harvested product (e.g., fish fillets are about half the mass of harvested fish), so prices of sold product may not be directly comparable to the costs of production below (which are on a harvest mass basis) (Table 8-1).

Table 8-1 Indicative capital and operating costs for a range of generic aquaculture development options
Costs are provided both per ha of growout pond and per kg of harvested produce, although capital costs scale mostly with the area developed and operating costs scale mainly with yield at harvest. Capital costs have been converted to an equivalent annualised cost assuming a 7% discount rate and that a quarter of the developed infrastructure was 15-year lifespan assets and the remainder had a 40-year lifespan. Indicative breakdowns of cost components are provided on a proportional basis.

PARAMETER	UNITS	PRAWN (EXTENSIVE)	PRAWN (INTENSIVE)	BARRAMUNDI	RED CLAW (SMALL SCALE)
Scale of development					
Growout pond area	ha	20	100	30	4
Total farm area	ha	25	150	100	10
Yield at harvest	t/y	30	800	600	32
Yield at harvest per pond area	t/ha/y	2	8	20	3
Capital costs of development (scale with area of growout ponds developed)					
Land and buildings	%	56%	26%	23%	30%
Vehicles	%	5%	2%	2%	11%
Pond-related assets	%	27%	67%	70%	41%
Other infrastructure and equipment	%	11%	6%	5%	17%
Total capital cost (year 0)	$/ha	$60,000	$115,000	$120,000	$135,000
Equivalent annualised cost	$/kg	3.35	1.20	0.50	1.41
	$/ha/y	5,022	9,626	10,045	11,300
Operating costs (vary with yield at harvest, except overheads)					
Nursery/juvenile costs	%	12%	9%	7%	1%
Feed costs	%	0%	26%	30%	8%
Labour costs	%	47%	13%	12%	57%
Electricity costs	%	16%	24%	30%	9%
Packing costs	%	2%	4%	3%	2%
Transport costs	%	6%	16%	16%	11%
Overhead costs (fixed)	%	17%	8%	1%	12%
Total annual operating costs	$/kg	15.73	10.16	10.13	14.50
	$/ha/y	23,595	81,280	202,600	116,000
Total costs of production					
Total annual cost	$/kg	19.08	11.36	10.63	18.27
	$/ha/y	28,617	90,906	212,645	54,800

Commercial viability of new aquaculture developments

Capital and operating costs differ between different types of aquaculture enterprises (Table 8-1), but these costs may differ even more between location (depending case-specific factors such as remoteness, soil properties, distance to water source, and type of power supply). Furthermore, there can be considerable uncertainty in some costs, and prices paid for produce can fluctuate substantially over time.

Table 8-2 Gross revenue targets required to achieve target internal rates of return for aquaculture developments with different combinations of capital costs and operating costs

All values are expressed per hectare of grow-out ponds in the development. Gross revenue is the yield per ha of pond multiplied by the price received for produce (averaged across products and on a harvest mass basis). Capital costs were converted to an equivalent annualised cost assuming a quarter of the developed infrastructure was 15-year lifespan assets and the remainder had a 40-year lifespan. Targets would be higher after taking into account risks such as initial learning and market fluctuations.

OPERATING ($/ha/y)	GROSS REVENUE REQUIRED TO BREAK EVEN ($/HA/Y)								
	Capital costs of development ($/ha)								
	60,000	70,000	80,000	90,000	100,000	110,000	125,000	150,000	175,000
3% target IRR									
20,000	23,203	23,737	24,271	24,805	25,339	25,873	26,674	28,008	29,343
50,000	53,203	53,737	54,271	54,805	55,339	55,873	56,674	58,008	59,343
100,000	103,203	103,737	104,271	104,805	105,339	105,873	106,674	108,008	109,343
150,000	153,203	153,737	154,271	154,805	155,339	155,873	156,674	158,008	159,343
200,000	203,203	203,737	204,271	204,805	205,339	205,873	206,674	208,008	209,343
250,000	253,203	253,737	254,271	254,805	255,339	255,873	256,674	258,008	259,343
7% target IRR									
20,000	25,022	25,859	26,696	27,533	28,371	29,208	30,463	32,556	34,648
50,000	55,022	55,859	56,696	57,533	58,371	59,208	60,463	62,556	64,648
100,000	105,022	105,859	106,696	107,533	108,371	109,208	110,463	112,556	114,648
150,000	155,022	155,859	156,696	157,533	158,371	159,208	160,463	162,556	164,648
200,000	205,022	205,859	206,696	207,533	208,371	209,208	210,463	212,556	214,648
250,000	255,022	255,859	256,696	257,533	258,371	259,208	260,463	262,556	264,648
10% target IRR									
20,000	26,574	27,669	28,765	29,861	30,956	32,052	33,695	36,434	39,174
50,000	56,574	57,669	58,765	59,861	60,956	62,052	63,695	66,434	69,174
100,000	106,574	107,669	108,765	109,861	110,956	112,052	113,695	116,434	119,174
150,000	156,574	157,669	158,765	159,861	160,956	162,052	163,695	166,434	169,174
200,000	206,574	207,669	208,765	209,861	210,956	212,052	213,695	216,434	219,174
250,000	256,574	257,669	258,765	259,861	260,956	262,052	263,695	266,434	269,174

