Fish habitat assessment and protection in the Barwon-Darling and Paroo Rivers

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Cover photos by Craig Boys: The Darling River near Bourke (left), Eulo weir pool, Paroo River (right).

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NON-TECHNICAL SUMMARY

Fish habitat assessment and protection in the Barwon-Darling and Paroo Rivers

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OBJECTIVES:

(1) Develop a framework for managing fish habitats in Australian dryland rivers;

(2) Assess the distribution of physical habitats in the Barwon-Darling and Paroo Rivers to identify functional river zones;

(3) Establish links between fish assemblages and the various physical habitat templates in each river zone;

(4) Determine the physical habitat use of different fish species in dryland rivers, based on the Barwon-Darling and Paroo Rivers; and

(5) Develop Action Plans for protecting or rehabilitating fish habitats in order to improve the sustainability of native fish in the Paroo and Barwon-Darling rivers.

NON TECHNICAL SUMMARY:

Introduction

There has been a decline in freshwater fish populations in many eastern Australia rivers, over the last century, indicating the need for better environmental management of the Murray-Darling Basin. The inland river systems of the Barwon-Darling support six fish species' that are formally listed by the International Union for the Conservation of Nature (IUCN) as either endangered or vulnerable. Furthermore, other evidence suggests that many more fish species may be classed as threatened, with recent surveys in the Barwon Darling River failing to collect 33% of the native fish previously reported from the area. While native fish species have undergone reductions in both distribution and abundance, introduced species such as carp (*Cyprinus carpio*) and gambusia (*Gambusia holbrooki*) have been reported throughout the Murray-Darling Basin. Although many key threats have been implicated as possible causes of the declining integrity of freshwater fish populations throughout the world, habitat degradation has been recognized as a significant cause.

In the face of declining native fish numbers and species in the Murray-Darling Basin, the Murray Darling Basin Commissions Native Fish Strategy has the long-term goal of rehabilitating all fish species to 60% of pre-European population levels. Thirteen key objectives have been set in order to achieve this, of which rehabilitating and protecting fish habitat is a major component. As part of the Native Fish Strategy, the Murray-Darling Basin Commission (MDBC) undertook a review on the habitat associations of native fish in the Murray-Darling Basin. A major outcome of this was key knowledge gaps do exist with respect to the habitat requirements of many native fish species in the rivers of the Basin. Further, understanding of fish-habitat associations was highlighted as being central to achieving the MDBC's goals set out in the Native Fish Strategy.

While studies into fish-habitat associations are not uncommon within tropical and temperate rivers of Australia (e.g. in south-east Queensland, or the River Murray and some of its tributaries) there is no set of principles to guide the assessment of fish-habitat associations and habitat condition within the large lowland rivers of the Murray-Darling Basin. This is of particular concern considering that the lowland sections comprise approximately 83% of the length of all rivers in the Basin. Although the MDBC review highlighted the need to further understand the habitat associations of native fish species, and subsequent recommendations on the protocols to guide fish habitat management and rehabilitation were canvassed, the review did not provide a framework by which fish-habitat associations can be investigated in large dryland rivers.

The current report addresses this deficiency in river management by developing a framework for assessing fish habitat within the large lowland rivers of eastern Australia. This framework was then used to determine fish-habitat associations in the Barwon-Darling and Paroo Rivers, and report on the condition of fish habitat and the fish assemblage in these respective rivers. The final aim was to use the science developed in this report to develop action plans for the protection of fish habitat in these rivers.

Framework for assessing fish habitat in large dryland rivers of eastern Australia

A review of the international literature revealed that scale is an essential consideration for understanding the use of habitat by fish. The scale of measurement influences how we view riverine ecosystems, the perceived distribution of an organism, and its habitat associations. Growing appreciation of this in recent years has seen increased use of multiscale investigations into habitat associations that operate within the context of hierarchy theory. That is, studies are collecting information at multiple scales, with smaller scales nested within larger ones (e.g. rivers within catchments, reaches within rivers, and riffles and runs within reaches). Not only does such an approach clarify the scales at which fish are associated with their environment, but it also highlights the logical and functional linkages among scales.

Despite the growing appreciation of the importance of scales and hierarchy in the context of fish habitat associations, the literature review highlighted that most studies to date have conducted sampling at limited spatial scales, such as micro-scale patches (i.e. fish associations with regard to velocity, depth and substrate) or meso-scale patches (i.e. pool, riffle sequences). The spatial extents used in most of these studies, even when hierarchical approaches were applied, were considered inappropriate for Australian lowland rivers. These river systems have distinctive features. They are geographically large, and flow through flat, arid landscapes. Discharge is predominantly base-flow, sourced from beyond the arid zone, with episodic high flows occurring less than 10% of the time.

Recent fish surveys conducted in eastern Australia have employed designs at the river basin scale. While these surveys resolve fish assemblage differences among geographic regions of different altitude (e.g. NSW Rivers Survey), and among different rivers and basins (e.g. NSW Rivers Survey, Integrated Monitoring of Environmental Flows and Sustainable Rivers Audit), they lack the scope to detect gradients of fish assemblage change within large rivers, or fish-habitat associations. From this review, we propose a framework that accommodates for the size and spatial variability of large dryland rivers of Australia. It employs an established hierarchy that describes the geomorphic and physical habitat within lowland rivers. This hierarchy spans scales from mesohabitats to catchments, and appreciates that a river consists of sections called functional process zones (FPZs) with relatively uniform flow and sediment supply. Furthermore, because this framework uses physical habitat structures that are easily recognised by the general public, it is readily applicable.

Fish habitat in the Barwon-Darling and Paroo Rivers during low flow

This fish habitat survey revealed clear and distinct patterns at the catchment, river, and FPZ scales in the Paroo-Barwon-Darling Rivers. Hence, it identified the spatial scales over which habitat changed along these rivers, in the context of processes responsible for creating and maintaining these differences.

The catchment scale structure of fish habitat was that the Darling River had deeper wet channels, with more irregular (eroded) bank cover than the Paroo River. These differences likely resulted from the different natural hydrological and geomorphological regimes of these rivers. There was marginally less smooth (deposited sand) bank and structural woody habitat cover in the Darling. At the river scale within the Barwon Darling, riverside vegetation (matted bank habitat as wads of tree roots, and structural woody habitat) became less abundant downstream. Furthermore, at the subsidiary FPZ scale, physical structures associated with fluvial processes (smooth bank, irregular bank, and wet-channel depth) varied. Upstream reaches usually were rich in structural woody habitat and smooth banks, while downstream reaches occasionally had deeper wet channels and irregular bank structures.

Collectively, these catchment-scale, river-scale, and FPZ-scale controls caused a systematic shift in physical habitat structures within these lowland rivers of Eastern Australia. These are the prevalent physical habitats of lowland rivers, because they represent the habitats available to fish during the low flow condition that occurs 90% of the time. Within the Barwon-Darling River, there were three distinct regions based on physical structures: the upper Barwon, the lower Barwon/upper Darling, and the Darling. Within the catchment, the Paroo River (except Nocoleche National Park) was distinctive from the Darling. Hence, it is clear that habitat structure can be defined over hierarchical spatial scales, and that the scale of investigation chosen can strongly influence what conclusions are drawn.

Fish habitat in the Barwon-Darling and Paroo Rivers during high flow

Although low flow habitat persists most of the time, thus is important for the integrity of fish populations, high flows are important for providing ephemeral habitat and connecting low flow habitats. It is during high flows that increases in fish recruitment have been recorded for golden perch (*Macquaria ambigua*) and silver perch (*Bidyanus bidyanus*). The hierarchical framework used to describe low flow habitat, was also used to survey the physical structure of high flow habitat. High flow habitats could also be described by geographic location: the upper Barwon, the lower Barwon-Darling, and the Paroo.

The upper Barwon River had U-shaped channels, with benches and vegetated point bars, and some river sections without bar-forms. The convex, gullied banks featured some undercutting. Tall riparian trees of medium density growth were sometimes clumped and overhung the river channel. Structural woody habitat included abundant small branches, and medium to large items of varying complexity were also present. The lower Barwon-Darling Rivers generally contained point bar, obstruction bar, and bench deposits in stepped, or flat U-shaped, channels. Concave banks with medium to steep slope were erosion-prone, and contained wide lower benches. Riparian vegetation ranged between sparsely vegetated sections, to sections densely vegetated with tall trees. Structural woody habitat was predominately large. The Paroo River was characterised by mid-channel bars, with stepped or box-shaped channels, with medium to steeply sloping banks in its upper section, or occluded channels with shallowly sloping banks in its lower section. Medium density riparian tree growth in the upper Paroo River was sometimes clumped and overhung the channel. In the lower Paroo River, riparian vegetation also contained relatively abundant shrub growth. Structural woody habitat included medium to small items of varying complexity.

These results highlight that flow variability in these rivers promotes the availability of structural habitat over time. It is therefore suggested that water resource development in the Barwon-Darling River, by limiting the magnitude and frequency of medium to large flow events, has limited the availability of instream habitats. For example the Darling River, which hosts a sizeable population of Murray Cod has limited availability of structural woody habitat during low flow while viable structural woody habitat exists during medium to high flows.

Fish-habitat associations in the Barwon-Darling and Paroo Rivers

The aim of this component of the study was to quantify the distribution and abundance of freshwater fish species and their associations with habitat during low flows within the Barwon-Darling and Paroo rivers. The survey involved electrofishing the six discrete mesohabitat units that were surveyed in chapter 2 (large wood, smooth bank, irregular bank, root matted bank, mid-channel and deep pool) using the hierarchical framework developed for fish habitat assessment in dryland rivers.

Due to extremely low water levels in the Paroo River, the degree of replication of the habitat units under investigation was not sufficient to adequately describe fish-habitat associations in the Paroo River. In the Barwon-Darling River, the fish assemblage did vary significantly between habitat types and at the larger river scale. Golden perch (*Macquaria ambigua*), Murray cod (*Maccullochella peelii peelii*) and common carp (*Cyprinus carpio*) were found to be strongly associated with large wood, but golden perch and Murray cod exhibited higher habitat specificity than carp. Bony herring (*Nematalosa erebi*) were more commonly found in shallow edgewater patches.

At the river scale, a regional difference in the fish assemblage was found to occur at scales closely corresponding to FPZs. These regional differences involve changes in the relative abundance of species rather than the addition or replacement of species. The Collarenebri to Brewarrina zone was characterised by a fish assemblage that was dominated by carp and relatively depauperate in native species when compared to other zones. In comparison, the Brewarrina to Bourke zone contained a higher abundance of golden perch, Murray cod, bony herring and carp.

Although strong associations were consistently found between a number of fish and structural woody habitat, the availability of structural woody habitat alone does not appear to be a good predictor of fish assemblage differences along the length of the Barwon-Darling River. It is hypothesised that the combination of habitat types (e.g. structural woody habitat in deeper water) and the unobstructed passage of fish along the river corridor may also be important in structuring the fish assemblage at the river scale. This emphasises that decisions regarding the reintroduction of suitable fish habitat cannot be made in isolation from processes that affect the fish assemblage at larger scales such as barriers to fish migration, river regulation and geomorphic patterns.

The protection and rehabilitation of fish habitat in the Barwon-Darling and Paroo Rivers

The hierarchical framework used in this survey support improvements in the efficiency of fish habitat surveys in inland rivers by allowing fish-habitat associations to be identified at multiple spatial scales, including mesohabitats, reaches, functional process zones and between rivers. It has been shown that through careful design and site selection based on riverine geomorphology, scale-specific information on fish assemblage differences and fish-habitat associations can be determined. This approach added no cost to the design or data collection phase, and showed that multiple scale assessments of fish habitat can be achieved in a cost effective way.

The Paroo River was dominated by carp (73% of the total catch), highlighting the possible need for carp control. The availability of wet channel was the factor limiting potential fish habitat in the Paroo River, when compared with the Darling River. Therefore it is essential that flow integrity be maintained in dryland rivers if they are to function as ecological refugia. Large-scale extraction of water from semi-permanent waterholes is likely to reduce the amount of habitat available to fish, or even worse totally remove these important refuges. This will result in a reduction in the abundance of long-lived native species and an increase in fast growing species such as carp, thus leading to a loss of biodiversity. It is important to protect the riparian zone and floodplain from degradation, whilst maintaining the episodic connectivity between the waterholes and these habitats.

This report highlighted several influences and key threats to the continued survival of the fish assemblage of the Barwon-Darling River. These operate at several scales, as indicated, and include:

1. Poor instream habitat in some regions relative to the whole river;

2. The presence of numerous weirs that have altered natural flows, and block the passage of fish;

3. The accessibility of medium and high-flow habitats to fish have potentially been reduced because of water resource development;

4. Indications of high levels of bank collapse in certain regions relative to the whole river. By increasing the localised availability of alluvium within river channels, while decreasing discharge and the frequency of overbank flows by water resource development, the capacity of rivers to mobilise alluvium may have changed. We observed sections of river that had shallow pools and runs, structural woody habitats smothered by sand, and sand bars that limited fish passage during low flow. Therefore habitat alteration and reduced water quality may result from accentuated bank collapse;

5. Riparian condition along the river is heterogenous. Certain regions have banks that are sparsely vegetated, sometimes from clear-felling, or dominated by shrubs;

6. The dominance of an alien fish species (carp) in certain locations.

This report recommends that remedial actions be undertaken to protect fish communities' of Australian dryland rivers, and facilitate recovery of populations. Appropriate remedial actions need to address the key threats, and a combination of actions can be implemented at various scales:

1. Regional scale actions include improving fish passage between functional process zones, by installing fishways suitable for native fish, and within functional process zones by environmental flows. Environmental flows periodically connect various habitats along

river valleys that are isolated during low flow, and provide the flow activity necessary for maintaining pools and runs. Implementation of carp control is appropriate at this scale.

2. Reach scale actions include maintaining channels that facilitate fish navigation within and between reaches. Activities that decrease sediment supply to the river in some areas will benefit native fish habitat. These may include bank revegetation and stabilisation, supplying varied flow levels, limiting water harvesting on the declining limb of hydrographs, and removing sand slugs from the river channel in targeted areas.

3. Local scale actions include maintaining and restoring habitats relevant to native fish in decline, such as bank vegetation that develop matted bank habitats, and dense aggregates of complex woody habitats, at low water levels on the eroded banks of meander bends.

It is also our view that the best step towards nurturing public support for rehabilitation in the Barwon-Darling River, and thus maximising the chance of success, is through the establishment of a model demonstration functional process zone. The main stretch of river channel from Brewarrina to Bourke is well suited as such a demonstration functional process zone because it:

1. Possesses a range of identified threats to river health;

2. Has a possibility for an untreated control reach nearby to monitor change;

3. Is degraded, but not to a degree that would prevent recovery;

4. In close proximity to significantly large township, which allows advertising of the rehabilitation actions among the general public. Bourke is a common stopover for tourists travelling to Cooper Creek and the Paroo;

5. Is a Functional Process Zone that can be managed at multiple scales. Its size demonstrates the scale of the problems present;

6. Has the potential for numerous rehabilitation works to be carried out simultaneously;

7. Has potential for the assessment of pre-condition as well as for the ongoing monitoring of ecological outcomes;

8. It supports existing management frameworks.

A demonstration functional process zone needs to be implemented with robust experimental design and hypothesis testing, adaptive management, agency collaboration and community engagement. When carried out with other demonstration functional process zones throughout the Murray-Darling Basin, rehabilitation activities will give a truly basin wide approach to restoring fish communities as proposed in the Native Fish Strategy.

1. BACKGROUND

1.1. The physical and biological nature of east Australian dryland rivers

Murray-Darling catchment (1,061,469 km^2) hosts a drainage network developed during the Cainozoic, of which the western rivers (Paroo, Warrego, Culgoa) are probably the youngest, and the Darling River is younger than the Murray (Thoms in press). The capacities of these rivers to transport water and sediment, combined with supplies of these materials (Bisson and Montgomery 1996), have shaped the environment in which native fish have evolved in the Darling River. The contemporary river character is one of long pools connected by channels with slow flowing, deep water. Australian native fish are highly endemic, having evolved from marine species relatively recently in geological time (Gehrke and Harris 2004), and have adapted to life in an arid continent with irregular rainfall.

Dryland Rivers that transect the interior of eastern Australia are so termed because they flow through semi-arid to arid regions where annual rainfall is below 500mm, and evaporative losses exceed recharge from local rainfall (Twidale 1968; Rodier 1985). These rivers are characteristically below 300m a.s.l., with low-gradient channels that rework fine sediment across expansive floodplains (Crabb 1997). Highly variable, allogenic flows infrequently flood vast regions, but the usual low flow regime is quickly re-established. During droughts, rivers can retract to a series of disconnected waterholes, but endemic fauna are well adapted to the flood-drought variability that underpins the ecological integrity of Australian dryland rivers (Thoms *et al*., 2004b).

Australia's dryland rivers are among the most hydrologically variable in the world (Walker *et al*. 1995; Puckridge *et al*. 1998; Puckridge 1999), with annual discharge in the Barwon-Darling River varying from 0% to 911% of the long-term average (Walker 1986). While Australian rivers are subject to large floods by world standards (McMahon *et al*. 1992), the Darling River at Menindee ceased flowing 48 times between 1885 and 1960, with one event lasting for 364 days (Crabb 1997). These frequent periods of low to zero flow mean that the ability of fish to tolerate poorer water quality associated with low flow, or to relocate to refuge habitats until conditions improve, may define those fish species capable of inhabiting dryland rivers. Fish subjected to highly variable hydrological regimes may adopt life history attributes such as opportunism, reproductive flexibility, and trophic generalism (Kodric-Brown 1981; Williams 1987; Poff and Allan 1995; Walker *et al*. 1995).

Periodic harsh events in rivers with variable discharge may be paramount to maintaining biodiversity, as predicted by Connell's (1978) 'intermediate disturbance hypothesis' (Ward and Stanford 1983; Puckridge *et al*. 1998). This is evident in the Murray-Darling Basin, where the Barwon-Darling and Paroo rivers have far more variable flows than the heavily regulated River Murray, and contain a much more diverse fish community than the River Murray (Gehrke *et al*. 1999).

Itinerant movement may play an important role in maintaining the diversity and distribution of species in ephemeral, dryland rivers. As long as some fish survive harsh periods of zero flow in refuge habitats, these fish can then recolonise upstream areas on the back of rising flows and replenish fish assemblages. If relocation coincides with an acceleration in breeding, then recolonisation can occur at an even quicker rate (Lake 1967). This is essential for maintaining genetic diversity within a watershed, and restricted genetic mixing caused by prolonged isolation can develop genetically distinct populations. The existence of genetically distinct golden perch in the Paroo River is a good example of this (Keenan *et al*. 1997). Although golden perch can migrate long distances (Reynolds 1983), the Paroo River is rarely connected to the main channel of the Barwon-Darling River, and consequently there is little mixing of populations.

1.2. The Barwon-Darling and Paroo Rivers

The Barwon-Darling River is Australia's longest dryland river. Originating in the Great Dividing Range, its headwaters feed the Macintyre River that marks the New South Wales/Queensland border (Crabb 1997). The Macintyre becomes the Barwon River at Mungindi, which then becomes the Darling River at the confluence with the Culgoa River (Appendix 2, Figure 1). The remarkably straight course of the Darling River is guided by a major fault in the underlying basement (Twidale 1968; Thoms *et al*. 2004a). The major tributaries of the Barwon-Darling River draining from the north include the Culgoa and Warrego, and from the south include the Gwydir, Namoi and Macquarie Rivers. The total length of the Barwon-Darling River from Mungindi to its confluence with the Murray River at Wentworth is 2740 km (Crabb 1997).

The Paroo River is a truly semi-arid river because its flow originates from a semi-arid catchment, rather than from the humid headwaters that feed most of the Murray-Darling (Walker 1994). The location of wet-season rains in the catchment, and the timing of merging tributary flows, influences the high flow variability along the Paroo River (Puckridge 1999). The 640km length of the Paroo River (Crabb 1997) drains south from South West Queensland into terminal lakes at Nocoleche National Park in New South Wales.

South of the Queensland-New South Wales border, the Paroo widens into an extensive network of permanent waterholes and wetlands known as the 'Paroo Overflow' (Goodrick 1984). Only during large floods does the Paroo River connect with the Darling River, upstream of Wilcannia. The Paroo River, however, is not considered to contribute flows to the Darling River, and more often than not, large flows result in the Darling River flowing into the Paroo River (Young 1999).

1.2.1. Physical character

The fluvial geomorphologies of the Barwon-Darling River and Paroo River result from their discharge regimes and sediment supply (Thoms and Sheldon, 2000a). Both rivers are transport limited, meaning that alluvium transport along river valleys is controlled primarily by the frequency of high flows that can move streambed sediment. The Barwon-Darling River, which flows more frequently than the Paroo River (Puckridge 1999), is a regime channel (Bisson and Montgomery 1996). Thus it is a low gradient, meandering, high order channel within unconstrained valleys. Shallow and deepwater areas are present, and point bars occur at meander bends. It has a predominantly sandy riverbed moulded into a predictable succession of bedforms, from small ripples to large, dune-like elevations and depressions. Sediment movement occurs at all flows, and is strongly correlated with discharge. The Paroo River is a low gradient, braided channel (Bisson and Montgomery 1996), also with sandy, easily eroded banks and bed-forms. Thus it has numerous sandbars scattered throughout a wide span of active channel. The locations of bars change frequently, unless stabilised by vegetation, and the active channel often migrates laterally.

1.2.1.1. Functional process zones

Dryland rivers can be viewed as hierarchically nested units, within which broad scale parameters control progressively finer scale parameters. Functional process zones subdivide rivers into sections with relatively uniform discharge and sediment regimes, defined from major breaks in slope, and styles of river channel and floodplain. Essentially they define river associations with valley floor trough (i.e. valley dimensions, gradient, stream power, boundary materials, and sediment yield), which impart physical characteristics that influence instream habitat and associated biological communities at finer scales. The functional process zone divisions for the Barwon-Darling and Paroo Rivers are shown in appendix 2.

1.2.1.2. Flow variability

Australian dryland rivers are among the most hydrologically variable in the world, and are influenced by inter-annual climate cycles that include the El Niño - Southern Oscillation. Puckridge (1999) used combined measures of hydrological variability to globally rank several large rivers, and Australian dryland rivers such as Cooper Creek, the Diamantina, and Paroo rivers were among the most variable. The Paroo River was 25% more variable than the Darling River, which was about 3 times more variable than rivers from tropical rainy climates such as the Mekong (Puckridge 1999).

Flow along the Barwon-Darling River displays seasonality, with high flows usually occurring during December to April (Thoms *et al*. 2004b). Flows along the Barwon-Darling River generally increase in volume towards Bourke (see map: Appendix 2, Figure 1). However, because flows are derived from beyond the arid zone, and evaporative losses in the arid zone are high, flows downstream of Bourke usually decrease (Thoms *et al*. 2004b).

Because the Barwon-Darling River serves agriculture and rural townships, humans have altered the natural flow variability to stabilise supply. There is a major impoundment at Menindee Lakes (lower Darling River) with a gross capacity of 2285 GL, and 15 smaller regulatory structures along its length (Crabb 1997). About 190 GL per year is abstracted from the upper Darling River and 210 GL from the lower Darling River (compared with about 24GL per year in the Paroo River)(Crabb 1997). The effects of water resource development on flows in the Barwon-Darling River (Thoms *et al*. 2004b) are:

- Reductions in median daily flows of between 24% (Walgett) and 73% (Wilcannia), relative to natural flow.
- Low flows that occur 80% of the time have increased by between 1.3x (Bourke) and 2.1x (Mungendi) natural flow.
- Some high flows that occur between 10-25% of the time have decreased to 0.6x (Mungendi and Walgett) natural flow.

Water resource development has therefore reduced flow, and frequencies of high flows, by various extents along the Darling River. Consequently, the contemporary Barwon-Darling River is less variable with regard to flow, with low flows predominating. As a result, the wetted channel available to fish, which naturally diminishes because of evaporative losses, is diminished further. Potential benthic habitat such as timber remains emergent on river banks for longer periods, and fish are more commonly restricted to habitats available during low flow.

1.2.2. Conservation status of fish assemblages

1.2.2.1. Barwon-Darling River

Of the 30 fish species recorded within the Darling River system (Gehrke and Harris 2004), a total of 21 species from 12 families inhabit the lowland reaches (<300m above sea level) of the Barwon-Darling River. It has been suggested that this is a relatively low number of species for a catchment of the Darling River's size (640, 000 km^2), as a result of Australia's geographic isolation coupled with the highly variable flows in the basin (Lake 1971; Harris 1984; Allen 1989). However, rather than being impoverished, the fish fauna of the Barwon-Darling River is actually fairly typical of similar-sized rivers flowing through semi-arid regions elsewhere in the world (Gehrke and Harris 2000).

In rivers, there is generally a downstream increase in the number of fish species. This occurs because flow increases as more tributaries join the main river, which increases depth, living space, habitat complexity and productivity (Sheldon 1968; Hynes 1970; Lotrich 1973; Hocutt and Stauffer 1975; Horwitz 1978; Cadwallader 1979; Evans and Noble 1979; Lake 1982; Schlosser 1987; Pusey and Kennard 1996). In the Barwon-Darling River, however, a downstream reduction in species richness has been observed (Gehrke and Harris 2004). As described in section 1.2.1.2, flow along the Barwon-Darling River diminishes downstream of Bourke. Consequently a discharge-related influence along this river may be the cause of the downstream decrease in species richness. Until more is known about how fish habitat changes along the Barwon-Darling River, such associations will remain speculative.

A downstream reduction in species richness may also be due to anthropogenic habitat alteration, as has been reported in disturbed rivers both in Australia (eg the Mary River Queensland: Pusey *et al.* 1993) and overseas (e.g. the Colarado River: Cross 1985). Diminished downstream flow along the Barwon-Darling River has been accentuated by water resource development (as discussed in section 1.2.1.2).

Recent fish surveys have identified a decline in freshwater fish populations in many south-eastern Australia rivers (Harris and Gehrke 1997), pointing to the need for better environmental management of the Murray-Darling Basin. The Barwon-Darling River, in particular, is home to six species of fish that are formally listed by the International Union for the Conservation of Nature (IUCN) as either endangered or vulnerable (Morris *et al.* 2001), and evidence suggests that many more species may be classed as threatened (Gehrke and Harris 2004). Recent surveys in the Darling River failed to collect 33 percent of the native fish previously reported from the area (Schiller *et al.* 1997), with many of the native species that have been found having undergone reductions in both distribution and abundance (Schiller *et al.* 1997). Introduced species such as common carp (*Cyprinus carpio*) and gambusia (*Gambusia holbrooki*) are encountered throughout the Murray-Darling Basin (Faragher and Lintermans 1997).

During the NSW Rivers Survey, only three sites were studied within the main channel of the Barwon-Darling River (with only one of these sites being located upstream of the Menindee storage). Since then 10 more sites have been sampled on the Barwon-Darling River as part of the Integrated Monitoring of Environmental Flows Project (IMEF: (Chessman and Jones 2001). The IMEF data (Hartley and Rayner 2002) show that silver perch (*Bidyanus bidyanus*) are a species of particular concern. This species, which is now regarded as threatened (Crook 2000), was only encountered at two sites in the upper Barwon River.

1.2.2.2. Paroo River

Relative to other rivers within the Murray-Darling Basin, the Paroo River contains one of the healthiest fish assemblages characterised by high species diversity, strong recruitment of native species, and relatively low incidence of carp (Gehrke, *et al*. 1995; Gehrke *et al*. 1999). The Paroo River is not subject to the heavy water abstractions of the Barwon-Darling River (Crabb 1997). Comparisons with regulated systems suggest that if large-scale agricultural abstractions were implemented on the Paroo River, ecological risks to the fish community would be high and would include reduced habitat availability during low flows, limited recruitment during higher flows and reduced biodiversity (Gehrke *et al*. 1999).

1.3. Need

While numerous factors have been implicated as possible causes of a decline in native fish populations in the Murray-Darling Basin (see (Cadwallader and Lawrence 1990), habitat alteration is recognised as the single largest threat to the integrity of freshwater fish populations in Australia and elsewhere (Allan and Flecker 1993; Wager and Jackson 1993; Maitland 1995; Abramovitz 1996; Kearney, Davis *et al*. 1999). Such a response to habitat alteration occurs because, like most animals, fish do not occupy habitats randomly. Both the distributions and compositions of fish assemblages are dictated by the patchiness of the physical habitat (Keast and Fox 1990; Kramer *et al*. 1997; Crook, Robertson *et al*. 2001).

Although it is believed that the reduction and degradation of fish habitat is largely responsible for the marked decline in native fish stocks in many Australian dryland rivers (Gehrke and Harris 2000), evidence of this link is sparse. This is due to the lack of definitive information on habitat requirements of most native fish (Allen 1989; Koehn and O'Connor 1990; Wager and Jackson 1993; Harris 1994; Harris 1995; Koehn 1995), and the condition of habitat within Australian rivers.

When it comes to instream and riparian habitat loss and degradation, several threatening processes have been identified (reviewed in Gippel and Collier 1998). Processes include restricted fish passage by weirs, dams, and levee banks, removal of in-channel structures such as snags, channel widening and dredging, cleared riparian vegetation, unrestricted stock access to the riparian zone, and introduced alien fish and vegetation. While we have come a long way in recognising these key threatening processes, efforts by environmental agencies and fishery managers over the last decade have not been adequate in arresting the declines in native fish populations (Schiller *et al*. 1997). In the Native Fish Strategy (MDBC 2003) the Murray-Darling Basin Commission has set the long-term goal of restoring native fish populations to 60% that of pre-European settlement. If we are to successfully arrest the declines in native fish stocks as well as move towards the goals set out in the Native Fish Strategy, important fish habitat needs to be firstly defined and then a systematic evaluation of fish habitat condition needs to be carried out. It is only then that effective riverine management such as reach restoration can be implemented efficiently upon a solid base of scientific understanding of the state of fish habitat, the scales of its variability, and its impact on the fish population.

This report will address this lack of information by defining habitats used by native and alien fish species during low flow conditions in the Barwon-Darling and Paroo rivers. The report also provides an inventory of fish habitats at different flow levels, and provides managers with an easily deployed framework on which to assess the condition of fish habitat in their region. The large-scale nature of the project, and its focus on low flow habitat, mean that results are transferable to habitat assessment and protection in other dryland rivers throughout eastern Australia.

2. FRAMEWORK FOR ASSESSING FISH HABITAT IN DRYLAND RIVERS OF EASTERN AUSTRALIA

2.1. Introduction

In the face of declines experienced in both the distribution and abundance of many Murray-Darling Basin fish species, the Native Fish Strategy (MDBC 2003) has been set with the long-term goal of rehabilitating all fish species to 60% of pre-European population levels. Thirteen key objectives have been set in order to achieve this, of which rehabilitating and protecting fish habitat is a major component (MDBC 2003). A review on the habitat associations of native fish in the Murray-Darling Basin (Treadwell and Hardwick 2004) was commissioned as part of the Native Fish Strategy. A major outcome of this was the realisation that there are still key knowledge gaps with regards to the habitat requirements of many native fish species. Further understanding of fish-habitat associations was highlighted as being central to achieving the Murray-Darling Basin Commission's goals set out in the Native Fish Strategy.

