

Freshwater-marine connectivity in the Great Barrier Reef catchment:

A review of current knowledge and a
case study of the Tully-Murray floodplain



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List of Acronyms

CSIRO Commonwealth Scientific and Industrial Research Organisation

GBR Great Barrier Reef

JCU James Cook University

MTSRF Marine and Tropical Sciences Research Facility

NERP National Environmental Research Program

RRRC Reef and Rainforest Research Centre Ltd.

Preface

This project continued research on the rivers and wetlands of the Wet Tropics of Queensland that commenced with the joint Catchment to Reef program of the Rainforest and Reef Cooperative Research Centres (2003-2006) and was sustained through the Marine and Tropical Science Research Facility (MTSRF) funding scheme (2006-2010) (Arthington and Pearson, 2007; Pearson *et al.* 2010a). At the completion of the MTSRF program this was one of several projects to receive MTSRF Transition funding prior to commencement of a new funding scheme (National Environmental Research Program, or 'NERP'). As of December 2010 the NERP program is still to be rolled out so the future of research into the rivers and wetlands of the Great Barrier Reef catchment is uncertain. However, the new Queensland initiative on wetland connectivity is a welcome recognition of the importance of this issue, and the importance of wetland ecosystems.

The Catchment to Reef, MTSRF and MTSRF Transition projects have included productive and successful collaborations between scientists and postgraduate students from Griffith University, James Cook University and the CSIRO. Many other people had substantial input and were acknowledged in our previous reports, cited above. Our understanding of the ecology and ecosystem health of waterways leading to the Great Barrier Reef has been advanced enormously during this period, and we look forward to reporting on this knowledge in the scientific literature.

We especially thank Drs Jim Wallace and Fazlul Karim (CSIRO) for their help in the early stages of the current project, which stemmed from our earlier collaboration. We hope to continue our joint research in the future.

We acknowledge funding provided by the Australian Government through the MTSRF and managed by the Reef and Rainforest Research Centre (RRRC), and we thank the RRRC for their assistance. We thank Marcus Sheaves and Stephanie Januchowski for comments on an earlier version of this report.

Executive Summary

This report describes a brief study, carried out between July and November 2010, which extended MTSRF wetlands [Project 3.7.3](#) in order to investigate the issue of wetland connectivity and its implications for ecosystem health in the Great Barrier Reef (GBR) catchment.

The ecological character of waterways (streams, rivers, estuaries and wetlands) in the Wet and Dry Tropics is outlined. Freshwater systems vary from perennial to intermittent running and still waters; estuaries may have permanent or seasonal salinity gradients.

The role of connectivity as an ecological driver is outlined. It is vital for maintenance of many biotic assemblages and processes, although natural lack of connectivity is also important.

Natural and anthropogenic barriers to connectivity and their effects are outlined. Constructed barriers range from dams and weirs to drop boards and embankments. Other barriers include weed beds and patches of low dissolved oxygen.

The fish fauna associated with the waterways of the GBR catchment is described and listed, along with the main ecological requirements of the species.

A field experiment is described in which connectivity between wetlands along drainage channels was investigated. It was found that many species could travel through channels with water as little as ten centimetres deep. Data on recruitment of species that must move to and from the estuary during their life cycles demonstrated that many wetlands were connected sufficiently for fish to be able to colonise them.

The results are discussed in the context of landscape/catchment models which should assist in understanding the connectivity process when developing management plans.

The importance of connectivity to fish and other animals in the GBR catchment is discussed, and the importance of maintaining and managing the whole catchment-to-reef continuum is highlighted.

Future possible scenarios for climate and land use and their possible effects on connectivity and ecosystem health are discussed. The discussion is limited by our restricted understanding of what scenarios might apply; however, loss of flow from the headwaters and through the catchment, and increasing incursion of saline water in the lowlands pose real threats to connectivity, biodiversity and ecosystem health.

Issues regarding the management of connectivity are discussed. It is pointed out that naturally occurring lack of connectivity (between catchments, upstream/downstream of waterfalls, etc.) can be important for maintaining particular biotic assemblages and evolutionary processes, and should be maintained. Anthropogenic barriers need to be removed (e.g. weed infestation) or bypassed (e.g. culverts and dams, using fish ways).

Indicators of connectivity are discussed in the context of pressures on natural systems, resulting ecosystem health and management responses. Indicators of connectivity can be readily developed from knowledge of the local biota and biophysical processes.

Some needs for future research projects are outlined, including a more extensive study on connectivity and the pressing need for understanding future climate scenarios and their likely effects, with a view to developing appropriate management strategies.

1. Introduction

This report outlines results from a short project supported by MTSRF Transition Funding ([Transitional Project 15](#)), which enabled further development of our understanding of a critical issue – connectivity – for biodiversity maintenance and management in the rivers and wetlands of the Great Barrier Reef (GBR) catchment.

Our main MTSRF project described the current status of streams and wetlands in the Wet Tropics, and identified indicators of freshwater ecosystem health. Limited research was undertaken on Dry Tropics systems by postgraduate students. Our projects identified several research needs for future management of the waterways of the GBR catchment. The final MTSRF workshop held in association with the [2010 MTSRF Annual Conference](#) (Pearson *et al.* 2010b) involved natural resource managers, scientists and land owners in a discussion of research needed to follow on from the achievements of Project 3.7.3 (Freshwater indicators and thresholds of concern) and [Project 3.7.4](#) (Wetlands and floodplains: connectivity and hydro-ecological function).

The following areas of further research were specifically identified:

1. Fish corridors and movement in floodplains and cane drainage systems;
2. Ecological condition of fish assemblages in floodplain wetlands given past wetland losses;
3. Macroinvertebrate monitoring program designs;
4. Focus on ‘whole of catchment’ research;
5. Grazing land research, methods and framework for monitoring and management;
6. Riparian health and its effect on water quality;
7. Groundwater dynamics and relationship to ecosystem health; and
8. Environmental flows for the Wet Tropics.

The MTSRF workshop recommended further research into the connectivity of waterbodies in wet and dry tropical landscapes in the GBR catchment, and highlighted the importance of connectivity for ecological processes and maintenance of biodiversity. In particular, the workshop identified the need to study the movements of fish into and out of floodplain wetlands to gain a better understanding of how natural stream channels and artificial cane drains can act as connectivity corridors, and how natural and artificial drains can act as habitat, replacing that destroyed during land-use developments on floodplains (Pearson *et al.* 2010a). The Catchment to Reef program and MTSRF funded research have demonstrated that fish can be affected by natural environmental gradients and anthropogenic stressors, including loss of connectivity. In floodplain systems, flow regime alterations and human influences on floodplain hydrology typically translate into changes in floodplain habitat structure, connectivity and quality, and ecological responses of aquatic biota (Junk *et al.* 1989; Overton *et al.* 2006). However, little is known about the interactions between natural and altered flow regimes, hydrological connectivity and freshwater and estuarine fishes and invertebrates in the tropical floodplains and wetlands of the Queensland Wet and Dry Tropics, which are likely to be impacted by marked losses in habitat, connectivity and water quality brought about by floodplain modifications and climate change.

The importance of connectivity in aquatic environments has recently been recognised by a new Queensland Government initiative, the Queensland Wetlands Program Wetland Connectivity – Tools for Decision Making – Stage 1, involving among others, researchers

from the current project. We anticipate that this MTSRF Transition project report will contribute to the development of concepts and research pathways to support that initiative. This project therefore aims to review the important ecological linkages that are governed by hydrological connectivity through waterways to the GBR lagoon, to undertake some preliminary field work to examine connectivity in one part of the landscape (waterways of the Tully-Murray floodplain), and to scope out the future research required to properly understand the issue and to apply that understanding to management.

The questions we address are as follows:

- What are the main species that require catchment-to-reef connectivity?
- How are these species distributed (Wet Tropics, Wet-Dry Tropics)?
- What are their ecological requirements?
- How is habitat connectivity for these species influenced by major environmental variables:
 - Flow regime and flow alteration (drainage works, water extraction, etc.)?
 - Barriers created by infrastructure (dams, weirs, drop boards, culverts, etc.)?
 - Barriers created by weeds?
 - Barriers created by poor water quality?
- How will future scenarios (flow, land use, etc.) affect connectivity?
- What are appropriate indicators of connectivity?

We view the GBR and its catchment as an integrated system (the GBR system) and aim to support management principles, strategies and practices that are also integrated at appropriate scales. Connectivity is a fundamental property of integrated systems, and must be understood and quantified if management is to address connectivity and dependent ecological processes appropriately. The objective of this document is to describe the waterways of the GBR catchment and their connectivity patterns, collate data on key ecological linkages between catchments and the GBR lagoon, and identify the main barriers to and indicators of connectivity in the GBR catchment.

This synthesis of published and newly derived knowledge defines the connectivity issue for the GBR catchment, indicates how to measure it as well as how it impinges on ecosystem health across systems, and discusses how to manage connectivity in the face of environmental impacts and global change.

2. Waterways in the GBR catchment

The GBR catchment includes short perennial rivers in the Wet Tropics and on Cape York Peninsula, short intermittent rivers in the Dry Tropics, and two large Dry Tropics rivers, the Burdekin and Fitzroy rivers. Some of these rivers have extensive floodplains (e.g. Tully-Murray and Herbert rivers in the Wet Tropics; Burdekin and Fitzroy rivers in the Dry Tropics) with complex wetlands and distributary channels. The characteristics of the major aquatic units in this landscape were outlined at a workshop held by MTSRF funded researchers (Projects 3.7.3 and 3.7.4) to investigate appropriate models for the biophysical dynamics of GBR catchment waterways (Wallace et al. 2007). In this section we summarise the workshop report and outline the main features of the catchment (Figures 1 and 2). The figures and summary refer explicitly to the continuum from streams to the marine environment, which is fundamental to catchments and relies on connectivity within and between components of the catchment.

Four major zones were recognised within the catchment, following a modified conceptual model, the Marine Catchment Basin concept (Caddy, 2000) (Figure 1). The model is useful in its presentation of key zones of the catchment, in which biophysical processes differ somewhat from those in other zones. Figure 2 indicates some of the important natural features of the catchments and many of the human impacts that influence them.

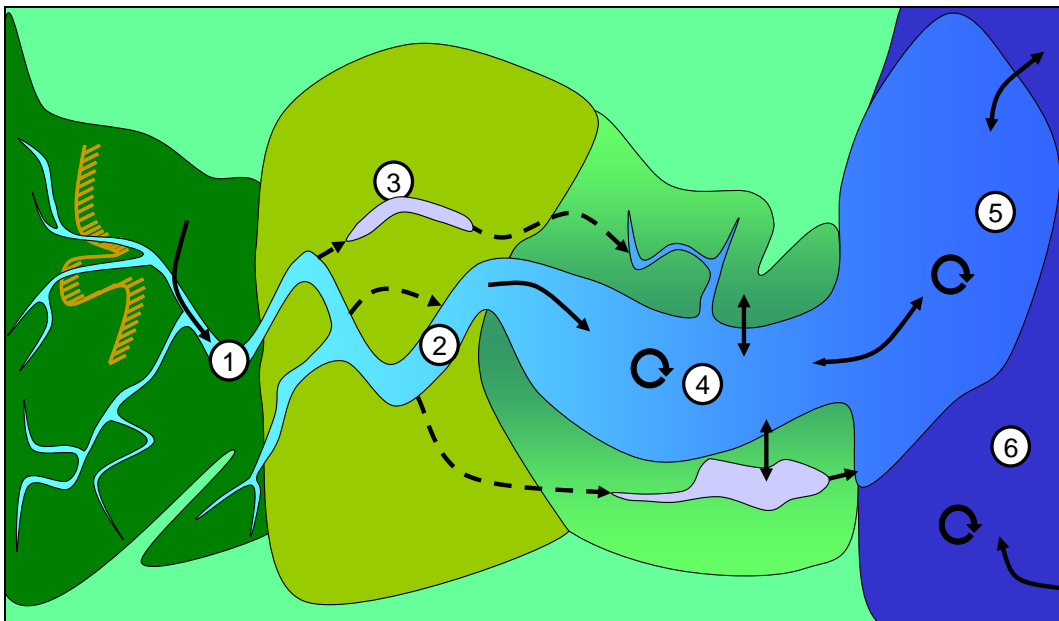


Figure 1: The Marine Catchment Basin Concept showing the major sub-components or zones of the catchment, floodplain, estuary and marine continuum. Arrows indicate the direction of major material transport within numbered zones. Dashed arrows identify typical floodwater movement on the floodplain. Circular arrows show major zones of material recycling. (1) River reaches upstream of the lowland floodplain; (2) Lowland river reaches; (3) Floodplain with freshwater wetlands; (4) Estuary with salt-tolerant riparian vegetation and brackish wetlands; (5) River plume extending seaward; and (6) Coastal waters outside the river plume. Modified from Gehrke and Sheaves' (2006) adaptation of Caddy's (2000) original concept.

2.1 Zone 1: Upstream slopes and river reaches

Wet Tropics

Small, upland streams of the Wet Tropics have a perennial and predictable seasonal flow regime with higher base flows and occasional but unpredictable floods during the wet season. The biodiversity and ecological processes in upland streams in the Wet Tropics are fairly well documented and understood following extensive work by Pearson and colleagues (e.g. Pearson *et al.* 1986; Cheshire *et al.* 2005). Like upland forest streams elsewhere, the food web is largely dependent on the input of terrestrial litter and dissolved organic matter. The litter undergoes decomposition by fungi and bacteria, and invertebrates that shred the leaf material; the resultant fine material then feeds the rest of the web (Cheshire *et al.* 2005). Shredders include various insect taxa and crayfish (Boyero *et al.* 2006; Coughlan *et al.* 2010). Other characteristic fauna include shrimps (Atyidae) and fish (the purple-spotted gudgeon, *Mogurnda adspersa*, and the eel, *Anguilla reinhardtii*). The main shrimp species, *Australaya striolata*, breeds in the streams, but its larvae are washed downstream to the estuaries where they develop; the eels migrate to the Coral Sea to breed and their offspring eventually return to the streams. These two examples demonstrate the connectivity between the landscape extremes of the GBR catchment – from headwater feeder streams to the local and distant marine environments.