Given this variation and uncertainty, a generic approach was taken to determine what would be required for new aquaculture enterprises to become commercially viable. The approach used here was to calculate the gross revenue that an enterprise would have to generate each year to achieve a target internal rate of return (IRR) for given operating costs and development costs (both expressed per hectare of grow-out ponds). Capital costs were converted to annualised equivalents on the assumption that developed assets equated to a mix of 25% 15-year assets and 75% assets with a 40-year lifespan (using a discount rate matching the target IRR). The target gross revenue is the sum of the annual operating costs and the equivalent annualised cost of the infrastructure development (Table 8-2).

In order for an enterprise to be commercially viable, the volume of produce grown each year multiplied by the sales price of that produce would need to match or exceed the target values provided above. For example, a proposed development with capital costs of $125,000/ha and operating costs of $200,000/ha/yr would need to generate gross revenue of $210,463/ha/yr to achieve a target IRR of 7% (Table 8-2). If the enterprise received $11/kg for produce (averaged across product types, on a harvest mass basis), then it would need to sustain average long-term yields of 19t/ha (= $210,463/ha/yr ÷ $11/kg × 1t/1000kg) from the first harvest. However if prices were $19/kg, average long-term yields would require 11t/ha (= $210,463/ha/yr ÷ $19/kg × 1t/1000kg) for the same $125,000 capital costs per hectare, or only 8t/ha prices if the capital costs were lowered to $100,000 per hectare. Target revenue would be higher after taking into account risks, such as learning and adapting to the particular challenges of a new location and periodic setbacks that could arise from disease, climate variability, changes in market conditions, or new legislation. (For an analysis of how various types of risk affect the financial viability of new developments, see the companion technical report on socio-economics (Stokes et al., 2017)).

Key messages

From this chapter, a number of key points are apparent about achieving commercial viability in new aquaculture enterprises:

- Operating costs are high and the amount spent each year on inputs can exceed the up front (year 0) cost of development (and the value of the farm assets). This means that the cost of development is a much smaller consideration for achieving profitability than ongoing operations and costs of inputs.
- High operating costs also mean that substantial capital reserves are required, beyond the capital costs of development, as there will be large cash outflows on inputs in the start-up years before revenue from harvested product starts to be generated. This is particularly the case for larger size classes of product that require multi-year grow-out periods before harvest. Managing cash flows would therefore be an important consideration at establishment and as yields are subsequently scaled up.
- Variable costs dominate the total costs of aquaculture production so most costs will increase as yield increases. This means that increases in production, by itself, would contribute little to achieving profitability in a new enterprise. What is much more important is increasing production efficiency, such a feed conversion rate or labour-efficient operations, so that inputs per unit of produce are reduced (and profit margins per kg are increased).

- Small changes in quantities and prices of inputs and produce would have a relatively large impact on net profit margins. These values could differ substantially between different locations (e.g., remoteness, available markets, soils and climate), and depending on the experience of managers. Even small differences from the indicative values provided above could render an enterprise unprofitable.
- Enterprise viability would therefore be very dependent on the specifics of each particular case and how the learning, scaling up, and cash flow were managed during the initial establishment years of the enterprise.