While studies into fish-habitat associations are not uncommon within Australia (e.g. the work of Pusey *et al.* (1993) in south-east Queensland, or the work on the River Murray and its tributaries, by Koehn (1987), Koehn *et al.* (1994), Koehn and Nicol (1997) and Bond and Lake (2003)), there is no set of principles to guide the assessment of fish-habitat associations and habitat condition at scales applicable to large dryland rivers of the Murray-Darling Basin. Although Treadwell and Hardwick (2004) highlighted the need to further understand the habitat associations of native fish species, and subsequent recommendations on the protocols to guide fish habitat management and rehabilitation were canvassed (Treadwell 2004), both reviews fell short of providing a framework with which these fish-habitat associations could be investigated in large dryland rivers.

Objectives:

In order to address this need, a review of the international literature was undertaken with the following objectives:

1. To identify procedures for assessing fish habitat from the international scientific literature that may translate directly to large dryland rivers of south-eastern Australia;

2. To design a rapid procedure for assessing fish habitat in large dryland rivers of eastern Australia, based on those options.

2.2. Methods

This review encompassed 4 reports, and 99 articles from 4 books, 32 journals and 5 symposia. The aim was to identify the physical attributes used by fish biologists to describe fish habitat, as well as noting the spatial scales under investigation. Scale was viewed in terms of precision (size of data unit) and extent (size of reach/region). Physical structures that fish ecologists have used for habitat descriptions were also reviewed, and the frequency that each structure was cited in the literature was recorded to indicate its perceived relevance as a habitat attribute. This information was then used to develop a framework for the assessment of fish habitat in large dryland rivers, which don't necessarily have all the physical attributes that occur across the world.

2.3. Results and discussion

2.3.1. Literature review

Habitats were commonly described by fish ecologists in terms of physical structures in river channels (Figure 2.2) or as river geomorphology (Figure 2.1). Physical structures in river channels that were commonly studied include river substrate, abundance of wood structures, and cover given by in-stream or overhanging plants (Figure 2.2). River geomorphology commonly used to describe fish habitat included planform attributes (e.g. catchment area), cross-sectional channel size and complexity, and long profile channel complexity (Figure 2.1).

Many of the attributes of river geomorphology commonly used in the international literature to describe fish habitat are only of relevance to coastal and upland streams (e.g. stream order and channel units of the pool-riffle sequences). These attributes have little relevance to large dryland rivers of eastern Australia, such as the Barwon-Darling River, which characteristically consist of long runs and pools. Further, attributes of river geomorphology directly applicable to dryland rivers, such as interactions between the river and floodplain, and river meander, were absent or rarely considered in fish habitat assessments (Figure 2.1). The review highlighted that although fluvial geomorphology was regularly used to describe fish habitat, many geomorphic structures relate to river systems that are not typical of inland Australia. Approaches used to describe fish habitat in coastal or upland streams often did not translate to large, lowland, dryland rivers.

Consideration of scale is essential for understanding habitat use by riverine biota (Wiens 1989; Menge and Olson 1990; Levin 1992; Horne and Schneider 1995; Poizat and Pont 1996; Inoue *et al*. 1997; Bult *et al*. 1998; Mason and Brandt 1999; Crook *et al*. 2001). The scale of measurement dictates how we view the riverine ecosystem (Levin 1992), and both the perceived distribution of an organism as well as its habitat associations may vary with the scale of measurement (Bult *et al*. 1998). Growing appreciation of this in recent years has seen increased use of multi-scale investigations into habitat associations that operate within the context of hierarchy theory (e.g. Hawkins *et al*. 1993; Reichard *et al*. 2002; Parsons *et al*. 2003). Not only does such an approach allow the scales at which organisms associate with their environment become self evident (Parsons *et al*. 2004), but the logical and functional linkages among scales are also highlighted (Wiens 1989). This markedly improves the understanding of how biological and physical patches are juxtaposed within a river system (Parsons *et al*. 2004). Despite this realisation, however, many ecological studies still use only single or a few scales of measurement, or use inappropriate scales with little ecological relevance (Essington and Kitchell 1999; Maddock 1999; Mason and Brandt 1999; Crook *et al*. 2001, Hawkins, Kersner *et al*. 1993; Bult, Haedrich *et al*. 1998).

Frissell *et al.* (1986) developed a conceptual model of river structure that was derived initially from a mountain stream in North America, and which involved hierarchical classification (Figure 2.3). While numerous fish habitat studies have adopted such a hierarchical approach in their sampling designs, most focus on micro-scale patches (i.e. fish associations with regard to velocity, depth and substrate as used, for example, in PHABSIM modelling of habitat availability) nested in meso-scale patches (i.e. pool, riffle sequences). For instance, Bult *et al*. (1998) used a multi-scale approach to study habitat selection by a single species (Atlantic Salmon *Salmo salar*) in a Canadian river.

Channel geomorphology
Criteria used to quantify or describe fluvial landforms

Cross-sectional attributes
Criteria specific to attributes that develop across the channel

Size

- c. *Width* The bank-full width of the channel.
- c. *Depth* The bank-full depth of the channel.
- r. *Wetted Perimeter* The length of wetted contact, from river bottom to waterline
- r. *Area* The channel area, from river bottom to waterline

Shape

- a. *Width:depth* The bank-full width relative to thalweg depth of the channel.
- a. *Form ratio*

Complexity

- c. *Irregularity* Bed irregularity measured, for example, using depths across a transect
- a. *Number of benches* The number of shelf-like steps on the banks.
- a. *Bench position* The position of shelf-like steps relative to bank-height.

General
Information not used by Thoms *et al.*, 2000 to characterise Australian dry-land rivers

- r. *Bank angle* The angle of the bank
- r. *Area of passage* The wetted area useful for fish migration
- r. *Wet width* The bank to bank width of wetted contact.

Plan-form attributes
Criteria specific to a birdseye view of the river

Pattern

- r. *Sinuosity* Length of thalweg relative to length of meander belt
- a. *Meander:wavelength ratio* The amplitude of a meander relative to the length of a wavelength

Floodplain interaction

- r. *Main:total channel length* The length of the main channel stem relative to the total length of channel

Catchment magnitude

- o. *Catchment length or area (and catchment area upstream from site)* The drainage dimensions that influence water yield and habitat area
- r. *Distance from stream source* Distance from river head.

General

- c. *Stream order* A stream ordering method such as the Strahler system.
- c. *Channel unit* Channel subdivisions (cascade, rapid, riffle, glide, pool)
- o. *Elevation* Height above sea level
- r. *Surface area* Pool area or wetted area
- r. *Floodplain/valley constriction*
- r. *Distance from sea* Distance from river mouth
- r. *Geology* Strata underlying landforms

Long-profile attributes
Criteria specific to attributes that develop along the channel

Complexity

- c. *Irregularity* Step development, or bed irregularity measured using depths along a channel
- a. *Complexity factor* Depth variation, measured as a coefficient of variance (linear regression of depth values) along a thalweg

Structure

- r. *Number of pools*

Bedforms

- r. *Dune, ripple, flume structures* Bed-forms that develop along the channel in response to flow.

General

- *Gradient* The height difference along a river section
- c. *Barriers to migration* Structures such as dams, weirs, waterfalls, and dry chanel that prevent fish migration

Figure 2.1. Frequency with which attributes of geomorphology are used in published descriptions of fish habitat. c = habitat descriptions commonly used in the international literature (top 1/3rd of citations). o = habitat descriptions observed in the literature. r = habitat descriptions rarely observed in the literature (bottom 1/3rd of citations). a = habitat descriptions absent from the fish-habitat literature.

In-channel habitat
Criteria used to quantify or describe physical habitat within a river channel

Substrate

Character

c. *Grainsize* Usually the Udden-Wentworth size scale for clastic sediments

o. *Cover* Generic shelter (e.g. boulders), substrate heterogeneity

r. *Organic matter*

r. *Embeddedness* The degree by which larger sediment (boulders, cobbles, rubble) are surrounded and covered by fine sediment.

r. *Composition* Sediment mineralogy (e.g. quartz, feldspar).

Riparian vegetation

Character

o. *In stream and shoreline plants* The type of vegetation growing in and near the channel

o. *Shading aspect* Shading/cover provided by riparian vegetation

Wood structures

Amount

o. *Number* The abundance of available habitat

Character

r. *Size* The size of timber structures

r. *Structural detail* Descriptive character (e.g. complexity, roughness) of timber structures

Channel stability

Character

r. *Bank structure* Descriptive character (e.g. levees, root mats).

r. *Bank erosion* Descriptions of bank stability and erosion

Figure 2.2. Frequency with which physical structures are used in published descriptions of fish habitat. *c* = commonly used habitat descriptions (top 1/3rd of citations). *o* = habitat descriptions observed in the literature. *r* = habitat descriptions rarely observed in the literature (bottom 1/3rd of citations). *a* = habitat descriptions absent from the fish-habitat literature.

Conceptual hierarchies of fluvial systems and their habitat subsystems

Location:		**Oregon, USA**	**East Australia**
Fluvial system:		**Mountain stream**	**Dryland river**
Author:		**Frissel et al., 1986**	**Thoms et al., in press**
Scale	1cm		Microhabitat
	10cm	Microhabitat	
	1m	Pool/Riffle	Functional Unit
	10m	Reach	
	100m	Segment	Functional Set
	1km	Stream	Reach
	10km		
	100km		Functional Process Zone
	1,000km		Drainage Basin

Relative frequency distributions of scales at which fish habitat units are described

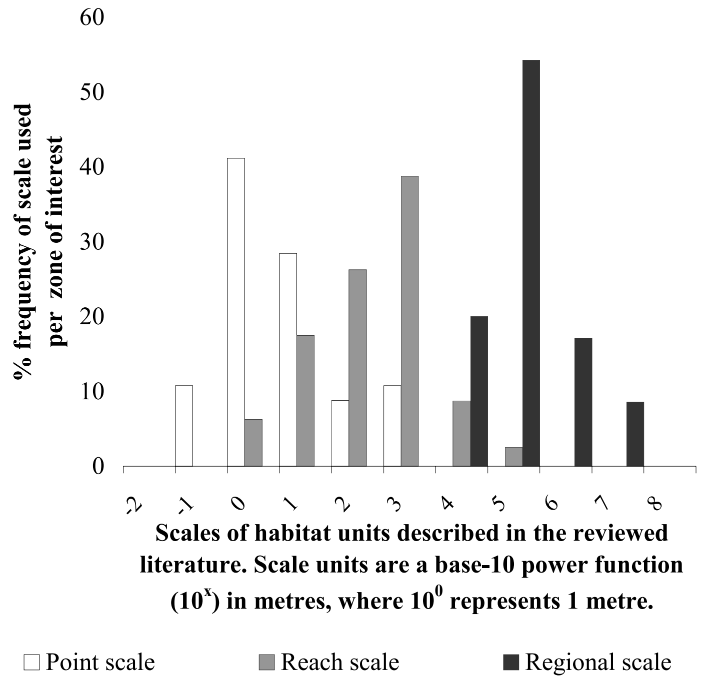


Figure 2.3. Scales used to describe the nested hierarchy of habitats. The table compares the scale used for mountain streams, with the scale used for dryland rivers. The histograms compare scales cited in the international literature, with the scales used to describe habitat in Australian dryland rivers (Thoms *et al.* in press).

In this study, the maximum scale investigated was no larger than several times the mean river width in a river that drained a catchment of only 73 km^2.

Hawkins *et al.* (1993) used a hierarchy to classify stream habitats based on three scales, with the coarsest being pools and riffles. Again the spatial extent examined was relatively small. These relatively fine hierarchical scales are inappropriate for large dryland rivers such as the Barwon-Darling, which is 2740 km long and drains a 650 000 km^2 catchment. It is a typical Australian dryland river that lacks the pool-riffle sequence, and is hydrologically variable (section 1.2).

During the usual low flow conditions, physical structures that may provide fish with habitat are limited largely to fallen trees located low within the incised channel, deeper pools on meander bends and shallower edge-water habitats of various kinds. The substrate consists of sand and silt and riparian vegetation has little relevance as cover as the largely incised channel does not contain significant riparian vegetation below bank-full level.

Fish habitat assessments performed within small spatial extents run the risk of not encompassing the total home range, and therefore habitat use, of migratory fish species (Fausch *et al*. 2002). This is particularly relevant to large dryland rivers of south-eastern Australia which are home to native fish capable of migrating over hundreds of kilometres within their lifetime (Mallen-Cooper 1989). This is not to say that studies have not assessed fish habitat and fish assemblage differences over very large spatial extents. American literature regularly uses regional classifications (e.g. Omernik 1987; Gallant *et al*. 1995) that subdivide ecoregions by soil, vegetation, landforms, and landuse. Fish assemblages have been shown to form distinct groupings that correspond with ecoregions and hydroregions (Hughes *et al*. 1987; Oswood *et al*. 2000; Van Sickle and Hughes 2000).

Large scale fish surveys conducted in south-eastern Australia have also employed hierarchical designs with strata at the top end of the spatial scale (e.g. river types and basins). But while these surveys can resolve fish assemblage differences among geographic regions of different altitude (e.g. New South Rivers Survey: NSWRS) or among different rivers and basins (e.g. NSWRS, Integrated Monitoring of Environmental Flows: IMEF and the Sustainable Rivers Audit: SRA), they lack the ability to detect longitudinal gradients of fish assemblage change within large rivers as well as fish-habitat associations.

This review indicates a clear emphasis within the international literature on assessing fish habitat at both the lower (i.e. microhabitats) and upper (i.e. catchment or ecoregions) ends of the spatial spectrum (see Figure 2.3). It is scales intermediate to this, however, that are critical in encompassing the home ranges of many fish (Fausch *et al*. 2002). Any design of fish habitat assessment undertaken in large rivers should therefore be based on a hierarchical framework that includes these intermediate spatial scales.

A hierarchy has been developed by (Thoms, *et al*.) 2004a) that describes the geomorphology and physical habitat within dryland rivers of Australia (Table 2.1, Figure 2.3), and the relatively large scales that Thoms *et al.* used for dryland rivers can be compared with those used for a mountain stream hierarchy by Frissell *et al*.(1986). Thoms *et al*. (2004a), described scales from mesohabitats to catchments, and recognised that rivers consist of functional process zones with characteristic discharge and sediment regimes (section 1.2.1.1), which they have defined for the Barwon, Darling and Paroo Rivers (Appendix 2, Figures 1, Figure 2). In the following section, this hierarchy forms the basis for the framework used to survey fish habitat in the Barwon, Darling and Paroo Rivers.

Table 2.1. The scale-dependent framework of fluvial geomorphology in Australian dryland rivers (Thoms *et al*. 2004b).

Spatial Scale	Description
The catchment	Area of the primary catchment.
River system	The river channel and floodplain from its source to its mouth or a defined distance downstream.
Functional process zone	Lengths of river with similar discharge and sediment regimes. Distinctive river geomorphologies, defined from major breaks in slope, and style of river channel or floodplain. Shaped by 10 to 100 year periodicities of dry and wet climates, and more recently by flow regulation through dams and weirs.
River reach	Repeated lengths of river channel within a process zone with similar channel style.
Functional sets	Channel units associated with specific landforms such as major cutoffs, aggrading floodplains, meander bends, or straight channels.
Functional units	Sections of erosional bank, channel, or depositional bank.

2.3.2. A hierarchical classification scheme for large dryland rivers in eastern Australia

A pilot survey of the Barwon-Darling River was used to identify the different physical structures that may be available to fish as habitat during low flow (Table 2.2). In order to detect the distribution of these habitat types at a variety of spatial scales spanning the large length of these dryland rivers, and encompassing the large home ranges of some of their resident fish species (Mallen-Cooper 1993), a hierarchical survey design was proposed. Shown in Figure 2.4 and Figure 2.5, this involved rapid-reconnaissance surveys of three replicate reaches within each functional process zone (FPZ), within each river. Reaches were further broken down into sub-reaches, which in turn were divided into 100m sample units at which the low flow structure of each bank was observed. A depth sounder was used to measure channel depth in these sample units. This method has the advantage of being fast and easily replicated.

Table 2.2. The total complement of physical structures available to fish during low flow conditions in the Barwon-Darling and Paroo Rivers.

Habitat attribute	Description
Smooth bank	Uniform sedimentary bank structure contacting the waterline. Identified as percent bank cover of 100m of channel.
Matted bank	Fine matted structure (root mats or lignum) contacting the waterline. Identified as percent bank cover of 100m of channel.
Irregular bank	Complexity at the waterline, caused by rotational shear of the bank or rock outcrops. Identified as percent bank cover of 100m of channel.
Structural woody habitat	Wood structure along the bank, contacting the water line. Identified as a tally per 100m of channel.
Open channel	Depths shallower then the 70^{th} percentile. Measured by depth-sound every 100m along the thalweg.
Deep water	Depths deeper than the 70^{th} percentile. Measured by depth-sound every 100m along the thalweg.

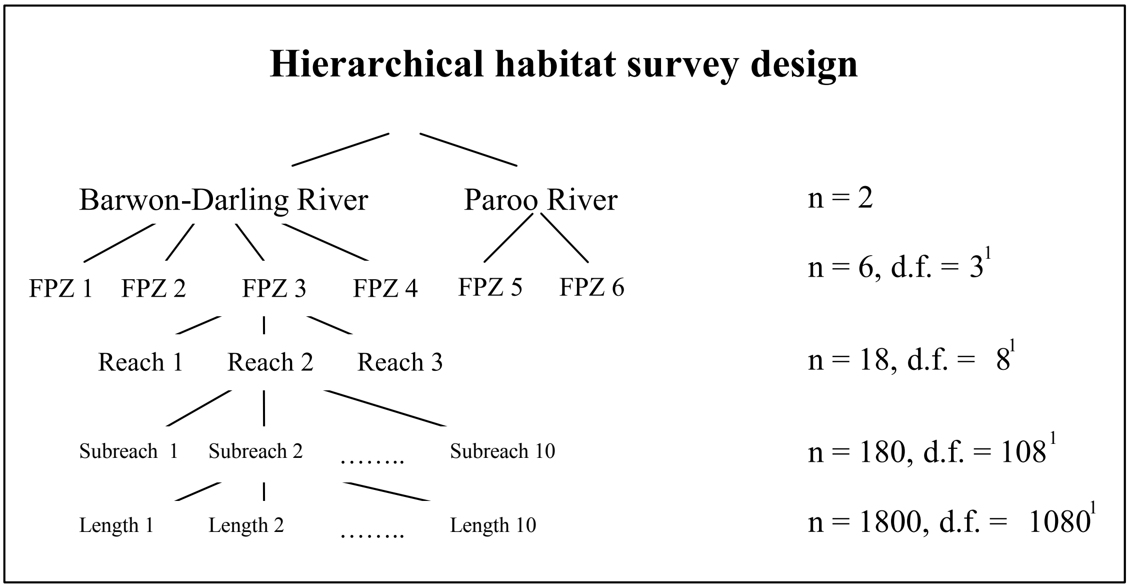


Figure 2.4. The framework used for assessing fish habitats in large dryland rivers as applied to the Barwon-Darling and Paroo Rivers. [1]Degrees of freedom for the Barwon-Darling River.

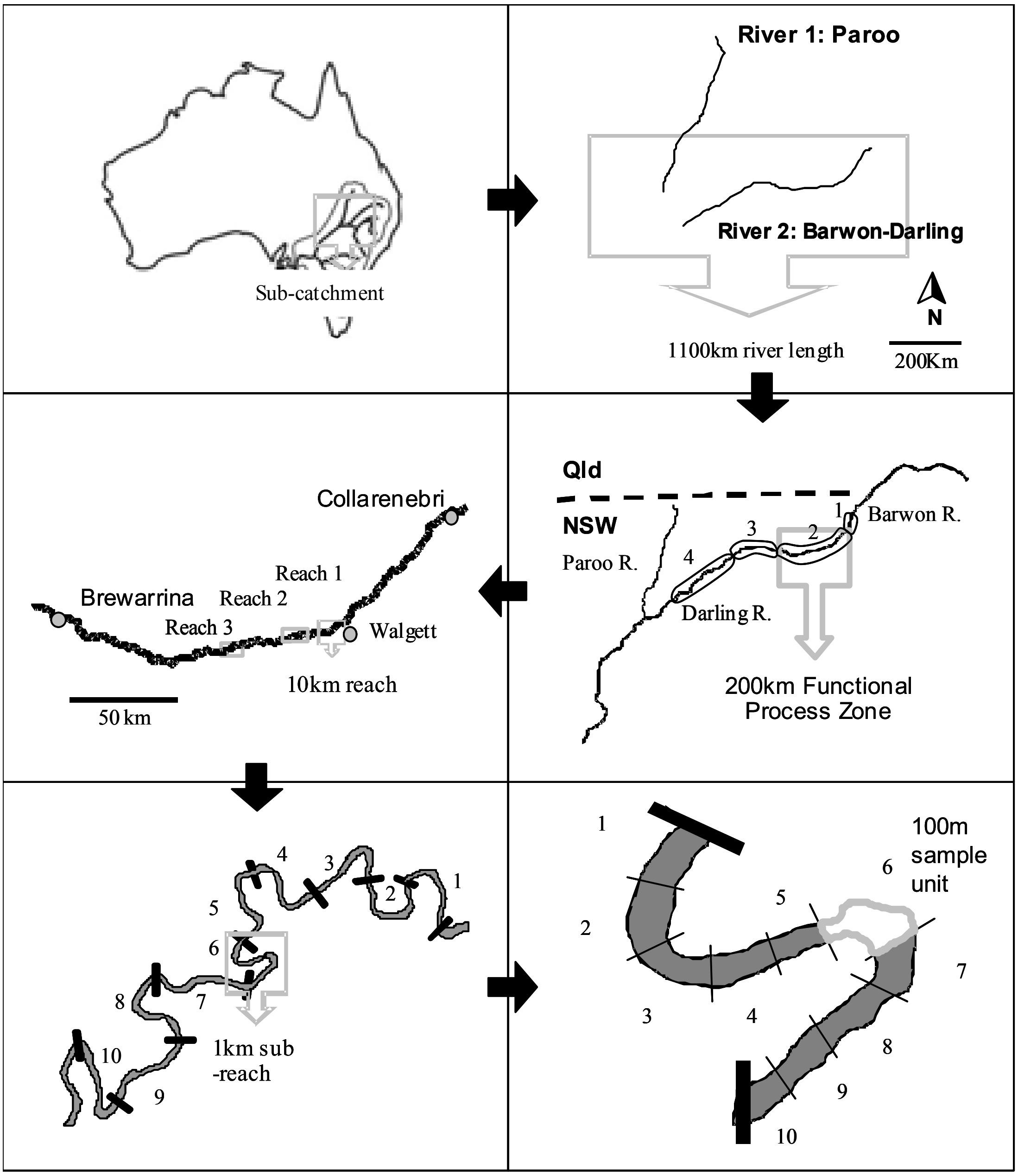


Figure 2.5. The geographic hierarchy used for surveying fish habitat in large dryland rivers.

3. FISH HABITAT IN THE BARWON-DARLING AND PAROO RIVERS DURING LOW FLOW

3.1. Introduction

Although numerous factors have been implicated as possible causes of the decline in native fish populations in the Murray-Darling Basin (see (Cadwallader and Lawrence 1990), habitat alteration may be the single largest threat to the integrity of freshwater fish populations (Allan and Flecker 1993; Wager and Jackson 1993; Maitland 1995; Abramovitz 1996; Kearney *et al*. 1999). However, in Australian dryland rivers, fish habitats are not well understood in the context of the riverine processes that underpin them.

In the literature review (chapter 2), fish communities (ichthyoregions) have been shown to correspond with ecoregions and hydroregions (Hughes *et al*. 1987; Oswood *et al*. 2000; Van Sickle and Hughes 2000), demonstrating that landscape influences community structure. Furthermore, in the review we observed that riverine ecologists and geomorphologists have developed conceptual models of habitat across several scales (Frissell *et al*. 1986), Poole 2002, Thoms *et al.,* 2004a). The conceptual models of riverine habitat that are most current, and relevant to understanding the distributions of fish habitat in dryland rivers, include hierarchical patch dynamic theory (Poole 2002) and the model of Australian dryland rivers (Thoms *et al.,*2004a).

Poole (2002) refers to river scale organisation spanning spatial scales (*trans-scale linkages*), where *contextual* patch structure refers to the juxtaposition and function of coarse scale river patches that frame fine scale patch organisation. Bottom-up trans-scale linkages (*metastructure*) refer to the converse situation of fine scale processes supporting the coarse scale patch structure, juxtaposition, and function. Hence, neighbouring physical structures can be amalgamated into a single encompassing template for observation at coarse spatial scales, or divided into several component templates for observation at fine scales. This concept can be applied directly to the model of Australian dryland rivers developed by Thoms *et al.* (2004a), which is based on *tran- scale* fluvial processes.

Hierarchical patch dynamic theory, when applied to east Australian dryland rivers, is a testable hypothesis. If fish habitats in Australian dryland rivers are underpinned by the fluvial processes of dryland rivers identified by Thoms *et al.* (2004a), their distributions will correspond with those riverine processes, and fish community responses to habitat availability will follow.

Objective:

To assess the distribution of physical habitats in the Barwon-Darling and Paroo Rivers to identify functional river zones.

3.2. Methods

3.2.1. Experimental design

The survey design is shown in chapter 2: Figure 2.4 and Figure 2.5. It involved surveying three replicate reaches within each functional process zone (FPZ), within both the Paroo (a relatively pristine river) and Barwon-Darling Rivers (a river that serves agriculture). Reaches were further divided into sub-reaches, which in turn were subdivided into 100 m sample units. The low flow habitat units (physical structures are listed in Table 2.2 were recorded on each bank. A depth sounder was used to measure channel depth in these sample units. The hierarchical design, as it applies to the Barwon-Darling and Paroo Rivers is shown in Figure 3.1.

3.2.2. Data collection

Surveys were conducted between December 2001 and July 2002 when discharge was at or below the 90th flow percentile (representative of the predominant base flow). Physical structures were observed from a dinghy, or from the bank in a few non-navigable river sections. Position was identified using a global positional system (Garmin GPS III, www.garmin.com). One 10 km reach was surveyed per day, and a total of 18 reaches were surveyed.

3.2.3. Analytical methods

The survey used nested ANOVA (GMAV® software, University of Sydney) to identify scales of habitat distributions along the Barwon-Darling River. Data for individual physical structures were transformed to improve conformity to normal distributions and to homogenize variances (tested for by Cochran's test, $\alpha = 0.05$) between sections of river being compared. Data were then translated to a uniform, ratio measurement (x_i/x_{max}, where x_i is a datum for a variable, and x_{max} is the maximum habitat cover measured for that variable). A map projection of each 10 km reach was used to display habitat cover (ArcView 8.2, www.esri.com).

After defining uniformities and differences in physical structures among 100 m, 1 km, 10 km, 70-200 km, 1100 km river lengths, we partitioned data by the mean cover afforded at each scale category. For the ensuing multivariate analyses, we only considered physical structures that differed significantly (i.e. only matted bank and wood structures differed between 70-200km lengths of river, pool depths were similar between 10 km lengths of river).

The Paroo River featured waterholes interspersed by dry channel, featuring joint absences of physical structures along dry channel lengths. Dry channels along the Paroo River were extensive, and it was sometimes necessary to represent reaches more than 10 km long to record significant wet channel. Therefore, in terms of distance, some reach lengths from the Paroo River were distorted. For example, the Eulo reach contained two wet channel lengths, 3.4 km and 2 km, spaced 6 km apart. This 11.4 km reach was distorted 1.14 times the standard 10 km reach length.

Availabilities of physical structures in wet channels of the Paroo and Darling were compared by independent t-tests (SPSS® software, SPSS® Chicago). For balance, we compared 100 m river lengths as sample units in reaches among the Darling and Paroo Rivers (Figure 3.1). To preserve the distance property of the data, missing data in dry channels of the Paroo River were accommodated by comparing wet channel lengths from both rivers, and removing channel lengths equivalent to the dry channel lengths observed in the Paroo. For example, 3.4 km and 2 km of wet channel in the 11.4 km Eulo reach (Paroo River) were compared with equivalent wet channel lengths in the 10 km Warraweena reach (Darling River). In this example, 6 km of intermediate dry channel in the Paroo, and a compensating 4.6 km of intermediate channel in the Darling, were removed.

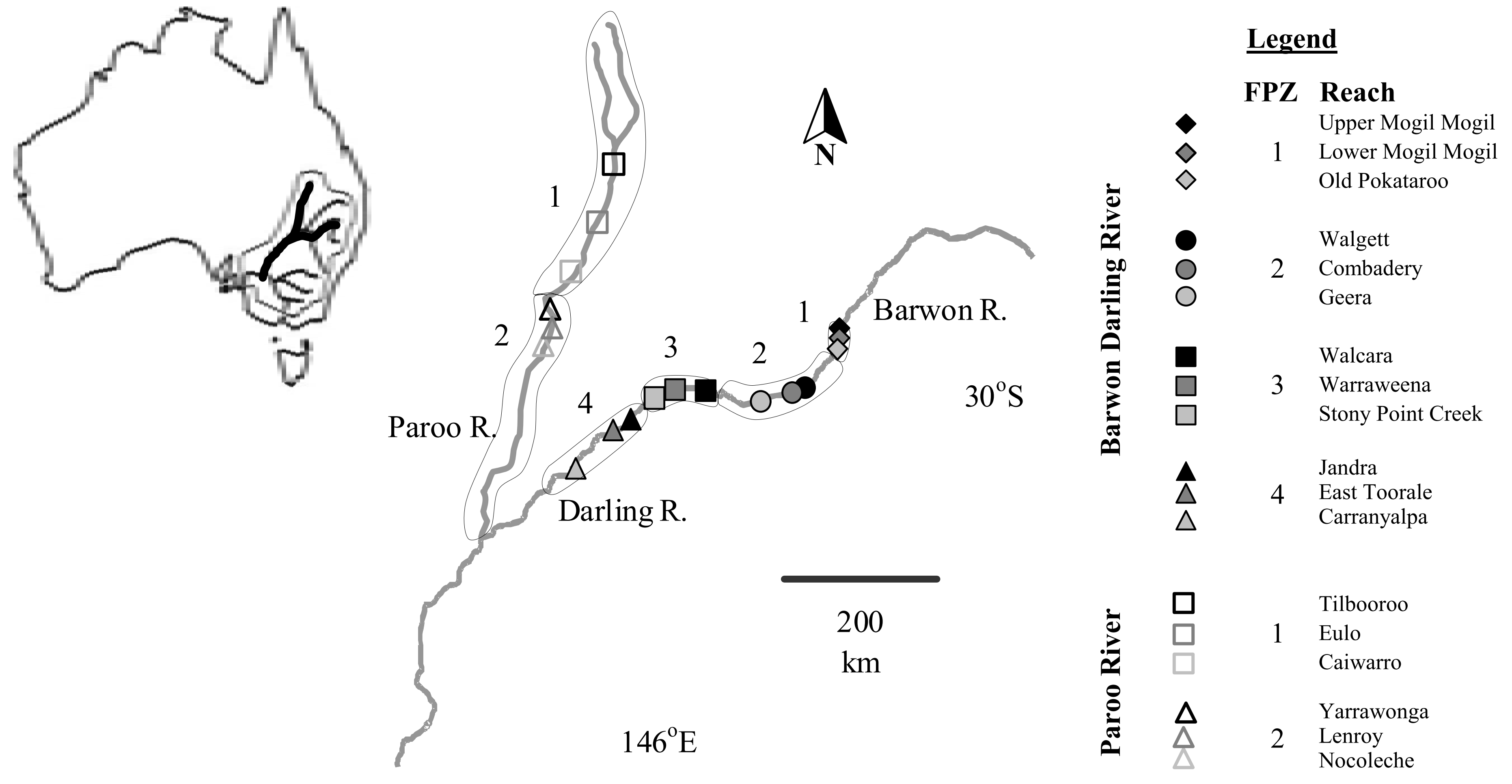


Figure 3.1. The dryland region surveyed for fish habitat, showing the location of reaches within functional process zones. The symbols correspond to those used in the ordinations and classification.