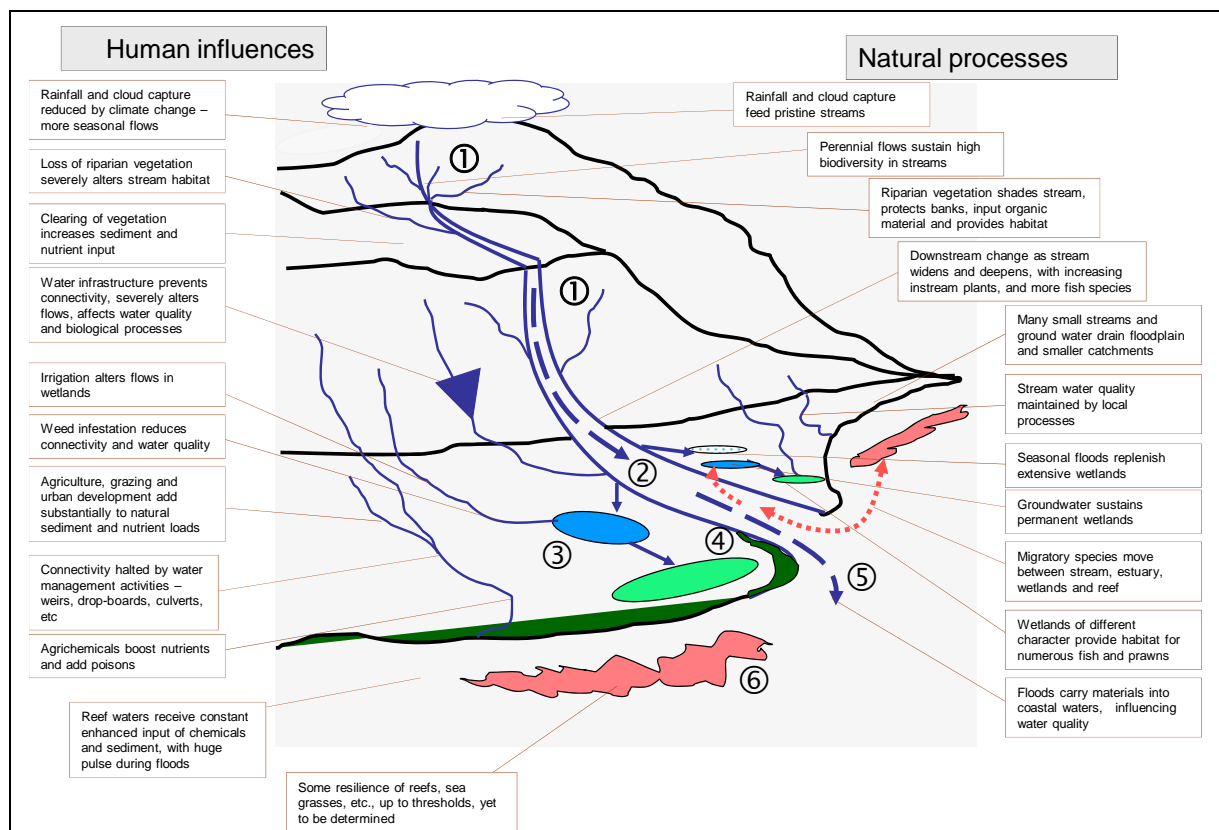


Figure 2: Stylised oblique view of a GBR catchment indicating key biophysical process and human impacts. Circled numbers represent the zones identified in Figure 1. Note that this catchment, like many in the Wet Tropics, includes a tableland. From Pearson and Stork (2007).

Spatial and temporal patterns of fish assemblage composition and relative abundance have been documented and related to flow regimes and habitat characteristics of upland and mid-reach streams of the Russell-Mulgrave and North and South Johnstone rivers; the dietary ecology and reproductive biology of some species have also been documented (see Hurtle and Pearson, 1990; Pusey and Arthington, 2003; Pusey *et al.* 1995; Pusey *et al.* 2000, Pusey and Kennard 1996; Pusey *et al.* 2004a,b, 2005, 2007b). The impacts of nutrients, sediments and low dissolved oxygen concentrations on stream macroinvertebrates and fish have been studied in the field and in laboratory experiments (Pearson and Connolly, 2000; Connolly *et al.* 2004; Connolly and Pearson, 2007; Butler and Burrows, 2007, Butler *et al.* 2007). The Catchment to Reef joint program of the former Rainforest and Reef Cooperative Research Centres (CRCs) has explored the effects of land use, water quality and riparian degradation on aquatic plants, invertebrates and fish, and from this work proposed a suite of indicators of stream ecosystem health (Arthington and Pearson, 2007).

Dry Tropics

Upstream conditions depend on the location of the tributaries. For example, the Burdekin River receives substantial inputs from Wet Tropics streams (as described above), which has a major bearing on the water quality in riverine waterholes as flows diminish in the dry season. Upstream tributaries in the Dry Tropics, however, are very different from those in the Wet Tropics as they are typically intermittent and are substantially affected by grazing pressure. Problems derive from overgrazing and erosion of the landscape (with consequent sediment deposition in streams), damage to stream banks as cattle access water holes in the dry season, concomitant fouling of remnant water holes with likely impacts on the biota, and smothering of native riparian vegetation with weeds such as rubber vine, with probable adverse consequences in the aquatic ecosystem.

2.2 Zone 2: River channel

Wet Tropics

The channel zones of Wet Tropics rivers have been studied less extensively than upland streams. In this zone there is still a definitive effect of the seasonal perennial flow regime, and so there is good longitudinal connectivity in the river channel, even during low-flow periods. Low-flow/no-flow ecology (e.g. recruitment, food-web dynamics) has important implications for the functioning of the river channel and its influences on river-floodplain connectivity and associated processes could have huge impacts. However, low-flow/no-flow processes are far more important in rivers of the Dry Tropics.

Floods have a major impact as they reset the river ecosystem (Rayner *et al.* 2008). Hydrological connectivity between the channel and floodplain waterbodies, and the associated transport of sediments, nutrients, organisms and propagules are achieved by overbank flows, but the return of materials and organisms from the floodplain to the river, typical of tropical rivers elsewhere (the flood-pulse concept: Junk *et al.* 1989; Junk and Wantzen, 2004; Sedell *et al.* 1989), is not as significant in the Queensland Wet Tropics, as flood waters are mostly distributed through separate streams on the floodplain (Figure 2).

Both primary productivity and terrestrial inputs contribute to the food web in this section of the river (Connolly *et al.* 2007b; Rayner *et al.* 2010). The fauna is diverse, with fish increasing in diversity with distance downstream (Pusey *et al.* 1995, 2007b). The connectivity of the river channel zone to the estuary is important, as this can influence river water quality, salinity, carbon sources and fish and invertebrate assemblages.

Dry Tropics

Rivers in the Dry Tropics are characterised by occasional high flows, with long dry spells in between. There can be a strong seasonal flood signal reflected in ecosystem dynamics, but this depends on the unpredictable magnitude and timing of events. For example, floods can reset habitats and ecosystems as demonstrated by Pusey and Arthington (1996) and Pusey *et al.* (1998) through different hydrological regimes which affect fish assemblages. However, such floods may not occur for years at a time, so the behaviour of over-bank flows varies with location. For example, upstream, flood water may return to the river as levels recede, but on the floodplain, floodwaters typically do not return to the main channel, but reach the sea via distributaries. This provides ecological connectivity on the floodplain, between lagoons and distributaries. Within river channels, floods provide substantial connectivity between previously remnant water holes and across barriers such as cascades and small falls.

After floods, and through much of the dry season, these rivers are shallow and meander across sandy beds, with much of the wetted area unshaded. Primary productivity (mostly algae) is high, with associated high secondary production reflected in abundant invertebrate and fish populations. Diversity is generally lower than in the Wet Tropics. For example, the number of fish species recorded in the Mulgrave, Herbert and Burdekin rivers, representing a gradient from Wet to Dry Tropics, is 53, 36 and 37 respectively (Pusey *et al.* 2004b), despite the rivers being progressively larger. This gradient relates to the diversity of reliable habitats available in the perennial Wet Tropics, compared with the restricted habitats that are continuously available in the occasionally non-perennial Dry Tropics.

2.3 Zone 3: Floodplain and freshwater wetlands

Three main freshwater habitats occur on GBR floodplains: (i) remnant lagoons, (ii) distributaries, and (iii) swamps, both permanent and intermittent. These habitats are substantially disturbed by land clearing, drainage, irrigation, agricultural chemicals and grazing, which variously affect water quantity and quality, and associated ecology (Pearson *et al.* 2010a).

Until recently, there was only limited knowledge of the hydrological dynamics of floodplain wetland systems in the GBR catchment, and of how hydrology and physical connectivity influence aquatic habitats, water quality, biological diversity and ecological processes (Hogan and Graham, 1994; Vallance and Hogan, 2004; Perna and Burrows, 2005; Pusey *et al.* 2007; Rayner *et al.* 2008). Recent work as part of the MTSRF program (Projects 3.7.3 and 3.7.4) described the hydrological dynamics and associated ecological relationships on the Tully-Murray floodplain (Wallace *et al.* 2009a,b; Karim *et al.* 2010; Pearson *et al.* 2010a). This report is based on an extension of that work.

Wet Tropics

In this zone, over-bank floods move across the floodplain. Off-stream habitats typically do not link back into the main river channel. Instead, water flows to the coast via distributary channels. At this time, movement of fish may allow reconnection between isolated habitats, but physical and water quality barriers (e.g. hypoxic reaches) may prevent such movements. Isolated lagoons and distributaries left after floods may be sustained by rainfall, inflow from small local catchments and groundwater (see Figure 2). The retention time of water in these floodplain areas has changed significantly as a result of changing land use and infrastructure development, with flow-on effects on water quality, habitat suitability, ecological patterns and processes, and especially connectivity.

The drivers of primary productivity and trophic structure in floodplain water bodies sustain aquatic biota during non-flood periods. These processes are expected to differ between wet and dry periods, but there is little information on this issue. Similarly, there is little information on the role of floodplain wetlands as habitat for aquatic biota and the importance of their connectivity with estuarine habitats. Furthermore, life-history and recruitment processes of the biota in these habitats were not well understood prior to MTSRF Projects 3.7.3 and 3.7.4 (Pearson *et al.* 2010a). The Tully-Murray wetlands were shown to be affected by land-use impacts, but have some resilience to these threats as a result of the regular high-flow events that occur through the year. Invertebrates and fish had strong habitat associations, and invasive weeds had a negative effect on the fish assemblages. Connectivity was found to be important to fish assemblages in the floodplain lagoons, and this finding led to the current extension of the research on this issue.

Dry Tropics

Floods (and so over-bank flows) do not happen every year in the Dry Tropics, so replenishment of floodplain wetlands and connectivity between them is unpredictable. Wetlands are permanent only if they receive sufficient groundwater input, or irrigation water (supply or drainage), as is the case on the Burdekin floodplain. Flood waters typically move through a series of lagoons and distributary channels and discharge through saline wetlands (e.g. Barratta Creek on the Burdekin floodplain). However, in some floodplains, wetlands connect in both directions – filling from and emptying back into the main river system (e.g. Fitzroy River).

Antecedent flood conditions, therefore, have important influences on productivity, connectivity and ecosystem dynamics on floodplains. Extensively agricultural development has led to a loss of wetlands and reduced water retention, affecting ecological patterns and processes. Development of floodplains has led to barriers to connectivity, such as drop boards that control water levels, weed infestations, and patches of poor water quality (Perna and Burrows, 2005).

When well connected, wetlands provide important fish habitat – for example, for juvenile barramundi (Sheaves *et al.* 2007). However, it is unclear to what extent wetlands are vital for these species' populations and to what extent they act as sinks for organic matter, including fish (Sheaves and Johnston, 2008).

Dry tropical systems have different rates of change in processes from those in the Wet Tropics. For example, the length of time between wet and dry periods varies enormously – in the Dry Tropics the interval may be up to five years. Productivity in riverine lagoons is strongly influenced by local features such as size and bathymetry of the water body, and landscape processes immediately contiguous with the water hole. Sources of productivity include algae in the shallows, extensive macrophyte beds in deeper water and phytoplankton in open waters. Inputs from the riparian vegetation can be important in smaller water holes, although litter from the most abundant riparian trees (e.g. *Melaleuca* species) breaks down very slowly. Many fish take advantage of terrestrial fruit and insects, derived from the riparian vegetation (Pusey *et al.* 2004b).

2.4 Zone 4: Estuary and brackish wetlands

An estuary receives marine and freshwater inputs, and thus forms a large mixing zone supporting resident euryhaline species and species that move between freshwater and tidal zones and *vice versa*. Typically estuaries are areas of sediment deposition, forming deltaic fans across which many small waterways meander, and on which a variety of salt-tolerant emergent vegetation grows. The character of the estuary, the contiguous waterways and the inter-tidal environment differs substantially between the Wet and Dry Tropics. Continuous freshwater inputs in the Wet Tropics sustain salinity gradients in the estuary that are typical of estuaries in much of the world, while in the Dry Tropics the lack of freshwater input means that the estuary becomes essentially a marine (or hypersaline) inlet in the dry season (Sheaves, 1998). The role of floods is important: the first flood of the year brings organic matter, sediment, nutrients and perhaps also pesticides. The effects of these constituents may be felt at all levels of the food web, and may ultimately influence estuarine productivity. Physical and water quality barriers may influence the movement patterns of aquatic biota, but little is known about such processes. Understanding of the ecology of tropical estuaries is quite limited, which is surprising given their importance to fishery and ecosystem values, although Sheaves and his group are making important research inroads in both Wet and Dry Tropics (e.g. Sheaves, 2005; Sheaves *et al.* 2010).

In the Wet Tropics the estuary can be offshore during high flows, whereas physical estuarine habitat (e.g. mangroves) is near shore. The upper intertidal area is covered in mangroves right through to the rainforest in the terrestrial zone as salinity remaining after the occasional king tides is rapidly diluted by rainfall.

In the Dry Tropics the estuary acts as an arm of the sea during low flows and the biotic communities are dominated by marine species in the sub-tidal area. On the intertidal flats, mangroves are limited in diversity because of the high salinities that occur as water evaporates leaving salt behind. Salt flats and associated vegetation are extensive. Nevertheless, the networks of permanent creeks are important habitat for many estuarine and marine species.

3. Connectivity as a key ecological driver

The many ecological roles of flow magnitude, flood frequency, timing and duration, low flows and other dimensions of flow regimes reported in many studies are captured in the Natural Flow Regime Paradigm (Poff *et al.* 1997). Bunn and Arthington (2002) proposed four guiding principles to illustrate how altered flow regimes can affect aquatic biodiversity (Figure 3). The relationship between biodiversity and the physical nature of the aquatic habitat is likely to be driven primarily by large events that influence channel form and shape (Principle 1). However, droughts and low flow events are also likely to play a role by limiting overall habitat availability. Many features of the flow regime influence life history patterns, especially the seasonality and predictability of the overall pattern, but also the timing of particular flow events (Principle 2). Some flow events trigger longitudinal dispersal of migratory aquatic organisms and other large events allow access to otherwise disconnected floodplain habitats (Principle 3). The native biota has evolved in response to the overall flow regime. Catchment land-use change and associated water resource development inevitably lead to changes in one or more aspects of the flow regime resulting in declines in aquatic biodiversity via these mechanisms. Invasions by exotic species are more likely to succeed at the expense of native biota if the former are adapted to the modified flow regime (Principle 4). Principle 3 states that “maintenance of natural patterns of longitudinal and lateral connectivity is essential to the vitality of populations of many riverine species. Loss of longitudinal and lateral connectivity through construction of barriers can lead to isolation of populations, failed recruitment and local extinction of fish and other aquatic biota”.