Part IV Discussion and summary

9 Discussion and Summary

This report broadly reviews current aquaculture production and practices in Australia, with emphasis on species and land-based aquaculture systems appropriate for northern Australia. The available land area suitable for land based aquaculture enterprises in the three study areas were assessed using LSM based on key water and land suitability criteria. Key risks for developing aquaculture enterprises in northern Australia and the potential for integration of aquaculture with other agricultural activities are discussed. And finally, an economic framework which can be used to assess the financial viability of aquaculture enterprises is provided.

Aquaculture is growing rapidly, both overseas and in Australia, with the sector now surpassing fisheries as the main contributor to edible seafood production globally (FAO, 2016). Although Australia remains a very small contributor to global aquaculture, Australian production has significantly and consistently increased over the past 20 years to a value of AUD$1.2 billion in 2014-2015 (Skirtun et al., 2013). Much of the increase in Australian aquaculture production has been confined to temperate species aquaculture, most notably the Atlantic salmon industry in Tasmania. Comparatively, industry development in northern Australia has been much slower. However, despite several challenges which have slowed industry development, northern Australia has many characteristics which suggest a significant opportunity for the expansion of aquaculture due to amenable environmental conditions, potentially available land, and proximity to the large Asian market.

The two obvious candidate species for aquaculture in northern Australia are the black tiger prawn *(Penaeus monodon)* and the barramundi (*Lates calcarifer*). Both species are suited to many marine and brackish water environments of northern Australia, have established land-based culture practices and well established markets for harvested products. Prawns could potentially be cultured in either extensive (low density, low input) or intensive (higher density, higher inputs) pond-based systems in northern Australia, whereas land-based culture of barramundi would likely be intensive. The red claw crayfish is another potential candidate freshwater species, currently cultured by a much smaller industry than the previous two species.

One potential advantage of northern Australia for land-based aquaculture is the availability of suitable land supplied with quality marine and freshwater resources. The availability of relatively inexpensive land in many areas of northern Australia, and the warmer water temperatures of coastal marine waters of the tropics, provides the potential for marine aquaculture based on less capital-intensive and labour-intensive pond-based systems, rather than RAS based enterprises which require higher capital investment and labour costs. While the remoteness of many areas of northern Australia from population centres and critical infrastructure does pose some challenges for industry development, there are also potential advantages in terms of the availability of quality water resources for pond-based aquaculture.

A broad-scale assessment of the volumes of water used during the culture of the three candidate species in ponds under typical farming scenarios was provided as context for the overall water requirements of aquaculture. An average crop of prawns farmed in intensive pond systems (8 t/ha over 150 days) is estimated to require 127 ML of marine waters, which equates to 15.9 ML of marine water for each tonne of harvested product. For pond culture of barramundi (30 t/ha over two years), 562 ML of marine water, or freshwater, is required per crop, equating to 18.7 ML of water for each tonne of harvested fish. For extensive red claw culture (3 t/ha over 300 days) 240 ML of freshwater is required per pond crop, equating to 16 ML of water for each harvested tonne of crayfish.

LSM was undertaken for the Fitzroy, Darwin and Mitchell catchments based on key water suitability and land suitability criteria. Water suitability criteria were focused on pond water temperature and salinity suitability, which considered tolerances of candidate tropical species, but also for salinity, the seasonal impacts of precipitation and evaporation. Land suitability criteria captured the key criteria of distance to marine water source, elevation, and slope, as applied in the former broad-scale GIS mapping of northern Australia to assess marine aquaculture potential (Mcleod et al., 2002). The land suitability assessment also included criteria of soil permeability, pH and depth, whether land contained acid sulfate soils, and aspects of soil/land type that influence construction ease and cost. The assessment involved the four combinations of two candidate aquaculture production systems (marine or freshwater) and two pond types (earthen or plastic-lined). Outcomes of assessments were rated using a 5-Class land suitability ranking (FAO, 1976; 1985), which applied a suitability term (ranging from suitable → currently unsuitable → unsuitable) and a limitations term (ranging from negligible → minor → moderate → severe → extreme). For each of the four candidate system and pond type combinations assessed, the quantum of land within each class was reported and illustrated using LSM.