For multivariate analyses, we calculated similarity metrics among river lengths using the Gower and Bray-Curtis metrics (Legendre and Legendre, 1998). The Gower metric identified physical structures relative to their natural range in the Barwon-Darling-Paroo River system. The Bray-Curtis metric identified rare and common physical structures equally, which was useful because rare physical structures essential to a fish species may have been overlooked (Legendre and Legendre, 1998). Reaches were classified by hierarchical agglomeration (flexible UPGMA, $\beta = -0.1$, PATN® software, CSIRO Canberra), which identified river lengths as physical templates grouped hierarchically by similarity metrics. Reaches were also ordinated by Semi-Strong Hybred (SSH) Multi-Dimensional Scaling (PATN® software, CSIRO Canberra), which geometrically ordered physical templates defined by their similarity metrics. These physical templates were graphically projected in two dimensions using Principal Axis Correlation.

3.3. Results and discussion

3.3.1. River scale distributions of physical structures along the Barwon-Darling

Scale was significant and influenced the magnitude of treatment effects (Sheskin, 1997), which measured the portion of variability on physical structure associated with channel position along the Barwon-Darling. Relatively high treatment effects at all scales (η^2 were greater than 0.15) showed that a significant portion of physical structure caused channel heterogeneity, even at the sub-reach (1 km) scale (η^2 were 0.15 – 0.33). Treatment effects generally increased with scale, with the largest portions of matted bank, irregular bank, and structural woody habitat cover contributing to channel heterogeneity at the FPZ (70 – 200 km) scale (η^2 were 0.52 – 0.88). This observation did not hold for smooth bank and depth, which had the largest treatment effects at the reach (10 km) scale (η^2 were 0.47 - 0.54). Therefore, we used the reach scale for observing spatial differences in physical structures along the Barwon Darling.

Along the Barwon-Darling, availabilities of matted bank and structural woody habitat cover differed among FPZ's, but availabilities of smooth bank, irregular bank and channel depth were uniform (Figure 3.2). The following environmental gradient occurred at the river scale:

FPZ 1 (upstream): This river length was rich in matted bank, and intermediate in structural woody habitat.

FPZ 2: This river length was rich in structural woody habitat, and intermediate in matted bank.

FPZ 3: This river length was intermediate in structural woody habitat, and depauperate in matted bank.

FPZ 4 (downstream): This river length was intermediate in matted bank, and depauperate in structural woody habitat.

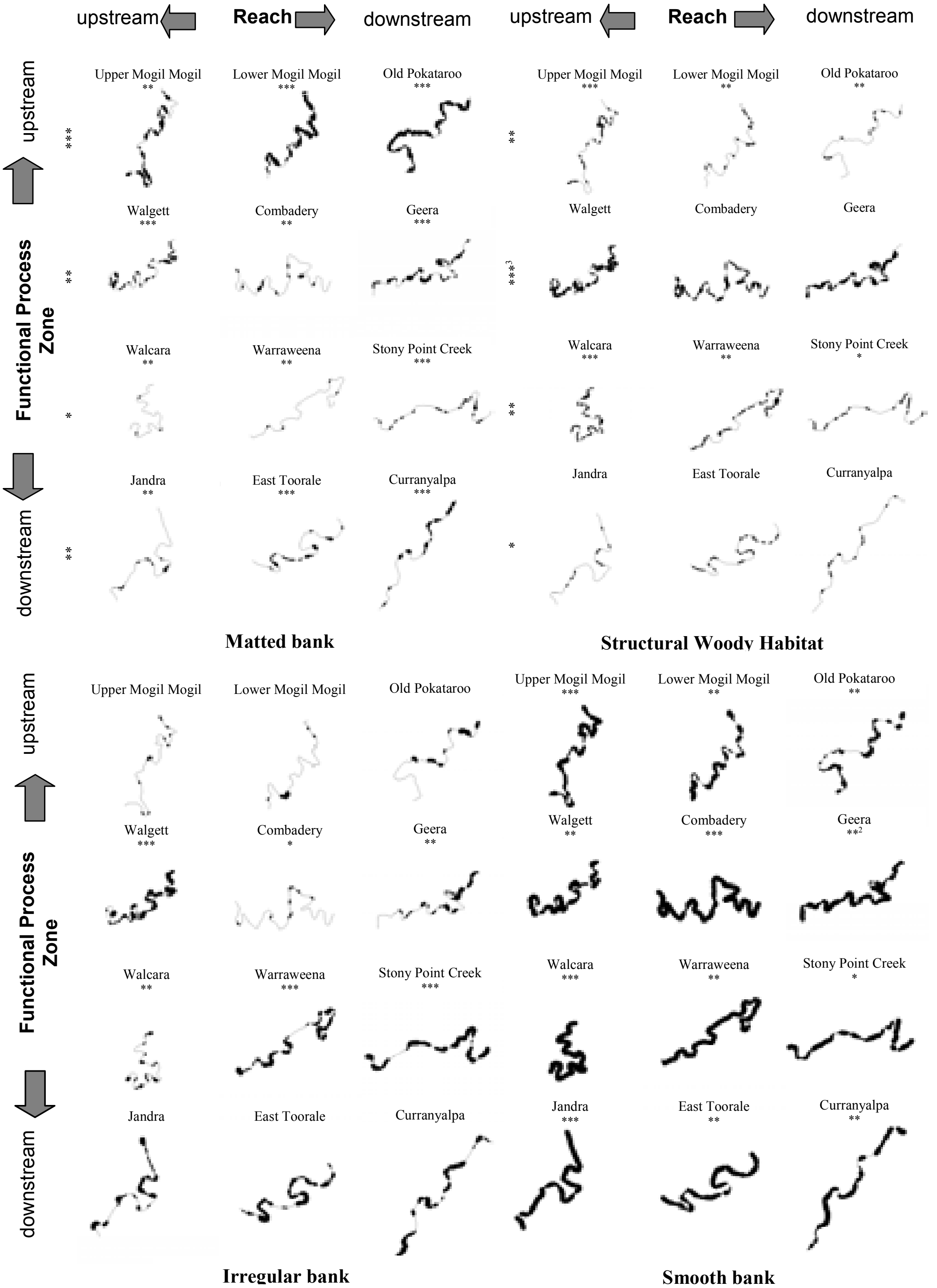


Figure 3.2. (continued on the next page). Relative abundances (line thickness) of habitat along reaches of the Barwon-Darling River. Statistically significant differences were (*** = more cover, ** = intermediate cover, * = less cover). No symbol represents statistically equivalent cover. 2Combadery had more smooth bank than Walgett and Geera. 3FPZ 3 had more structural woody habitat than FPZ 4, while FPZ 1 and FPZ 4 had equivalent structural woody habitat cover.

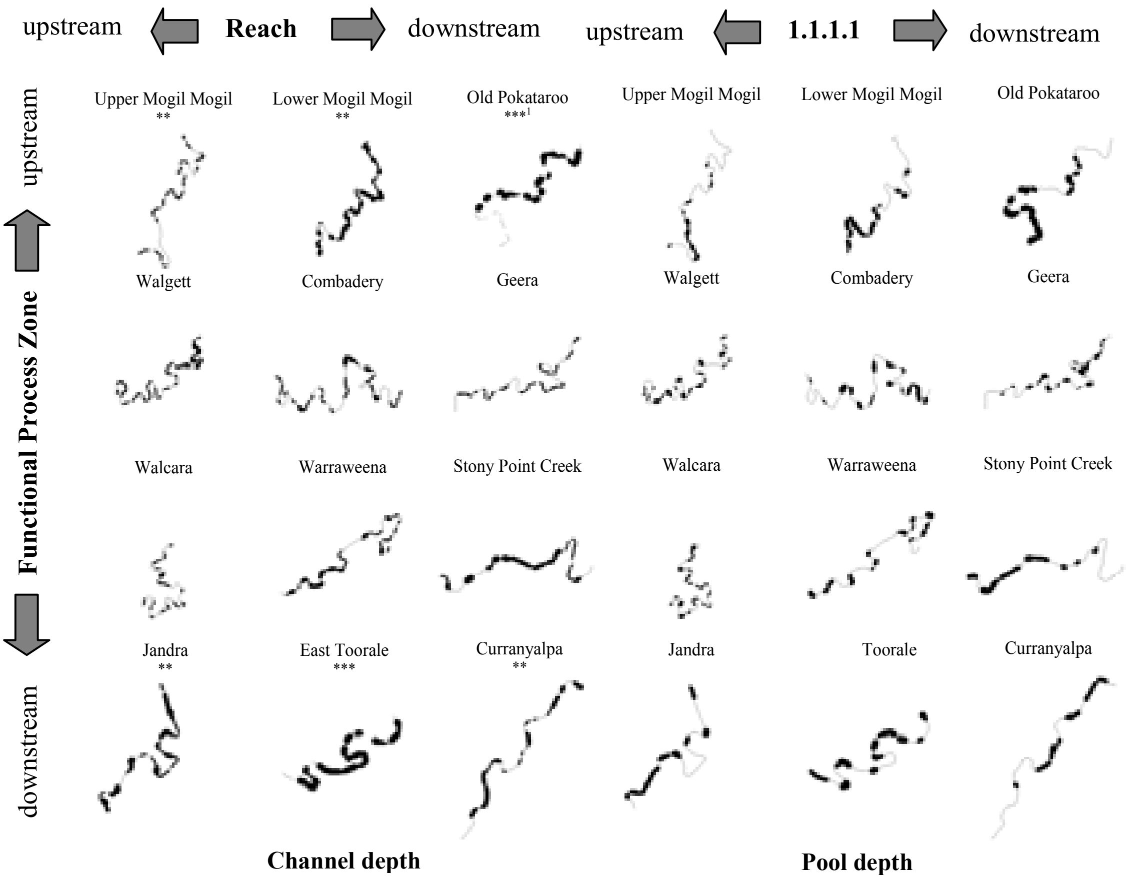


Figure 3.2. (Continued from previous page) 1Old Pokataroo had deeper channels than Upper Mogil Mogil only.

A second environmental gradient occurred within FPZ's (Figure 3.2). In the Barwon section, matted bank was distributed counter-current to the river scale gradient:

Upstream: Upstream reaches were generally rich in smooth bank (in FPZ's 1, 3 and 4), occasionally shallow (in FPZ 1) and rich in structural woody habitat (in FPZ's 1 and 3), while matted bank was generally lacking (in FPZ's 1, 3, 4).

Downstream: Downstream reaches were rich in matted bank habitat (in all FPZ's), occasionally rich in irregular bank (in FPZ 3) and deep channel (in FPZ 1), and lacking in smooth bank (in FPZ's 1, 3 and 4) and structural woody habitats (in FPZ's 1 and 3).

These scale-dependent distributions of physical structures collectively underpinned the juxtaposition and nature of physical templates in the Barwon-Darling River

3.3.2. The regional-scale gradient of habitat templates

The Gower metric defined large lengths of Barwon-Darling as distinctive physical templates (Figure 3.3): the upper Barwon (FPZ 1) at 66% similarity, the lower Barwon/upper Darling (FPZ 2 and part of FPZ 3) at 60% similarity, and the Darling (part of FPZ 3 and FPZ 4) at 70% similarity. These large, encompassing, physical templates occurred along a river-scale gradient (Figure 3.4).

Nested in the river scale gradient was another FPZ scale gradient of component physical templates, which upstream of FPZ 3 was counter-current to the river scale gradient, but downstream of FPZ 3 reinforced the river scale gradient (Figure 3.4). This nested hierarchy of physical templates (Figure 3.3) corresponded with the Thoms *et al*. (2004a) geomorphic classification of the Barwon-Darling (Figure 2.5).

The FPZ scale gradient of physical templates was emphasised by the Bray Curtis metric (Figure 3.3). The lower Barwon/Darling subdivided into two groups of physical templates (D and E) at 66% similarity: (D) Downstream reaches within FPZ's 2, 3 and 4. (E) Upstream reaches within FPZ's 2, 3 and 4. The upstream reach of FPZ 2 was non-conformist, and possibly influenced by its close proximity to the Walgett weir (3.2 km downstream from the weir).

3.3.3. Differences in physical habitat between Barwon-Darling and Paroo Rivers

At the regional scale, the Paroo and Darling had distinctive physical templates (Figure 3.3). Physical templates in the Paroo were 52% similar, except for Nocoleche National Park (lower Paroo) (Figure 3.1) that resembled the lower Barwon/upper Darling (Figure 3.3, Figure 3.4). This was a significant observation since it was found during fish sampling (chapter 5), that Nocoleche Nature Reserve also contained a fish assemblage more closely related in structure to the lower Barwon-Darling than to the upper Paroo (Figure 5.2). Nocoleche National Park was the only reach in the Paroo completely represented by wet channel. Physical templates along the Paroo graded from upstream reaches dominated by dry channel, to downstream reaches containing more extensive wet channels featuring smooth bank and structural woody habitat (Figure 3.1, Figure 3.3, Figure 3.4).

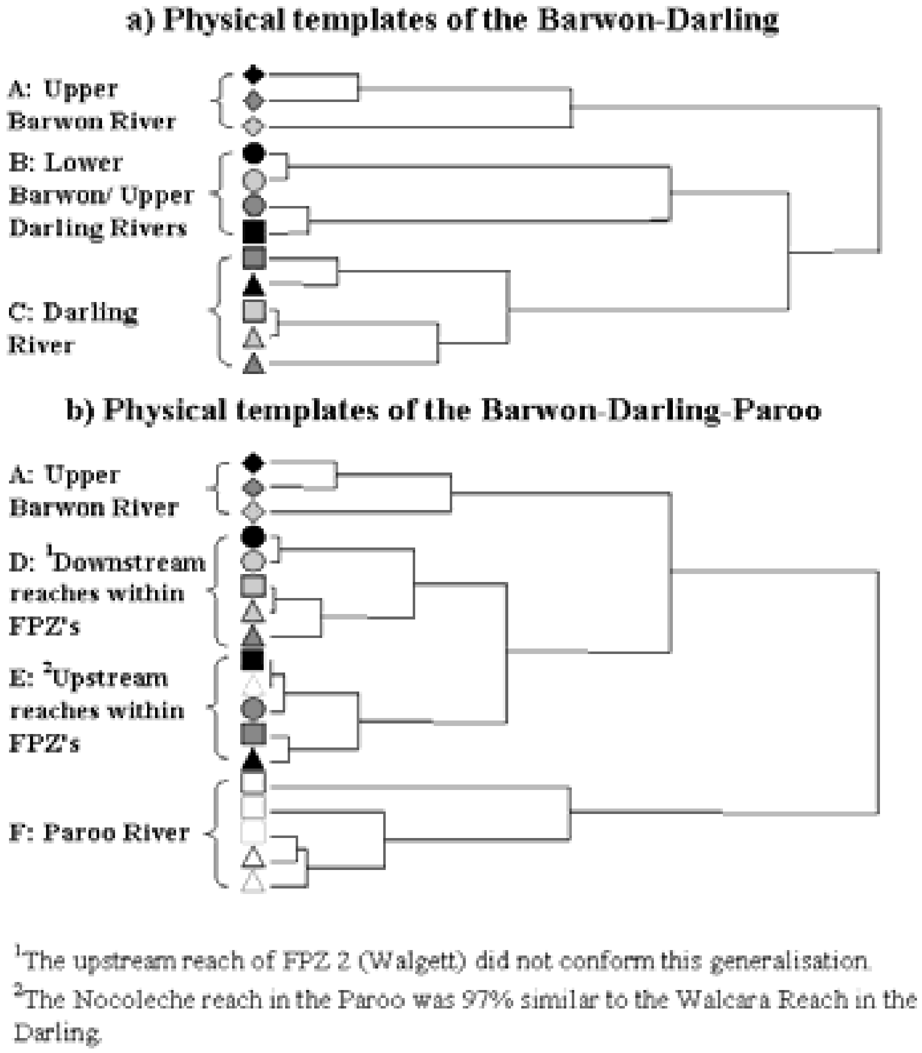


Figure 3.3. Hierarchical classifications of habitat templates in dryland rivers based on the Gower metric a) and the Bray-Curtis coefficient b). Symbols correspond to the legend provided in Figure 3.1.

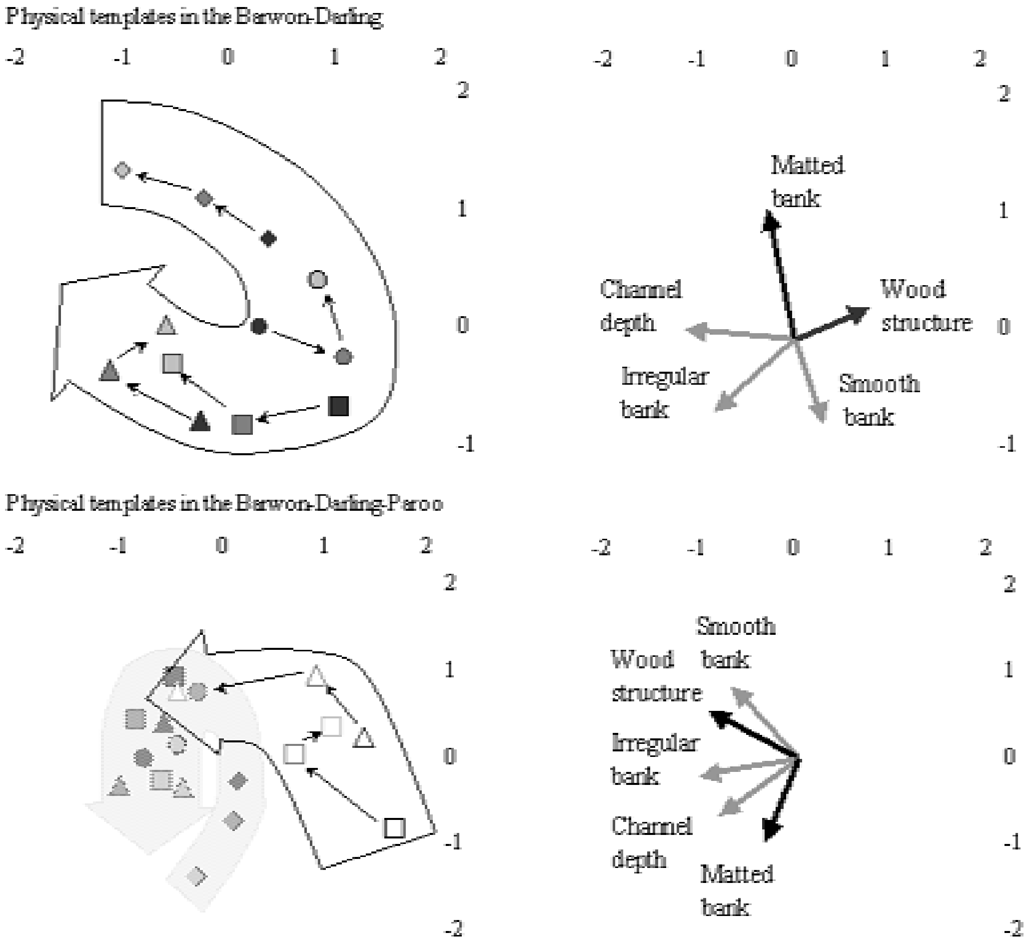


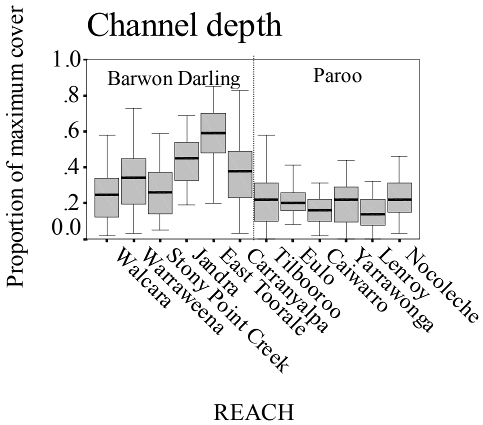
Figure 3.4. The left biplots show ordinations of reaches, identified by symbols listed in Figure 3.1, using the Gower (top graph) and Bray-Curtis (bottom graph) metrics. Open arrows show the progressive downstream structure of physical templates in these dry-land rivers. Within the open arrows, are subsidiary arrows that show the progressive downstream structure of physical templates in FPZ's. The right biplots show ordination vectors. Black vectors contribute to physical structure at along the Barwon-Darling, and at subsidiary FPZ scales. Grey vectors contribute to physical structure within FPZ's. Stress for both ordinations were below 0.2.

3.3.4. The physical habitat in wet channels of two dry-land rivers

There were significant and substantial habitat differences among rivers. The Darling was deeper, with more irregular bank, than the Paroo (Figure 3.5). Large-magnitude treatment effects meant that a substantial proportion of 100 m river lengths contributed to these differences.

Depth: Wet channels of the lower Barwon-Darling were on average ≈18% deeper than the Paroo (Fig. 6; t(503) = 14.03, $p < 0.00$, power > 0.99). The treatment effect showed that 23% of 100 m river lengths contributed to this difference.

Irregular bank: Wet channels of the lower Barwon-Darling had on average ≈11% more irregular bank cover than the Paroo (Fig. 6: t(342) = 10.55, $p < 0.00$, power > 0.99). The treatment effect showed that 15% of 100m river lengths contributed to this difference.



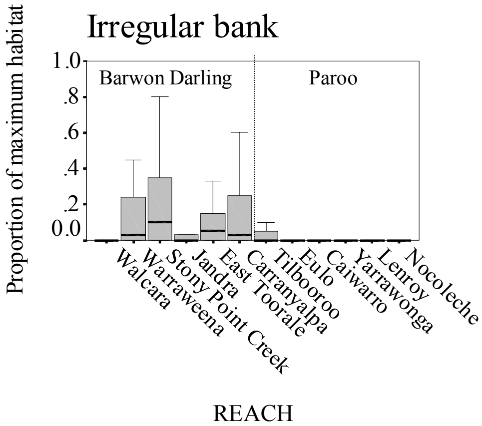


Figure 3.5. Relative abundances of channel depth and irregular bank habitat in the Paroo and Barwon-Darling rivers.

There were also significant, but less substantial, differences among rivers. The Darling had less smooth bank and structural woody habitats than the Paroo (Figure 3.6). Small to medium-magnitude treatment effects meant that only a small proportion of 100m river lengths contributed to these differences.

Smooth bank: Wet channels of the lower Barwon-Darling had on average ≈10% less smooth bank cover than the Paroo (Fig. 7: t(605) = 6.56, $p < 0.00$, power > 0.99). The treatment effect showed that 6% of 100m river lengths contributed to this difference.

Structural woody habitat: Wet channels of the lower Barwon-Darling had on average ≈5% less structural woody habitat than the Paroo (Fig. 7: t(618) = 5.36, $p < 0.00$, power > 0.99). The treatment effect showed that 4% of 100m river lengths contributed to this difference.

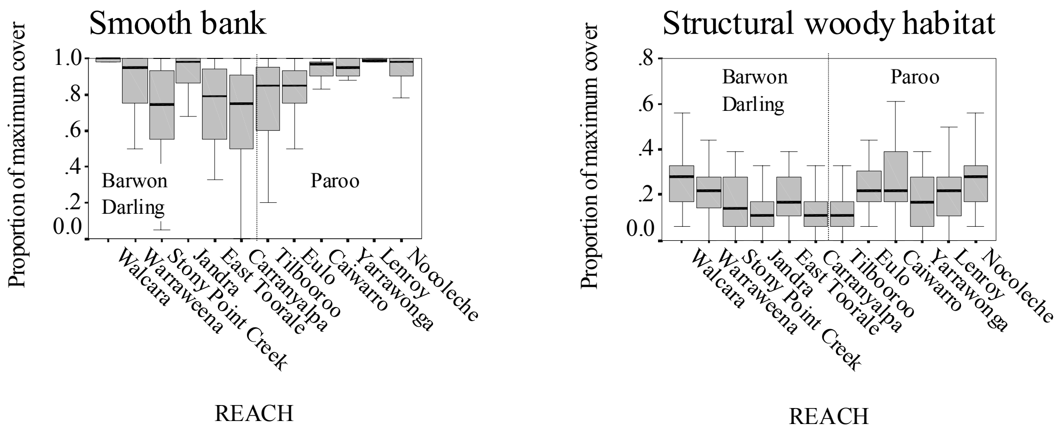


Figure 3.6. Relative abundances of smooth bank and structural woody habitat in the Paroo and Barwon-Darling Rivers.

There were also similarities among the rivers, in terms of matted bank availability. Both rivers had on average ≈10% of the maximum possible matted bank cover available as 100m river lengths in the Darling-Paroo system (Fig. 8: $t(636) = 0.44$, $p = 0.66$, power = 0.17). The low power of this test meant that even with the substantial representation of 323 sample units from each river, statistically there was only a small probability (17%) that a true difference in matted bank cover of magnitude ≥0.5% was detectable. However, the absence of treatment effect (0.00%) supported the conclusion of no difference on matted bank cover between the two rivers.

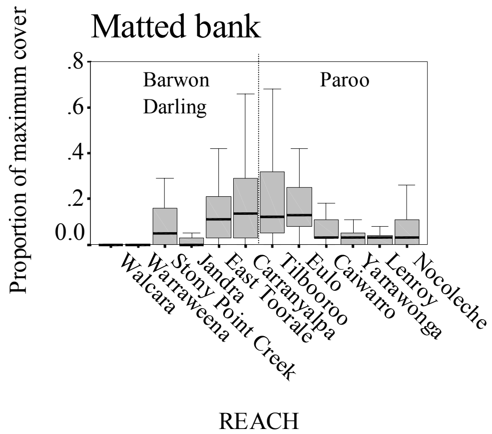


Figure 3.7. Relative abundances of matted bank habitat in the Paroo and Darling rivers.

3.4. Conclusion

Using a survey design stratified in accordance with the hierarchical framework of dryland river geomorphology, scale-dependent shifts in habitat structure became evident. This aspect of physical habitat structure would have been missed by a totally randomised survey design. Downstream gradients of habitat change were evident at between river, whole river and FPZ scales.

Between rivers, the habitat differed mainly with respect to the amount of wet channel and irregular bank available. The Paroo River is an unmodified, ephemeral river (consisting of permanent waterholes), which contained substantially less wet channel than the Barwon-Darling River. Further downstream in the Paroo River, the size and therefore permanency of these waterholes increased. As the amount of wet channel increased downstream in the Paroo River, the habitat templates of this river changed to more closely resemble those of the lower Barwon-Darling.

Within the Barwon-Darling River, there were three distinct regions based on the characteristic habitat structures available during low flows: the upper Barwon, the lower Barwon/Darling and the Darling. The upper Barwon had physical templates with abundant matted bank, and structural woody habitat, which were less abundant downstream in the Darling. Therefore riparian vegetation influenced habitat templates at the river scale. There were also FPZ-scale influences among reaches. Smooth bank cover usually decreased downstream, while matted bank usually increased. Therefore, sediment and discharge regimes (which define FPZ's) have influenced physical templates at the FPZ scale.

It is clear that dryland rivers of the Barwon-Darling-Paroo system are a hierarchical patchwork of physical templates at the catchment, river, FPZ, and reach scales. The encompassing physical template of east Australian dryland rivers can be described and understood by defining the context and metastructure of physical structures in each river hierarchy. By defining the river structure, complex biotic community responses might be explained. This will be the subject of chapter 5.

4. FISH HABITAT IN THE BARWON-DARLING AND PAROO RIVERS DURING HIGH FLOW

4.1. Introduction

The proceeding chapter has described the scales of habitat distribution in two dryland rivers during base flows that predominate for much of the time. It is important to note, however, that infrequent, high, flows also play an ecologically important role by increasing the connectivity and availability of habitats along the river valley. Mallen-Cooper and Stuart (2003) have shown that recruitment for two potamodromous species of fish in the Murray-Darling Basin can coincide with times of high, within-channel flows. During these times, when large-scale within-channel movement is possible, river-scale availabilities of high flow habitats may become particularly relevant to these mobile fish that can potentially travel hundreds of kilometres (Mallen-Cooper 1989).

Objective:

The objective was to assess the distribution of physical habitats that are only available to fish during high flows along the Barwon-Darling and Paroo Rivers.

4.2. Methods

4.2.1. Experimental design

The survey design is shown in chapter 2: Figure 2.4 and Figure 2.5. As with the low flow habitat surveys, it involved surveying three replicate reaches within each functional process zone (FPZ), within both the Paroo and Barwon-Darling Rivers. Reaches were further broken down into sub-reaches, which in turn were divided into 100m sample units. It is at these sample units that the predominant emergent habitat features (Table 4.1) were recorded. The hierarchical design, as it applies to the Barwon-Darling and Paroo Rivers is shown in Figure 3.1. This enabled the comparison of emergent habitat structure in a river impacted by water resource development (Barwon-Darling River) and a river minimally modified by water resource development (Paroo River).

4.2.2. Data collation

Surveys were conducted between December 2001 and July 2002 at times when the flow was at or below the 90th flow percentile (representative of the predominant base flow). Emergent habitat (habitat above the waterline) were observed from a dinghy, or from the bank in a few non-navigable river sections. Position along a 10 km reach was determined using a global positional system (Garmin GPS III, www.garmin.com). One 10 km reach was surveyed per day, and a total of 18 reaches were surveyed. A total of 32 habitat attributes were tallied at the 100 m sample unit and partitioned into 5 subsets: riparian vegetation, structural woody habitat, bank structure, in-channel sedimentation or channel form (Table 4.1). Each were recorded as either absolute frequency, or assigned to a scaled category. Scaled categories were developed from visual estimations of magnitude, shrub cover, tree cover, percent overhang, and vegetation height. Riparian tree cover was estimated and assigned to one of the following three categories: sparse (<33% cover), medium density (33-66% cover), or dense (>66% cover). The density of riparian cover in a 10 km reach was then estimated by multiplying the mid-point of each category (i.e. 17%, 50% and 83%) by the frequency that it occurred and summing for the entire reach.

Table 4.1. Attributes used to identify high-flow habitat.

Habitat Category	Habitat attribute
Riparian vegetation (growth density and characteristics).	Sparsely vegetated (unvegetated, isolated/scattered). Medium density vegetation (regularly spaced). Medium density vegetation (clumped growth). Densely vegetated (semi-continuous or continuous growth). Overhang (<25%, 25-50%, >50%). Height (<10m, 10-20m, 20-30m). Tree cover (<30%, 30-60%, >60%). Shrub cover (<30%, 30-60%, >60%).
Structural woody habitat	Number. Short (<10m). Medium length (10-20m). Long (20-30m). Single trunk (class 1 after (Hughes and Thoms 2002)). Bifurcating trunk (class 2 after (Hughes and Thoms 2002)). Third order branches (class 3 after (Hughes and Thoms 2002)). Structurally complex (class 4 after (Hughes and Thoms 2002)).
Bank structure	Gullying (gully or anabranch). Mass wasting (rotational shear). Stepped bank. Convex bank. Concave bank. Steep sloping bank (60-90 ^{o}). Medium sloping bank (30-60 ^{o}). Gentle sloping bank (<30 ^{o}).
In-channel sedimentation	Bar-forms absent. Unvegetated point bar. Vegetated point bar. Mid channel bar. Obstruction bar. Low on bank (between 0-1/3 of bank height). Middle of bank (between 1/3 – 2/3 of bank height). High on bank (between 2/3 to 1 of bank height).
Channel form (After Anderson, 1993)	U shape. Flat U-shape. Stepped. Box-shape. Occluded.