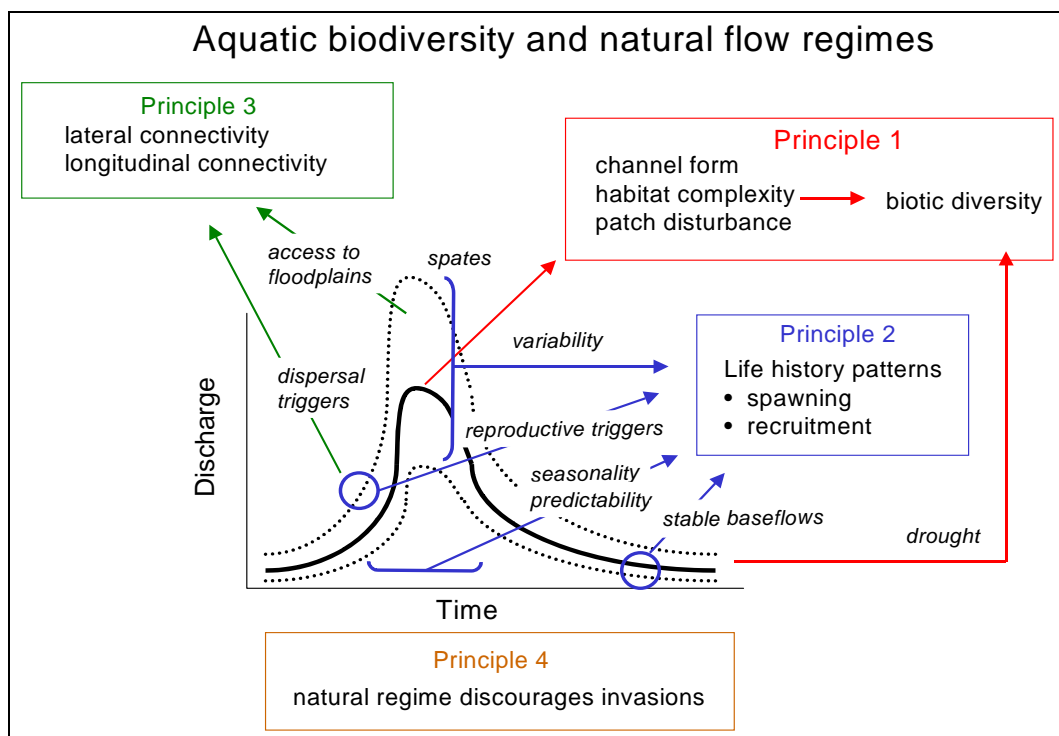


Figure 3: Relationships between natural flow regime of a river and aquatic biodiversity. From Bunn and Arthington (2002).

Figures 1 to 3 and the above brief outline of habitat characteristics across a catchment clearly demonstrate that from small headwater streams to estuaries, and from intermittent wetlands to permanent lagoons, there is a continuum of aquatic habitat sustained by the hydrological cycle of rainfall, surface and groundwater storage, and surface and groundwater flow. The continuum is not always permanent as it may be broken by barriers created by natural processes such as drying of waterways in the dry season, by waterfalls and by anthropogenic structures and activities.

Connectivity is important in most ecosystems, at a variety of scales (e.g. Sheaves, 2009). It provides for exchange and transport of materials and nutrients, mostly downstream in freshwater systems, with land- and water-derived materials being transported. On floodplains, and in tidal waterways, water movement can reverse, depending on the state of the flood or the tide. Thus in many floodplain systems, lagoons fill from the river in flood, via linking channels, then slowly feed water back to the river as the water level recedes. This pattern of water and material transport is described by the flood-pulse concept (Junk *et al.* 1989) which applies to many tropical systems (e.g. the Fly River in Papua New Guinea, and the Fitzroy in the GBR catchment), but not to all (e.g. in the GBR catchment, Wet Tropics rivers and the Burdekin River).

Rivers play important roles as corridors for the transport of water, sediments, organic matter, chemicals and living organisms, from seeds to large woody debris and even whole trees (Nilsson and Svedmark, 2002). Many species can, therefore, be dispersed passively: for example, many invertebrates are carried by the river current, in a process called drift, allowing them to disperse downstream. In free-flowing rivers, floating plant propagules are rapidly transported downstream during floods (a process termed hydrochory) (notable are the viable stems of invasive aquatic grasses and the seeds of many invasive aquatic and terrestrial species such as rubber vine). Plant propagules may also be moved upstream – not in the water, but along riparian corridors. Thus the pollen of *Melaleuca* trees, the dominant species in many riparian zones, is transported upstream by fruit and blossom bats (Chong, 2008). Connectivity in the riparian zone is also vital for many terrestrial animal species that are averse to crossing open space.

Connectivity is vital for the movement of many species that use different parts of the catchment for different parts of their life cycles. In the GBR catchment there are stream-dwelling species that are dependent on estuaries or the marine environment for different stages of their life cycle (e.g. jungle perch and eels – Pusey *et al.* 2004b – and atyid shrimps – Smith, 1987) and so need to be able to access both ends of the catchment continuum. Notably eels and shrimps are able to cross barriers such as waterfalls that prevent passage by other species, such as the jungle perch. Some species move within freshwater systems to breed; thus catfish inhabiting large rivers seek out gravel beds small intermittent streams in which to lay their eggs. Conversely, barramundi juveniles move into floodplain wetlands and rivers to pass through a major early growth phase of their life cycle. Other species may be non-obligate dispersers through the continuum – for example, the mangrove jack is usually regarded as a marine/estuarine species, but it is a normal member of the fish assemblage in accessible freshwater reaches of lowland rivers.

4. Barriers to connectivity

4.1 Natural barriers

Waterfalls and cascades are major natural barriers to connectivity that prevent passage of many aquatic species. In the GBR catchment, particularly in the Wet Tropics, many streams flow directly east to the coast, crossing the escarpment of the coastal range via steep streams and falls. These formations make habitats upstream inaccessible to most aquatic species other than insects. A few species are able to surmount these barriers, for example eels can navigate around falls and even cross wetted dry land. Shrimps can climb falls, and the gudgeon *Mogurnda adspersa* also seems able to climb up falls. The contrast between streams above and below waterfalls can be stark. Upstream, in the absence of major fish predators, it is common to see freshwater prawns (*Macrobrachium* spp.) grazing over rocks during the day, whereas downstream in the presence of predators they only do so at night.

Natural barriers also occur in streams and rivers that have intermittent flow. Remnant riverine lagoons may sustain the biota in dry periods, but dry stretches of stream bed prevent movement. If the lagoons themselves dry out, the biota may perish or survive as propagules or resistant stages, in the case of many plants and some of the invertebrate fauna. Even where lagoons are permanent, they are unable to support a biota that normally requires running water, so these systems typically have lower diversity than perennial systems.

Nevertheless, barriers may lead to adaptation and important evolutionary processes. Where diversity is lower it may be different, and isolated ecological systems may differ from those that are more connected. Moreover, genetic studies have shown that some species maintain quite separate populations even in tributaries of the same catchment (e.g. Bunn and Hughes, 1997). Therefore, from a conservation perspective it is important to maintain habitat refuges and the natural barriers in these partly isolated systems, including intermittent waterways and streams upstream of waterfalls.

4.2 Anthropogenic barriers

Human structures and activities create a range of barriers to instream connectivity, which influences the movement of biota, especially fish (Figure 4). Built structures, especially road and rail embankments, dams and weirs, are normally impassable by fish other than eels, unless fish ladders or other aids to movement are in place (Pusey *et al.* 2004b). During large floods, weirs may be drowned out, allowing fish passage around the margins, but larger dams are usually impassable. The ecological impact increases with distance downstream. Thus, for example, the Paluma dam, in the upper Burdekin catchment, blocks only two or three small streams and thereby affects a tiny proportion of those habitats; moreover its downstream influence on the flow regime is rapidly mitigated by other tributaries. The Burdekin Falls dam, on the other hand, isolates the whole of the upper Burdekin catchment, blocking the upstream movement of many fish species as well as the estuarine crocodile, and preventing gene flow in an upstream direction. Its effects on downstream flow are huge given that it blocks and regulates flow for a major portion of the lower river, and is normally the major contributor to the total flow in the lower reaches.

When dams disrupt the longitudinal pathway of normal river flows, plant dispersal by hydrochory is reduced and plant communities can become fragmented. In impounded rivers, current velocity is often low and floating plant propagules either sink or become swept ashore by winds (Jansson *et al.* 2000). This reduces the normal travel distances of seeds and alters the distribution of species along the riparian zone. Given that dams regulate most of the world's rivers, floristic disruptions of riparian corridors may be a global phenomenon (Nilsson

and Svedmark, 2002), with many negative consequences for river biota and ecosystem functioning (e.g. Pusey and Arthington, 2003).



Figure 4: Connectivity issues: (a) dams (Burdekin Falls); (b) weirs (Ross River); (c) drop boards (d) fish way around drop boards; (e-f) blockage of waterways by invasive plants; (c-f) located on the Burdekin floodplain. Photographs courtesy of R. G. Pearson.

A second type of structural barrier is the drop-boards that are used on various floodplains. They are boards that are placed in a frame across irrigation/drainage channels and are used to maintain optimal water levels for pumping irrigation water on to the adjacent fields. While they do not present a very high barrier, it is nevertheless too high for fish to cross easily, preventing estuarine species from accessing floodplain wetlands. Dispersal of freshwater species probably still occurs during floods when the drop-boards are drowned out.

A third structural barrier is the culverts that occur on crossings of smaller waterways. They are typically either too shallow or have too strong a current for fish to negotiate and they offer no alternative route. Lawson *et al.* (2010) recently identified artificial physical barriers (road and rail crossings, flood mitigation works) in the Wet Tropics bioregion, through a desktop GIS analysis of the stream/river and transport networks. A total of 5,536 potential artificial, physical barriers to fish passage were identified in a stream network of 19,764 km at a scale of 1:100,000. However, the total number of potential physical barriers to fish passage in the region may be many times higher given that barriers smaller than fifty metres were not identified in the mapping exercise. They may have major effects on fish passage in small streams in the uplands, where there is low but still important diversity, and in the lowlands, in which there may be very high diversity.

Invasive weeds can be so profuse that they block smaller waterways entirely. Their growth is enhanced by fertilisers in the runoff and by the absence of riparian shade. *Hymenachne* (*Hymenachne amplexicaulis*) and para grass (*Urochloa mutica*) are the main introduced weeds in the GBR catchment that have this effect, and occur in many waterways. Invasive weeds can have another effect, for example water hyacinth (*Eichhornia crassipes*) grows profusely in lagoons and can rapidly cover the whole surface. Although not blocking passage below (it is a floating plant), it prevents oxygen exchange with the air, so that hypoxia (caused by bacterial respiration of organic material) rapidly ensues. Hypoxic zones can act as a barrier to fish movement. For example, in lagoons on the Burdekin floodplain, removal of hyacinth allowed the return of many fish species, such that the species count increased from 3 to 16 in just three months (C. Perna, pers. comm.).

Whatever the cause, restricting movement of animals has impacts beyond the individual species. Taking out the top predators from streams and wetlands – and many fish species have this role – will have cascading effects on the species assemblage and food web below. So far, these effects have not been studied in the Wet or Dry Tropics.

5. Fishes of the GBR catchment and their ecological requirements

We have reviewed the current knowledge of the ecological requirements of fish of the GBR catchment, particularly with regard to movements and the need for connectivity. Table 1 lists those species that spend their whole lives in fresh waters, and indicates those that are known or thought to undertake breeding migrations within fresh waters. The migratory species among this list include some of the terapontid grunters (*Hephaestus* spp.) and neosilurid catfishes that migrate as adults upstream and laterally from main channel to tributary or floodplain habitats (e.g. ephemeral drains) in GBR catchments for the purpose of breeding and rearing (Pusey *et al.* 2004b; Pearson *et al.* 2010a). Temporal variability associated with the occurrence of channelised low flow rearing habitat and the accessibility to floodplain spawning habitat contributes to the variation in the timing of movement. Other species will, of course, undertake dispersal and random movements across the available habitat from time to time and this is demonstrated in studies of the efficiency of fish ways situated on Queensland river barrages (Pusey *et al.* 2004b). Table 2 lists species that spend substantial parts of their life cycle in fresh waters, but require saline waters for breeding. Some spend most of their adult lives in fresh waters (e.g. jungle perch), while others are opportunistic visitors to fresh waters but nevertheless important components of the freshwater assemblage when access is available (e.g. mangrove jack). It excludes some goby species that have recently been recorded in short coastal streams only (P. Thuesen, T. Rayner, S. Januchowski, pers. comm.).

Diadromous freshwater fish species occupying GBR catchments are dominated by members belonging to the Gobiidae (10 species) and Eleotridae (5 species) families as well as several representatives within the Chandidae (glassfish), Anguillidae (eels) and Sygnathidae (pipefish) families (Table 2). Movement from freshwater to estuarine/marine habitat occurs by adult migrating (e.g. *Hypseleotris compressa*) or larvae drifting (e.g. *Redigobius bikolanus*) downstream to spawning or rearing habitat that is found in the estuaries of the GBR catchments and the GBR lagoon. A study of the recruitment dynamics of freshwater fishes in Wet Tropics rivers reveals inter-specific differences among the diadromous members with different species migrating between freshwater and estuarine under different flow conditions in response to variation in resource (food, habitat) availability (P. Godfrey, unpublished data).

In addition, there are a large number of species occupying GBR catchments where information on their movement biology remains unknown. This aspect of their ecology is in need of study.

Appendix 1 lists the same species, but in taxonomic order, and provides notes on their ecological requirements. Appendix 2 lists some other estuarine and marine species that occur less commonly in fresh waters.

Table 1: Wholly freshwater fish species of the GBR catchment and their propensity for movement.

Family	Species	Common name	Mobility
Osteoglossidae	Scleropages leichardtii Scleropages jardinii	Saratoga	
Clupeidae	Nematolosa erebi	Bony bream	1
Ariidae	Arius graeffei Arius midgleyi		? 1
Plotosidae	Neosilurus hyrtlili Neosilurus ater Neosilurus mollespiculum Porochilus rendahli Tandanus tandanus	Hyrtl's catfish Black catfish Soft-spined catfish Rendahli's catfish Eel-tailed catfish	1 1
Hemirhamphidae	Arrhamphus sclerolepis	Snub-nosed garfish	
Belonidae	Strongylura krefftii	Freshwater long-tom	1
Atherinidae	Craterocephalus stercusmuscarum	Fly-specked hardyhead	
Melanotaeniidae	Cairnsichthys rhombosomoides Melanotaenia splendida Melanotaenia eachamensis Melanotaenia utcheensis Melanotaenia maccullochi	Cairns rainbowfish Eastern rainbowfish Lake Eacham rainbowfish Utchee Creek rainbowfish MacCullochi's rainbowfish	1
Pseudomugilidae	Pseudomugil signifer Pseudomugil gertrudae	Pacific blue-eye Spotted blue-eye	
Synbranchidae	Ophisternon gutturale Ophisternon spp.? Monopterus albus	One-gilled swamp eel	1
Chandidae	Ambassis agassizii Denarius bandata	Agassiz's glassfish Pennyfish	
Percichthyidae	Macquaria ambigua Guyu wujalwujalensis	Bloomfield River cod	
Terapontidae	Amniataba percoides Leiopotherapon unicolor Hephaestus fuliginous Hephaestus tulliensis Scortum hillii Scortum parviceps	Barred grunter Spangled perch Sooty grunter Tully grunter Leathery grunter Small-headed grunter	1 1 1 1 1
Apogonidae	Glossamia aprion	Mouth almighty	
Toxotidae	Toxotes chatareus	Seven-spot archerfish	
Gobiidae	Glossogobius bellendenensis	Mulgrave River goby	
Eleotridae	Oxyeleotris lineolatus Oxyeleotris selheimi Oxyeleotris cf. aurensis Giurus margaritacea Hypseleotris galii Hypseleotris sp. 1 Hypseleotris klunzingeri Gobiomorphus australis Mogurnda adspersa Mogurnda mogurnda Philypnodon grandiceps Philypnodon sp.	Sleepy cod Striped sleepy cod Aru gudgeon Snake-headed gudgeon Firetailed gudgeon Midgely's carp gudgeon Western Carp gudgeon Striped gudgeon Purple-spotted gudgeon Northern trout gudgeon Flathead gudgeon Dwarf flathead gudgeon	1

Table 2: Freshwater fish species of the GBR catchment that move between marine/estuarine and fresh waters.