LSM found over 511,000 ha of coastal land was suitable (i.e. Class 1, 2 or 3) for marine aquaculture using earthen ponds across the three study areas, with the Darwin (260,000 ha) and Mitchell catchments (216,000 ha) in particular having considerable land area for marine aquaculture, based on the LSM criteria employed. Of this area, 9500 ha was identified as Class 1 (suitable, negligible limitations) across the three study areas, with the largest area in the Mitchell catchment (5800 ha). For lined ponds, 710,000 ha of coastal land was identified as suitable across all study areas, again with the most area found in the Darwin (420,000 ha) and Mitchell catchments (235,000 ha). Large areas in both the Darwin (86,000 ha) and Mitchell catchments (138,000 ha) were identified as Class 1 for marine aquaculture using earthen ponds.

LSM found considerable land on the coast and further inland was suitable (i.e. Class 1, 2 or 3) for freshwater aquaculture. For earthen ponds, 3,230,000 ha of land was found suitable across the three catchments based on the criteria employed. The largest quantity of suitable land was found in the Mitchell catchment (1,900,000 ha), but large areas were also identified in the Fitzroy (660,000 ha) and Darwin (670,000 ha) catchments. For lined ponds, 13,000,000 ha of land was identified as suitable for freshwater aquaculture, with large areas identified in all catchments. Large areas were identified as Class 1 across all three study areas (6800,000 ha).

To give a sense of scale of the potential land identified in the LSM for marine aquaculture using earthen ponds, if only 10% of the 9,500 ha of suitable Class 1 land across the three study areas was used for prawn farming, this would provide a culture area roughly equivalent to the entire current Australian prawn farming industry (about 900 ha). If areas of Class 2 land were also considered, as little as 0.7% of the 136,500 ha of Class 1 and 2 land would equate to the current Australian prawn farming footprint. And if considering marine faming using lined ponds, only 0.4% of the identified Class 1 land would equate to the current prawn industry footprint.

For freshwater culture, the land available across the Assessment area - particularly the Mitchell catchment which possesses the most suitable land area - dwarfs the land currently used in northern Australia for freshwater aquaculture. Again, to give an idea of the scale, less than 0.5% of available Class 1 land from each study area would equate to the current footprint of the Queensland red claw industry.

On the basis that 10% of the Class 1 land identified in the Darwin and Mitchell catchments as suitable for marine culture in earthen ponds (900 ha) was used for intensive farming of prawns, and based on an average yearly production of 8 t/ha, such an extension of the Australian prawn farming industry would see more than a doubling of current industry production (from 5000 tonnes to 12,000 tonnes). A 7000 tonne increase in annual prawn farming production would require 111 GL of marine waters, based on the estimates of water requirements noted above. If freshwater was used to manage salinities, based on an average rate of 0.1 ML per (1 ha) pond per day, a total of 13 GL of freshwater would be required to meet this enhanced production. On the basis that 40% of the Class 1 land identified across all three study areas for freshwater culture in earthen ponds was used for farming of red claw, and based on an average yearly production of 2 t/ha, such a development would see this industry producing a quantum of product equivalent to that projected for the expanded prawn farming industry above (13,600 tonnes). Assuming that virtually all this farming was from new initiatives in northern Australia, a 13,000 t increase in annual red claw production would require 208 GL of freshwater, if using estimates of water requirements noted above based on 3 t/ha values.

There are opportunities for integrating aquaculture with other agricultural industries in northern Australia. These include the opportunity to use raw agricultural plant products directly as a feed source in the culture of red claw, and potentially also prawns and barramundi. There is potential for processed agricultural products to be used as feed ingredients in formulated pelletised diets for prawns and barramundi. However, this opportunity would depend largely on whether there is a feed mill located in northern Australia. There is also the opportunity to use large quantities of agricultural plant for managing 'bio floc' aquaculture systems in northern Australia. Moreover, there is considerable potential for 'Novacq™' to be produced in northern Australia using available plant materials as the primary carbon source required for production.

As for any agricultural enterprise, there are many potential risks present which need to be considered when developing an aquaculture enterprise, some of which are more generalised and others very site-specific. Beyond the risks present for all aquaculture enterprises, such as the increasing demands on fishery resources used in fish meals and disease, there are some particular risks for aquaculture development in northern Australia. The presence of chemicals in waters or sediments which impact pond productivity or saleability of harvested aquaculture products poses potential risk in some areas, particularly in regions more proximal to urban and major agricultural industries which use pesticides that may impact the health of aquaculture organisms and may transfer into the aquatic environment. Pathogens introduced into the pond systems either through incoming waters, via seedstock, or through other vectors also pose risks and necessitate effective biosecurity and sound pond management to mitigate disease risks. Knowledge of risks posed to pond culture by both chemical toxicants and pathogens, and means for mitigating risks of both, are critical when selecting sites and developing operational protocols for any proposed aquaculture enterprise. Other risks that also need to be considered include regulatory and legal issues, product suitability to the consumer, and factors influencing business profitability.