4.2.3. Analytical methods

The survey used nested ANOVA (GMAV® software, University of Sydney) to identify scales of habitat distributions along the Barwon-Darling River, and also habitat attributes that were invariant across the region (these were disregarded from further analyses). Data for each habitat variable had been transformed to improve normal distributions and develop uniform variances (tested for by Cochran's test, $\alpha = 0.05$), and then standardised to a uniform, ratio measurement ranged between 0 and 1.

For multivariate analyses, we chose the χ^2 metric to define habitat templates. This metric suits long environmental gradients where attributes replace each other (Legendre and Legendre 1998). Average habitat cover over 10 km reaches, were classified by hierarchical agglomerative clustering (flexible UPGMA, $\beta = -0.1$), which hierarchically grouped reaches based on predominant habitat type (PcOrd, MJM Software, Oregon). Reciprocal averaging was used to ordinate these habitat templates.

Availabilities of emergent habitat in the Paroo and Barwon-Darling Rivers were compared by independent-samples t-tests (SPSS® software, Chicago), to support interpretations of habitat distributions among rivers developed from the multivariate analyses. One km sub-reaches were used as sample units. To balance data from both rivers, equivalent wet-channel lengths from both rivers were compared: FPZ's 3 and 4 between Brewarrina and Tilpa (Barwon-Darling River), versus FPZ's 1 and 2 between Tilbooroo Homestead and Nocoleche National Reserve (Paroo River).

4.3. Results

Within the Barwon Darling River, nested ANOVA showed that distributions of several physical structures varied among functional process zones, and that distributions of almost all physical structures varied among reaches. Physical templates of the upper Barwon Functional Process Zone were different from physical templates' further downstream. Five types of physical structure contributed to this result:

1. *Riparian vegetation:* Along the upper Barwon, riparian vegetation provided more overhanging cover than along the lower Barwon and the Darling in turn (3 degrees of freedom, $F = 20.10$, $p < 0.00$: FPZ 1 > FPZ 2 > FPZ's 3,4).

2. *Structural woody habitat:* Along the upper Barwon were relatively more small timber objects, such as branches, less than 10m long in the main channel (3 degrees of freedom, $F = 5.03$, $p = 0.03$: FPZ 1 > FPZ's 2,3,4).

3. *Bank structure and erosion:* The upper Barwon had more convex bank cover than the lower Barwon-Darling River further downstream (3 degrees of freedom, $F = 12.63$, $p = 0.002$: FPZ 1 > FPZ 4 ≥ FPZ 2 ≥ FPZ 3). This was usually the result of root mats stabilising banks from erosion.

4. *Channel alluvium:* The upper Barwon had more channel without bar-form deposits, compared with the lower Barwon-Darling further downstream (3 degrees of freedom, $F = 5.01$, $p = 0.03$: FPZ 1 ≥ FPZ 2 ≥ FPZ 4 ≥ FPZ 3). By contrast, the lower Barwon-Darling River had more channel with point-bar deposits (3 degrees of freedom, $F = 6.52$, $p = 0.015$: FPZ 3 > FPZ's 1,2,4). Obstruction-bar deposits were more abundant in the Darling (3 degrees of freedom, $F = 6.77$, $p = 0.014$: FPZ's 3,4 > FPZ's 1,2).

5. *Channel form:* The Darling had more channel with flat-U cross-sections (3 degrees of freedom, F = 15.22, p = 0.001: FPZ's 2,3,4 > FPZ 1). Stepped channel forms were less abundant in the lower Barwon (3 degrees of freedom, F = 15.51, p = 0.001: FPZ's 1,3,4 > FPZ 2).

There were subsidiary differences, among reaches within the FPZ context, of all habitat attributes except flat channel form, stepped channel form, and channels without barform deposits. These latter three habitat attributes were different only at a larger scale, among FPZ's within the Barwon-Darling River.

4.3.1. Riparian vegetation

Mean differences between the Paroo and Darling Rivers showed that Paroo sub-reaches had 11 to 35% more shrub cover ($t(46) = 3.78$, $p<0.000$) while Darling sub-reaches had 8 to 33% more tree cover ($t(56) = 3.28$, $p=0.002$). Darling sub-reaches had 5 to 28% more sections of sparse vegetation ($t(74) = 3.74$, $p<0.000$), while Paroo sub-reaches had 6 to 26% more medium density vegetation growth ($t(62) = 3.31$, $p=0.002$). Trees along the Darling were 8 to 24% taller ($t(56) = 3.80$, $p<0.000$), but trees along the Paroo offered 8 to 26% more overhang ($t(43) = 3.97$, $p<0.000$). Hence there were river-scale differences in physical templates related to vegetation density and type.

Functional Process Zone 1 of both the Paroo and Barwon-Darling was wooded with tall trees of medium to high-density growth, which overhung the river and were sometimes clumped (Figure 4.1). Along the Paroo, FPZ 2 had a distinctive, medium density, riparian vegetation structure that was predominantly shrub. Along the Barwon Darling, FPZ 3 and parts of FPZ's 2 and 4 had relatively sparsely vegetated shrub growth. Hence, there were also FPZ scale differences in vegetation related physical habitats within these two rivers.

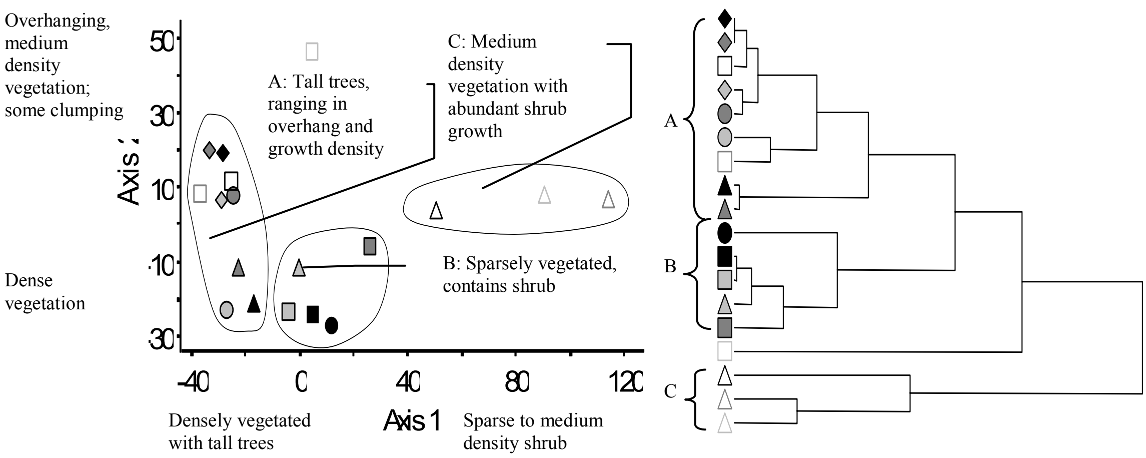


Figure 4.1. Habitat templates related to riparian vegetation along the Paroo-Barwon-Darling river system. For legend of symbols refer to Figure 3.1.

4.3.2. *Structural woody habitat*

At the river scale, mean differences between the Paroo and Darling showed that Darling sub-reaches had up to 21% less cover offered by timber objects smaller than 10 m ($t(67) = 3.97$, $p=0.03$), and 14 to 33% more cover by timber objects bigger than 10 m ($t(62) = 5.04$, $p<0.000$). Otherwise, both rivers had similar abundances and structural complexity of woody habitat.

At the functional process zone scale, structural woody habitat derived from riparian trees varied regionally with respect to distributions of branches less than 10 m long. The upper Barwon and the lower Paroo (FPZ's 1 and 2 respectively) had greater availabilities of small branches (Figure 4.2). Otherwise, structural woody habitat templates varied non-systematically among FPZ's of the Paroo-Barwon-Darling. Hence, at the river and functional process zone scales, we observed heterogenous distributions of small timber structures within dry land river channels.

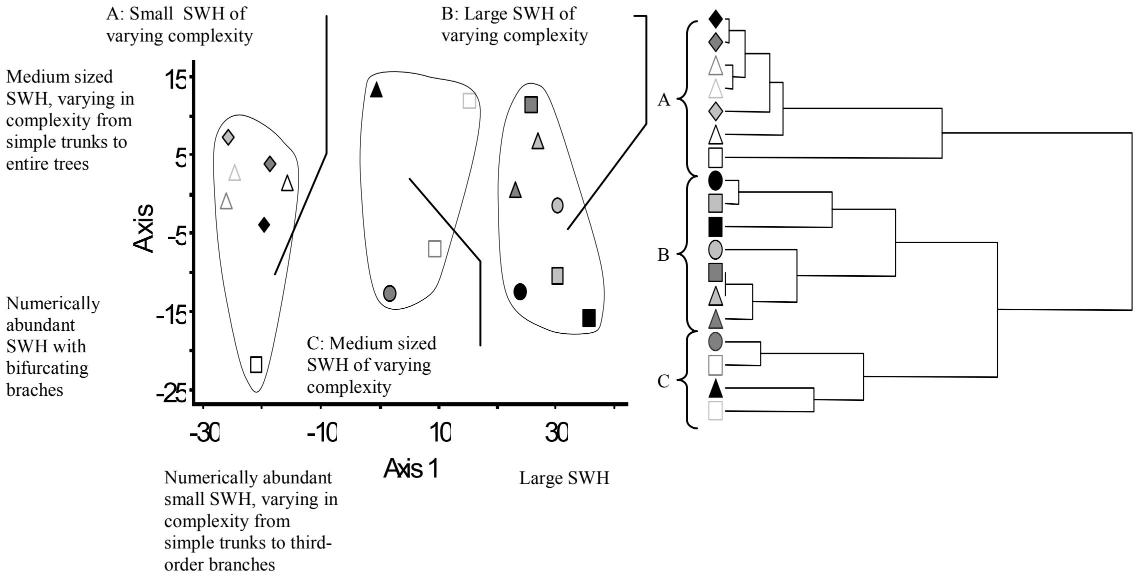


Figure 4.2. Templates related to structural woody habitat along the Paroo-Barwon-Darling river system. For legend of symbols refer to Figure 3.1.

4.3.3. *Channel form*

At the river scale, mean differences between the Paroo and Darling showed 52 to 79% more occluded bank along Paroo sub-reaches ($t(74) = 9.89$, $p<0.000$), and 39 to 72% more flat-U channels along Darling sub-reaches ($t(74) = 6.902$, $p<0.000$). This confirmed that the Darling and Paroo rivers had different channel forms.

Among functional process zones were four distinctive channel forms. (Figure 4.3). The lower Paroo (FPZ 2) had occluded channels. The upper Barwon (FPZ 1) had U and deep-U shaped channels. The lower Barwon and Darling (FPZ's 2,3,4) had stepped, or flat U-shaped, channels. One reach in FPZ1 of the Paroo River (Tilbooroo station) had a distinctive 1 km sub-reach of box-shaped channel formed between root mats of riparian eucalypts.

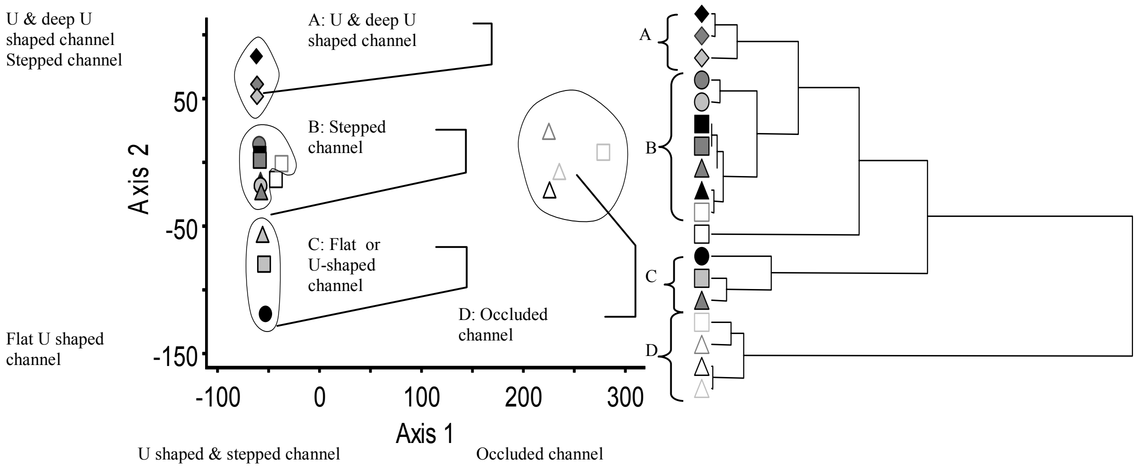


Figure 4.3. Habitat templates related to channel form along the Paroo-Barwon-Darling river system. For legend of symbols refer to Figure 3.1.

4.3.4. Bank structure

At the river scale, mean differences showed that Darling River sub-reaches had up to 21% more steep bank cover (t(66) = 2.19, p=0.03), 36 to 59% more medium bank cover (30-60^o slope) (t(48) = 8.33, p<0.000), and 38 to 63% less shallow bank cover (t(56) = 7.73, p<0.000). There was 12 to 27% more cover by stepped banks (t(74) = 4.97, p<0.000), and 23 to 34% more incidents of mass wasting (t(39) = 10.27, p<0.000) in the Darling River.

Among functional process zones, the lower Paroo (FPZ 2) had shallow banks (<30^o slope) that distinguished this river from the Barwon-Darling River, which had medium to steep banks (>30^o slope)(Figure 4.4). The Barwon-Darling River graded from convex, gullied banks in the upper Barwon (FPZ 1), to stepped, concave banks with wide lower benches and mass wasting in the Darling River (FPZ's 2,3,4)(Figure 4.4). Undercut banks occurred in FPZ 1 of both the Barwon-Darling River and Paroo River (Figure 4.4).

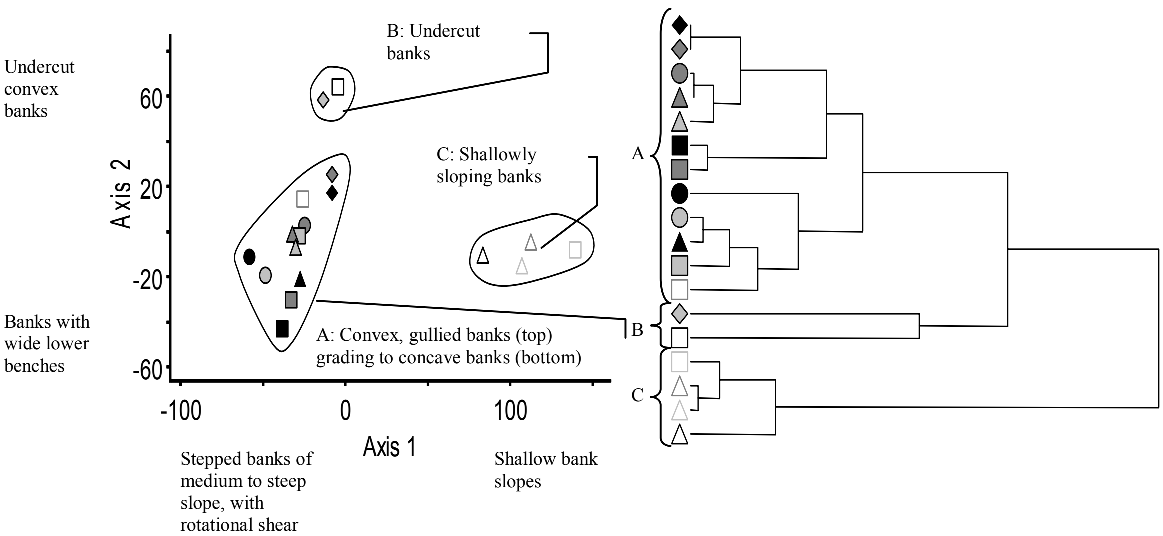


Figure 4.4. Habitat templates related to bank structure along the Paroo-Barwon-Darling river system. For legend of symbols refer to Figure 3.1.

4.3.5. Sedimentation in river channels

There were river-scale differences in bar-form deposits. Mean differences showed that Paroo sub-reaches had 24 to 56% more mid-channel bars ($t(68) = 5.20$, $p<0.000$). The Darling had 27 to 45% more point bars ($t(41) = 8.52$, $p<0.000$), up to 33% more vegetated point bars ($t(51) = 3.48$, $p=0.001$), and 33 to 54% more obstruction bars ($t(74) = 8.89$, $p<0.000$). The Darling also featured up to 32% more bench deposits at all bank levels ($t(58 \text{ to } 71) = 3.82 \text{ to } 4.56$, $p<0.000$).

At the FPZ scale, the Barwon (FPZ1 and part of FPZ 2) featured relatively minor channel alluvium, deposited as point bars that were occasionally vegetated, and benches (Figure 4.5). Further downstream along the Darling (part of FPZ 2 down to FPZ 4), alluvium deposits in the channel were point bars, obstruction bars, and benches (Figure 4.5). Alluvium in the Paroo channels was characteristically mid-channel bars (Figure 4.5).

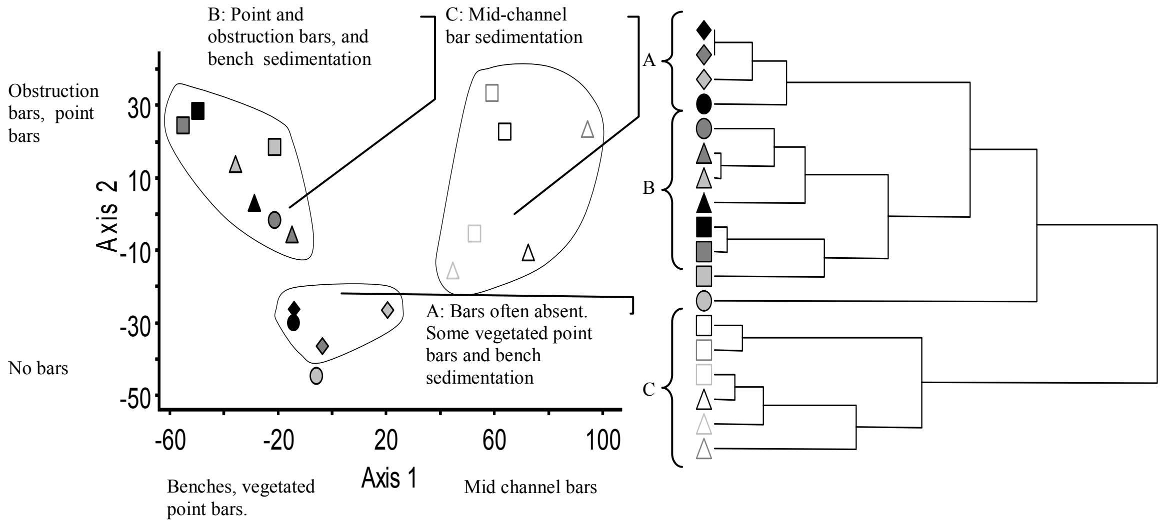


Figure 4.5. Habitat templates related to within-channel sedimentation along the Paroo-Barwon-Darling river system. For legend of symbols refer to Figure 3.1.

4.3.6. Discussion

4.3.6.1. Physical habitats available to fish during high flows

We identified that physical templates available during high flow events occurred as heterogeneous patches at three scales; river, functional process zone, and reach. River scale differences related to different flow styles between the ephemeral Paroo River, and the perennial Barwon Darling River. The Paroo is a truly semi-arid river with flow originating from a semi-arid catchment, rather than from the humid headwaters that feed the Darling (Walker, 1994). Consequently, physical templates relating to channel structure reflect the braided and regime nature of these respective rivers.

At the functional process zone scale, channel forms were influenced by fluvial processes, causing sub-reaches in the Paroo to characteristically have mid-channel bars and islands that provide slack-water habitats (Boulton, 1999), which would result in varied hydraulic habitat. The upper Paroo (FPZ 1) and lower Paroo (FPZ 2) were distinguishable by channel forms and bank structures

(Figures 4.3 and 4.4), with the weakly confined lower Paroo river allowing enhanced potential for floodplain interaction. The substantial riparian scrub of the lower Paroo contrasted with the upper Paroo, which had tall trees that hung over the channel and bunched occasionally (Figure 4.1), and influenced waterhole structure. For example riparian trees formed shaded, box-shaped channels in the Tilbooroo waterhole (Figures 4.1 and 4.3). The upper Barwon (FPZ 1) had a distinctive combination of channel form (Figure 4.3), overhang provided by riparian vegetation (Figure 4.1), small timber objects (often branches) fallen into the river channel (Figure 4.2), and lacked bar-form sedimentation (Figure 4.5). This functional process zone had a different physical template from the lower Barwon-Darling that set the context for finer scale physical structures, because the distinguishing channel form and lack of bar-form sedimentation varied only at the functional process zone scale.

At the reach scale, all recorded physical structures had patchy occurrences (except for channel forms and sections of channel lacking bar form deposits), set in the context of larger scale fluvial controls. Furthermore we observed vegetation metastructure influencing riverine structure at coarser scales. In FPZ 1 of both the Paroo and the Barwon Darling rivers, riparian vegetation influenced physical templates with respect to overhanging shelter, downthrown timber objects, and tree roots stabilising channel form. At the river scale, influences of agricultural clearing of vegetation were evident. We observed that 5-28% of 1 km sub-reaches along the Darling were more sparsely vegetated relative to the Paroo, because land along the Darling had been more intensively clear-felled for agriculture.

4.3.6.2. Why templates available during high flows are relevant to fish

Ecologically important high flow events connect aquatic, or temporarily aquatic, environments along river valleys. During high flows, native fish can relocate along rivers or onto floodplains, and can use local physical structures submerged by rising waters. We have identified several physical templates in dry land rivers that contribute to aquatic environments during high flows. The Paroo's weak confinement in FPZ 2 allows emergent channels and floodplains to become available to fish during ephemeral wet-season flows (Young, 1999). Leaf litter accumulations on dry riverbeds support in-stream heterotrophy (Boulton, 1999), and therefore the food chain that supports carnivorous fish. Small wood objects mobilised during high flows accrete into high-density structures, which may become favourable habitat for some native fish (Koehn, 1996; Nicol *et al*., 2002). Overhanging riparian vegetation offers shade (Platts *et al*., 1983), and tree trunks submerged during overbank flow can offer velocity refuges to fish (Koehn, 1996).

Sub-bankfull high flows along the incised Barwon-Darling river channel connect emergent benches, gullies, and anabranches that may provide Murray Cod and Golden Perch with slack-water habitat during high flow (Koehn, 1996), and also provide organic substrates to in-stream heterotrophs (McGinness *et al*, 2002). The eco-geomorphological significance of riparian vegetation and structural woody habitat include velocity refuges during overbank flow (Koehn, 1996), overhanging branches offer shaded habitat, and shed branches in the channel may become structural woody habitat used by native fish (Koehn, 1996; Nicol *et al*., 2002). In the Darling River (FPZ's 3 and 4), the large size and varying complexities of emergent structural woody habitat are attributes of potential habitats that become available during high flow (Fig. 4). These attributes are important because large timber objects with complex branching, in particular those positioned against the erosional banks of meander bends, are favourable habitats for Golden Perch and Murray Cod (Theim, 2002).

5. FISH-HABITAT ASSOCIATIONS IN THE BARWON-DARLING AND PAROO RIVERS

5.1. Introduction

Managing riverine ecosystems to arrest the decline in native fish stocks requires better understanding of fish-habitat associations, including the spatial heterogeneity (i.e. patchiness) of both habitat and assemblage structure. The majority of studies assessing fish-habitat associations in this context have been conducted in North America and most aspects of habitat use of Australian fish species still remain poorly understood (Maitland 1987; Allen 1989; Koehn and O'Connor 1990; Wager and Jackson 1993; Harris 1994; Harris 1995; Koehn 1995; Morris *et al*. 2001). To date there has been limited research on the association between habitat heterogeneity and fish assemblage structure in systems with semi-arid to arid (dryland) climatic regimes. This general lack of knowledge is a major issue considering that 83 percent of Australia's lowland rivers are dryland systems (Thoms 2001). It is doubtful that many of the ecological principles developed in temperate, tropical and regulated systems can be applied equally to large unregulated rivers in dryland regions which are hydrologically much more variable by comparison (Davies *et al*. 1994).

When attempting to understand the spatial heterogeneity of both riverine habitat and fish assemblages, it is widely acknowledged that riverine systems cannot be viewed independently from issues of scale (Wiens 1989; Menge and Olson 1990; Levin 1992; Hawkins, Kersner *et al*. 1993; Horne and Schneider 1995; Poizat and Pont 1996; Inoue *et al*. 1997; Bult *et al*. 1998; Mason and Brandt 1999; Crook *et al*. 2001). Riverine systems can be viewed as a nested hierarchy (Bisson *et al*. 1982; Frissell *et al*. 1986; Hawkins *et al*. 1993) with large-scale features impacting on lower-level systems nested within them. Despite this realisation, most ecological studies are still criticised for using only single or few scales of measurement or for selecting arbitrary scales with little ecological relevance (Essington and Kitchell 1999; Maddock 1999; Mason and Brandt 1999; Crook *et al*. 2001, (Hawkins *et al*. 1993; Bult *et al*. 1998).

Large-scale fish surveys conducted recently in eastern Australia employ designs with strata at the top end of the spatial scale (e.g. river types and basins). But while these surveys can resolve fish assemblage differences among geographic regions of different altitude (e.g. NSWRS) or among different rivers and basins (e.g. NSWRS, IMEF and SRA), they lack the ability to detect longitudinal gradients of fish assemblage change within large rivers as well as fish-habitat associations.

As a result of a review of the international literature (chapter 2), a hierarchical framework for assessing fish habitat in large dryland rivers was developed. This framework proved a success in detecting the scales of variation of both low and high flow physical structures along the Barwon-Darling and Paroo Rivers (chapters 3 and 4). Although, this provides an inventory of physical structures in these respective rivers, if the structures are to be viewed as habitat for fish, then distinct fish-habitat associations must be found.

Objective:

To identify any fish-habitat associations and river scale differences in the fish assemblages of the Barwon-Darling and Paroo Rivers using the hierarchical framework developed in chapter 2.

5.2. Methods

5.2.1. Experimental design

Fish surveys were conducted at the same sites at which the habitat surveys were conducted. That is, three replicate 10 km reaches were sampled within six functional process zones (Figure 5.1). A reach length of 10 km was judged as being sufficient to provide a representative number of each habitat type and to allow a sample size large enough to detect rare species with an open, single pass fish sampling protocol (Paller 1995). The location of these functional process zones (FPZs) in the Barwon-Darling and Paroo rivers and the study reaches within are shown in Appendix 2 (Figures 1 and 2). Unlike the continuous channel of the Barwon-Darling River, the Paroo River at low flow consists of a series of unconnected billabongs and waterholes. A site on the Paroo River therefore consists of the sum of the waterholes located within a randomly selected 10 km reach of river. One of the study reaches in the lower FPZ of the Paroo River was not surveyed for fish due to its inaccessibility to the electrofishing boat (project site no. 16, Lenroy Station).

Sixty sampling 'shots' were performed during daylight hours and were stratified equally among the six discrete low flow habitat units identified and surveyed in chapters 2 and 3 (i.e. smooth bank, structural woody habitat, matted bank, irregular bank, mid channel and deep pool). Restrictions in the length of wet channel and the absence of certain habitat units on the Paroo River meant that sampling at these sites was limited and a maximum of 30 replicates was rarely achieved.

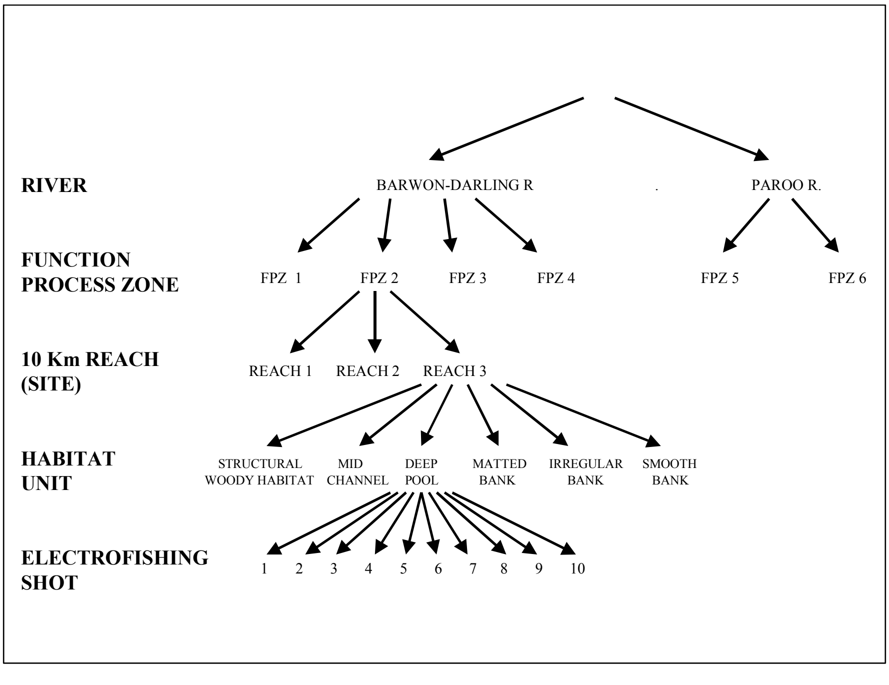


Figure 5.1. Hierarchical experimental design showing sites or reaches nested within functional process zones. Fish sampling within each reach is stratified among the six low flow habitat types.

5.2.2. Fish sampling methods

Fish surveys were conducted once at each site between November 2001 and March 2002 using boat electrofishing. Three different research vessels were utilised in the study (*FRV Electricus, FRV Sparkticus and FRV PoleVolt*). The majority of sites were sampled with *FRV Electricus*, a 5 m, twin-hulled aluminium boat mounted with a 7.5 kW Smith-Root Model GPP 7.5 H/L electrofishing unit. Two anodes were suspended from the bow and two cathodes mounted to the sides of the hull. Two Barwon-Darling River sites were sampled with *FRV Sparkticus*. This vessel is a 4.5 m, single-hulled vessel with a 7.5 kW Smith-Root Model GPP 7.5 H/L electrofishing unit.

In the Paroo River, where depths were too shallow to adequately manoeuvre the larger vessels, *FRV Polevolt* was used. *FRV Polevolt* is a 3.6 m, flat-hulled aluminium boat equipped with a 2.5 kW boat mounted Smith Root Model 2.5 H/L electrofishing unit. As with the other two vessels, two anodes are suspended from the bow and two cathodes are mounted to the sides of the hull. *FRV Polevolt* is a scaled-down version of the other vessels and as such is not capable of electrical field outputs as large as the other boats. This was not a problem in the current study because *FRV Polevolt* was only used in very shallow waters where its output was more than adequate to attract and immobilise fish.

Electrofishing was conducted with a single pass in an upstream direction, with intermittent pulsing carried out for two minutes as the boat was moved adjacent to the habitat unit. Once immobilised, fish were removed from the water, identified, measured, inspected for abnormalities and returned to the water alive. Fork lengths to the nearest mm were recorded for species with forked tails and total length for other species. Fish immobilised and positively identified but not removed from the water were recorded as “observed” and added to the number “caught” in order to determine the total abundance.