Family	Species	Common name	Mobility: Adults	Larvae
Megalopidae	<i>Megalops cyprinoides</i>	Tarpon	1	
Anguillidae	<i>Anguilla obscura</i>	Pacific short-finned eel	1	
	<i>Anguilla reinhardtii</i>	Long-finned eel	1	
Muraenidae	<i>Gymnothorax polyuranodon</i>	Freshwater moray	1?	
Syngnathidae	<i>Hippichthys heptagonus</i>	Reticulated freshwater pipefish		1
	<i>Microphis brachyurus</i>	Short-tailed river pipefish		1
Scorpaenidae	<i>Notesthes robusta</i>	Bullrout	1	
Chandidae	<i>Ambassis agrammus</i>	Sailfin glassfish	1	
	<i>Ambassis miops</i>	Flag-tailed glassfish	1	
Centropomidae	<i>Lates calcarifer</i>	Barramundi	1	
Kuhliidae	<i>Kuhlia rupestris</i>	Jungle perch	1	
Lutjanidae	<i>Lutjanus argentimaculatus</i>	Mangrove jack	1	
Gobiidae	<i>Glossogobius aureus</i>	Golden goby	1?	
	<i>Glossogobius giurus</i>	Flathead goby	1?	
	<i>Glossogobius bicirrhosus</i>	Bearded goby		1
	<i>Glossogobius</i> sp. 1	Mountain goby		1
	<i>Awaous acritosus</i>	Roman-nosed goby	1	
	<i>Mugilogobius notospilus</i>	Pacific mangrove goby	1	
	<i>Redigobius bikolanus</i>	Speckled goby		1
	<i>Sicyopterus lagocephalus</i>	Rabbithead goby		?
	<i>Stenogobius</i> cf. <i>watsoni</i>		?	?
	<i>Schismatogobius</i> sp.	Scaleless goby		1?
Eleotridae	<i>Eleotris melanosoma</i>	Ebony gudgeon	?	?
	<i>Eleotris fusca</i>	Brown gudgeon		
	<i>Eleotris acanthopoma</i>		?	?
	<i>Bunaka gyrinoides</i>	Greenback gauvina	?	?
	<i>Hypseleotris compressa</i>	Empire gudgeon	1	

Table 3: Fyke net sampling design in five floodplain lagoons of the Tully-Murray River, May 2008 to May 2009. The score refers to the number of paired fyke nets deployed in each lagoon.

Habitat	Barrett's	Digman's	Selby's	Zamora's	Kyambul
Lagoon margin	3	2	3	2	2
Channel (inlet)	-	1	-	1	1
Channel (outlet)	1	1	1	1	1

6. Demonstration of movement dynamics in the Tully-Murray fish assemblage

6.1 Background

In the previous MTSRF study of the Tully-Murray wetlands, Pearson and colleagues (2010a) sampled plankton, invertebrates and fish regularly in a number of lagoons, and found that connectivity was a key issue for the ecology of this waterway complex. Data from five lagoons were used to illustrate the influence of season and hydrology on changes in the size structure in several fish species that migrate between channel and floodplain habitats during their life history. The intent was to demonstrate the importance of connectivity for fish populations and the fish assemblages living in floodplain lagoons. Subsequently, we aimed to demonstrate actual movements by sampling in connecting drains immediately after a flood. We were also interested in whether fish used drains and lagoons as spawning habitat. Here we outline the results of these studies.

6.2 Methods

Up to three pairs of dual winged, fine-mesh fyke nets were set facing bi-directionally (i.e. back-to-back) around the margin of each of five lagoons in areas of about one to two metres depth, with the tips of the wings approximately five metres apart (Figure 5). In addition, pairs of nets were set where inlet and outlet channels meet each lagoon (Table 3, page 16). Fyke nets had two wings, each two metres long, by 1.5 metres deep, with five supporting hoops (0.5m diameter) and a stretched mesh size of two millimetres. The nets were deployed at midday and retrieved approximately 24 hours later. The duration of sampling was noted for each net for subsequent calculation of standardised abundance, where abundance represented the number of individuals collected per net set per 24 hour soak time.

An experiment was conducted in a floodplain channel between 28 and 31 October 2009 to identify the critical water depth that is required for fish to move through channels between floodplain habitats during the non-flood period. This information was used to inform CSIRO hydrologists (from MTSRF Project 3.7.4) in setting the minimum depth parameter for the one-dimensional hydrodynamic model for simulating connectivity between floodplain lagoons and the channel network in the Tully-Murray river system (Karim *et al.* 2010).

All fishes collected by fyke netting were placed into a plastic sorting tray and those that could be identified were individually measured (standard length, L_s) and released alive at the point of capture (except alien fishes which were euthanised on site in accordance with the Queensland Fisheries Act 1994). In the case of very large catches, a random sub-sample of one hundred individuals was preserved in a solution of 10% formalin (37% aqueous solution of formaldehyde, diluted in water) for identification and length measurement in the laboratory. Individuals representing the early developmental stages were also preserved in formalin for subsequent identification in the laboratory. Preserved fish were taken to the laboratory, where they were identified to species, counted and measured using a dissecting microscope and eyepiece graticule.

Two species – the black catfish *Neosilurus ater* and empire gudgeon *Hypseleotris compressa* (Figure 6) – illustrate the diversity of reproductive strategies that involve migration between floodplain, channel and estuarine habitat in Wet Tropics river-floodplains and are used here to demonstrate the influence of hydrological connectivity on their population dynamics. The catfish migrate to breeding habitat contained in tributary streams and on the floodplain (Pusey *et al.* 2004b, Pearson *et al.* 2010a), while the empire gudgeon migrates

downstream from freshwater habitat and spawns in the estuary and in near-shore marine environments (P. Godfrey, unpublished data). Juveniles of both species recruit into the permanent floodplain lagoons during the non-flood period via an extensive network of natural channels and cane drains (Pearson *et al.* 2010a). Hydrological connectivity diminishes with the passage of the dry season (Karim *et al.* 2010) restricting the extent of fish movement between floodplain habitats (Pearson *et al.* 2010a).



Figure 5: Location of fyke netting at the inlet channel to Digman's Lagoon.

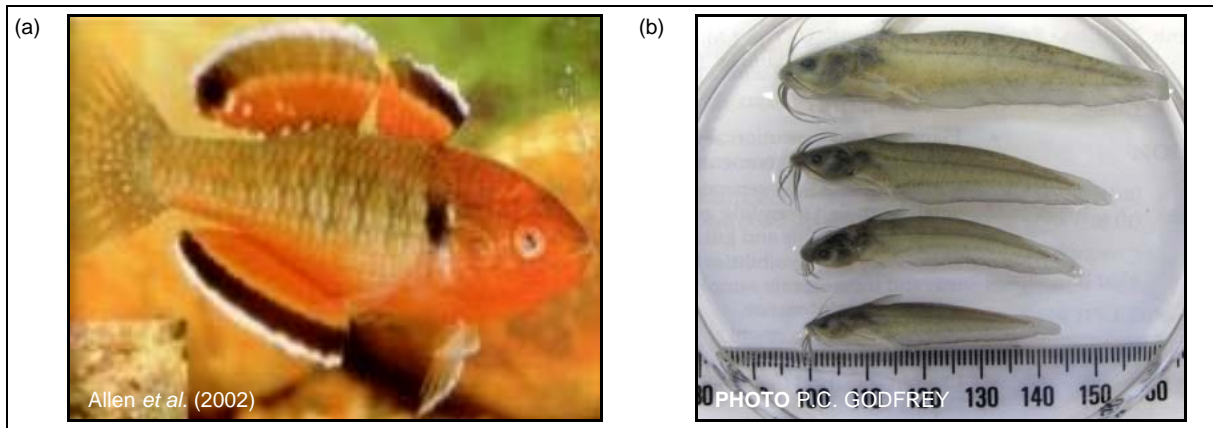


Figure 6: (a) Adult *Hypseleotris compressa*, and (b) a developmental series for *Neosilurus ater*.

A modified version of the fyke net described above was deployed in five channels up- and downstream of Digman's, Selby's, Bunta and Zamora's lagoons and in the Murray River (Figure 6a). The modified fyke nets were set for three-hour intervals at a series of random positions along each water course in water depth ranging 10-170 mm. Water depth was measured to the nearest millimetre with a ruler at the commencement and conclusion of the three-hour trapping period to capture change in depth over time (Figure 6b). The water depth reported in the results is the average of these two depth values. Fishes collected in each net were identified, grouped into developmental stage and relocated to lagoon habitat located upstream/downstream to minimise the opportunity of their recapture over the remaining sampling period.

6.3 Results

Data for *Neosilurus ater* were only presented from Digman's Lagoon because this species was patchily distributed among lagoons/channels across the Tully-Murray catchment. Fish length and abundance data recorded from nets positioned at the inlet and outlet habitat were compared with data collected from nets positioned in the lagoons to compare differences in the abundance and size structure of *N. ater* between channel and lagoon habitats. Data are presented as an average across n number of nets deployed in the channel and lagoon habitat. Recruitment patterns for the empire gudgeon are presented from data collected across all five lagoons given their wide distribution across the catchment. These five lagoons represent a gradient of hydrological connectivity between the lagoons and channel network from lagoons that remain permanently connected to those that disconnect with the passage of the dry season (Karim *et al.* 2010). A similar comparison of length and abundance of fishes recorded in channel and lagoon habitats is presented for *H. compressa*, although only data collected from the outlet channel (capturing upstream migration from the estuary) was included.

There was a five-fold increase in the number of *N. ater* recorded in the channels surrounding Digman's Lagoon between November 2008 and March 2009. A similar pattern of change in abundance was evident in Digman's Lagoon over this period although the increase in fish numbers was smaller in the lagoon than in the channel (Figure 8). There was a corresponding fall in mean length of the population recorded in both habitats over time with the population marginally smaller in the channels than in the lagoon. The populations of *N. ater* were of comparable length and in similar numbers in May 2008 and May 2009, suggesting a strong cyclic pattern in its population dynamics. Although the precise location of spawning in *N. ater* was not identified, it appears that reproduction occurs over the wet

season in habitat surrounding Digman's Lagoon and is followed by juveniles migrating to the lagoon via the surrounding channel network on the declining limb of the wet-season hydrograph.

The population dynamics of *H. compressa* were influenced by the seasonal pattern of river discharge and potentially by the extent of hydrological connectivity between the lagoon, the stream network and the estuary. There was inter-annual variation in the timing of larvae/juvenile *H. compressa* first appearing in each of the five lagoons (Figure 9). Larval/juvenile *H. compressa* were not detected across all five lagoons prior to July in 2008 whereas these life-history stages occurred in (or were recorded entering) all five lagoons by May 2009 (i.e. two months earlier than in the previous year). This may indicate that spawning occurred several months earlier in 2009 than in 2008, or that the upstream migration of the new recruits was inhibited in 2008, delaying their arrival in the lagoons by several months.

Variation in the extent of hydrologic connectivity between the lagoons and the stream network during the period of channelised flow appeared to contribute to spatial differences in the mean length of *H. compressa*. The recruitment of larval/juvenile *H. compressa* between May and July 2008 resulted in a shorter average length in the population of empire gudgeon across all five lagoons (Figure 9). The pattern of change in mean population size of *H. compressa* over subsequent surveys varied among lagoons and was influenced by the extent of larvae/juvenile recruitment into each of the five lagoons. An increase in mean length of *H. compressa* was detected in Digman's and Kyambul lagoons between July and September while this trend was delayed by three months in Barrett's and Selby's lagoons.

Hydrological modelling during 2007 (i.e. the year preceding the biological investigation) illustrates the existence of a gradient in hydrological connectivity among floodplain lagoons that is driven by spatial variation in rainfall, elevation and lagoon position of the floodplain with respect to the Tully and Murray rivers (F. Karim, pers. comm.). The most probable explanation for the difference in size structure of *H. compressa* among lagoons over 2008 and 2009 is the variation in the timing and duration of connectivity that exist between individual lagoons and the stream network.

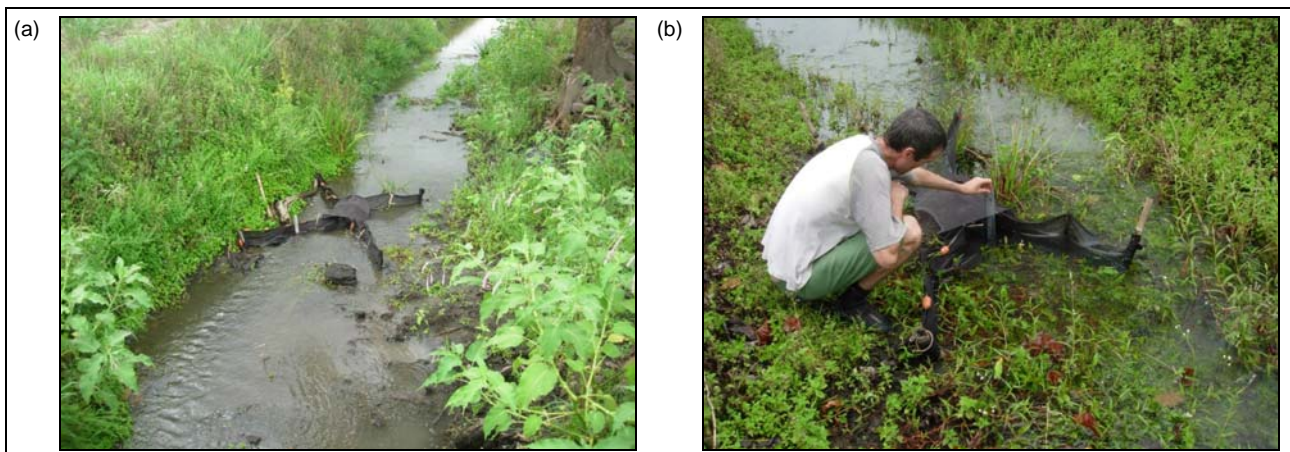


Figure 7: (a) Modified fyke net set in a drain, and (b) measurement of water depth at the net mouth.