A framework for assessing the financial viability of aquaculture enterprises in northern Australia was developed based on indicative costs for a range of aquaculture enterprises that differ in species farmed, scale and intensity of production. Operating costs are high, and annual expenditure on inputs can exceed the initial cost of development. Variable costs dominate the total costs of aquaculture production, and even small changes in quantities and prices of inputs and produce can have a relatively large impact on net profit margins. These values could differ substantially between different locations and experience of operator, and even small differences from the indicative costs or prices provided could significantly impact profitability.

Based on the natural advantages that northern Australia possesses in terms of political stability, proximity to large global markets, and a climate suited to farming of valuable tropical species, and through the large areas identified as suitable for aquaculture in the three study areas assessed using LSM in the present report, there appears considerable opportunity for aquaculture development in northern Australia. While challenges to the development and operation of aquaculture enterprises do present in terms of regulatory barriers, global cost competitiveness, and other challenges that the current remoteness of much of the available land areas may present, the potential to exploit the natural advantages of northern Australia and develop modern and sustainable aquaculture industries appears a compelling opportunity.

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Part V Appendices

Appendix A Limitation table

A.1 Constraints and rules used to determine land suitability for marine and earthen ponds

Apx Table A-1 Constraints and rules used to determine land suitability for marine and earthen ponds

CONSTRAINT	RULE	MARINE EARTHEN	MARINE LINED	FRESHWATER EARTHEN	FRESHWATER LINED
Distance to marine water	<500 m	1	1		
	500 – 1000 m	2	2		
	1000 – 2000 m	3	3		
	>2000 m	5	5		
Elevation	0 – 5 m	3	3		
	5 – 15 m	1	1		
	15 – 20 m	2	2		
	20 – 25 m	4	4		
	>25 m	5	5		
Slope % (STRM)	Slope <2%	1	1	1	1
	2% <slope <4%	2	2	2	2
	4% <slope <5%	3	3	3	3
	5% <slope	5	5	5	5
Clay (%) to 2 m depth	>30%	1	1	1	1
	20 - 30%	2	1	2	1
	10 - 20%	4	2	4	2
	<10%	4	3	4	3
pH average to 1 m depth	6.0 – 7.0			2	1
	7.0 – 8.8			1	1
	>8.8			3	1
	<6.0			3	1
Acid sulfate soils (STRM)	High probability occurrence	3	3	3	3
	Low probability occurrence	2	1	2	1
	No known occurrence	1	1	1	1
Soil depth	<0.5	5	5	5	5
	0.5 – 1	3	3	3	3
	1.0 – 1.5	2	2	2	2
	>1.5	1	1	1	1
Permeability	Very slowly	1		1	
	Slowly	3		3	
	Moderately	4		4	
	Rapidly	5		5	

CONSTRAINT	RULE	MARINE EARTHEN	MARINE LINED	FRESHWATER EARTHEN	FRESHWATER LINED
Rockiness	Not rocky or significantly rocky	1	1	1	1
	Rocky	4	4	4	4
Microrelief (Gilgai)	No gilgai or significant gilgai	1	1	1	1
	Gilgai significantly present	2	2	2	2

Glossary

Acid sulfate soils: Anaerobic soils containing iron sulphide minerals. Form sulphuric acid and release toxic compounds including heavy metals when exposed to air. Common in many areas of the northern Australian coastline.

Alkalinity: The ability of a water volume to chemically neutralise or buffer acids.

Ammonia: The primary nitrogenous waste product in aquaculture systems.

Anchovetta: Small, oily saltwater fish used to produce fish meal and oil in aquaculture feeds.

Anaerobic: Living in an environment without air or oxygen.

Antibiotic: Natural or synthesised products used to inhibit or kill microorganisms.