5.2.3. Environmental variables

Water quality measurements were taken with a ‘HORIBA U10’ water quality meter at three depths (the surface, one and three metres) and averaged. Five attributes were measured: temperature, pH, turbidity, electrical conductivity and dissolved oxygen. Other habitat variables measured included observations on the substratum, littoral and instream flora, availability of cover and flow conditions. These results are reported for each site in Appendix 2: Figures 3-19.

5.2.4. Analytical methods

Fish assemblage data associated with each zone and habitat type were analysed with PRIMER V5.2.7 (Plymouth Marine Laboratories) using a suite of non-parametric multivariate techniques. Assemblage analysis was performed on species totals (caught and observed) pooled across the 10 habitat replicates for each site in order to conform with the data limits in PRIMER.

Non-metric multidimensional scaling ordinations (nMDS: Kruskal and Wish 1978) were generated using Bray-Curtis similarities (Bray and Curtis 1957) on fish assemblages among all sites. Similarity matrices were calculated on forth root transformed data, which has the effect of down-weighting the importance of highly abundant species so that less common species can also contribute to the calculation of similarity (Clarke and Warwick 2001).

While nMDS can help visualise assemblage differences between samples, analysis of similarity (ANOSIM: Clarke 1993) was used to statistically test for differences between groups of samples (defined *a priori*). ANOSIM is the multivariate analogue of the univariate ANOVA and compares the similarity among samples within treatments with the similarity among samples between treatments.

One-way ANOSIM was carried out to test for the effect of river type on fish community composition. Due to the unbalanced design between the two rivers, calculations were performed on relative abundance data for each site. Pairwise comparisons for fish assemblage differences among functional process zones and habitat types within the Barwon-Darling River were done using two-way ANOSIM. The probability of observed results was determined by comparing to a sample variance determined under 999 randomisations (simulations under a null hypothesis).

SIMPER (SIMilarity PERcentages: Clarke and Warwick 2001) analyses were used to determine the contribution that each species makes to the mean dissimilarity in assemblage composition between functional process zones and habitat types and to the mean similarity within habitat types.

5.3. Results

5.3.1. Spatial differences in fish assemblage structure

5.3.1.1. Catch summary

Details of fish catches are summarised in Appendix 1: Table 1. A total of 5526 fish were recorded from all sites in the Barwon-Darling River. Of these, 86% were native and 14% alien fish. The native fish caught were mostly bony herring, with medium numbers of golden perch also caught. Only small numbers of Murray cod (*Maccullochella peelii*), freshwater catfish (*Tandanus tandanus*), gudgeons (*Hypseleotris sp.*) and the threatened silver perch (*Bidyanis bidyanis*) were encountered. The alien species were predominantly carp (*Cyprinus carpio*), with goldfish (*Carassius auratus*) and gambusia (*Gambusia holbrooki*) also recorded.

All of the fish recorded have been caught previously either during the NSW Rivers Survey (Harris and Gehrke 1997) or the Integrated Monitoring of Environmental Flows (IMEF) project. There were, however, four species encountered in these two studies that were not caught in the present study. They were the fly-specked hardyhead (*Craterocephalus stercusmuscarum)*, spangled perch (*Leiopotherapon unicolor*), crimson-spotted rainbow fish (*Melanotaenia fluviatilis*) and Australian smelt (*Retropinna semoni*). It should be noted, however, that both Fly-specked hardyhead and spangled perch were also absent from one of the three years of sampling during IMEF (NSW Fisheries unpublished data).

A further four species predicted from the area, based on data published by Llewellyn (1983) and McDowell (1996), were not encountered during the present study. These were the flathead gudgeon (*Philypnodon grandiceps*), Darling River hardyhead (*Craterocephalus amniculus*), purple-spotted gudgeon (*Mogunda adspersa*) and olive perchlet (*Ambassis agassizii*). The latter two species are listed as threatened under the NSW Fisheries Management Act 1994.

A total of 484 fish were recorded from all sites in the Paroo River (Appendix 1: Table 1). Of these, 50% were native and 50% alien fish. The native fish caught were mostly bony herring, with large numbers of golden perch also caught. Small numbers of the native species Hyrtl's tandan (*Neosilurus hyrtlii*), silver perch and Spangled perch (*Leiopotheropon unicolour*) were also found. Carp was the most abundant species found, comprising 42% of the total catch. Goldfish was the other alien species encountered.

5.3.1.2. Differences in fish assemblages between rivers

Ordination (Figure 5.2) and one-way ANOSIM (*R*=0.821, *P*<0.01) demonstrate that there is a difference in the composition of fish assemblages between the Barwon-Darling and Paroo rivers. Figure 5.3 and Figure 5.5 show the differences in catch per unit effort of various species in the Barwon-Darling and Paroo River sites. These plots demonstrate that the Barwon-Darling River has more Murray cod and bony herring than the Paroo River, with Murray cod being totally absent from the Paroo River. In comparison, the Paroo River fish assemblage contains relatively more golden perch, Hyrtl's tandan (absent from the Barwon-Darling River) and alien goldfish. Two species known to occur in the Barwon-Darling River, crimson-spotted rainbowfish and Spangled perch, were absent from those sites and only found in small numbers in the Paroo River. In chapter 3, a downstream change in habitat structure in the Paroo River towards a condition more reminiscent of the lower Barwon-Darling River was observed (Figure 3.3). It is interesting to note that a similar shift is seen in the fish assemblage (Figure 5.2).

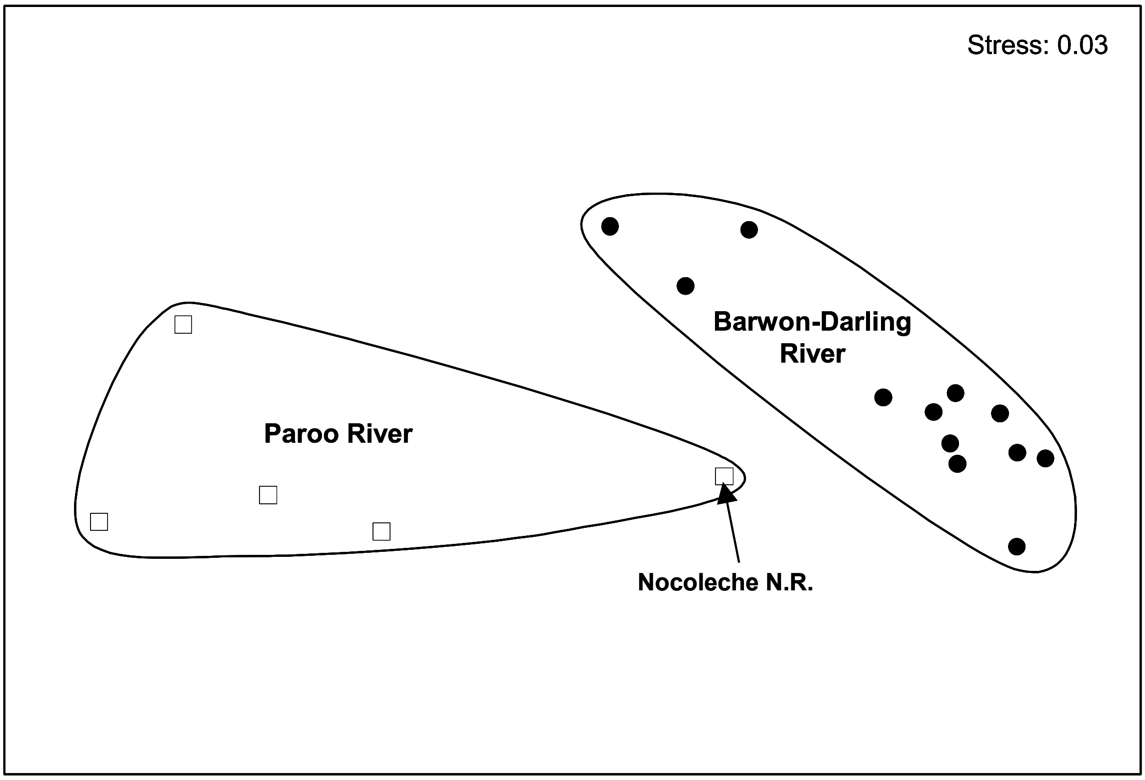


Figure 5.2. Two-dimensional MDS ordination of Barwon-Darling and Paroo River sites based on similarities between fish assemblages. A significant difference is evident between the composition of fish assemblages among rivers (one-way ANOSIM: R=0.821, P<0.01).

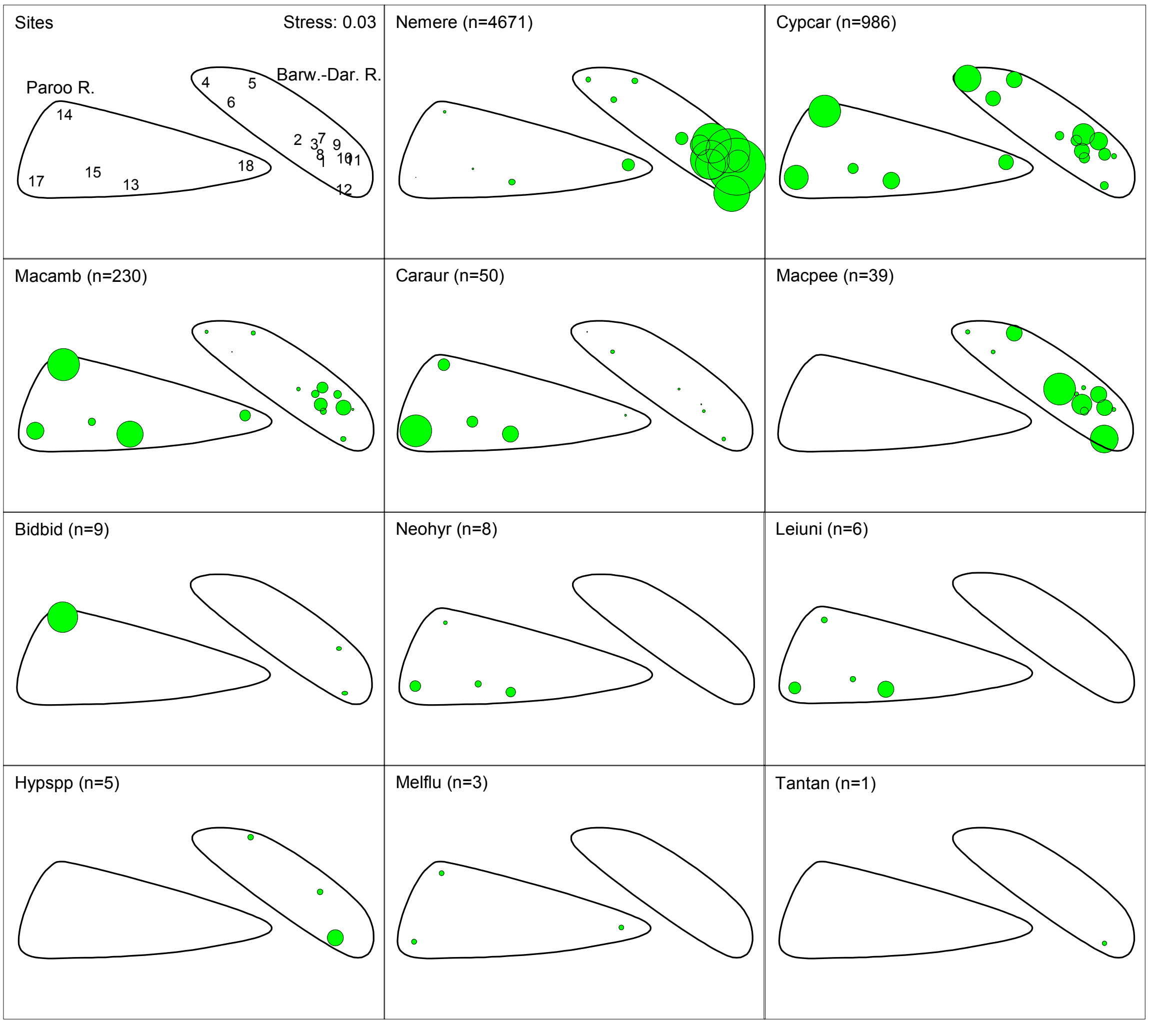


Figure 5.3. MDS ordination from Figure 5.2 with superimposed circles of increasing size representing increasing catch per unit effort at each site (site numbers correspond to maps in Appendix 2) for 11 fish species. Total number of each species recorded is also given. Note that circles are scaled only for within species comparison at sites, not for between species comparison. Full species names and abundances for each site are provided in Appendix 1 Table 1.

5.3.1.3. Zonal differences in fish assemblage structure within the Barwon-Darling River

From ordination of rivers based on fish assemblage structure, it has been shown that lowland sites from the Murray-Darling form a tight group representing a distinct fish assemblage when compared to other rivers and regions throughout New South Wales (Gehrke and Harris 2000; NSW Fisheries unpublished data). The present study examined the Barwon-Darling River in more detail than previously and the results reveal that there is spatial variation within the larger Barwon-Darling River fish assemblage. Based on differing abundances of individual species, the Barwon-Darling River fish assemblage can be subdivided into four zones that closely correspond to the function process zones (Figure 5.4).

Brewarrina - Bourke zone

The reaches within the Brewarrina to Bourke zone form a distinct group in ordination space (Figure 5.4) with classification indicating grouping at the 90% similarity level. One-way ANOSIM complemented the ordination by detecting significant differences in the composition of the fish assemblage of this zone and the two upstream zones: Collarenebri to Brewarrina and Presbury weir to Collarenebri (Table 5.1).

Species contributing most to the differences between fish assemblages in the Brewarrina to Bourke zone and the two upstream zones were bony herring, carp and golden perch, with bony herring and golden perch being more abundant in the Brewarrina to Bourke zone than the other two zones. The Brewarrina to Bourke zone also contained more carp than the Presbury weir to Collarenebri zone but similar numbers of carp to the Collarenebri to Brewarrina zone (Figure 5.5 and SIMPER analysis; Table 5.2).

Bourke - Tilpa zone

There is a large amount of variation in the composition of the fish assemblage within the Bourke to Tilpa zone, attributable partly to the low numbers of fish recorded from site 11 when compared to sites 10 and 12. Site 12, the furthest downstream site, had the highest species richness of all the Barwon-Darling River sites, with the rare Freshwater catfish, silver perch and Gudgeon all recorded (Figure 5.3). Because these three rare species were only recorded at one of the three reaches within the zone, they cannot be used reliably to discriminate between the Bourke to Tilpa zone and other zones (SIMPER analysis: consistency ratios <1.00). The large within zone variation made the fish assemblage of the Tilpa to Bourke zone inseparable from that of the two adjacent upstream zones (ANOSIM; Table 5.1).

Ordination (Figure 5.4) suggests that site 10 has a fish assemblage more representative of the Brewarrina to Bourke zone, an observation supported by classification, which indicates a grouping between site 10 and the Brewarrina to Bourke sites at the 90% similarity level. This is not surprising considering the close proximity of site 10 and the Brewarrina to Bourke zone (Appendix 2: Figure 1).

Collarenebri - Brewarrina zone

Ordination reveals that the Collarenebri - Brewarrina zone fish assemblage is distinctly different in composition to all other Barwon-Darling River zones (Figure 5.4). This finding was further supported by site classification, which indicated a grouping based on fish assemblage similarity at the 70% level and by one-way ANOSIM which detected a significant difference in the composition of the fish assemblage between the Collarenebri to Brewarrina zone and all other zones (Table 5.1).

The difference in fish assemblage composition between the Collarenebri to Brewarrina zone and all other zones is attributable to the lower abundances of native species (bony herring, golden perch and Murray cod) and higher abundances of alien species (carp and goldfish) (SIMPER analysis; Table 5.2). This becomes evident when the percentage composition of native and alien species is viewed for each site (Appendix 1: Table 1). The proportion of natives to alien species drops dramatically in the Collarenebri to Brewarrina zone (sites 4, 5 and 6) attributable mainly to a large reduction in the abundance of bony herring, but also due to a drop in golden perch and Murray cod numbers. A large increase in the abundance of carp and to a lesser extent goldfish is also evident in site 4.

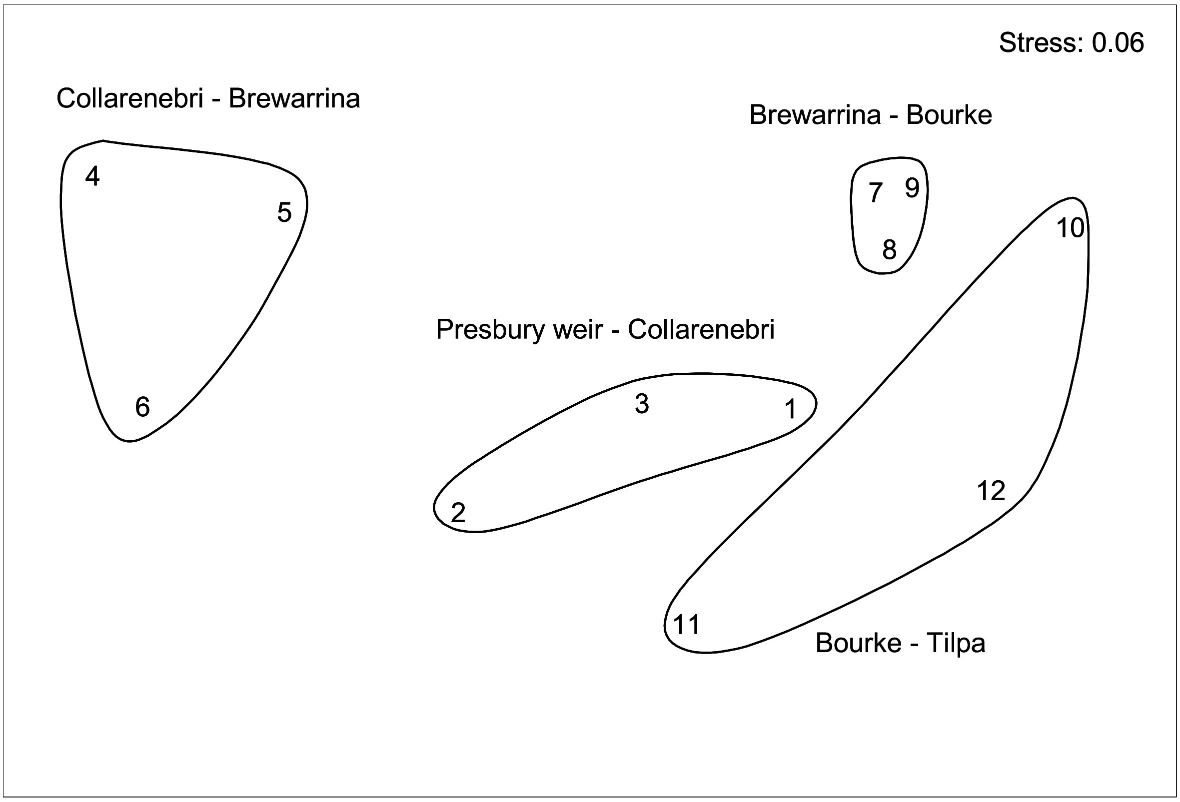


Figure 5.4. Two-dimensional MDS ordination of Barwon-Darling River sites based on similarities between fish assemblages. Reaches grouped by functional process zone. Full list of site names provided in Appendix 2.

Presbury weir - Collarenebri zone

Ordination based on fish assemblage structure indicates that a clear separation exists between the Presbury weir to Collarenebri zone and the Brewarrina to Bourke and the Collarenebri to Brewarrina zones (Figure 5.4), a finding supported by one-way ANOSIM (Table 5.1). The Presbury weir to Collarenebri zone contained substantially fewer fish than the Brewarrina to Bourke zone. It did contain, however, a healthier fish assemblage than the Collarenebri to Brewarrina zone, with more native golden perch and Murray cod and fewer exotic carp (SIMPER analysis: Table 5.2).

Table 5.1. Summary of one-way ANOSIM testing for group differences between functional process zones. Degree of assemblage difference established according to criteria of Clarke and Gorley ((2001)) and is as follows: *ns = not separable (R<0.3), * = overlapping but clearly different (R>0.3), ** = well separated (R>0.75).*

Zones	R	Assemblage difference
Among all Zones	0.614 (*P=0.003*)	*
Bourke-Tilpa *v*. Brewarrina - Bourke	0.148	*ns*
Bourke-Tilpa *v*. Collarenebri - Brewarrina	1	**
Bourke-Tilpa *v*. Presbury weir - Collarenebri	-0.074	*ns*
Brewarrina - Bourke *v*. Collarenebri - Brewarrina	1	**
Brewarrina - Bourke *v*. Presbury weir - Collarenebri	0.704	*
Collarenebri - Brewarrina *v*. Presbury weir - Collarenebri	1	**

Table 5.2. Species contributing most to differences in fish assemblages between functional process zones (SIMPER analysis). The mean dissimilarity indicates the magnitude of difference between assemblages in each zone. The percent contribution indicates the average contribution each species makes to the dissimilarity between zones. The consistency ratio is a measure of the reliability of using the particular species to discriminate between two zones, with larger ratios (approximately>1.0) indicating greater consistency as a discriminating species.

Species	Mean abundance		Consistency ratio	Contribution %	Cumulative %
	Collaren.- Brewarrina	Bourke-Tilpa		Mean dissimilarity = 37.07	
Nematalosa erebi	78.33	548.33	4.45	62.82	62.82
Cyprinus carpio	88.67	38.67	1.59	15.26	78.08
Macquaria ambigua	5.00	14.33	1.35	7.43	85.51
Carassius auratus	1.67	1.33	1.11	4.65	90.16
Maccullochella peelii	2.00	4.00	1.17	3.38	93.54
Hypseleotris spp.	0.33	1.00	0.95	3.04	96.58
	Collaren.- Brewarrina	Brewarrina- Bourke		Mean dissimilarity = 33.76	
Nematalosa erebi	78.33	581.33	19.94	70.87	70.87
Macquaria ambigua	5.00	20.33	2.33	11.21	82.09
Cyprinus carpio	88.67	85.33	1.33	5.68	87.77
Carassius auratus	1.67	0.33	1.13	4.17	91.94
Maccullochella peelii	2.00	3.33	1.13	2.96	94.90
	Collaren.- Brewarrina	Presb. Weir- Collarenebri		Mean dissimilarity = 26.39	
Nematalosa erebi	78.33	298.00	2.92	57.53	57.53
Cyprinus carpio	88.67	11.00	1.82	18.94	76.47
Macquaria ambigua	5.00	45.00	1.31	8.94	85.41
Carassius auratus	1.67	1.67	1.31	6.54	91.95
Maccullochella peelii	2.00	3.67	1.06	5.68	97.63
	Brewarrina- Bourke	Presb. Weir- Collarenebri		Mean dissimilarity = 19.47	
Nematalosa erebi	581.33	298.00	2.01	52.80	52.80
Cyprinus carpio	85.33	45.00	2.84	18.38	71.18
Macquaria ambigua	20.33	11.00	1.64	8.87	80.05
Carassius auratus	0.33	1.67	1.39	6.74	86.80
Maccullochella peelii	3.33	3.67	1.49	5.98	92.78
	Bourke-Tilpa	Presb. Weir- Collarenebri		Mean dissimilarity = 18.21	
Nematalosa erebi	548.33	298.00	1.48	53.81	53.81
Cyprinus carpio	38.67	45.00	1.62	10.73	64.53
Macquaria ambigua	14.33	11.00	1.25	8.93	73.46
Carassius auratus	1.33	1.67	1.25	8.52	81.98
Maccullochella peelii	4.00	3.67	1.20	7.21	89.19
	Bourke-Tilpa	Brewarrina- Bourke		Mean dissimilarity = 16.23	
Nematalosa erebi	548.33	581.33	1.66	34.58	34.58
Cyprinus carpio	38.67	85.33	1.95	25.51	60.08
Macquaria ambigua	14.33	20.33	1.54	13.21	73.29
Carassius auratus	1.33	0.33	0.95	6.05	79.34
Maccullochella peelii	4.00	3.33	1.17	5.58	84.92
Hypseleotris spp.	1.00	0.33	0.95	5.37	90.29

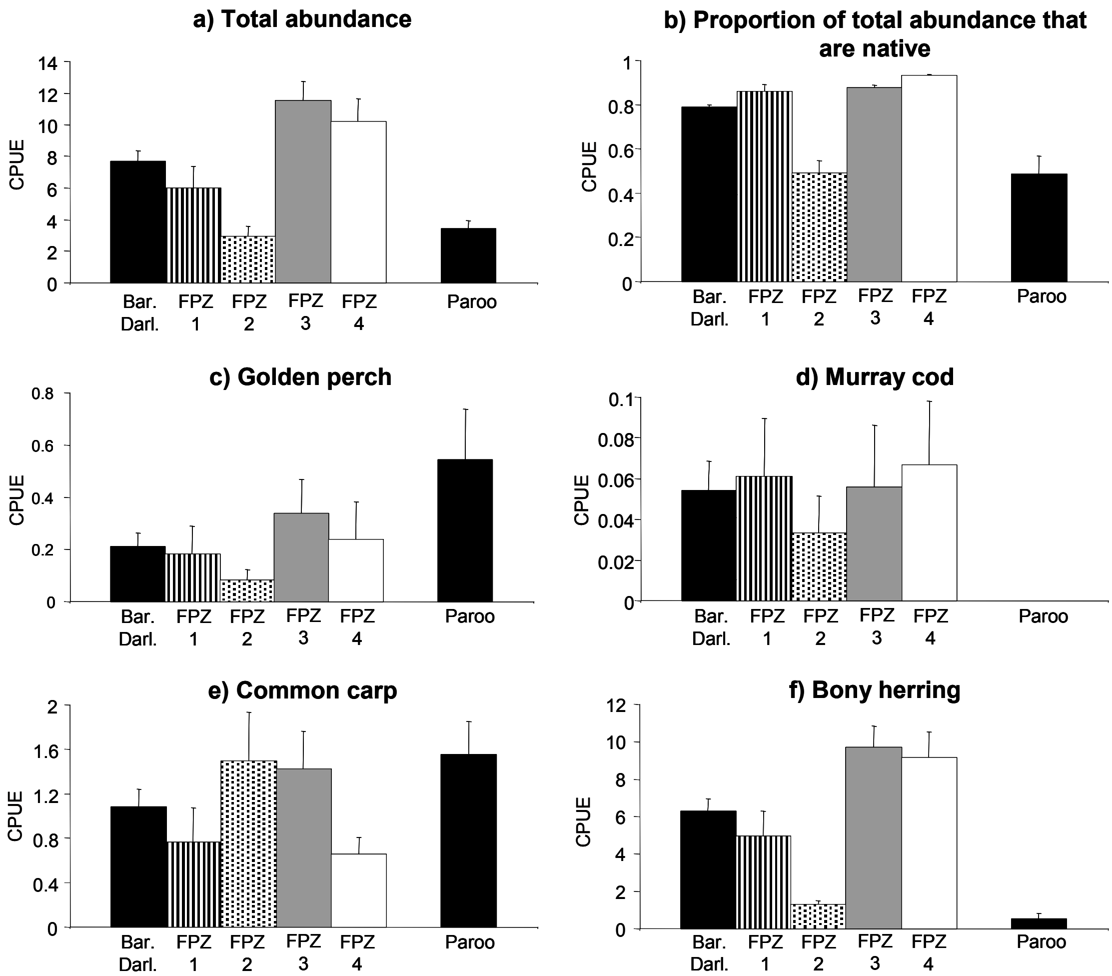


Figure 5.5 Mean total fish abundance (±S.E.) (a), proportion of native species in total catch (b) and abundance of four fish species (c to f) per unit effort (electrofishing shot) for the Barwon-Darling River and its four functional process zones and the Paroo River. Presbury weir – Collarenebri (FPZ 1), Collarenebri – Brewarrina (FPZ 2), Brewarrina – Bourke (FPZ 3), Bourke – Tilpa (FPZ 4).

5.3.2. Fish habitat preferences

A severe drought and extremely low water levels during the sampling period resulted in a failure to obtain adequate replication of samples for the entire complement of habitat types in the Paroo River. As a result, the analysis of habitat associations of fish was restricted to the Barwon-Darling River, although catch per unit effort data are reported for what habitat was sampled in the Paroo River (Figure 5.7 and Figure 5.8).

Two-dimensional ordination and ANOSIM reveal that both habitat complexity and longitudinal spatial differences along the river interact to explain the total variation in the composition of fish communities in the Barwon-Darling River (Figure 5.6 and Table 5.3). A separation of reaches along the x-axis generally appears to follow a change in structural complexity, with fish communities associated with structural woody habitat grouping at the top of the MDS plot (Figure 5.6). A further separation occurs in a top to bottom direction, in what appears to be a decrease in structural complexity: matted and irregular bank, then smooth bank, then mid-channel and deep pool habitats.

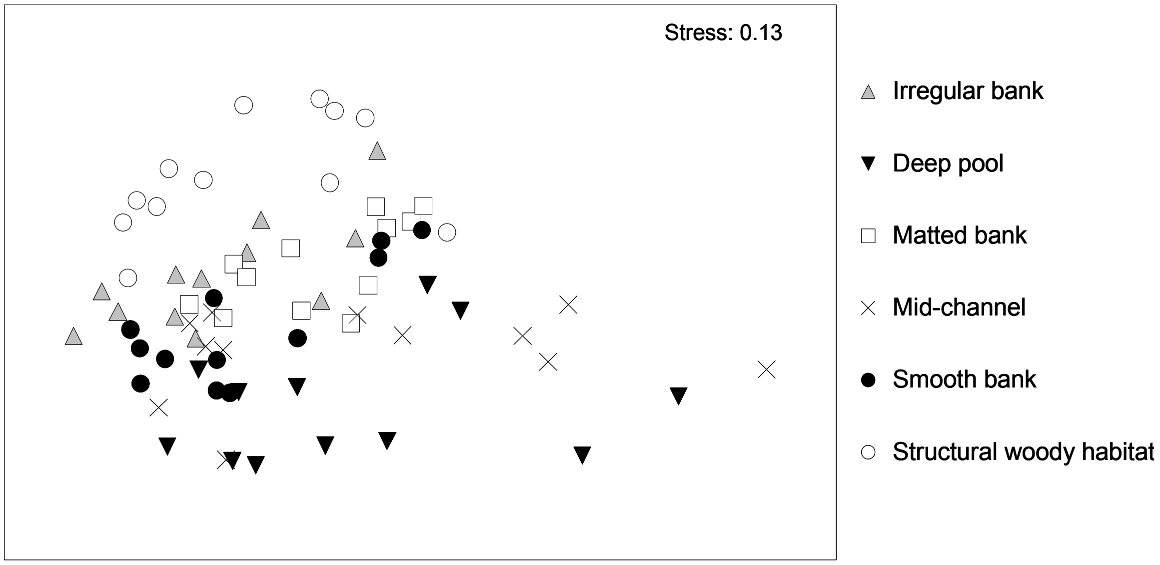


Figure 5.6. Two-dimensional MDS ordination of habitat types based on similarities between fish assemblages on the Barwon-Darling River.

5.3.2.1. Mid-channel and deep pool

There was no difference found between the composition of the fish communities of mid-channel and deep pool habitats (two-way ANOSIM: Table 5.3). This is reflected in the ordination, in which there is no clear separation of the two groups of habitat types based on fish assemblage composition (Figure 5.6). Both mid-channel and deep pool habitat, however, were found to have a significantly different assemblage composition to all other habitat types (two-way ANOSIM: Table 5.3).