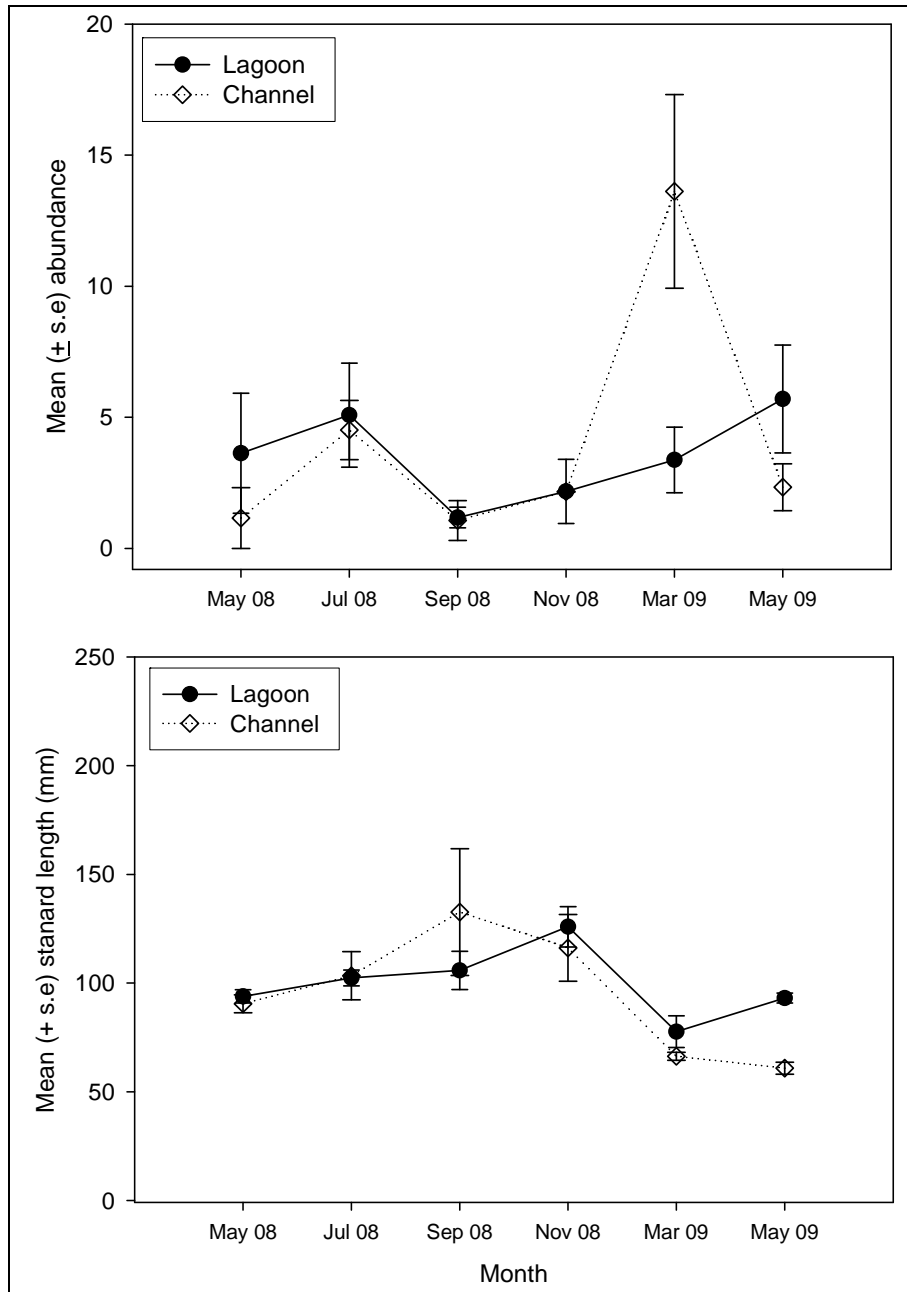


Figure 8: Abundance and standard length plots for *Neosilurus ater* recorded in Digman's Lagoon and channel on six sampling occasions, May 2008 to May 2009. Fish abundance is averaged across the nets deployed in each habitat.

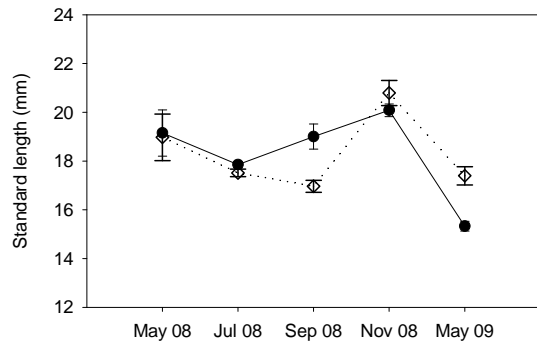
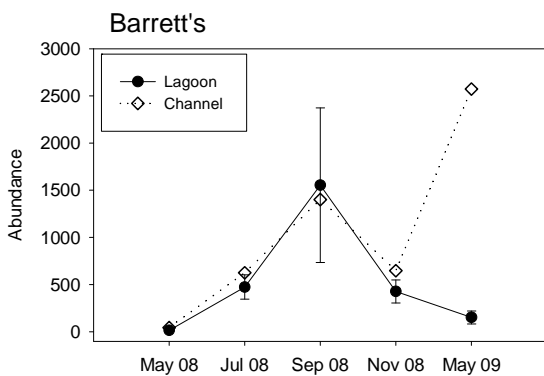
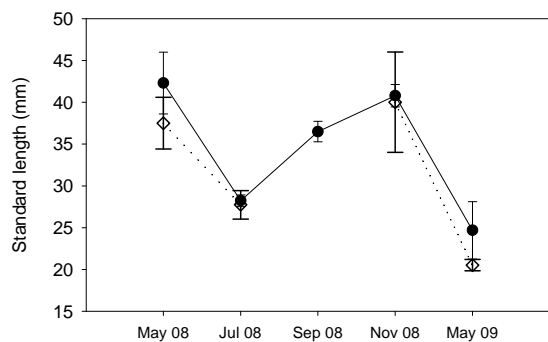
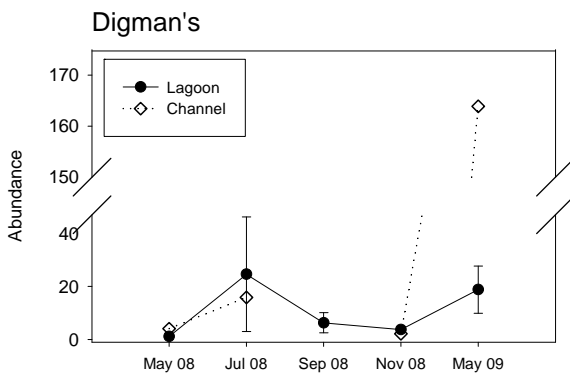
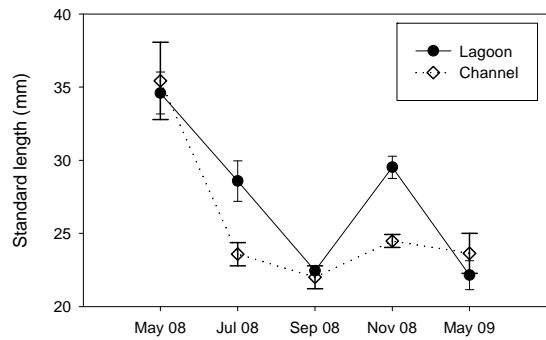
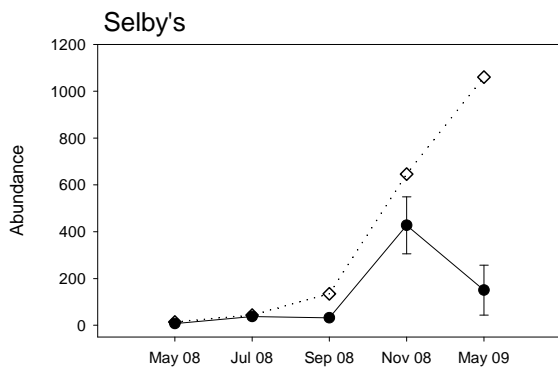
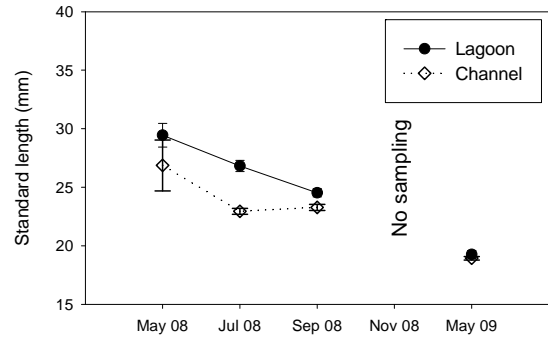
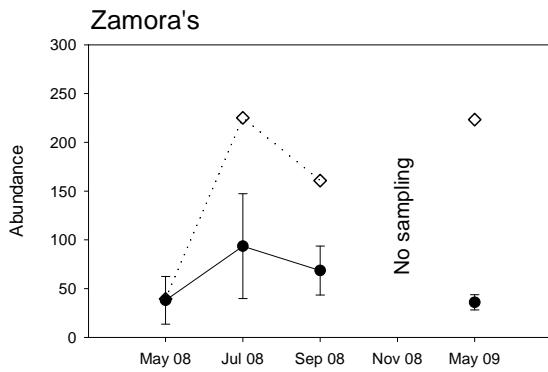
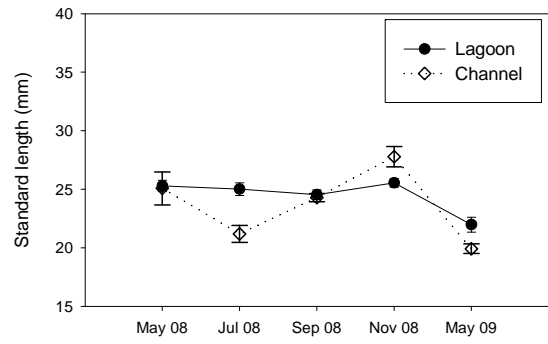
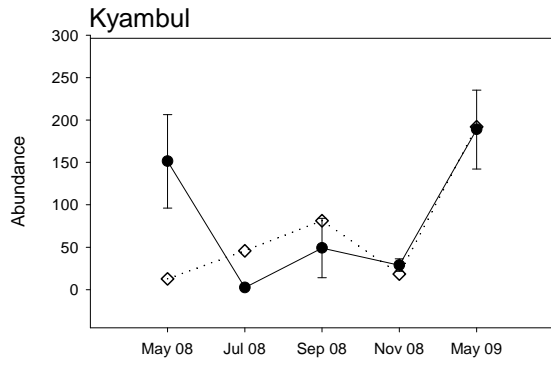


Figure 9 (Page 22): Abundance and standard length plots for *Hypseleotris compressa* recorded in five lagoons on five sampling occasions. Lagoon fish abundance is presented as the mean (\pm s.e.) of five nets.

A total of 518 fish representing eight species (within five families) were recorded in fyke nets in the depth experiment (Table 4). *Hypseleotris compressa* (71%) and *Hypseleotris* sp. 1 (19%) collectively contributed 90% of all fish recorded in the modified fyke nets, which reflects the patterns of fish abundance from the floodplain lagoons.

Table 4: Number of fish recorded in fyke nets in five floodplain channels on the Tully-Murray floodplain, October 2008.

Species	Developmental stage	Total abundance
<i>Craterocephalus stercusmuscarum</i>	Juvenile	5
<i>Melanotaenia s. splendida</i>	POF/ML	1
<i>Melanotaenia s. splendida</i>	Juvenile	7
<i>Pseudomugil gertrudae</i>	Juvenile/adult	1
<i>Pseudomugil signifer</i>	Adult	5
<i>Glossamia aprion</i>	Juvenile	3
<i>Hypseleotris compressa</i>	Juvenile	369
<i>Hypseleotris</i> sp. 1	POF/ML	89
<i>Hypseleotris</i> sp. 1	Juvenile/adult	7
<i>Mogurnda adspersa</i>	Juvenile	31

Figure 10 illustrates the relationship between fish abundance and channelised water depth from data aggregated among the five channel sites. Five of the eight species were recorded in nets set in less than 25 mm of water including *Melanotaenia s. splendida* (20 mm), *H. compressa* (15 mm), *Hypseleotris* sp. 1 (15 mm), *Mogurnda adspersa* (10 mm) and *Pseudomugil signifier* (10 mm).

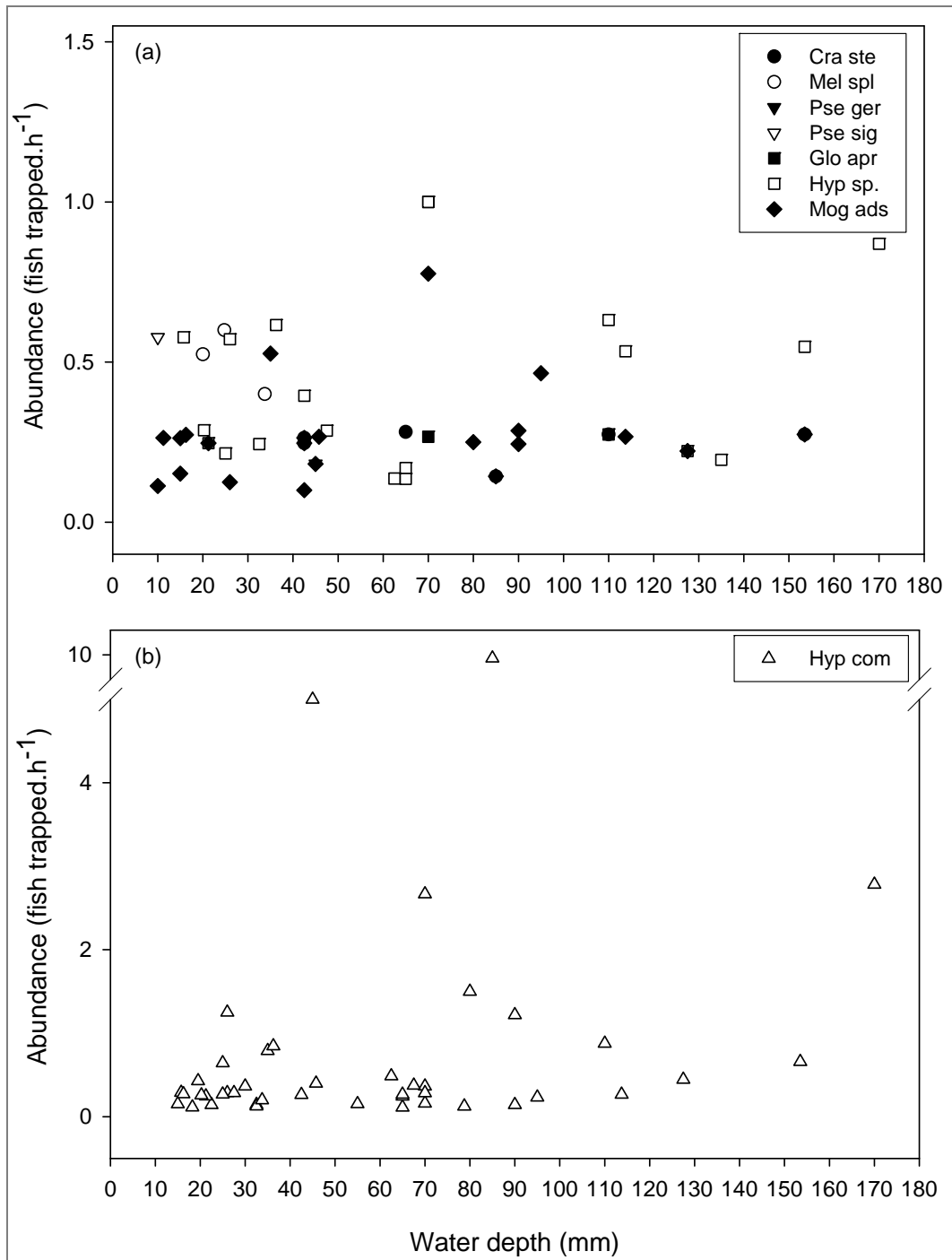


Figure 10: Relationship between channelised water depth (mm) and fish abundance for (a) six fish species, and (b) *Hypseleotris compressa*. Species abbreviations represent the first three letters of the generic and species epithets (see Table 1 for full nomenclature).