***Artemia* (brine shrimp):** Small crustaceans used as a food source for larval animals in hatcheries.

Benthic: The bottom zone of a body of water including the top sediment layers.

Biofloc: A protein-rich combination of organic material and microorganisms.

Biomass: The total amount of stock present in an aquaculture system at a particular time.

Bioremediation: A waste management technique involving the use of organisms to remove or breakdown pollutants from an effluent water source.

Biosecurity: Measures designed to protect a facility from the entry and/or spread of disease.

Bivalve: A mollusc with a body enclosed in a shell consisting of two hinged parts (e.g. oysters).

Brackish: Water salinity levels between fresh and salt water.

Broodstock: Mature animals used for breeding in aquaculture.

Detritus: Decaying organic material on the pond bottom.

Earthen: Formed by soils such as clay.

Endemic: Found only in a particular region or country.

Euryhaline: Tolerance to a wide range of water salinity.

Eutrophication: The process where water is enriched with dissolved nutrients that stimulate the growth of aquatic plant life.

FCR (Feed conversion ratio): Ratio of the amount of feed provided to the level of animal body weight produced.

Fingerling: A juvenile fish similar in appearance to the adult and roughly the size of a human finger.

Freshwater: A water body with little to no salinity (typically from 0 to 5ppt).

Grow-out: The phase of culture after the nursery period and ending at harvest.

HAT (Highest Astronomical Tide): The elevation of land above sea level where the highest tide of the year will reach.

Hatchery: Buildings and infrastructure involved in the maintenance and spawning of broodstock and the rearing of larvae.

Husbandry: The management and maintenance of culture stock.

Intertidal: The area of land exposed at low tide and submerged at high tide.

Larvae or larval: The immature first stage of a life cycle after emerging from an egg.

Long-line system: A suspended line to which baskets or other settlement materials are clipped or hung from in an aquatic environment to rear species such as oysters and mussels.

Low-value white fish: Freshwater fish with white flesh produced in high volumes (predominately in Asia) such as Asian catfish, carp and tilapia.

Metamorphosis: The transformation of appearance and character from one life stage into another.

Nauplii: The first larval stage of most crustaceans.

Nursery: Period of culture from the completion of larval stages to small juvenile animals.

Non-fed species: A cultured species which relies solely on natural productivity for nutrition. Typically, aquatic plants (seaweed) and bivalves (e.g. oysters).

Omnivorous: Consuming both animal and plant material.

Osmoregulation: The active regulation of internal water and salt concentrations in aquatic organisms.

Ozone: Reactive form of oxygen used to sterilise water in aquaculture systems.

Pathogen: An organism (e.g. bacteria; virus) that can cause disease.

pH: Water chemistry measure of acidity. On a scale of 0 to14, <7 is increasingly acid; 7 is neutral and >7 is increasingly alkaline.

Plankton: Minute animal (zoo) and plant (phyto) life which forms the basis of food chains in aquatic ecosystems.

Postlarvae (PL): Juvenile prawns that have completed larval stage metamorphosis.

Prebiotic: Feed ingredients that help the growth or activity of beneficial microorganisms.

Probiotic: Live organisms that beneficially affect the microbial balance within a host animal.

Raceway: Artificial channels used to hold and culture aquatic organisms.

‘**Rack and Rail’ system**: Containers or trays holding bivalves (e.g. oysters) that are supported by a fixed rack built into the aquatic environment.

Recirculating aquaculture system (RAS): Method of intensive aquaculture involving the use of tanks and filtration equipment with low water exchange. Usually land based, indoor and climate controlled.

Rotifer: Microscopic aquatic animals used as a feed source for larval animals in hatcheries.

Salt water: Water volumes with salinity ranges of 30 to 36 ppt. Also referred to as sea, marine or oceanic water.

Smoltification: The process of transitioning freshwater juvenile salmonid fish to saltwater.

Spawning: The release of eggs or sperm by aquatic animals.

Spat: Juvenile bivalves (e.g. oysters) that have transitioned from the plankton stage and have settled on an underwater object for further development.

Stocking density: The number of animals in a defined area or volume of water.

Subtidal: The area below low tide which is covered by water.

Turbidity: A measure of the clarity of water.

UV: Ultraviolet light used to sterilise water in aquaculture systems.

WSSV (WSD): White spot syndrome virus that can cause ‘white spot’ disease in prawns.

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