The fish assemblage of mid-channel and deep pool habitats is characterised by low fish abundance (Figure 5.7a) and is dominated by bony herring, which on average contribute over 90% and 97% to the total similarity of fish assemblage composition within mid-channel and deep pool habitats respectively (SIMPER analysis: Figure 5.10). Low numbers of carp occur in mid-channel and deep pool habitats and golden perch and Murray cod are rarely found to be associated with these habitat types (Figure 5.8 and Figure 5.9).

5.3.2.2. Structural woody habitat

Ordination (Figure 5.6) and two-way ANOSIM (Table 5.3) revealed a clear difference between the fish assemblage associated with structural woody habitat (traditionally known as snags or large woody debris) and the fish assemblage found in mid-channel/deep pool habitat. Species contributing most to this difference were bony herring, carp, golden perch and Murray cod (SIMPER analysis: Table 5.4), with carp, golden perch and Murray cod being more abundant in structural woody habitat than any other habitat type (Figure 5.8 and Figure 5.9). Bony Herring were less abundant in structural woody habitat than they were along smooth or irregular banks (Figure 5.8d). SIMPER analysis also shows that carp, golden perch and Murray cod make a larger contribution to the total fish assemblage similarity within structural woody habitat than they do for any other habitat type (Figure 5.10).

In spite of the fact that the availability of structural woody habitat was higher in the Collarenebri to Brewarrina zone (Figure 5.12), the fish associations with structural woody habitat were consistent across a range of scales and across the different functional process zones. Between 55-80% of the total catch of golden perch and Murray cod were associated with structural woody habitat at both the whole river scale and for each individual functional process zone (Figure 5.11). While carp were often found to be associated with structural woody habitat, they were less specific than golden perch and Murray cod in their choice of habitat, with 30-40% of total carp catch being associated with structural woody habitat across all zones (Figure 5.11). Less than 20% of the total catch of bony herring was found to be associated with structural woody habitat (Figure 5.11).

5.3.2.3. Smooth and irregular bank

There was no difference found between the composition of the fish assemblage of irregular and smooth bank habitat (two-way ANOSIM: Table 5.3). This is reflected in the ordination, in which there is no clear separation of the two groups of habitat types based on fish assemblage composition (Figure 5.6). However, both these 'bare bank' habitat types were found to be significantly different in fish assemblage composition from all other habitat types (two-way ANOSIM: Table 5.3).

The species contributing most to these differences was bony herring (SIMPER analysis: Table 5.4), which were more abundant in smooth and irregular bank habitats than any other habitat type (Figure 5.8d). Since bony herring are a highly abundant schooling fish, their higher abundance also resulted in irregular bank habitat having the highest total abundance of fish of any of the habitat types (Figure 5.7). The fish assemblage of smooth and irregular banks is different to places where the banks have woody cover (structural woody habitat and matted banks) in that they consistently contain lower abundances of golden perch, Murray cod and carp (Figure 5.8, SIMPER analysis: Table 5.4).

5.3.2.4. Matted bank

Differences were found in the composition of the fish community between matted banks and all other habitat types (two-way ANOSIM: Table 5.3). As was seen for structural woody habitat, carp and golden perch made a larger percentage contribution to total similarity within matted banks than they did within mid-channel/deep pool and smooth/irregular bank habitats (SIMPER analysis: Figure 5.10). Matted banks have lower fish abundance when compared to most other habitat types (Figure 5.7), possessing fewer bony herring than other habitat types (Figure 5.8d).

Table 5.3. Summary of two-way ANOSIM on the Barwon-Darling River fish assemblage with zones and habitat types as factors. Degree of assemblage difference established according to criteria of Clarke and Gorley ((2001)) and is as follows: *ns = not separable (R<0.3), * = overlapping but clearly different (R>0.3), ** = well separated (R>0.75).*

Factors	1.1.1.1.1.	Probability	Assemblage difference
Among zones	0.455	<0.001	*
Tilpa-Bourke *v*. Bourke-Brewarrina	0.179	0.048	ns
Tilpa-Bourke *v*. Brewarrina-Collarenebri	0.691	<0.001	*
Tilpa-Bourke *v*. Collarenebri-Presbury weir	0.241	0.029	ns
Bourke-Brewarrina *v*. Brewarrina-Collarenebri	0.815	<0.001	**
Bourke-Brewarrina *v*. Collarenebri-Presbury weir	0.506	<0.001	*
Brewarrina-Collarenebri *v*. Collarenebri-Presbury weir	0.377	<0.001	*
Among habitat types	0.460	<0.001	*
Structural woody habitat *v*. Irregular bank	0.407	0.006	*
Structural woody habitat *v*. Deep pool	0.657	<0.001	*
Structural woody habitat *v*. Matted bank	0.639	<0.001	*
Structural woody habitat *v*. Mid-channel	0.778	<0.001	**
Structural woody habitat *v*. Smooth bank	0.750	<0.001	**
Irregular bank *v*. Deep pool	0.509	0.005	*
Irregular bank *v*. Matted bank	0.491	0.004	*
Irregular bank *v*. Mid-channel	0.481	0.002	*
Irregular bank *v*. Smooth bank	0.269	0.026	ns
Deep pool *v*. Matted bank	0.574	<0.001	*
Deep pool *v*. Mid-channel	0.259	0.048	ns
Deep pool *v*. Matted bank	0.574	<0.001	*
Matted bank *v*. Mid-channel	0.361	0.004	*
Matted bank *v*. Smooth bank	0.611	<0.001	*
Mid-channel *v*. Smooth bank	0.389	0.003	*

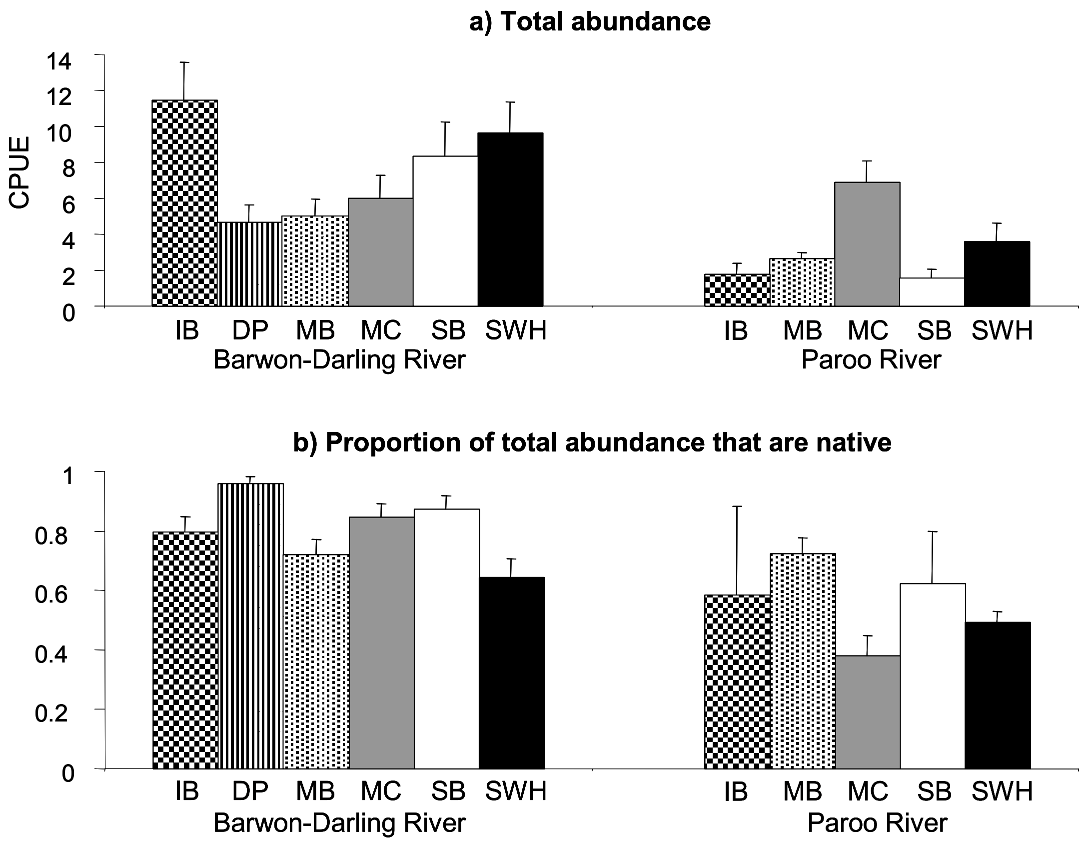


Figure 5.7. Mean total abundance (±S.E.) and proportion of total abundance that are native species per unit effort (electrofishing shot) at each habitat type in the Barwon-Darling and Paroo rivers. Irregular bank (IR), deep pool (DP), matted bank (MB), mid-channel (MC), smooth bank (SB) and structural woody habitat (SWH).

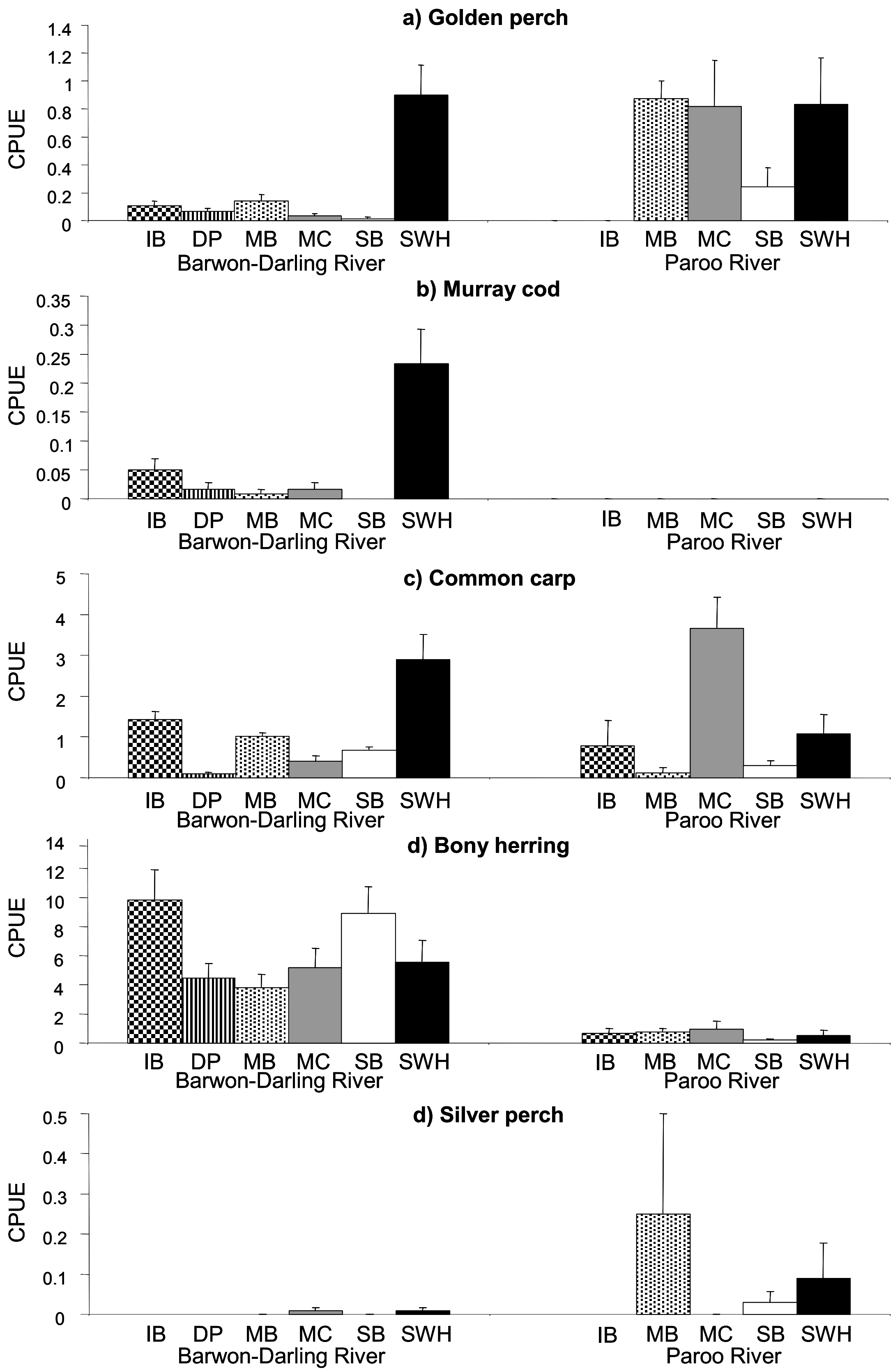


Figure 5.8. Mean abundance (±S.E.) of five common fish species per unit effort (electrofishing shot) at each habitat type in the Barwon-Darling and Paroo rivers. Irregular bank (IR), deep pool (DP), matted bank (MB), mid-channel (MC), smooth bank (SB) and structural woody habitat (SWH).

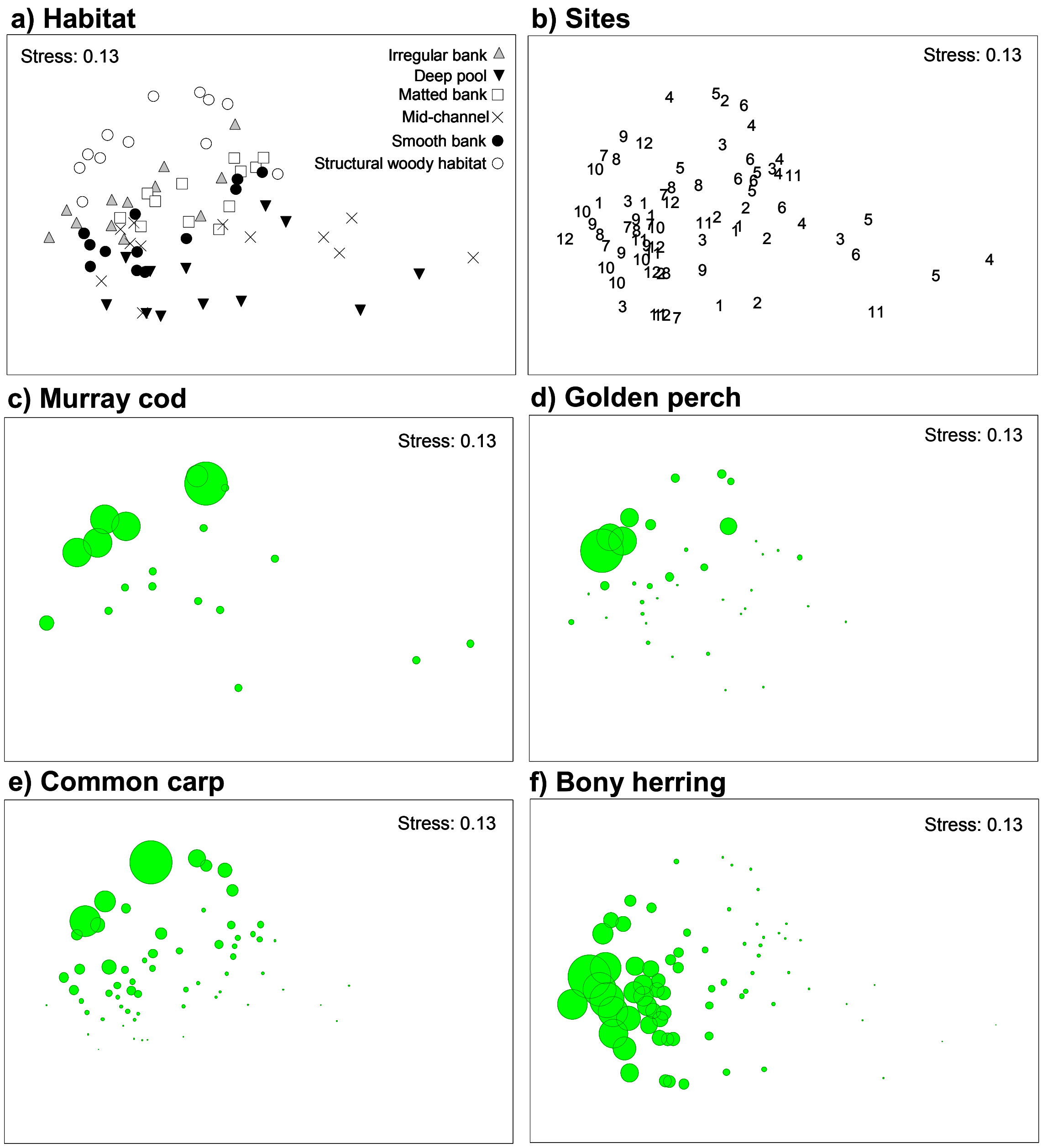


Figure 5.9. MDS ordination from with superimposed circles of increasing size representing increasing catch per unit effort for four abundant species in relation to the overall assemblage pattern at each habitat type at each site. Note that circles are scaled only for within species comparison not for between species comparison. A clear preference for structural woody habitat can be seen for Murray cod (c), golden perch (d), and to a slightly lesser extent carp (e). In comparison, bony herring (f) appear to be more abundant at smooth and irregular bank and also display a downstream spatial change in abundance with many more found at sites downstream of Brewarrina (> site 6).

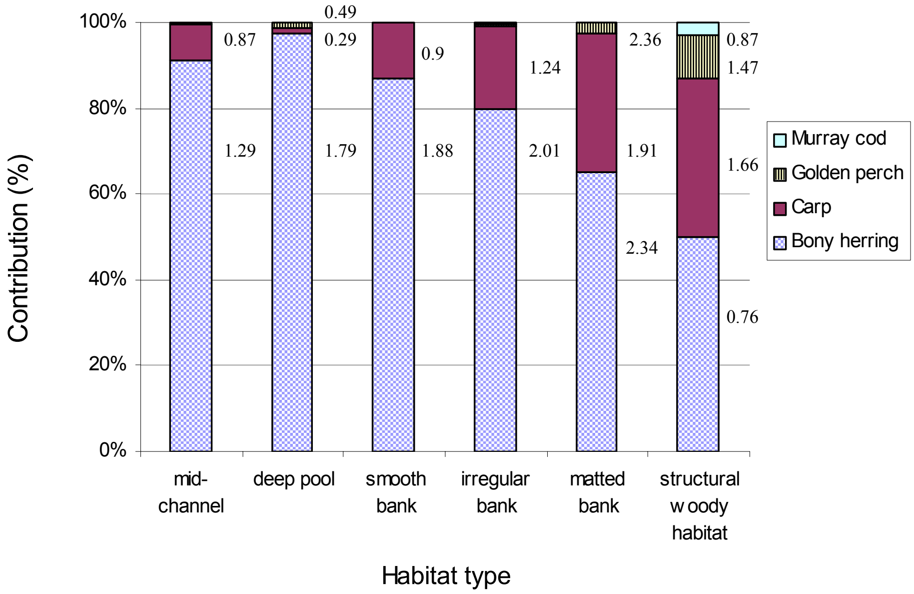


Figure 5.10. Results of SIMPER analysis highlighting the species contributing most to fish assemblages within habitat types on the Barwon-Darling River. The percentage contribution gives the average contribution that each species makes to the total similarity within each habitat type. Consistency ratio values are also given and indicate the consistency with which each species contributes to communities. Ratio values greater than one generally indicate higher consistency and low variability.

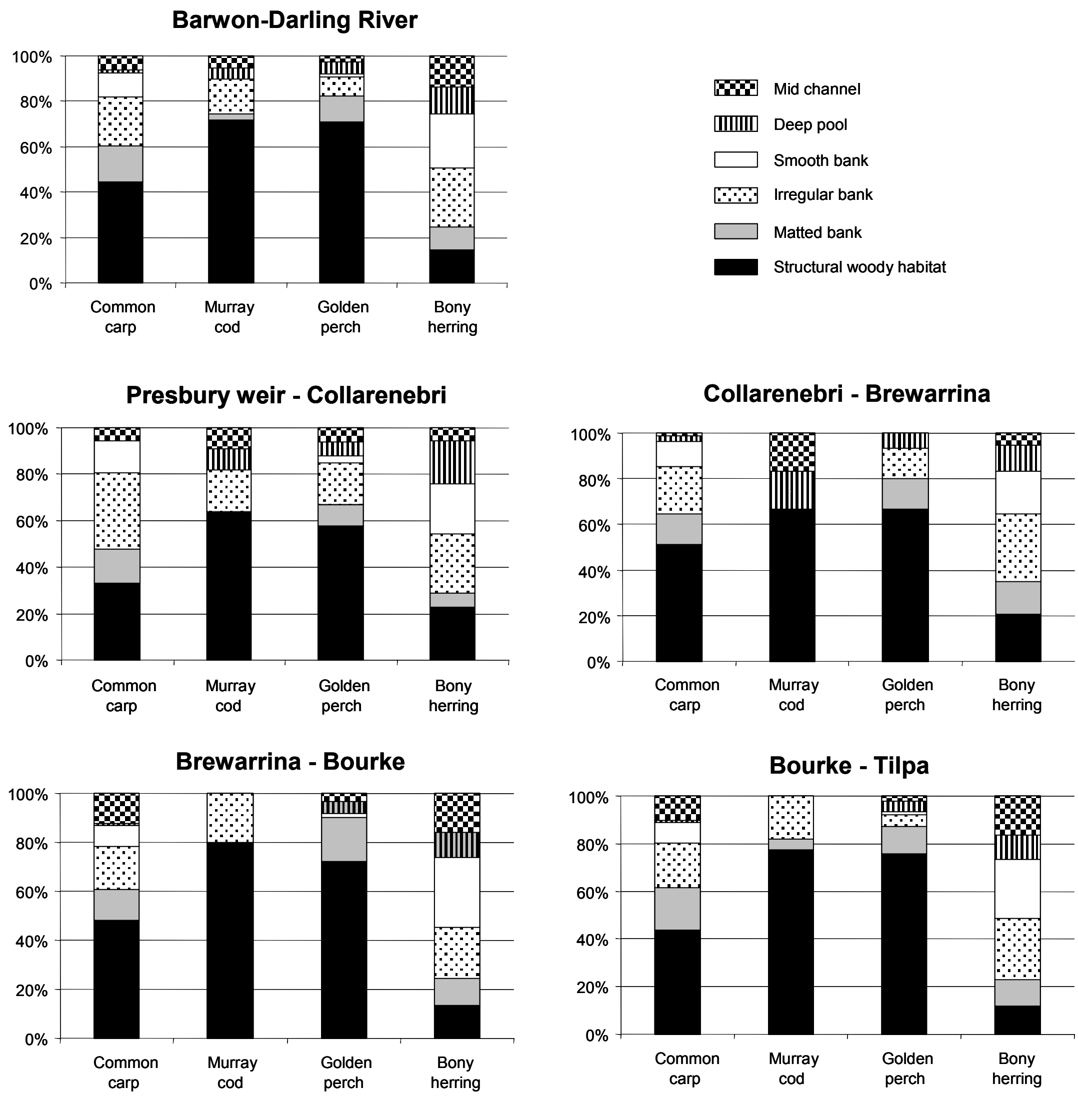


Figure 5.11. Proportion of total catch of abundant species found associated with each mesohabitat unit at the whole Barwon-Darling River scale and for each functional process zone.

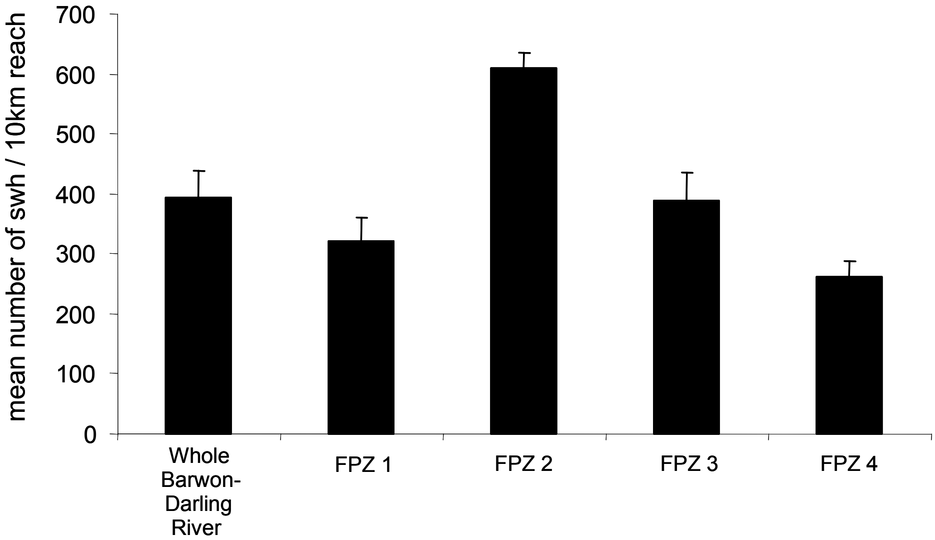


Figure 5.12. Mean number of structural woody habitat units per 10 km reach (±S.E.) for the entire Barwon-Darling River and its four functional process zones. Presbury weir – Collarenebri (FPZ 1), Collarenebri – Brewarrina (FPZ 2), Brewarrina – Bourke (FPZ 3), Bourke – Tilpa (FPZ 4).

Table 5.4. Species contributing most to differences in fish assemblages between habitat types (SIMPER analysis). The mean dissimilarity indicates the magnitude of difference between assemblages at each habitat. The percent contribution indicates the average contribution each species makes to the dissimilarity between habitat types. The consistency ratio is a measure of the reliability of using the particular species to discriminate between two habitat types, with larger ratios (approximately>1.0) indicating greater consistency as a discriminating species.

Species	Mean abundance		Consistency ratio	Contribution %	Cumulative %
	Structural woody hab.	Mid-channel	Mean dissimilarity = 62.97		
Nematalosa erebi	55.42	51.50	1.53	54.89	54.89
Cyprinus carpio	28.83	4.08	1.18	30.93	85.82
Macquaria ambigua	9.00	0.33	1.31	10.02	95.84
Maccullochella peelii	2.33	0.17	0.86	3.18	99.03
	Structural woody hab.	Deep pool	Mean dissimilarity = 62.32		
Nematalosa erebi	55.42	44.25	1.50	51.45	51.45
Cyprinus carpio	28.83	0.92	1.41	34.43	85.88
Macquaria ambigua	9.00	0.67	1.37	9.93	95.81
Maccullochella peelii	2.33	0.17	0.92	3.26	99.07
	Irregular bank	Mid-channel	Mean dissimilarity = 55.94		
Nematalosa erebi	98.25	51.50	1.66	80.07	80.07
Cyprinus carpio	13.75	4.08	0.91	16.98	97.06
Macquaria ambigua	1.08	0.33	0.93	1.32	98.38
Maccullochella peelii	0.50	0.17	0.71	0.72	99.09
	Irregular bank	Deep pool	Mean dissimilarity = 55.41		
Nematalosa erebi	98.25	44.25	1.71	77.24	77.24
Cyprinus carpio	13.75	0.92	1.15	19.78	97.02
Macquaria ambigua	1.08	0.67	1.02	1.40	98.42
	Matted bank	Mid-channel	Mean dissimilarity = 55.09		
Nematalosa erebi	38.17	51.50	1.80	76.48	76.48
Cyprinus carpio	10.17	4.08	1.00	19.54	96.02
Macquaria ambigua	1.42	0.33	0.88	2.80	98.82
Maccullochella peelii	0.08	0.17	0.43	0.67	99.49
	Structural woody hab.	Smooth Bank	Mean dissimilarity = 55.07		
Nematalosa erebi	55.42	88.92	1.46	63.67	63.67
Cyprinus carpio	28.83	6.67	1.18	23.44	87.11
Macquaria ambigua	9.00	0.17	1.35	8.89	95.99
Maccullochella peelii	2.33	0.00	0.93	2.85	98.84
	Deep pool	Mid-channel	Mean dissimilarity = 53.95		
Nematalosa erebi	44.25	51.50	1.66	88.80	88.80
Cyprinus carpio	0.92	4.08	0.99	8.02	96.83
Macquaria ambigua	0.67	0.33	0.70	1.82	98.65
	Smooth Bank	Mid-channel	Mean dissimilarity = 53.53		
Nematalosa erebi	88.92	51.50	1.59	87.41	87.41
Cyprinus carpio	6.67	4.08	0.72	10.57	97.98
	Deep pool	Smooth Bank	Mean dissimilarity = 52.67		
Nematalosa erebi	44.25	88.92	1.71	85.51	85.51
Cyprinus carpio	0.92	6.67	0.88	12.09	97.60
Macquaria ambigua	0.67	0.17	0.79	1.07	98.68

(Table 5.4 continued over page)

(Table 5.4 continued)

Species	Mean abundance		Consistency ratio	Contribution %	Cumulative %
	Deep pool	Matted bank	Mean dissimilarity = 51.27		
Nematalosa erebi	44.25	38.17	1.61	72.02	72.02
Cyprinus carpio	0.92	10.17	1.4	23.96	95.98
Macquaria ambigua	0.67	1.42	0.90	2.87	98.85
	Structural woody hab.	Matted bank	Mean dissimilarity = 50.90		
Nematalosa erebi	55.42	38.17	1.40	54.85	54.85
Cyprinus carpio	28.83	10.17	1.20	29.18	84.02
Macquaria ambigua	9.00	1.42	1.38	10.65	94.68
Maccullochella peelii	2.33	0.08	0.98	3.93	98.60
	Structural woody hab.	Irregular bank	Mean dissimilarity = 50.36		
Nematalosa erebi	55.42	98.25	1.51	68.69	68.69
Cyprinus carpio	28.83	13.75	1.01	19.45	88.14
Macquaria ambigua	9.00	1.08	1.24	8.08	96.23
Maccullochella peelii	2.33	0.50	0.89	2.48	98.70
	Irregular bank	Matted bank	Mean dissimilarity = 47.64		
Nematalosa erebi	98.25	38.17	1.68	85.12	85.12
Cyprinus carpio	13.75	10.17	1.04	10.80	95.92
Macquaria ambigua	1.08	1.42	0.98	2.11	98.03
Maccullochella peelii	0.50	0.08	0.79	0.75	98.78
	Matted bank	Smooth Bank	Mean dissimilarity = 47.39		
Nematalosa erebi	38.17	88.92	1.72	88.96	88.96
Cyprinus carpio	10.17	6.67	1.24	7.29	96.25
Macquaria ambigua	1.42	0.17	0.86	2.33	98.58
	Irregular bank	Smooth Bank	Mean dissimilarity = 43.07		
Nematalosa erebi	98.25	88.92	1.57	85.18	85.18
Cyprinus carpio	13.75	6.67	1.17	11.57	96.74
Macquaria ambigua	1.08	0.17	0.90	1.31	98.05

5.4. Discussion

5.4.1. Paroo River

Due to the absence or low availability in the Paroo River of many of the mesohabitat types under investigation, we have been unable to get a good indication of the habitat preferences of fish in the Paroo River. The drying water holes encountered in the Paroo typically consisted of shallow pools with smooth banks and the occasional area of structural woody habitat. If other habitat types were present at all, adequate replication was usually not possible and statistical analysis could not be undertaken. It is highly likely that fish in the drying Paroo River waterholes are associated with particular habitat types purely because they are forced to rather than because they choose to. If useful conclusions regarding the habitat preferences of fish are to be drawn from habitat association data, it is essential that the entire range of habitat variables be well represented in the stream studied (Morantz *et al*. 1987).Otherwise detailed measurements of habitat availability must be taken to establish a preference ratio (habitat use/habitat availability).