7. Discussion

This synthesis of published and newly derived knowledge aimed to define the connectivity issue for the GBR catchment, and presents some early thinking as to how it may impinge on ecosystem health and fish assemblages across systems. We also discuss the ecological implications of loss of connectivity, or impaired connectivity, in the face of environmental impacts, especially river flow regulation, and global climate change.

7.1 Landscape and connectivity patterns of the GBR catchment

The Marine Catchment Basin concept – based on Caddy (2000) – presents a useful model of the key zones of a coastal catchment, and a construct to compare and contrast biophysical processes across these zones. This report has identified the characteristics and processes of these zones, including the freshwater river reaches upstream of the lowland floodplain, the lowland river reaches, floodplains with freshwater wetlands, the estuary with salt-tolerant riparian vegetation and brackish wetlands, the river plume extending seaward and coastal waters beyond the river plume. Our knowledge of the first four zones and their ecological processes has been compared across the Wet and Dry Tropics, based on published literature, and our ongoing research.

We promote the fact that there are clear and strong connectivity patterns and processes between and across these zones, extending from small headwater streams to estuaries and from intermittent wetlands to permanent lagoons. This continuum of aquatic habitat is sustained by the hydrological cycle of rainfall, surface and groundwater storage, and surface and groundwater flow. This connectivity continuum is not always permanent and may be broken by barriers created by natural processes such as drying of waterways in the dry season or, for some elements of the system, by waterfalls. Human developments have also created substantial barriers to connectivity in many area of the GBR catchment.

7.2 Importance of connectivity to fish

Fish and other animals (from shrimps to river dolphins) use different habitats at different times, and longitudinal migrations may be an obligatory component of life histories, especially if migration is associated with breeding. Longitudinal migrations may occur within a river, and to and from river and sea or lake. All such movements put animals at risk from physical, chemical and biological stress in various parts of their habitat at different times. Long-lived species with low reproductive rates are likely to be the most vulnerable to barriers. The presence of an impassable barrier can lead to isolation of populations, failed recruitment, reduced gene flow and local extinction of fish and other aquatic biota (Hughes *et al.* 2009; Northcote, 2010). Diadromous fishes, which migrate long distances within the main channels and larger tributaries of rivers (and to and from oceans), are particularly sensitive to barriers to longitudinal passage because obstruction of their migratory pathways may interfere with the completion of the life cycle (McDowall, 2006).

The effects of dams on migratory fish vary with the position of an impoundment within its catchment. Barriers to movement situated in low-lying parts of catchments may cause isolation or extirpation of all or most upstream migratory species. A series of barrages and dams starting at the estuary/freshwater interface, as many do, and built at intervals along the lower reaches of a large river may progressively filter out migratory species. A large dam in the headwaters of a river system can affect the flow regime of the entire river and disrupt dispersal right to its footings by altering cues to movement and the availability of suitable depths and velocities for fish passage. In highly fragmented rivers with many dams, only

small portions of previously large, viable populations may remain. Isolating fishes in short stream fragments increases the chances that random environmental events such as a severe drought will extirpate these populations from the basin (Rieman and McIntyre, 1995). Thus, even if a species is still present after regulation it may be more vulnerable to local extinction events, and its isolation because of habitat fragmentation may inhibit recolonisation from previously connected river basins. Connectivity with other basins is critical to provide demographic support and gene flow among populations (Fausch *et al.* 2010).

The impact of barriers on mobile organisms is not confined to very large structures. Even small in-stream barriers, such as v-notch gauging weirs, can impede the movement of fish, for example the western minnows *Galaxias occidentalis* in forest streams of south-west Australia (Pusey *et al.* 1989). Invertebrates as well as fish can be affected by barriers to upstream movement. Damming of the lower reaches of one of the main drainages of the Caribbean National Forest in Puerto Rico has had a major impact on shrimp recruitment. More than fifty percent of migrating larvae were drawn into water intakes for municipal supplies, and juvenile shrimps returning upstream faced severe predation below the dam (Pringle and Scatena, 1999). Cessation of water abstraction during evening periods of peak nocturnal larval drift, upkeep of a functional fish ladder, and maintenance of a minimum flow could significantly reduce impacts of the dam and its operations.

In this report we have reviewed current knowledge about the ecological requirements of fish of the GBR catchment, especially with regard to movements and the need for connectivity pathways between estuarine, riverine and wetland habitats. Some fish spend most of their adult lives in fresh waters (e.g. jungle perch) while others are opportunistic but nevertheless important components of the freshwater assemblage when access is available (e.g. mangrove jack).

Two species – black catfish *Neosilurus ater* and empire gudgeon *Hypseleotris compressa* – illustrate the diversity of reproductive strategies that involve migration between floodplain, channel and/estuarine habitat in Wet Tropics river-floodplain. They thus demonstrate the influence of hydrological connectivity on reproductive strategies and population dynamics.

The neosilurid catfish migrates to breeding habitat in tributary streams and wetlands on the floodplain (Pusey *et al.* 2004b; Pearson *et al.* 2010a), Although the precise location of spawning in *N. ater* was not identified during this study, it appears that reproduction occurs over the wet season in habitat surrounding Digman's Lagoon. Juveniles then migrate to the lagoon via the surrounding channel network as floods recede.

In contrast, the empire gudgeon migrates downstream from freshwater habitat and spawns in the estuary and near-shore marine environment (P. Godfrey, unpublished data). Juveniles of both species recruit into the permanent floodplain lagoons during the non-flood period by moving through an extensive network of natural channels and cane drains (Pearson *et al.* 2010a). The most probable explanation for differences in size structure of *H. compressa* among lagoons over 2008 and 2009 is the variation in the timing and duration of connectivity that exist between individual lagoons and the stream network. Hydrological connectivity diminishes with the passage of the dry season (Karim *et al.* 2010) restricting the extent of fish movement between floodplain habitats (Pearson *et al.* 2010a).

MTSRF research on the Tully-Murray floodplain recorded clear seasonal variation in the fish assemblage structure with the temporal changes being driven in part by the appearance of new recruits in floodplain lagoons. Two broad fish recruitment strategies have been identified within the lagoon fish assemblage – freshwater species that recruit *in situ* and those that migrate between the estuary/marine environment and floodplain lagoons. These findings add to the growing body of knowledge that coastal floodplain lagoons provide habitat for the early

life-history stages of several iconic species (e.g. the barramundi, *Lates calcarifer*) and species of conservation significance (Pusey *et al.* 2004b; Gehrke and Sheaves, 2006). Differences in the extent of hydrologic connectivity among individual lagoons and the estuary (via the stream network) clearly contribute to the differences in fish assemblage structure across the ten lagoons studied (Gehrke and Sheaves, 2006; Karim *et al.* 2010b). These relationships are all potentially subject to disruption by environmental change.

Early results from this MTSRF funded project suggest that most fish species are able to move through shallow streams and cane drains at depths of about ten centimetres. The Catchment to Reef program found that changes in stream habitat structure associated with immersion tolerant alien vegetation appeared to inhibit the upstream migration of fish species with a marine or estuarine interval in their life history (Pusey *et al.* 2007b). Natural streams and cane drains on the floodplains of Wet and Dry Tropics rivers appear to be vulnerable to plant invasion and blockage such that fish movements may be inhibited. Again, such connections are vulnerable to future environmental change and this aspect of connectivity warrants further investigation.

7.3 Links between catchment and reef

This section is derived from Pearson and others (2010a). The Tully-Murray lagoons investigated in this project are discrete permanent waterholes but, as we have shown, they are not disconnected from other water bodies or from the surrounding and distant parts of the landscape. They have clear connections with riverine and marine systems. The lagoons have many characteristics in common, but each lagoon also has its own characteristics, partly reflected in the biota. Each links to other systems by the network of natural waterways and drains, and each links to its immediate surroundings and catchment through direct inputs of materials, and through surface and groundwater flow. The lagoons might, then, be regarded as replicated systems nested within a pool of possible systems, lying within a catchment. Thus we expect the catchment to influence the condition of the lagoons via overland, in-stream and groundwater transport. The character of each lagoon is therefore a reflection of the character of its surroundings. The extent of these surroundings (immediate or distant) depends on connectivity via the surface and subsurface water regime.

Catchment links can vary substantially from system to system. With the regular flows in the Tully-Murray system, there is frequent if not constant connectivity among elements of the freshwater landscape. In contrast, where flows are much more seasonal, as in the Burdekin system (Pusey and Arthington, 1996; C. Preite, M. Blanchette and R.G. Pearson, unpublished data), or at a much smaller scale, in intermittent stream pools (Smith and Pearson, 1987), pools and lagoons can quite substantially diverge in character as local factors come into play. The lack of differentiation observed in the aquatic communities in the Tully-Murray reflects this regular or constant connectivity and at least partial melding of characteristics and biota.

The sites described here form part of a complex of wetlands in the Tully-Murray floodplain that interlink across the landscape, into the Tully and Murray rivers and estuaries and thereby into the GBR lagoon (Figure 10). The catchment and its waterways are traditionally regarded as the source of materials (contaminants) for marine waters, and over recent years have received much attention (including through the MTSRF program) focused on reducing anthropogenically enhanced delivery of these materials. This focus on delivery has taken little notice of the importance of streams and wetlands in slowing or retaining these materials through a variety of processes, especially during non-flood periods; instead they have been regarded as simple conduits.

The extent of the connectivity between catchment waterways and the GBR lagoon discussed in this report needs to be further quantified so that we might manage it as part of the 'Greater Barrier Reef' system. Figure 11 indicates the range of scales that are involved in this physical and ecological connectivity.



Figure 11: The complexity of interactions within and between catchment and reef, showing various scale of processes, with physical and ecological linkages between components at each scale.

7.4 How will future scenarios (flow, land use, etc.) affect connectivity?

Flow regime alterations and human influences on floodplain hydrology typically translate into changes in floodplain habitat structure, connectivity and quality and hence, ecological responses of aquatic biota (e.g. Junk *et al.* 1989; Overton *et al.* 2006). The freshwater and estuarine fishes of the tropical floodplains and wetlands of the Queensland Wet and Dry Tropics are likely to be impacted by marked losses in habitat, connectivity and water quality brought about by floodplain modifications and climate change. However, these possible effects of various climate predictions have not yet been analysed.

Predictions for climate change in the tropics of Queensland suggest higher temperatures, as globally, and more seasonal rainfall, although the rainfall predictions have a high degree of uncertainty (Suppiah *et al.* 2007). Higher temperatures may be expected to increase stress in waterways which are already at temperatures close to the physiological tolerance of species – this is likely in the Dry Tropics especially, but even in the Wet Tropics, distributions of organisms are partly governed by temperature. For example, it appears that some caddisfly and stonefly species are restricted to cool uplands (Pearson, 2005), like many terrestrial vertebrates (Williams and Pearson, 1997). Increased seasonality of the rainfall may be exacerbated by a separate process: increased atmospheric temperature will raise the cloud layer, reducing the interaction of clouds with mountain ranges, and reducing associated rainfall and particularly cloud interception, which can account for a large proportion of stream flow in the dry season (McJannet *et al.* 2007). As the small headwater streams account for a large proportion of stream length in a catchment (S. Januchowski and R.G. Pearson, unpublished data), this loss of flow could be significant, with loss of habitat and connectivity for many species, including species that move between streams and estuaries. Furthermore, much of the organic matter that is at the basis of the food web, especially in the upper catchment, is generated through instream processing of allochthonous litter, by microbes and invertebrates (Cheshire *et al.* 2005; Boyero *et al.* 2006). Loss of stream habitat through drying

could severely affect these processes. Warming of streams may also have substantial effect on such processes, causing a change from invertebrate-dominated to microbe-dominated decomposition, with potentially substantial effects on carbon sequestration (Boyero *et al* 2011).

Climate change may well lead to changes in land use, which could change the level and type of impact on rivers and wetlands. Contrasts between the impacts of pastoralism, cropping, forestry, etc. that can be currently observed will likely apply under new scenarios. However, given the complexities of interactions for temperature, rainfall, flow and land use alluded to above, we can only speculate on the impacts on aquatic ecosystems until we have firmer predictions as to the nature of climate changes for the region.

Climate change may also lead to sea-level rise and further saltwater intrusion to freshwater rivers and wetlands. This is a major threat, given the substantial loss of wetlands following European colonisation of Australia and given the relatively small length of higher-order rivers on the floodplains. Currently we have no estimate of the possible extent of this problem under different climate scenarios.

7.5 Management of connectivity

Management of connectivity is clearly a fundamental need if we are to retain normal biodiversity and ecosystem processes. Strictly, this means maintaining natural connectivity, and lack of it – that is, maintaining natural barriers where they occur (this of course has a bearing on inter-basin transfer of water, which creates connectivity where it previously did not exist). But the main effort required is to maintain natural flows and linkages in rivers and other waterways, and to remove or otherwise mitigate the effects of anthropogenic barriers. Action plans should be developed to encourage strategic approaches. For example, action might be prioritised to address major bottlenecks first, such as large dams that block a great proportion of their catchments, and even apparently small structures like drop boards that may preclude access to large areas of wetland. Actions to consider include, as required:

- Restitution of normal flow regime, especially the cycle of flood, base flow and/or drought;
- By-passing or removing structures that impede movements of fish and flightless invertebrates (dams, weirs, drop boards, culverts) by means of fish ladders, fish ways, baffles, etc.;
- Removal of emergent vegetation that clogs streams and drains (e.g. para grass) by means of riparian shade, mechanical removal and/or herbicides;
- Removal of floating vegetation that can create hypoxic barriers to animal movement by preventing gas exchange with the atmosphere, by mechanical removal and/or pesticides or other chemical means (e.g. brine); and
- Removal of other physicochemical barriers such as hot or contaminated water from industry, wastes from feedlots, and so on.

Although there are engineering solutions to the barrier effects of dams (fish bypass facilities, locks, ladders and elevators), they seldom restore the original capacity of a river system to allow free movement of biota throughout the basin network (Lucas and Baras, 2001). Dams in tropical regions are generally constructed without appropriate fish ways or fish passes, or fish ways are based upon designs that are suitable only for salmonids, and thus they obstruct the migrations of fish with different swimming speeds and other necessary behavioural capacities (Roberts, 2001).

7.6 Indicators

Connectivity is, of course, only one of several processes that are vital to maintaining healthy ecosystems (Figure 12). Each component needs to be maintained to sustain normal biodiversity and ecological processes. Figure 12 shows how major processes interlink – from the natural physical environment and anthropogenic influences, through biophysical ecosystem processes, to management responses. Across these processes, monitoring and evaluation are possible by means of indicators. We have demonstrated appropriate indicators of ecosystem health for streams and wetland lagoons (Arthington and Pearson, 2007; Pearson *et al.* 2010a); here we have demonstrated that individual species' distribution and recruitment patterns (e.g. catfish, or empire gudgeon) can be appropriate indicators of connectivity for fishes among floodplain wetlands.

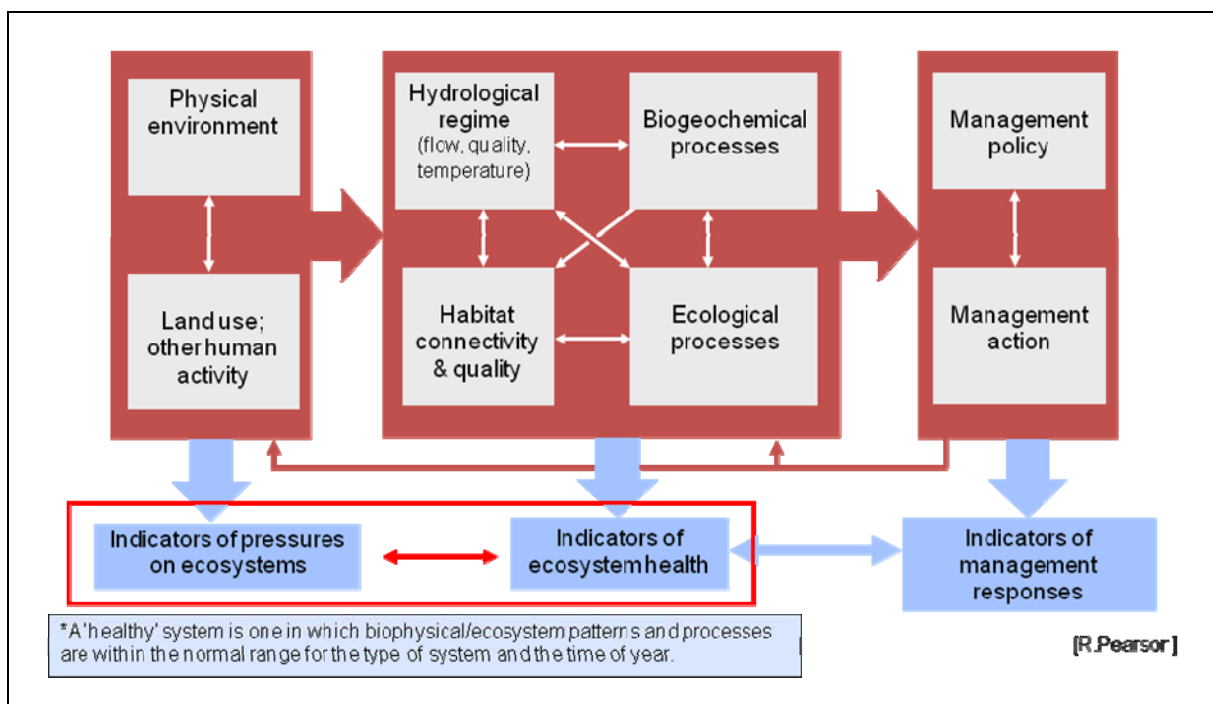


Figure 12: Conceptual model of a freshwater system and the links between the different drivers and processes.

7.7 Future research plans

MTSRF collaborative research between CSIRO Land and Water, James Cook University (JCU) and Griffith University has developed an exciting new application of hydrodynamic models to quantify the connectivity of floodplain wetlands and the impact of this on fish species that use connectivity pathways to access fluctuating wetland resources (Karim *et al.*, in review). These models offer the potential to predict the ecological implications of various scenarios of floodplain hydrological alteration on fish assemblages and recruitment patterns in wetlands. To further develop this area of research, a Postdoctoral Fellowship application has been submitted to the CSIRO/JCU to develop the following research program in collaboration with Griffith University:

1. Carry out new field measurements of fish (species, numbers, reproductive status, population age structure) in a range of wetland types;

2. Identify wetland types, habitat features and water quality characteristics that promote fish diversity and recruitment within wetlands;
3. Correlate spatial and temporal patterns of fish diversity and recruitment within wetlands with field evidence of directional movements along particular connectivity pathways;
4. Seek relationships with calculations of the timing, frequency, duration and spatial pattern of wetland connectivity (to be carried out by CSIRO Land and Water); and
5. Develop models that clarify the hydro-ecological links between catchment and reef environments.

We also need to have a much better understanding of how climate change might affect tropical river and wetland ecosystems. We need to establish how climate change will affect upland and lowland systems through changes in flow regimes, temperature, riparian vegetation and water quality (Pusey and Arthington, 2003; Pusey *et al.* 2005). As Pusey and colleagues (2004b) point out, “management in anticipation of future scenarios of change is required now, but is dependent on a high level of understanding of ecological and evolutionary processes in the Wet Tropics region”. Here we see a research imperative that links not only to climate and connectivity but to the full spectrum of ecological patterns and processes (Figure 12) across the aquatic environments of the tropics.

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Appendix 1

Table A1: Freshwater fish of GBR catchments: distribution, larval habitat and movement biology. ECY = eastern Cape York Peninsula; WT = Wet Tropics; CQ = central Queensland; FW = freshwater; E/M = estuarine or marine. Includes all freshwater obligates and predominant opportunistic E/M species.

Family	Species name	Common Name	Distribution			Larval habitat		Movement biology		Reference
			ECY	WT	CQ	FW	E/M	Adult	Young of the year	
Osteoglossidae	<i>Scleropages leichardtii</i>	Saratoga			1	1?		Little known about movement biology	?	Pusey <i>et al.</i> 2004
	<i>Scleropages jardinii</i>		1			1?				
Megalopidae	<i>Megalopes cyprinoides</i>	Tarpon	1	1	1		1	Movement associated with reproduction is downstream to estuarine/marine (E/M) spawning habitat	Seasonal phenology of upstream movement in leptcephali unknown	Davis, 1988; Pusey <i>et al.</i> 2004; Godfrey, unpublished data
								Spawning coincident with monsoonal wet season		
Anguillidae	<i>Anguilla obscura</i>	Pacific short-finned eel	1	1	1		1	Downstream passage to E/M spawning habitat	Temporal variability associated with upstream recruitment of glass eels/elvers	Pusey <i>et al.</i> 2004; Godfrey, unpublished data
								Size and age of spawning individuals unknown		
								Summer floods act as possible spawning migration trigger		
	<i>Anguilla reinhardtii</i>	Long-finned eel	1	1	1		1	Description of movement biology for <i>A. obscura</i> applies for <i>A. reinhardtii</i>	Upstream migration of glass eels/elvers occurs over an extended period	Shiao <i>et al.</i> 2002

Family	Species name	Common Name	Distribution			Larval habitat		Movement biology		Reference
			ECY	WT	CQ	FW	E/M	Adult	Young of the year	
Muraenidae	<i>Gymnothorax polyuranodon</i>	Freshwater moray		1			1	Unknown; adult are likely to move downstream to E/M spawning habitat	Unknown	Allen <i>et al.</i> 2002; Godfrey, unpublished data
Clupeidae	<i>Nematolosa erebi</i>	Bony bream	1	1	1	1		Migrate entirely in FW to still-water (backwaters and off-channel waterbodies) breeding habitat	Juveniles re-colonise	Bishop <i>et al.</i> 2001; Godfrey, unpublished data
								Increase in summer water temperature may influence spawning migration		
Ariidae	<i>Arius graeffei</i>				1	1	?	Unknown	Unknown	Pusey <i>et al.</i> 2004
	<i>Arius midgleyi</i>		1			1	?	Extensive lateral (and longitudinal) migration into floodplains during period of flood inundation	Unknown	Pusey <i>et al.</i> 2004
Plotosidae	<i>Neosilurus hyrtlil</i>	Hyrtl's catfish	1	1	1	1		Extensive lateral (and longitudinal) movement associated with spawning	Movement from ephemeral to permanent waterbodies on descending limb of wet season hydrograph	Pusey <i>et al.</i> 2004; Pearson <i>et al.</i> 2010
								Increase in river discharge stimulates spawning migration		

Family	Species name	Common Name	Distribution			Larval habitat		Movement biology		Reference
			ECY	WT	CQ	FW	E/M	Adult	Young of the year	
	<i>Neosilurus ater</i>	Black catfish	1	1	1	1		Extensive lateral (and longitudinal) movement associated with spawning	Movement from ephemeral to permanent waterbodies on descending limb of wet season hydrograph	Orr and Millward 1984; Pearson <i>et al.</i> 2010
								Increase in river discharge stimulate spawning migration		Pusey <i>et al.</i> 2004
	<i>Neosilurus mollespiculum</i>	Soft-spinned catfish			1	1		Inconclusive; location unknown; wet season spawners	Unknown	Pusey <i>et al.</i> 2004
	<i>Porochilus rendahli</i>	Rendahl's catfish	1	1	1	1		Lateral migration to floodplain (lagoons) spawning habitat		Bishop <i>et al.</i> 2001; Pusey <i>et al.</i> 2004
	<i>Tandanus tandanus</i>	Eel-tailed catfish		1	Translocated	1		None known in WT; spawning occurs in rainforest streams over dry season baseflow conditions	Unknown	Pusey <i>et al.</i> 2004; Godfrey, unpublished data
Hemirhamphidae	<i>Arrhamphus sclerolepis</i>	Snub-nosed garfish		1	1	1	?	Unknown	Unknown	Pusey <i>et al.</i> 2004
Belonidae	<i>Strongylura krefftii</i>	Freshwater long-tom		1	1	1		Lateral movement into floodplain habitats occurs although it's unknown if this movement is associated with spawning	Unknown	Bishop <i>et al.</i> 2001; Godfrey, unpublished data

Family	Species name	Common Name	Distribution			Larval habitat		Movement biology		Reference
			ECY	WT	CQ	FW	E/M	Adult	Young of the year	
Atherinidae	<i>Craterocephalus s stercusmuscarum</i>	Fly-specked hardyhead	1	1	1	1		Limited evidence of spawning migration	Extended breeding season in floodplain lagoons; peak spawning activity in perennial streams occurs over dry season	Pusey <i>et al.</i> 2004; Pearson <i>et al.</i> 2010
Melanotaeniidae	<i>Cairnsichthys rhombosomoides</i>	Cairns rainbowfish		1		1		Migration limited in extent; no known spawning migration		Pusey <i>et al.</i> 2004
	<i>Melanotaenia s splendida</i>	Eastern rainbowfish	1	1	1	1		Laterally and longitudinal migration observed in highly seasonal environments; none observed in perennial flowing systems.		Pusey <i>et al.</i> 2004
	<i>Melanotaenia eachamensis</i>	Lake Eachan rainbowfish		1		1		No information available on the extent or pattern of movement	Extended breeding season in floodplain lagoons; peak spawning activity in perennial streams occurs over dry season	Pusey <i>et al.</i> 2004
	<i>Melanotaenia utcheesis</i>	Utchee Creek rainbowfish		1		1		No information available on the extent or pattern of movement	Greatest larval production occurs prior to the onset of the wet season	Pusey <i>et al.</i> 2004
	<i>Melanotaenia maccullochi</i>	MacCulloch i's rainbowfish	1	1		1		No information available on the extent or pattern of movement		Pusey <i>et al.</i> 2004

Family	Species name	Common Name	Distribution			Larval habitat		Movement biology		Reference
			ECY	WT	CQ	FW	E/M	Adult	Young of the year	
Pseudomugilidae	<i>Pseudomugil signifer</i>	Pacific blue-eye	1	1	1	1		None known		Pusey <i>et al.</i> 2004
	<i>Pseudomugil gertrudae</i>	Spotted blue-eye	1	1		1		None known		
Syngnathidae	<i>Hippichthys heptagonus</i>	Reticulated freshwater pipefish		1			1	None known	Post-flexion larvae drift from freshwater to brackish/estuarine natal habitats in perennial flowing WT systems	Godfrey, unpublished data
	<i>Microphis brachyurus brachyurus</i>	Short-tailed river pipefish					1	None known	Movement pattern as per <i>H. heptagonus</i>	Godfrey, unpublished data
Synbranchidae	<i>Ophisternon gutturale</i>	One-gilled swamp eel		1		1?		None known		
	<i>Ophisternon</i> spp. ?		1	1	1	1?		None known		Pusey <i>et al.</i> 2004; Carter and Tait 2008
	<i>Monopterus albus</i>		1	1	1	1?		Reported moving overland between waterholes		Pusey <i>et al.</i> 2004
Scorpaenidae	<i>Notesthes robusta</i>	Bullrout		1	1		1	Downstream movement to E/M of reproductively mature individuals	Larvae/juveniles migrate upstream on the declining limb of the flood hydrograph in WT systems	Pusey <i>et al.</i> 2004; Godfrey, unpublished data

Family	Species name	Common Name	Distribution			Larval habitat		Movement biology		Reference
			ECY	WT	CQ	FW	E/M	Adult	Young of the year	
								Stimulus and phenology of downstream movement unknown		
Chandidae	<i>Ambassis agassizii</i>	Agassiz's glassfish		1	1	1		Little quantitative information concerning movement biology		Pusey <i>et al.</i> 2004
	<i>Ambassis agrammus</i>	Sailfin glassfish	1	1	1		1	Possible movement downstream from tributaries to main channel habitat associated with spawning	Upstream movement occurs after hatching in brackish water of the main river channel over the dry season	Pusey <i>et al.</i> 2004; Godfrey, unpublished data
	<i>Ambassis miops</i>	Flag-tailed glassfish	1	1			1	None known although downstream migration may occur as per <i>A. agrammus</i>	Migration pattern as per <i>A. agrammus</i>	Pusey <i>et al.</i> 2004; Godfrey, unpublished data
	<i>Denariusa bandata</i>	Pennyfish	1	1		1		Little evidence of migration between habitats		Pusey <i>et al.</i> 2004
Centropomidae	<i>Late calcarifer</i>	Barramundi	1	1	1		1	Young males make downstream migration prior to spawning after spending 3-5 years in freshwater	Larvae drift from estuaries/inshore marine habitat to supralittoral swamps near river mouth where they develop over several months	Pusey <i>et al.</i> 2004; Russell and Garrett 1983, 1985
								Spawning takes place in elevated salinity	Migrate to tidal creeks/wetlands (and beyond); disperse widely across freshwater habitat during 1+	

Family	Species name	Common Name	Distribution			Larval habitat		Movement biology		Reference
			ECY	WT	CQ	FW	E/M	Adult	Young of the year	
Percichthyidae	<i>Macquaria ambigua</i>				Translocated	1				Pusey <i>et al.</i> 2004
	<i>Guyu wujalwujalensis</i>	Bloofield River cod		1		?		None known	None known	Pusey <i>et al.</i> 2004
Terapontidae	<i>Amniataba percooides</i>	Barred grunter	1	1	1	1		Varied in extent and phenology; no obligatory spawning movement		Pusey <i>et al.</i> 2004
	<i>Leiopotherapon unicolor</i>	Spangled perch	1	1	1	1		Movement associated with reproduction occurs up-, downstream and laterally over the start of the wet season		Pusey <i>et al.</i> 2004
	<i>Hephaestus fuliginosus</i>	Sooty grunter	?	1	1	1		Movement associated with reproduction occurs upstream in Queensland Rivers, in Wet Tropics spawning occurs in tributary streams	Y-O-Y possibly migrate downstream from tributary streams to main channel rivers	Pusey <i>et al.</i> 2004
								Adults may return to main channel habitats after spawning in tributary streams		
	<i>Hephaestus tulliensis</i>	Tully grunter		1		1		Movement as per <i>H. fuliginosus</i>	Movement as per <i>H. fuliginosus</i>	Pusey <i>et al.</i> 2004
	<i>Scortum hillii</i>	Leathery Grunter			1	1		Upstream migration prior to spawning		Pusey <i>et al.</i> 2004