5.4.2. Barwon-Darling River

The results described in this chapter demonstrate that fish in the Barwon-Darling River exploit a range of mesohabitats available to them during low flow conditions. It is also evident that certain species display a distinct bias for particular mesohabitat types and do this in a consistent way along the entire length of the study area. At the larger river scale, regional differences in fish assemblage structure were also noted.

At the meso-scale, both Murray cod and golden perch are strongly associated with large wood (traditionally referred to as large woody debris or snags). Strong preferences of Murray cod and golden perch for structural woody habitat have also been documented in studies of fish habitat use in other south-eastern Australian Rivers (Koehn 1996; Koehn and Nicol 1997; Crook *et al*. 2001).

The beneficial role played by structural woody habitat in providing structurally complex habitat for riverine fish is widely recognised (Angermeier and Karr 1984; Harmon *et al*. 1986) and the ecological processes driving this are discussed in detail by Crook and Robertson (1999). In riffle sections of upland rivers, boulders and cobbles afford much of this structural complexity. In large dryland rivers, however, rock habitats are rare and the bed structure consists of fine silts and clays interspersed by slugs of coarser sand. In dryland rivers such as the Barwon-Darling River, structural woody habitat is the predominant source of habitat heterogeneity. It is likely that through increased habitat heterogeneity, structural woody habitat provides important foraging sites for golden perch and Murray cod. These perchcithyids are ambush predators, feeding on mobile prey such as shrimps, crayfish and other fish (Cadwallader and Backhouse 1983; Harris and Rowland 1996). The predominance of sand, silt and clay in dryland rivers such as the Barwon-Darling River means that structural woody habitat is often the only hard substratum available for the colonisation of algae and invertebrates. Sheldon and Walker (1998) have shown that structural woody habitat within the main channel of the Darling River has an invertebrate assemblage of higher abundance and richness than that found on fine sediment, with the genera *Paratya*, *Cardina* and *Macrobrachium* dominating the assemblage.

Carp were also found to be more strongly associated with structural woody habitat than with any other habitat type, although these associations were much weaker than for golden perch and Murray cod. Our observation that carp utilise a larger proportion of habitats available to them than species such as Murray cod and golden perch is consistent with reports from radio-tracking studies of golden perch and carp in the Broken River (Crook *et al*. 2001). Carp were commonly found associated with structural woody habitat, although they were comparatively less specific in their mesohabitat associations than golden perch. Crook *et al.* (2001) suggested that this may be a result of the different feeding behaviour and mobility of the two species. Unlike the ambush feeding of golden perch, carp tend to be poor predators of motile prey and feed predominately on food particles by sifting through fine benthic sediments (Lammens and Hoogenboezem 1991). This foraging behaviour is conducive to higher mobility.

Bony herring is a pelagic schooling species that feeds on detritus, algae and aquatic insects (Briggs and McDowall 1996). It is also a species for which large upstream migrations have been documented (Mallen-Coopert *et al*. 1995). All these behaviours suggest that bony herring would generally be found at most habitat types within the main channel. This was verified in the current study, but there was a weaker association detected between bony herring and structural woody habitat than for edgewater habitats without snags. If predators can alter prey distributions, then the weak association of bony herring for structural woody habitat may reflect the preference for structural woody habitat by the larger piscivorous native species (golden perch and Murray cod). The use of edgewater habitats by smaller fish has been reported in other studies and may be a result of using the shallower water to reduce the predation risk from larger fish (Power 1987; Schlosser 1987; Gehrke 1992; Lamouroux *et al*. 1999), which generally select deeper habitats.

There are distinct regional differences in the composition of the fish assemblage in the Barwon-Darling River. These regional differences involve changes in the relative abundance of species rather than the addition or replacement of species. Two bioregions of particular note within the Barwon-Darling River closely correspond to the functional process zones from Collarenebri to Brewarrina and from Brewarrina to Bourke. The fish assemblage in the Collarenebri to Brewarrina functional process zone contains a larger proportion of carp (an introduced species) than the other zones, with significantly fewer bony herring, golden perch and Murray cod. In comparison, the Brewarrina to Bourke functional process zone immediately downstream has a fish assemblage characterised by comparatively higher abundances of the native species bony herring, golden perch and Murray cod.

The current results have shown strong preferences of a number of species for particular habitat types at the mesohabitat scale. But are these mesohabitat scale associations consistent with the spatial variation in the fish assemblage structure that exists along the Barwon-Darling River? That is, do any differences in the fish assemblage along the river reflect differences in the availability of preferred habitat types?

Geomorphic features, through their impact on localised physical habitat such as stream width and depth may be responsible for these observed differences in assemblage structure. This has been documented elsewhere in the world with geomorphic features being useful in the prediction of trout abundance in Wyoming streams (Lanka *et al*. 1987). Within the Barwon-Darling River, we have been able to demonstrate that there are differences in the availability of physical habitat at low flows among functional process zones (chapter 3).

The Collarenebri to Brewarrina zone is characterised by being much richer in structural woody habitat than any of the other functional process zones (Figure 5.12). In spite of this, it is dominated by carp and has fewer golden perch and Murray cod than other zones. In comparison, the Brewarrina to Bourke zone has more fish despite the fact that it has a much lower density of structural woody habitat than the Collarenebri to Brewarrina zone. This counterintuitive relationship between structural woody habitat density and the abundance of golden perch, Murray cod and carp at the whole river scale is surprising considering that strong associations have been found between fish and structural woody habitat at the mesohabitat scale both in our study and others (e.g. Lehtinen *et al*. 1997; Thevenet and Statzner 1999; Crook *et al*. 2001).

Our results emphasise that fish are associated with habitat units over a range of spatial scales. Throughout this report we have stressed the importance of viewing the riverine ecosystem in a hierarchical manner. Similarly, it has been suggested that fish may select habitat in a hierarchical way by first selecting a suitable region of river, then selecting suitable mesohabitat features within these regions and finally selecting suitable microhabitat features (Kramer *et al*. 1997). If this is the case, it may be likely that habitat occurrence at scales larger than the mesohabitat level may be influencing regional assemblage structure. Thus, while wood structures appear to provide good habitat for native species such as golden perch and Murray cod within reaches, its density alone does not appear to be adequate in predicting fish assemblage structure at the larger river scale.

We hypothesise that the juxtapositioning of habitat types may play a crucial role in whether habitat is used by fish. That is, it is the combination of habitat types within a reach that dictates the resident assemblage. For example, golden perch have been shown to be more strongly associated with structural woody habitat found in deeper water than that in shallower riffles (Crook *et al*. 2001). This may be a response of bigger fish to predation pressure from overhead predators, which may drive them to deeper waters (Power 1987; Harvey and Stewart 1991). Although the

Collarenebri to Brewarrina zone is richer in structural woody habitat, it is also negatively associated with depth (chapter 3). It may be possible that this lack of structural wood in deeper water may be responsible for fewer golden perch and Murray cod inhabiting this zone.

Another difference between the Collarenebri to Brewarrina and the Brewarrina to Bourke zones relates to regulation of their tributaries. The study sites in the Collarenebri to Brewarrina zone are downstream of the highly regulated Namoi River. In comparison, the sites of the Brewarrina to Bourke zone are found downstream of the unregulated Culgoa and Bokhara Rivers. Flow regulation in rivers has been implicated as a potential threat to the conservation of fish in lowland rivers, reducing the resilience of native fish communities to invasion by alien species (Scheidegger and Bain 1995; Merigoux and Ponton 1999; Gehrke and Harris 2001). It has been suggested that flow regulation favours habitat generalist such as carp, allowing them to exert dominance over habitat specialists such as golden perch and Murray cod (Bain *et al*. 1988; Gehrke *et al*. 1995). Furthermore, bony herring have been found to be among the native species most affected by river regulation (Gehrke and Harris 2001). It is not known, however, whether tributary inputs from the Culgoa and Bokhara Rivers are large enough to exert an influence on assemblage structure in the Brewarrina to Bourke zone.

Large migrations of fish have been recorded during high flows in the Barwon-Darling River (Mallen-Cooper and Edwards 1991; Harris *et al*. 1992; Mallen-Cooper and Thorncraft 1992). These large-scale migrations strongly influence the assemblage structure within the Barwon-Darling River by allowing species to replenish populations along the river corridor. Our data suggests that the Brewarrina town weir may be creating enough of a barrier to fish migration to cause a partitioning in assemblage structure above and below it. Modelling of washout frequency and duration has suggested that this weir will wash out sufficiently to allow fish passage for only 10% of the time (Cooney 1994). Recent extended periods of drought and the ensuing low flow conditions have ensured that aggregations of native fish species downstream of the Brewarrina weir infrequently gain access to the denser structural woody habitat areas upstream.

6. THE PROTECTION AND REHABILITATION OF FISH HABITAT IN THE BARWON-DARLING AND PAROO RIVERS

6.1. The value of using a large-scale hierarchy to assess fish habitat condition in large dryland rivers

The hierarchy of physical structures used here can provide a sound basis for the survey of fish within large dryland rivers. By selecting mesohabitats and functional process zones as strata in the hierarchy, we obtained a level of resolution appropriate for detecting fish assemblage differences at both the meso- and regional-scale. This degree of resolution is an improvement over that obtained by recent fish survey designs used in south-eastern Australia. The improvement lies in the ability to detect longitudinal habitat structure in a large river as well as fish-habitat associations. This information is crucial if river managers are required to effectively identify priority areas for regional rehabilitation programs. Such a fine level of resolution is not possible with the stratified, randomised New South Wales Rivers Survey approach (NSWRS: (Harris and Gehrke 1997), which cannot resolve assemblage differences at scales finer than altitude ranges within drainage basins.

The NSWRS provided support for the management of the Barwon-Darling River and its tributaries as a distinct entity based on its fish assemblage. This idea can now be taken further because the present results indicate that the fish assemblage is heterogenous along its length. The longitudinal gradient of assemblage change provides biological justification for setting regional scale management objectives within the Barwon-Darling River. This helps to isolate regional factors that may be compromising the fish assemblage and the focus on the entire assemblage allows managers to set realistic objectives targeted at the sustainability of the riverine ecosystem rather than just sustaining single species.

Other large-scale fish sampling exercises (eg IMEF and SRA) have expanded on the hierarchical design of the NSWRS by including functional process zones as a suitable level for fish surveys. They do not, however, conduct fish surveys at the level of mesohabitat. As a result, while reach and river specific information can be obtained for ongoing assemblage monitoring, little information regarding fish-mesohabitat associations can be obtained. This is less than desirable if the objective of a monitoring program is to link assemblage changes to possible changes in habitat integrity.

Describing regional differences in the fish assemblage along large rivers is not new. Longitudinal fish “zonation” concepts (Huet 1959) have been used for decades in Europe (see (Aarts and Nienhuis 2003)), and refined versions still play an important role in present day riverine fish surveys. The main drawback of fish zonation concepts is that while they describe longitudinal changes in the fish assemblage, they do little to explain why such changes occur. In order to enhance the use of fish surveys as a tool in river monitoring programs, assemblage data obtained through such surveys need to be interpreted ecologically, i.e. by associating information on fish assemblage heterogeneity with information about riverine habitats and processes. This link cannot be made effectively if fish surveys are conducted randomly at single scales or at scales arbitrarily selected and having little ecological relevance. Herein lies another advantage of using the proposed framework to conduct fish surveys in large dryland rivers. By conducting fish surveys systematically at multiple scales commonly used to classify habitats in large dryland rivers (Thoms *et al*. 2004a), not only is much of the spatial heterogeneity inherent in these rivers accounted for, but the interpretation of biotic information in the context of habitat structure or the functional processes operating at each scale is facilitated.

From the present study it is clear that the interpretation of results is closely linked to the scale at which an investigation is conducted. The current study was designed in a way that enabled associations to be determined among multiple spatial scales, including mesohabitats, reaches, functional process zones and between rivers. This was achieved through careful design and site selection based on an appreciation of the geomophological character of the river. It didn't, however, take any longer than a purely randomised approach would, in either the design or data collection phases. The careful consideration of scale in the project planning phase can therefore greatly increase the interpretability of the data set, without increasing the project's operating costs.

6.2. Action plan for protecting fish habitat in the Paroo River

The Paroo River is a natural dryland river system that is essentially free-flowing with no regulation and very little water extraction (Kingsford 1999). It consists primarily of permanent waterholes that are only connected during large floods. These waterholes act as important dryland rufugia for fish populations, which remain disconnected from the Barwon-Darling River for much of the time. As an indication of the degree of this isolation, it is believed that golden perch have diversified into a distinct Paroo River genetic strain (Keenan *et al*. 1997).

It is apparent from the present study that the availability of water is the factor that most likely limits access to potential fish habitat in the Paroo River. Fish sampling was conducted during the worst drought in recent history. Many landowners reported having "permanent waterholes" on the brink of being completely dry, and many reported not seeing water levels this low in the last three decades. It is essential that water be maintained in these waterholes if they are to function as ecological refugia. Large-scale extraction of water from the Paroo River is likely to reduce the amount of habitat available to fish or even worse, totally remove these important refugia. This will result in a reduction in the abundance of long-lived native species and an increase in fast growing, exotic species such as carp, thus leading to a loss of biodiversity (Gehrke *et al*. 1999). Large floods in dryland rivers lead to blooms in algal growth, increases in habitat availability and increases in invertebrate prey abundance, thus fuelling episodic booms in fish populations (Ruello 1976). It is therefore important to protect the riparian zone and floodplain from degradation, whilst maintaining the episodic connectivity between the waterholes and these habitats. An intergovernmental agreement between New South Wales and Queensland signed by the respective State Premiers in 2003 should ensure that the Paroo is protected from further abstractions and water resource development.

6.3. Action plan for the rehabilitation of fish habitat in the Barwon-Darling River: the case for a demonstration functional process zone from Brewarrina to Bourke

The lowland drainage system encompassing the Barwon-Darling River has been listed as an Endangered Ecological Community (*Fisheries Management Act 1994*). Under the *Act*, it is essential that once key threats to the survival of the listed community have been identified, action plans be formulated to ensure the protection and recovery of the community. This report highlights the existence of several key influences on, and threats to, the continued survival of the fish community of the Barwon-Darling River. These include influences of physical habitat at different scales:

River to functional process zone scale

1. The presence of numerous weirs that regulate natural flows, and block the passage of migrating fish species.

2. The reduced accessibility of fish to habitat located higher up on the bank due to water resource development.

Reach scale

3. Higher levels of bank collapse in certain regions relative to the whole river. This may contribute to both habitat alteration and reduced water quality in many sections of the river, because sand slugs can decrease channel depth, infill pools, and smother structural woody habitat.

4. Some lengths of river were shallow, which may restrict fish movement during low flow conditions.

5. Riparian condition varies along the river, and certain regions have banks that have been clear-felled to the rivers edge. In some reaches, melaleuca trees have stabilised alluvium within river channels, and provided matted bank structure.

Local scale

6. A low abundance of suitable instream habitat in some regions relative to the whole river. Some sections of river lacked structural woody habitat and root mats.

We recommend that appropriate remedial action be undertaken to protect the ecological community of the Barwon-Darling River and to facilitate its recovery. There is a substantial body of work concerning the protocols and guidelines to be used when implementing restoration works in the Murray-Darling Basin (see review by (Treadwell 2004). The review recommends that these guidelines now be tested and refined within the confines of demonstration reaches. Demonstration reaches involve the rehabilitation of the ecological community (i.e. the whole community rather than individual species) through the simultaneous and integrated implementation of several key interventions (Barrett 2004). It is envisaged that demonstration reaches will enhance public awareness of how an integrated and adaptive approach to ecosystem management can have positive consequences for river health. They are also seen as a crucial step to the refining of guidelines for the restoration of rivers elsewhere in the Basin. It has been suggested that the following criteria be used to judge the suitability of a site for implementation of a demonstration reach (Barrett 2004; Treadwell 2004):

1. The reach must possess a range of identified threats to river health;
2. There should be an untreated control reach nearby against which to monitor change;
3. The reach should be degraded, but not sufficiently degraded to prevent recovery;
4. The reach should be in close proximity to significantly large township;
5. The reach should be large, but still small enough to be manageable. The size should dictate the scale of the problems present;
6. A number of rehabilitation works need to be carried out simultaneously;
7. Potential must exist for the assessment of pre-condition as well as for the ongoing monitoring of ecological outcomes;
8. The demonstration reach would have to fit in with existing management frameworks.

The applicability of these criteria should be evaluated using sound and location-specific scientific information regarding the key threats and the state of fish and fish habitat in the proposed region. Our findings can be used to guide the rehabilitation of habitat within the Barwon-Darling River. It is also our view that the best step towards nurturing community support behind rehabilitation in the Barwon-Darling River, and thus maximising the chance of success, is through the establishment of model demonstration functional process zones. Based on the above criteria, it is recommended that the main channel from Brewarrina to Bourke, which represents a functional process zone that requires restorative actions at different levels, be chosen. The following sections will address each of the criteria in turn, with supporting evidence provided from the findings of our study.

6.3.1. A range of key threats that can be abated through the simultaneous implementation of numerous rehabilitation works

It would be naive to assume that any one factor is solely responsible for the current condition of the Barwon-Darling fish community. This study has highlighted a number of key threats to the survival of the Barwon-Darling fish community. There is no single solution or 'quick-fix' and each threat must be addressed simultaneously in an integrative and adaptive way (Figure 6.1).

6.3.1.1. Rehabilitation of instream habitat

The results of our report highlight the importance of structural woody habitat (SWH) for a number of lowland river fish. In particular, very strong associations were found between SWH and both golden perch and Murray cod (chapter 5). We have also shown that the abundance of SWH changes quite significantly along the course of the Barwon-Darling River (chapter 3), with most of the Brewarrina to Bourke zone (downstream of Wolkara: see Appendix 2, Figure 1, reach number 7) containing significantly less instream wood than reaches upstream of Brewarrina. It is the view of many freshwater scientists (see reviews by (Lovett and Price 1999; Price and Lovett 1999; Nicol *et al*. 2002) that improvements in habitat diversity and therefore native fish populations, can be made through the reintroduction of SWH (resnagging) in degraded reaches. Based on this, we recommend that resnagging works be included in any rehabilitation undertaken as part of a Brewarrina to Bourke demonstration functional process zone.

The positive effects that resnagging can have on native fish have been documented in recent studies in south-eastern Australia. Results from the Williams River in New South Wales have found that, after the addition of SWH, total fish numbers increased to 220% of that observed pre-modification, as well as an increase being observed in the average number of species from 6.5 to 9 (Brooks *et al*. 2003). Although the speed of the response suggests that much of the increase in fish abundance and diversity may be due to redistribution, this study has shown that local improvements in fish communities can be observed shortly after rehabilitation works. Similar results have been reported after the addition of rocks and logs in a short reach of the Owens River in Victoria. Surveys conducted just three years after the works demonstrated a nine-fold increase in the two-spined blackfish (*Gadopsis bispinosis*) population (Koehn 1987). In the River Murray the resnagging of test reaches is being met with optimistic results within the first 12 months. Not only have golden perch, Murray cod and trout cod been shown to utilise reintroduced SWH, but it has also been found that the higher the density of resnagging in a reach section, the greater the response shown by native fish (Nicol *et al*. 2002).

The riparian zone plays an important role in the recruitment of new wood into the river channel. Recent research has shown that a linear relationship exists between riparian density and the wood loading in many eastern Australian rivers (Marsh *et al*. 2001). Such a relationship may be a possible explanation for the spatial differences in SWH we observed in the Barwon-Darling River. At the river scale, regions downstream of Wolkara, with lower SWH abundance, were found to approximately correspond to those regions with sparser riparian zones consisting predominantly of smaller shrubs (chapters 3 and 4). This highlights the need for active reintroduction of wood into the channel in this region, as the natural recruitment of trees resulting from erosion of the riparian zone is unlikely.

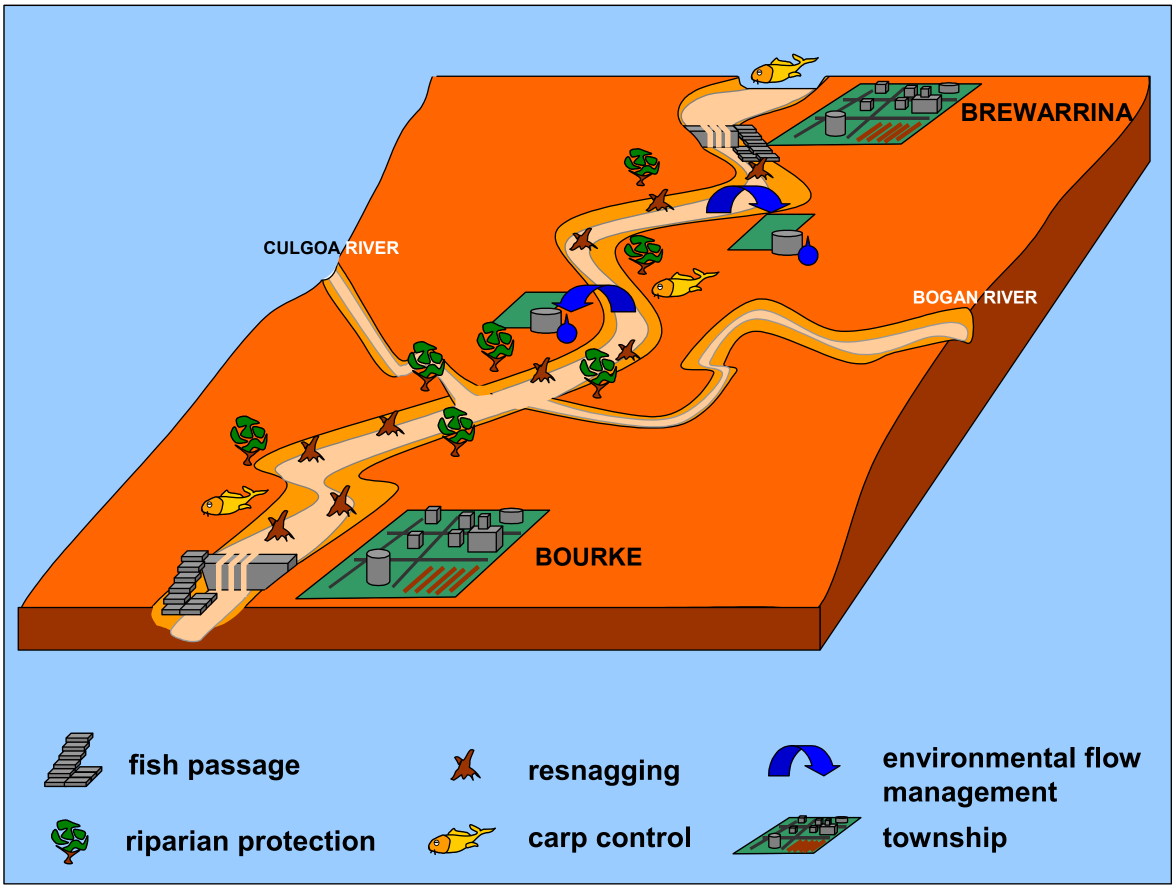


Figure 6.1. A conceptual diagram depicting the main components of a Brewarrina to Bourke demonstration functional process zone (modified from (Barrett 2004)).

Decisions regarding the optimal placement of SWH into the demonstration functional process zone should only be made after careful consideration of the likely ecological and geomophological responses. A substantial amount of work has been undertaken to develop suitable templates for the reintroduction of SWH between Yarrawonga and Tocumwal in the River Murray (Hughes and Thoms 2002; Nicol *et al*. 2002). Although the geomorphology and hydrology of the highly regulated Murray is substantially different from that of Barwon-Darling, a comparison of preliminary results by (Thiem) (2002) and the work of (Hughes and Thoms) (2002) and (Nicol *et al*.) (2002) enable some similarities to be drawn between the two rivers.

(Thiem) (2002) surveyed a 10 km section of river upstream of Bourke (Warraweena: see Appendix 2, Figure 1, reach number 8) and found that SWH was twice as abundant on the outside of bends as on the inner bank. The SWH on the outside of bends tended to be more complex and was commonly associated with steeper banks and drop-offs. This SWH was found to be the preferential habitat of golden perch and Murray cod (Thiem 2002). It is recommended that this information be used to set hypotheses about the utilisation of SWH by fish, as well as the distribution of SWH within reaches and within bends in the Barwon-Darling River. These hypotheses can be properly tested within the bounds of a demonstration functional process zone and can provide information that will allow resnagging practices to be refined for future rehabilitation works in dryland rivers.

In this respect, the resnagging of a demonstration functional process zone should be attempted in a systematic way, with emphasise given to positions low in the channel in order to maximise habitat accessibility for fish during predominant low flow conditions.

6.3.1.2. Riparian protection

In chapter 4 it was noted that although tall, overhanging trees were abundant in the upper Barwon-Darling River, mid to lower regions of the river consisted primarily of shrubs. Further, sections of this riparian zone were sparsely vegetated relative to the entire Barwon-Darling-Paroo system. Until the possible links between riparian attributes and ecosystem processes in large rivers are properly quantified (currently being investigated by the CRCFE), it is hard to know to what extent these regional differences are influencing river health. A healthy riparian zone is, however, undoubtedly important to river health through the input of carbon to the channel, the stabilisation of river banks, the provision of shading, or as habitat for terrestrial macroinvertebrates (Lovett and Price 1999).

Removal of riparian vegetation accelerates erosion in a watershed. This can lead to a loss in instream habitat diversity through the aggradation of pool habitats (filling in) and the embedding of gravels that are used for spawning by species such as freshwater catfish. (Reeves *et al.*)(1993) found that instream habitat in North American basins with low levels of tree harvesting (<25%) were more diverse than habitats in those basins with high harvest levels (>25%).

The riparian zone is an important source for the recruitment of structural woody habitat into rivers. This wood not only serves as important habitat for fish in its own right, but also increases channel diversity through the formation of scour and backwater pools. (Marsh *et al.*)(2001) found that wood loading in streams across eastern Australia was linearly related to tree volume in the riparian zone. In North American basins, paired comparisons have shown that streams in basins with low levels of tree harvesting had 2-12 times more pieces of large wood per 100 m than those streams in basins with high levels of harvesting (Reeves *et al*. 1993).

At the reach scale, there is evidence that the condition of the riparian zone influences the utilisation of habitat by fish. (Growns *et al.*) (1998) have shown in the Nepean River (coastal eastern Australia) that both the number of fish species as well as the total abundance of fish were significantly higher adjacent to vegetated banks. It therefore seems reasonable to assume that by protecting the riparian zone from further vegetation removal, and by revegetating bare areas and restricting activities that lead to bank destabilisation (e.g. stock access), beneficial outcomes for the health of the mid to lower Barwon-Darling River may be achieved.

6.3.1.3. Environmental flow management

Through the deleterious effects on both the volume and frequency of mid to large flow events it is likely that water resource development has reduced the accessibility of fish to a substantial amount of instream habitat over time (chapter 4). The rapid draw-down of water that results from increased pumping on the falling limb of floods, may also be responsible for an acceleration in bank erosion, and therefore for the frequent slumping observed in the lower Barwon-Darling River (chapter 4). Based on this, it is likely that improvements in the diversity of habitat available to fish, as well as the quality of water can be made through careful management of environmental flows.

It must be appreciated that there is a perception throughout the general community that the problem concerning environmental flows centres around periods of low and zero flow (Thoms 2001). The public needs to be educated in the fact that extended periods of low-flow are actually a natural feature of the variability of dryland rivers. It is the maintenance of the timing and duration of variable events that is so important to the functioning of the dryland river ecosystem. Under such regimes, the availability of low flow habitats is extremely important. The current report demonstrates that there is a large degree of spatial variability in the availability of low flow habitat in the Barwon-Darling River. It is this habitat that is essential to the integrity of drought refuges and thus fish populations, enabling them to capitalise of periods of high flow, or boom times (Walker *et al*. 1997).

6.3.1.4. Improvements in fish passage

Native fish are known to migrate along rivers for breeding and recruitment, or for the colonisation of existing or new territories. Instream barriers such as weirs prevent this movement and are therefore a major threat to the survival of native fish populations. The MDBC has identified 18 priority barriers in the MDB (not associated with the River Murray) at which fish passage improvements are required (for a complete list see (MDBC 2003)). The weirs at Brewarrina and Bourke are two that have been prioritised for the installation of fishways. The Brewarrina Weir is of higher priority and as a result, a vertical slot fishway has been approved for installation in late 2005. The improvement of fish passage through the Brewarrina weir is timely as the findings of the current report would suggest that there are accumulations of native fish in the zone immediately downstream of Brewarrina. There are also relatively fewer native fish upstream of Brewarrina, despite having a greater availability of instream structural woody habitat. The installation of the Brewarrina fishway will allow migrating fish species to attain critical upstream habitats and is therefore well placed within the framework of a Bourke to Brewarrina demonstration functional process zone.

The implementation of a Brewarrina to Bourke demonstration functional process zone should increase the priority given to the construction of a fishway at Bourke. Its construction will ensure a consistent and coordinated approach to fish passage throughout the region. The cost benefit analysis of the fishway installation should now be aligned with the expected social and environmental benefits that will be derived from the demonstration functional process zone.

6.3.2. Nearby control reach

The current study involved the collection of information on the status of both fish and fish habitat from Mungindi to Tilpa. This information, combined with data obtained from several other existing NSW Fisheries survey sites along the Barwon-Darling river, provides researchers with both upstream and downstream options for the setup of a control reach.

6.3.3. Degraded but not beyond repair

The Brewarrina to Bourke zone can be classed as degraded for all the reasons outlined in previous pages. A major prerequisite to the rehabilitation of riverine environments is that the system be capable of responding to rehabilitation (Rutherford *et al*. 1998). Within the Barwon-Darling River, fish species such as golden perch, Murray cod, freshwater catfish and silver perch are in various stages of decline, but none are yet extinct. It is believed that by removing the key threats to their survival, population declines can be arrested. While as a whole, this is a large task, it can be achieved through the simultaneous implementation of, what are individually, very manageable interventions. As an example, resnagging the Barwon-Darling River is more a case of enhancing existing instream habitat rather than providing instream structure in areas totally devoid of it.

6.3.4. Close proximity to Bourke and Brewarrina

One of the main criteria of a demonstration functional process zone is that it be in close proximity to a major town. Not only must the rehabilitation works be easily visible to the local community to ensure continued enthusiasm, but skilled labour and resources will also need to be sourced from the town. A Brewarrina to Bourke demonstration functional process zone would benefit from its close proximity to two major outback centres, each with its respective local governments, businesses, population and recreational angling clubs.

6.3.5. Manageable size with clearly defined borders

The current study was able to detect a downstream gradient of change in both the availability of fish habitat and the structure of the fish assemblage along the Barwon-Darling River. This highlights the fact that, although the problem of habitat degradation and native fish declines may be representative of the whole Barwon-Darling River, there is evidence of definite regional differences. Such a notion lends itself to the management of the Barwon-darling River as a system of smaller Riverine Management Zones (RMZs) (MDBC 2003). A RMZ should have its key threats determined and its own specific management plan that is a subset of the overall plan for the river. It is at smaller subsets within RMZs that priority sites for a demonstration functional process zone can be determined. The zone of river from Brewarrina to Bourke covers 212 river km and is therefore slightly larger than the 100 km that has been arbitrarily suggested by (Barrett) (2004). The Brewarrina to Bourke zone is flanked by two major townships, two major weirs, and contains a fish assemblage that is of significantly different composition to all other zones in the river. Based on this, the Brewarrina to Bourke zone is well defined both physically and biotically.