Family	Species name	Common Name	Distribution			Larval habitat		Movement biology		Reference
			ECY	WT	CQ	FW	E/M	Adult	Young of the year	
	<i>Scortum parviceps</i>	Small-headed grunter			1	1		Limited evidence suggests suggests a compenstarory upstream migratory migration prior to spawning		Pusey <i>et al.</i> 2004
Kuhliidae	<i>Kuhlia rupestris</i>	Jungle perch	1	1	1		1	Adults move downstream to E/M spawning habitat	Juveniles migrate on the declining limb of the wet season hydrograph	Pusey <i>et al.</i> 2004; Godfrey, unpublished data
								Timing of movement unknown		
Apogonidae	<i>Glossamia aprion</i>	Mouth almighty	1	1	1	1		Not observed to move widely	None known	Pusey <i>et al.</i> 2004
Lutjanidae	<i>Lutjanus argentimaculatus</i>	Mangrove jack	1	1	1		1	Downstream movement to off-shore marine spawning grounds - extent and phenology unknown	Upstream movement of juveniles occurs over th elevated and declining limbs of the wet season hydrograph.	Carter <i>et al.</i> 2008, Rayner <i>et al.</i> 2008; Russell and McDougall 2005
Toxotidae	<i>Toxotes chatareus</i>	Seven-spot archerfish	1	1	1	1		No spawning migration none; small scale movements in search of food observed		Pusey <i>et al.</i> 2004; Carter and Tait 2008, 2008, Rayner <i>et al.</i> 2008
Gobiidae	<i>Glossogobius aureus</i>	Golden goby	1	1			1	Adults migrate downstream to marine breeding habitat; extent and timing unknown	Unknown	Pusey <i>et al.</i> 2004; Godfrey, unpublished data

Family	Species name	Common Name	Distribution			Larval habitat		Movement biology		Reference
			ECY	WT	CQ	FW	E/M	Adult	Young of the year	
	<i>Glossogobius giurus</i>	Flathead goby	1	1	1		1	Migration pattern as per <i>G. aureus</i>	Unknown	Pusey <i>et al.</i> 2004
	<i>Glossogobius bellendenensis</i>	Mulgrave River goby		1		1		No spawning migration known; can complete life history entirely in freshwater	None known	Hoese and Allen, 2009; Pusey <i>et al.</i> 2004; Godfrey, unpublished data
	<i>Glossogobius bicirrhosus</i>	Bearded goby	?	1	?		1		Larvae drift downstream from freshwater to estuarine natal habitat	Godfrey, unpublished data; Fishbase
									Variation in the timing of upstream migration over early life history	
	<i>Glossogobius</i> sp. 1	Mountain goby	1	1			1	Unknown	Pre-flexion larvae drift downstream from freshwater to estuarine natal habitat in WT river systems	Pusey <i>et al.</i> 2004; Godfrey, unpublished data
									Post-flexion larvae/juveniles migrate upstream from estuarine to freshwater habitat over the declining limb of the wet season hydrograph	

Family	Species name	Common Name	Distribution			Larval habitat		Movement biology		Reference
			ECY	WT	CQ	FW	E/M	Adult	Young of the year	
	<i>Awaous acritosus</i>	Roman-nosed goby	1	1	1		1	Adults migrate downstream to E/M breeding habitat;	In WT rivers, larvae/juveniles migrate upstream from estuarine to freshwater habitat.	Pusey <i>et al.</i> 2004; Godfrey unpublished data
								Increase in river discharge may stimulate spawning migration		
	<i>Mugilogobius notospilus</i>	Pacific mangrove goby		1			1	Adults migrate downstream to marine breeding habitat; stimulus for movement unknown		Pusey <i>et al.</i> 2004
	<i>Redigobius bikolanus</i>	Speckled goby	1	1	1		1		Pre-flexion larvae drift downstream from freshwater to estuarine natal habitat in WT river systems	Pusey <i>et al.</i> 2004
									Bulk of larvae production occurs over the dry season	
	<i>Stenogobius cf. watsoni</i>			1		?	?	Unknown	Unknown	Pusey <i>et al.</i> 2004; Godfrey, unpublished data
	<i>Schismatogobius</i> sp.	Scaleless goby		1			1	Unknown	Limited understanding – Post-flexion larvae occur in estuarine habitat	Pusey <i>et al.</i> 2004; Godfrey, unpublished data
Eleotridae	<i>Eleotris melanosoma</i>	Ebony gudgeon	1	1			1?	Unknown	Unknown	Pusey <i>et al.</i> 2004

Family	Species name	Common Name	Distribution			Larval habitat		Movement biology		Reference
			ECY	WT	CQ	FW	E/M	Adult	Young of the year	
	<i>Eleotris fusca</i>	Brown gudgeon	1	1			1	Adults possible migrate downstream to brackish water in main river channel	Post-flexion larvae/juveniles possible upstream migrate from brackish water to freshwater	Pusey <i>et al.</i> 2004; Godfrey unpublished data
								Spawning occurs over the dry season		
	<i>Eleotris acanthopoma</i>			1			1?			Allen <i>et al.</i> 2002
	<i>Bunaka gyrinoides</i>	Greenback gauvina	1	1			1?	Unknown	Unknown	Pusey <i>et al.</i> 2004
	<i>Oxyeleotrislineolatus</i>	Sleepy cod	1	1	1	1		None reported	None reported	Pusey <i>et al.</i> 2004
	<i>Oxyeleotrisseilheimi</i>	Striped sleepy cod	1	?	?	1		None reported	None reported	Pusey <i>et al.</i> 2004
	<i>Oxyeleotris cf. aurensis</i>	Aru gudgeon	1	1			1?	No information available		Pusey <i>et al.</i> 2004
	<i>Giurus margaritacea</i>	Snake-headed gudgeon	1	1	1		1?	None reported from Queensland rivers although adults possibly migrate laterally onto floodplain spawning habitat		Pusey <i>et al.</i> 2004; Coates, 1992; Pearson <i>et al.</i> 2010
	<i>Hypseleotris compressa</i>	Empire gudgeon	1	1	1		1	Adults migrate downstream to E/M breeding habitat	Larvae migrate upstream on the declining limb of the wet season hydrograph	Pusey <i>et al.</i> 2004

Family	Species name	Common Name	Distribution			Larval habitat		Movement biology		Reference
			ECY	WT	CQ	FW	E/M	Adult	Young of the year	
								Increase in wet season river discharge stimulates spawning migration in WT rivers		
	<i>Hypseleotris galii</i>	Firetailed gudgeon		Translocated	1	1		None reported	None known	Pusey <i>et al.</i> 2004
	<i>Hypseleotris</i> sp. 1	Midgely's carp gudgeon		1	1	1		None reported	None known	Pusey <i>et al.</i> 2004
	<i>Hypseleotris Klunzingeri</i>	Western Carp gudgeon			1	1		None known	None known	Pusey <i>et al.</i> 2004
	<i>Gobiomorphus australis</i>	Striped gudgeon			1	1?		Unknown	Unknown	Pusey <i>et al.</i> 2004
	<i>Mogurnda adspersa</i>	Purple-spotted gudgeon	1	1	1	1		May undertake small scale migration although the purpose of this movement is unclear	None known	Pusey <i>et al.</i> 2004
	<i>Mogurnda mogurnda</i>	Northern trout gudgeon	1	1		1		No spawning migration known	Unknown	Pusey <i>et al.</i> 2004
	<i>Philypnodon grandiceps</i>	Flathead gudgeon			1	1?		Unknown	Unknown	Pusey <i>et al.</i> 2004
	<i>Philypnodon</i> sp.	Dwarf flathead gudgeon			1	1		Unknown	Unknown	Pusey <i>et al.</i> 2004

Appendix 2

Table A2: Estuarine fish of GBR catchments commonly found upstream of the estuary.

Family	Species name	Common name	Reference
Carcharhinidae	<i>Carcharhinus leucas</i>	Bull shark	Carter and Tait, 2008
Clupeidae	<i>Anodontostoma chacunda</i>	Chacunda gizzard shad	Godfrey, unpublished data; Sheaves <i>et al.</i> 2010
	<i>Herklotsichthys castelnaui</i>	Sandy sprat	Cater and Tait, 2008
	<i>Nematolosa come</i>		Sheaves <i>et al.</i> 2010
Engraulidae	<i>Stolephorus</i> sp.		
	<i>Thryssa hamiltoni</i>		Carter and Tait, 2008
Elopidae	<i>Elops hawaiiensis</i>	Giant herring	Sheaves <i>et al.</i> 2010
Belonidae	<i>Tylosurus crocodilus</i>	Crocodile longtom	Godfrey, unpublished data
Hemiramphidae	<i>Zenarchopterus buffonis</i>	Northern river garfish	Pusey <i>et al.</i> 2004
	<i>Hyporhamphus (Reporhamphus) quoyi</i>	Short-nosed garfish	Godfrey, unpublished data
Platycephalidae	<i>Platycephalus indicus</i>	Bar-tailed flathead	Godfrey, unpublished data
	<i>Platycephalus fuscus</i>	Dusky flathead	Godfrey, unpublished data
Ambassidae	<i>Ambassis gymnocephalus</i>	Bald glass glassfish	Godfrey, unpublished data
	<i>Ambassis interruptus</i>	Long-spined glassfish	Godfrey, unpublished data
	<i>Ambassis vachelli</i>	Vachelli's glassfish	Godfrey, unpublished data
Terapontidae	<i>Mesophristes argenteus</i>	Sand bream	Rayner <i>et al.</i> 2008
	<i>Terapon jarbua</i>	Crescent perch	Godfrey, unpublished data
Apogonidae	<i>Apogon hyalosoma</i>	Humpbacked cardinalfish	Godfrey, unpublished data
Sillaginidae	<i>Sillago analis</i>		Sheaves <i>et al.</i> 2010
	<i>Sillago ciliata</i>		Godfrey, unpublished data
	<i>Sillago maculata</i>	Trumpter whiting	Godfrey, unpublished data
	<i>Sillago sihama</i>		Sheaves <i>et al.</i> 2010

Family	Species name	Common name	Reference
Carangidae	<i>Caranx ignobilis</i>	Giant trevally	Rayner <i>et al.</i> 2008
	<i>Caranx sexfasciatus</i>	Bigeye trevally	Rayner <i>et al.</i> 2008
Leiognathidae	<i>Leiognathus decorus</i>	Ornate ponyfish	Godfrey, unpublished data
	<i>Leiognathus equulus</i>	Common ponyfish	Rayner <i>et al.</i> 2008, Godfrey, unpublished data
	<i>Leiognathus splendens</i>	Black-tipped pony-fish	Godfrey, unpublished data
Lutjanidae	<i>Lutjanus russelli</i>	Moses perch	Godfrey, unpublished data
Gerreidae	<i>Gerres filamentous</i>	Threadfin silver biddy	Godfrey, unpublished data
	<i>Gerres ovata</i>	Common silver biddy	Godfrey, unpublished data
Sparidae	<i>Acanthopagrus australis</i>	Yellowfin bream	Rayner <i>et al.</i> 2008
	<i>Acanthopagrus berda</i>	Pikey bream	Godfrey, unpublished data
Sciaenidae	<i>Johnius vogleri</i>	Little jewfish	
	<i>Nibea soldado</i>	Silver jewfish	Carter and Tait, 2008
Toxotidae	<i>Toxotes jaculatrix</i>	Banded archerfish	Godfrey, unpublished data
Monodactylidae	<i>Monodactylus argenteus</i>	Silver batfish	Carter and Tait, 2008
Mugilidae	<i>Mugil cephalus</i>	Sea mullet	Rayner <i>et al.</i> 2008, Carter and Tait, 2008
	<i>Valamugil buchanani</i>	Bluetailed mullet	Carter and Tait, 2008
	<i>Liza vaigiensis</i>	Diamond-scale mullet	Carter and Tait, 2008
Blenniidae	<i>Omobranchus anolius</i>	Oyster blenny	Godfrey, unpublished data
Eleotridae	<i>Butis butis</i>	Crimson-tipped gudgeon	
	<i>Butis koilomatodon</i>	Mud sleeper	Godfrey, unpublished data
	<i>Ophiocara porocephala</i>	Spangled gudgeon	
Gobiidae	<i>Caragobius</i> sp.		Godfrey, unpublished data
	<i>Acentrogobius viridipunctatus</i>	Spotted green goby	Godfrey, unpublished data
	<i>Bathygobius</i> sp.		Godfrey, unpublished data
	<i>Drombus halei</i>		Godfrey, unpublished data

Family	Species name	Common name	Reference
	<i>Drombus globiceps</i>		Godfrey, unpublished data
	<i>Exyrias puntang</i>		Godfrey, unpublished data
	<i>Favonigobius</i> sp.		Godfrey, unpublished data
	<i>Glossogobius circumspectus</i>	Circumspect goby	Godfrey, unpublished data
	cf. <i>Gobiopsis</i> sp.		Godfrey, unpublished data
	<i>Lophogobius bleekeri</i>		Godfrey, unpublished data
	<i>Mangarinus</i> cf. <i>waterousi</i>		Godfrey, unpublished data
	<i>Parkraemeria ornata</i>		Godfrey, unpublished data
	<i>Psammogobius biocellatus</i>	Sleepy goby	Godfrey, unpublished data
	<i>Silhouettea evanida</i>		Godfrey, unpublished data
	<i>Yongeichthys nebulosus</i>	Hair-finned goby	Godfrey, unpublished data
	<i>Gobiopterus</i> sp.		Godfrey, unpublished data
	<i>Oxyurichthys</i> sp.		Godfrey, unpublished data
	<i>Pandaka</i> sp.		Godfrey, unpublished data
	<i>Pseudogobius</i> sp.2		Godfrey, unpublished data
	<i>Redigobius balteatus</i>		Godfrey, unpublished data
	<i>Redigobius chrysosoma</i>		Godfrey, unpublished data
	<i>Apocryptodon madurensis</i>	Peppered mudskipper	Godfrey, unpublished data
	<i>Periophthalmus argentilineatus</i>		Godfrey, unpublished data
	<i>Periophthalmus</i> cf. <i>gracilis</i>		Godfrey, unpublished data
	<i>Periophthalmus</i> sp.		Godfrey, unpublished data
	<i>Scartelaos histophorus</i>	Blue-mudhopper	Godfrey, unpublished data
Microdesmidae	<i>Parioglossus</i> cf. <i>palustris</i>	Borneo hoverer	Godfrey, unpublished data
Scatophagidae	<i>Scatophagus argus</i>	Spotted scat	Godfrey, unpublished data
	<i>Selanotoca multifasciata</i>	Banded scat	Godfrey, unpublished data

Family	Species name	Common name	Reference
Siganidae	<i>Siganus lineatus</i>	gold-lined spinefoot	
Sphyraenidae	<i>Sphyraena jello</i>	Giant seapike	Godfrey, unpublished data
Tetraodontidae	<i>Marilyna</i> sp.	Toadfish	Godfrey, unpublished data