6.3.6. Baseline and ongoing monitoring

While the success of habitat rehabilitation works is often measured in terms of achieving the desired habitat change, emphasis is rarely given to assessing whether there has been a significant affect on the fish assemblage. Smokorowski *et al.* (1998) reviewed 78 documented habitat rehabilitation projects in North America and found that few monitored the biotic outcomes. Of the projects that did look at biotic changes, 27% reported an increase in the biomass and/or abundance of target fish species. Generally it was not assessed whether these increases were produced by an increase in the fecundity or growth of the fish, or whether they were due to the redistribution and concentration of fish in the rehabilitated habitat. Evidence of redistribution was found in 17% of the studies.

The presence of data from the current study, as well as historical data fish data from existing NSW Fisheries sites (namely Stoney Point Pump Hole and Wolkara) provide a substantial amount of baseline data for the Brewarrina to Bourke zone. In addition to this, the University of Canberra has extensive geomorphological data in the area, collected over the last decade. Furthermore, the Department of Infrastructure Planning and Natural Resources (DIPNR) manage both simulated and real hydrological data for the region.

Assessment and monitoring of both the progress of rehabilitation works and the biological responses is crucial to success of a demonstration functional process zone. Ongoing monitoring should be undertaken with the following points in mind:

- Existing baseline data should be synthesised with any new data. A detailed freshwater database capable of achieving this is already managed by NSW Fisheries;
- All future monitoring of fish populations should be conducted in a standardised way (possibly similar to that used in the SRA) to allow for meaningful basin-wide comparisons to be made;
- Regular review of rehabilitation outcomes should be made against agreed targets to ensure that desirable progress is being made;

- An adaptive management process should ensure that the results obtained from monitoring are used to review and refine rehabilitation works so that the best possible outcome can be achieved;

- Regular dissemination of information to partner groups and stakeholders to ensure continued support;

- Given the presence of long-lived species, it is desirable for monitoring to persist for sufficiently long enough to detect population changes (10-15 years).

6.3.7. Fits in with existing management frameworks and research projects

Ultimately the Brewarrina to Bourke demonstration functional process zone will provide a perfect opportunity to develop and test river rehabilitation in a semi-arid zone. In conjunction with other demonstration functional process zones, it will give the MDBC a truly basin-wide approach to river rehabilitation in line with the objectives set out in the Native Fish Strategy. In addition to this, a Brewarrina to Bourke demonstration functional process zone is also aligned with other management programs currently underway in the Murray-Darling Basin. Examples of this include:

- The development and implementation of species recovery plans for the Darling River Endangered Ecological Community (*Fisheries Management Act 1994*);

- Monitoring will coincide with a basin-wide assessment of river health that will be undertaken as part of the Sustainable Rivers Audit (SRA);

- Improved fish passage at Bourke and Brewarrina weirs is already an objective of a basin-wide fish passage program coordinated by the MDBC;

- The construction of a Brewarrina fishway has already been approved and monitoring of its effectiveness is aligned with other NSW Fishery research;

- Carp control will be consistent with the objectives of the National Management Strategy for Carp Control.

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APPENDIX 1: SPECIES LIST AND CATCH DETAILS

Table 1. Number of fish recorded (caught and observed) from the Barwon-Darling and Paroo River sites.

Site		12	11	10	9	8	7	6	5	4	3	2	1	18	17	15	14	13	Total
Waterbody		Darling River					Barwon River							Paroo River					
Number of replicates		60	60	60	60	60	60	60	60	60	60	60	60	29	27	30	28	20	
Number of alien species		2	1	1	2	2	1	2	1	2	1	2	2	2	2	2	2	2	
Number of native species		6	3	3	4	3	4	3	4	3	3	3	3	3	5	4	6	4	
Total number of species		8	4	4	6	5	5	5	5	5	4	5	5	5	7	6	8	6	
Native species																			
Bidyanus bidyanus	Silver perch	1			1												7		9
Hypseleotris spp	Gudgeon	3					1		1										5
Leiopotherapon unicolor	Spangled perch														2	1	1	2	6
Macculochella peelii	Murray cod	7	1	4	4	5	1	1	4	1	1	8	2						39
Macquaria ambigua	Golden perch	10	4	29	15	25	21	1	8	6	14	7	12	10	15	7	29	17	230
Melanotaenia fluviatilis	Crimson-spotted rainbowfish													1	1		1		3
Nematalosa erebi	Bony herring	512	318	822	628	552	568	80	87	68	280	179	435	83	3	10	16	30	4671
Neosilurus hyrtlii	Hyrtl's tandan														3	2	1	2	8
Tandanus tandanus	Freshwater catfish	2																	2
Alien species																			
Carassius auratus	Goldfish	4				1		4		1		2	3	1	16	6	6	6	50
Cyprinus carpio	Common carp	38	24	56	83	71	102	69	75	125	50	39	49	34	51	24	70	26	986
Gambusia holbrooki	Gambusia				1														1
Percent toal native species		92.7	93.1	93.9	88.5	89.0	85.3	52.9	57.1	37.3	85.5	82.6	89.6	72.9	26.4	40.0	42.0	61.4	82.7
Percent toal alien species		7.3	6.9	6.1	11.5	11.0	14.7	47.1	42.9	62.7	14.5	17.4	10.4	27.1	73.6	60.0	58.0	38.6	17.3
Total native fish		535	323	855	648	582	591	82	100	75	295	194	449	94	24	20	55	51	4973
Total alien fish		42	24	56	84	72	102	73	75	126	50	41	52	35	67	30	76	32	1037
Grand Total		577	347	911	732	654	693	155	175	201	345	235	501	129	91	50	131	83	6010

APPENDIX 2: SITE DETAILS

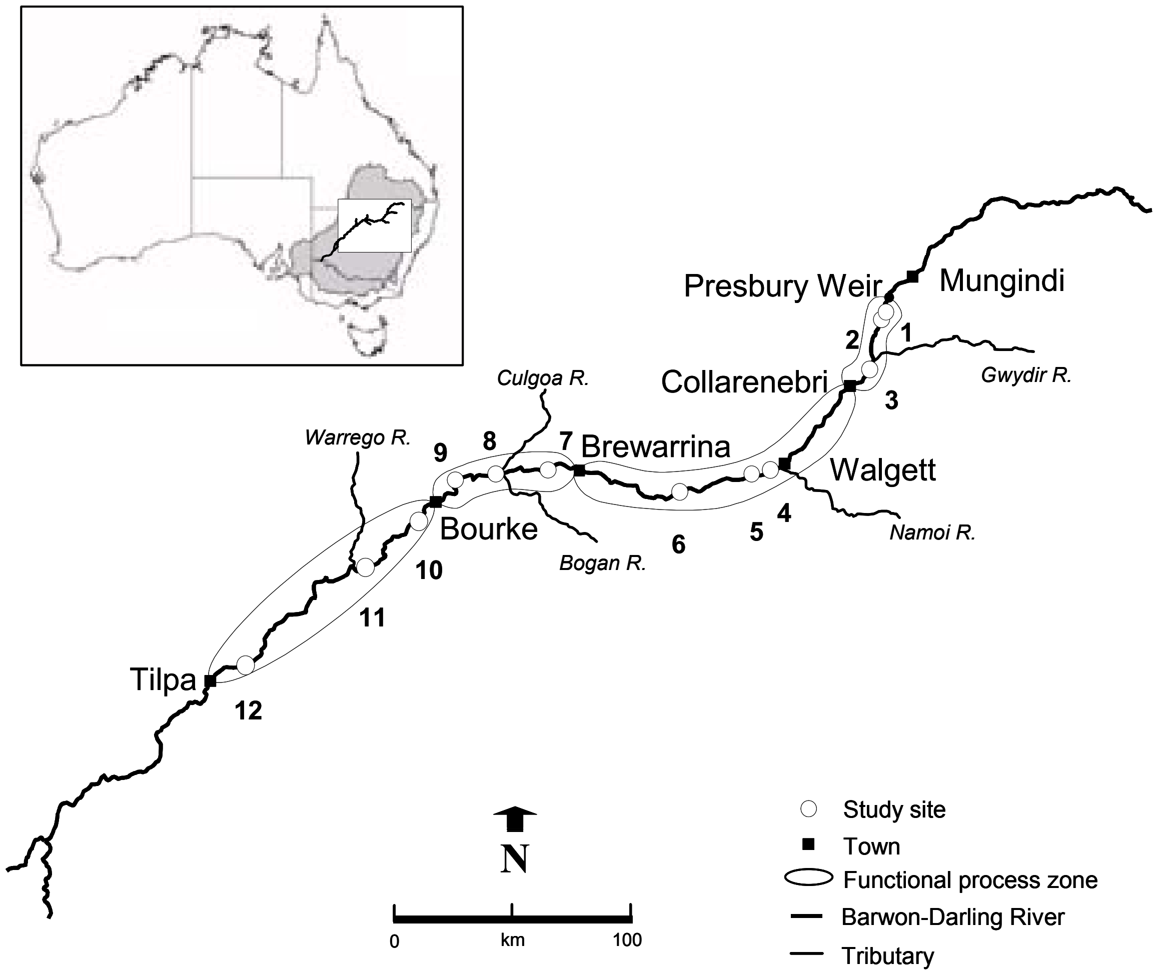

Figure 1. Location of functional process zones and study sites on the Barwon-Darling River.

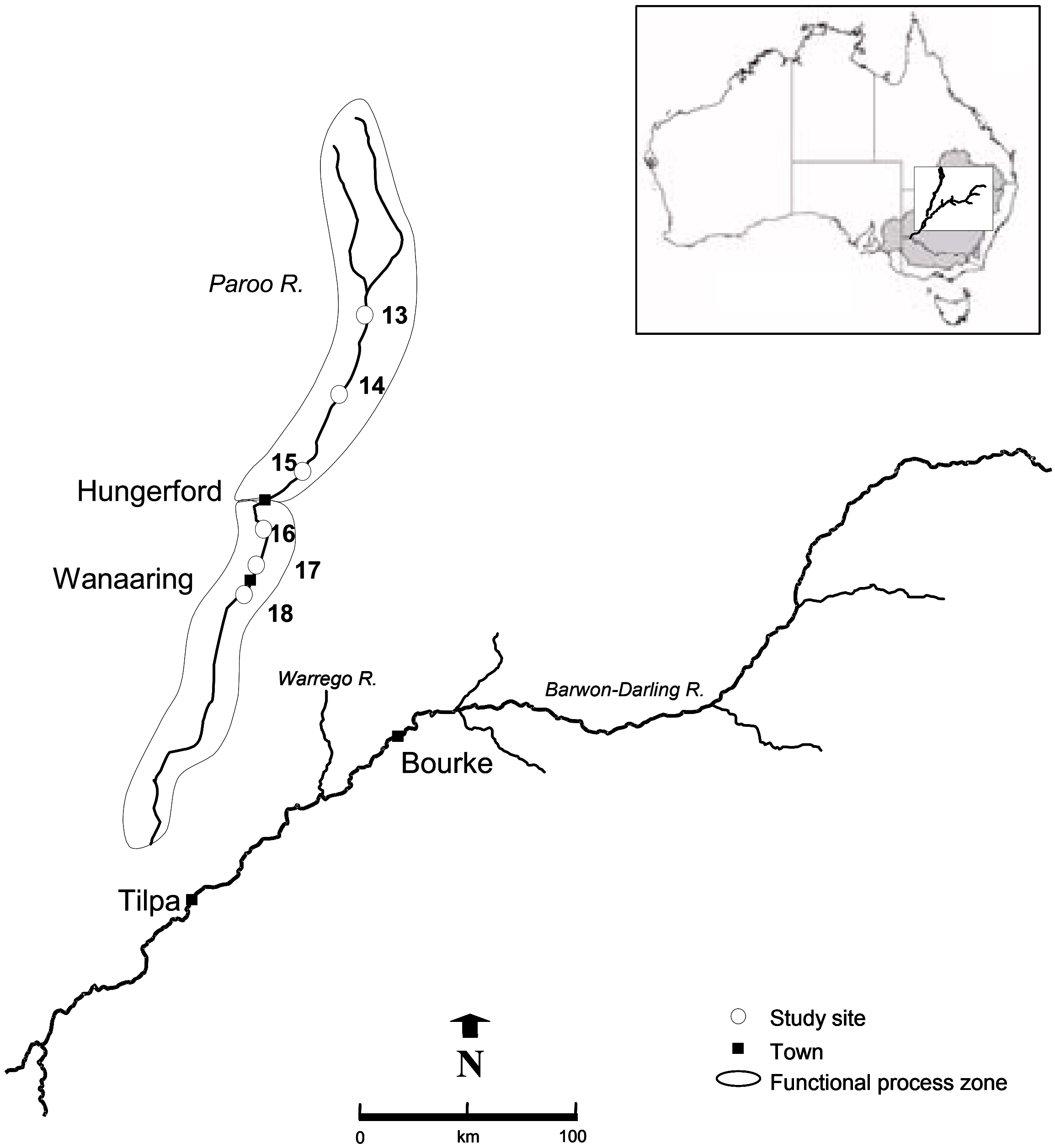

Figure 2. Location of functional process zones and study sites on the Paroo River.

Project ID.	1	**Project Site Name**	Upper Mogil Mogil
NSW Fisheries ID.	604	**NSW Fisheries Site Name**	Upper Mogil Mogil
Functional Process Zone ID.	1	**Functional Process Zone Name**	Presbury weir - Collarenebri

Waterbody	Barwon River	**Altitude**	150 m
Latitude	-29.28767708	**Longitude**	148.7223088
		Reach Length	10 km

NO PHOTOGRAPH AVAILABLE

Substratum	Grade
Bedrock	R
Boulder	-
Cobble	-
Gravel	-
Sand	O
Mud/Silt	O
Clay	-
Unknown	R

Flora	Grade
Native Trees	F
Exotic Trees	-
Shrubs	R
Terrestrial Grass	R
Rushes, Sedges	R
Littoral Grasses	-
Floating Macrophytes	-
Submerged Macrophytes	-
Algae	-

Cover	Grade
Rock	-
Timber	R
Undercuts	-
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Waterbody Type	Channel
Flow	Low and Falling
Velocity	Slow (<0.1 m/s)

Water Quality	
Temp (^{o}C)	27.8
pH	7.8
Conductivity (µs/cm)	0.299
Turbidity	High
Dissolved Oxygen (mg/L)	3.60

Project ID.	2	**Project Site Name**	Lower Mogil Mogil
NSW Fisheries ID.	603	**NSW Fisheries Site Name**	Lower Mogil Mogil
Functional Process Zone ID.	1	**Functional Process Zone Name**	Presbury weir - Collarenebri

Waterbody	Barwon River	**Altitude**	149 m
Latitude	-29.33133596	**Longitude**	148.6952388
		Reach Length	10 km

NO PHOTOGRAPH AVAILABLE

Substratum	Grade
Bedrock	-
Boulder	-
Cobble	-
Gravel	-
Sand	R
Mud/Silt	F
Clay	F
Unknown	R

Flora	Grade
Native Trees	F
Exotic Trees	-
Shrubs	R
Terrestrial Grass	R
Rushes, Sedges	-
Littoral Grasses	-
Floating Macrophytes	-
Submerged Macrophytes	-
Algae	R

Cover	Grade
Rock	-
Timber	O
Undercuts	R
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Waterbody Type	Channel
Flow	Low and Steady
Velocity	Slow (<0.1 m/s)

Water Quality	
Temp (^{o}C)	27.2
pH	7.8
Conductivity (μs/cm)	0.201
Turbidity	High
Dissolved Oxygen (mg/L)	4.37

Project ID.	3	**Project Site Name**	Old Pokataroo
NSW Fisheries ID.	102	**NSW Fisheries Site Name**	Old Pokataroo
Functional Process Zone ID.	1	**Functional Process Zone Name**	Presbury weir - Collarenebri

Waterbody	Barwon River	**Altitude**	145 m
Latitude	-29.5203523	**Longitude**	148.661241
		Reach Length	10 km

NO PHOTOGRAPH AVAILABLE

Substratum	Grade
Bedrock	R
Boulder	R
Cobble	-
Gravel	R
Sand	F
Mud/Silt	R
Clay	-
Unknown	R

Flora	Grade
Native Trees	O
Exotic Trees	-
Shrubs	R
Terrestrial Grass	O
Rushes, Sedges	R
Littoral Grasses	R
Floating Macrophytes	-
Submerged Macrophytes	-
Algae	R

Cover	Grade
Rock	R
Timber	O
Undercuts	-
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Waterbody Type	Channel
Flow	Low
Velocity	Slow (<0.1 m/s)

Water Quality	
Temp (^{o}C)	26.8
pH	7.4
Conductivity (µs/cm)	0.198
Turbidity	High
Dissolved Oxygen (mg/L)	4.13

Project ID.	4	**Project Site Name**	Walgett
NSW Fisheries ID.	602	**NSW Fisheries Site Name**	Walgett
Functional Process Zone ID.	2	**Functional Process Zone Name**	Collarenebri - Brewarrina

Waterbody	Barwon River	**Altitude**	131 m
Latitude	-30.024654496	**Longitude**	148.0577957
		Reach Length	10 km

Substratum	Grade
Bedrock	-
Boulder	-
Cobble	-
Gravel	-
Sand	R
Mud/Silt	A
Clay	-
Unknown	-

Flora	Grade
Native Trees	F
Exotic Trees	-
Shrubs	-
Terrestrial Grass	F
Rushes, Sedges	R
Littoral Grasses	A
Floating Macrophytes	-
Submerged Macrophytes	-
Algae	-

Cover	Grade
Rock	-
Timber	R
Undercuts	-
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Waterbody Type	Channel
Flow	Low and Steady
Velocity	Slow (<0.1 m/s)

Water Quality	
Temp (^{o}C)	24.4
pH	8.0
Conductivity (µs/cm)	0.386
Turbidity	High
Dissolved Oxygen (mg/L)	6.64

Project ID.	5	**Project Site Name**	Combadgery
NSW Fisheries ID.	601	**NSW Fisheries Site Name**	Combadgery
Functional Process Zone ID.	2	**Functional Process Zone Name**	Collarenebri - Brewarrina

Waterbody	Barwon River	**Altitude**	125 m
Latitude	-30.03469302	**Longitude**	147.9230779
		Reach Length	10 km

Substratum	Grade
Bedrock	-
Boulder	-
Cobble	-
Gravel	-
Sand	R
Mud/Silt	A
Clay	-
Unknown	-

Flora	Grade
Native Trees	A
Exotic Trees	-
Shrubs	-
Terrestrial Grass	F
Rushes, Sedges	R
Littoral Grasses	R
Floating Macrophytes	-
Submerged Macrophytes	-
Algae	-

Cover	Grade
Rock	-
Timber	O
Undercuts	-
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Waterbody Type	Channel
Flow	Low
Velocity	Slow (<0.1 m/s)

Water Quality	
Temp (^oC)	26.5
Ph	8.1
Conductivity (µs/cm)	0.386
Turbidity	High
Dissolved Oxygen (mg/L)	6.94

Project ID.	6	**Project Site Name**	Old Borooma
NSW Fisheries ID.	105	**NSW Fisheries Site Name**	Old Borooma
Functional Process Zone ID.	2	**Functional Process Zone Name**	Collarenebri - Brewarrina

Waterbody	Barwon River	**Altitude**	120 m
Latitude	-30.11835762	**Longitude**	147.4567448
		Reach Length	10 km

Substratum	Grade
Bedrock	-
Boulder	-
Cobble	-
Gravel	-
Sand	-
Mud/Silt	A
Clay	-
Unknown	-

Flora	Grade
Native Trees	F
Exotic Trees	-
Shrubs	-
Terrestrial Grass	-
Rushes, Sedges	R
Littoral Grasses	R
Floating Macrophytes	-
Submerged Macrophytes	-
Algae	-

Cover	Grade
Rock	-
Timber	R
Undercuts	-
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Water Quality	
Temp (^{o}C)	28.1
pH	8.2
Conductivity (µs/cm)	0.393
Turbidity	High
Dissolved Oxygen (mg/L)	8.02

Waterbody Type	Channel
Flow	Low and Falling
Velocity	Moderate

Project ID.	7	**Project Site Name**	Wolkara Station
NSW Fisheries ID.	106	**NSW Fisheries Site Name**	Wolkara Station
Functional Process Zone ID.	3	**Functional Process Zone Name**	Brewarrina - Bourke

Waterbody	Barwon River	**Altitude**	110 m
Latitude	-29.95615236	**Longitude**	146.6165436
		Reach Length	10 km

Substratum	Grade
Bedrock	-
Boulder	-
Cobble	-
Gravel	-
Sand	F
Mud/Silt	O
Clay	-
Unknown	-

Flora	Grade
Native Trees	F
Exotic Trees	-
Shrubs	-
Terrestrial Grass	-
Rushes, Sedges	-
Littoral Grasses	-
Floating Macrophytes	R
Submerged Macrophytes	-
Algae	-

Cover	Grade
Rock	-
Timber	O
Undercuts	-
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Waterbody Type	Channel
Flow	Low and Rising
Velocity	Slow (<0.1 m/s)

Water Quality	
Temp (^{o}C)	28.4
pH	8.1
Conductivity (µs/cm)	0.114
Turbidity	Moderate
Dissolved Oxygen (mg/L)	6.71

Project ID.	8	**Project Site Name**	Warraweena
NSW Fisheries ID.	600	**NSW Fisheries Site Name**	Warraweena
Functional Process Zone ID.	3	**Functional Process Zone Name**	Brewarrina - Bourke

Waterbody	Darling River	**Altitude**	107 m
Latitude	-29.96753076	**Longitude**	146.3086693
		Reach Length	10 km

Substratum	Grade
Bedrock	-
Boulder	-
Cobble	-
Gravel	-
Sand	R
Mud/Silt	A
Clay	-
Unknown	-

Flora	Grade
Native Trees	F
Exotic Trees	-
Shrubs	-
Terrestrial Grass	F
Rushes, Sedges	R
Littoral Grasses	A
Floating Macrophytes	-
Submerged Macrophytes	-
Algae	-

Cover	Grade
Rock	-
Timber	R
Undercuts	-
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Waterbody Type	Channel
Flow	Low and Steady
Velocity	Slow (<0.1 m/s)

Water Quality	
Temp (^{o}C)	24.4
pH	8.0
Conductivity (µs/cm)	0.386
Turbidity	High
Dissolved Oxygen (mg/L)	6.64

Project ID.	9	**Project Site Name**	Stony Point Pump Hole
NSW Fisheries ID.	107	**NSW Fisheries Site Name**	Stony Point Pump Hole
Functional Process Zone ID.	3	**Functional Process Zone Name**	Brewarrina -Bourke

Waterbody	Darling River	**Altitude**	150 m
Latitude	-29.9711561	**Longitude**	146.0256873
		Reach Length	10 km

Substratum	Grade
Bedrock	-
Boulder	-
Cobble	-
Gravel	-
Sand	-
Mud/Silt	A
Clay	-
Unknown	-

Flora	Grade
Native Trees	F
Exotic Trees	-
Shrubs	-
Terrestrial Grass	-
Rushes, Sedges	R
Littoral Grasses	R
Floating Macrophytes	-
Submerged Macrophytes	-
Algae	-

Cover	Grade
Rock	-
Timber	R
Undercuts	-
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Waterbody Type	Channel
Flow	Low and Falling
Velocity	Slow (<0.1 m/s)

Water Quality	
Temp (^oC)	28.5
pH	8.4
Conductivity (µs/cm)	0.525
Turbidity	Moderate
Dissolved Oxygen (mg/L)	7.53

Project ID.	10	**Project Site Name**	Jandra
NSW Fisheries ID.	108	**NSW Fisheries Site Name**	Jandra
Functional Process Zone ID.	4	**Functional Process Zone Name**	Bourke - Tilpa

Waterbody	Darling River	**Altitude**	100 m
Latitude	-30.18035048	**Longitude**	145.7899464
		Reach Length	10 km

Substratum	Grade
Bedrock	R
Boulder	-
Cobble	-
Gravel	-
Sand	F
Mud/Silt	O
Clay	-
Unknown	-

Flora	Grade
Native Trees	F
Exotic Trees	-
Shrubs	R
Terrestrial Grass	R
Rushes, Sedges	R
Littoral Grasses	-
Floating Macrophytes	R
Submerged Macrophytes	-
Algae	-

Cover	Grade
Rock	R
Timber	R
Undercuts	-
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Waterbody Type	Channel
Flow	Low
Velocity	Slow (<0.1 m/s)

Water Quality	
Temp (^{o}C)	27.7
pH	8.3
Conductivity (µs/cm)	0.620
Turbidity	Low
Dissolved Oxygen (mg/L)	4.53

Project ID.	11	**Project Site Name**	East Toorale
NSW Fisheries ID.	16	**NSW Fisheries Site Name**	East Toorale
Functional Process Zone ID.	4	**Functional Process Zone Name**	Bourke - Tilpa

Waterbody	Darling River	**Altitude**	100 m
Latitude	-30.43226311	**Longitude**	145.3880628
		Reach Length	10 km

Substratum	Grade
Bedrock	R
Boulder	-
Cobble	-
Gravel	-
Sand	O
Mud/Silt	O
Clay	-
Unknown	-

Flora	Grade
Native Trees	F
Exotic Trees	-
Shrubs	R
Terrestrial Grass	R
Rushes, Sedges	R
Littoral Grasses	R
Floating Macrophytes	-
Submerged Macrophytes	-
Algae	-

Cover	Grade
Rock	R
Timber	R
Undercuts	R
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Waterbody Type	Channel
Flow	Low
Velocity	Slow (<0.1 m/s)

Water Quality	
Temp (^{o}C)	28.9
pH	8.6
Conductivity (μs/cm)	0.148
Turbidity	Low
Dissolved Oxygen (mg/L)	7.78

Project ID.	12	**Project Site Name**	Curranyalpa
NSW Fisheries ID.	110	**NSW Fisheries Site Name**	Curranyalpa
Functional Process Zone ID.	4	**Functional Process Zone Name**	Bourke - Tilpa

Waterbody	Darling River	**Altitude**	90 m
Latitude	-30.88375752	**Longitude**	144.6986067
		Reach Length	10 km

Substratum	Grade
Bedrock	O
Boulder	-
Cobble	-
Gravel	-
Sand	O
Mud/Silt	O
Clay	O
Unknown	-

Flora	Grade
Native Trees	F
Exotic Trees	-
Shrubs	-
Terrestrial Grass	R
Rushes, Sedges	-
Littoral Grasses	-
Floating Macrophytes	-
Submerged Macrophytes	R
Algae	R

Cover	Grade
Rock	R
Timber	R
Undercuts	R
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Water Quality	
Temp (^{o}C)	17.4
pH	8.1
Conductivity (µs/cm)	0.094
Turbidity	High
Dissolved Oxygen (mg/L)	6.12

Waterbody Type	Channel
Flow	Low and Falling
Velocity	Slow (<0.1 m/s)

Project ID.	13	**Project Site Name**	Tilbooroo
NSW Fisheries ID.	608	**NSW Fisheries Site Name**	Tilbooroo
Functional Process Zone ID.	5	**Functional Process Zone Name**	Hungerford -North

Waterbody	Paroo River	**Altitude**	168 m
Latitude	-27.861	**Longitude**	145.1465333
		Reach Length	

Substratum	Grade
Bedrock	R
Boulder	-
Cobble	-
Gravel	-
Sand	-
Mud/Silt	A
Clay	-
Unknown	-

Flora	Grade
Native Trees	F
Exotic Trees	-
Shrubs	R
Terrestrial Grass	R
Rushes, Sedges	-
Littoral Grasses	-
Floating Macrophytes	-
Submerged Macrophytes	-
Algae	-

Cover	Grade
Rock	-
Timber	R
Undercuts	R
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Waterbody Type	Waterhole
Flow	Low and Falling
Velocity	Zero

Water Quality	
Temp (^{o}C)	24.8
pH	8.0
Conductivity (µs/cm)	0.108
Turbidity	High
Dissolved Oxygen (mg/L)	4.59

Project ID.	14	**Project Site Name**	Eulo
NSW Fisheries ID.	607	**NSW Fisheries Site Name**	Eulo
Functional Process Zone ID.	5	**Functional Process Zone Name**	Hungerford -North

Waterbody	Paroo River	**Altitude**	155 m
Latitude	-28.16005	**Longitude**	145.0371666
		Reach Length	

Substratum	Grade
Bedrock	-
Boulder	-
Cobble	-
Gravel	-
Sand	R
Mud/Silt	A
Clay	-
Unknown	-

Flora	Grade
Native Trees	F
Exotic Trees	-
Shrubs	O
Terrestrial Grass	R
Rushes, Sedges	-
Littoral Grasses	-
Floating Macrophytes	-
Submerged Macrophytes	-
Algae	-

Cover	Grade
Rock	-
Timber	R
Undercuts	-
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Waterbody Type	Waterhole/Weir Pool
Flow	Low and Falling
Velocity	Zero

Water Quality	
Temp (^{o}C)	24.7
pH	8.1
Conductivity (µs/cm)	0.123
Turbidity	High
Dissolved Oxygen (mg/L)	2.16

Project ID.	15	**Project Site Name**	Caiwarro
NSW Fisheries ID.	606	**NSW Fisheries Site Name**	Ningaling Station
Functional Process Zone ID.	5	**Functional Process Zone Name**	Hungerford-North

Waterbody	Paroo River	**Altitude**	140 m
Latitude	-28.8936666	**Longitude**	144.5876666
		Reach Length	

Substratum	Grade
Bedrock	-
Boulder	-
Cobble	-
Gravel	-
Sand	-
Mud/Silt	A
Clay	-
Unknown	-

Flora	Grade
Native Trees	F
Exotic Trees	-
Shrubs	O
Terrestrial Grass	-
Rushes, Sedges	-
Littoral Grasses	-
Floating Macrophytes	-
Submerged Macrophytes	-
Algae	-

Cover	Grade
Rock	-
Timber	R
Undercuts	-
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Waterbody Type	Waterhole
Flow	Low and Falling
Velocity	Zero

Water Quality	
Temp (^{o}C)	25.8
pH	8.58
Conductivity (µs/cm)	0.161
Turbidity	High
Dissolved Oxygen (mg/L)	6.05

Project ID.	16	**Project Site Name**	Lenroy Station
NSW Fisheries ID.	-	**NSW Fisheries Site Name**	-
Functional Process Zone ID.	6	**Functional Process Zone Name**	Hungerford - South

Waterbody	Paroo River	**Altitude**	-
Latitude	-29^{o}30.7	**Longitude**	144^{o}19.96
		Reach Length	

Site not electrofished.

Project ID.	17	**Project Site Name**	Yarrawonga
NSW Fisheries ID.	605	**NSW Fisheries Site Name**	Backwood Station
Functional Process Zone ID.	6	**Functional Process Zone Name**	Hungerford -North

Waterbody	Paroo River	**Altitude**	112 m
Latitude	-29.3438833	**Longitude**	144.41348
		Reach Length	

Substratum	Grade
Bedrock	R
Boulder	-
Cobble	-
Gravel	-
Sand	-
Mud/Silt	A
Clay	-
Unknown	-

Flora	Grade
Native Trees	F
Exotic Trees	-
Shrubs	R
Terrestrial Grass	-
Rushes, Sedges	-
Littoral Grasses	-
Floating Macrophytes	-
Submerged Macrophytes	-
Algae	-

Cover	Grade
Rock	-
Timber	R
Undercuts	-
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Water Quality	
Temp (^{o}C)	-
pH	-
Conductivity (µs/cm)	-
Turbidity	High
Dissolved Oxygen (mg/L)	-

Waterbody Type	Waterhole
Flow	Low and Falling
Velocity	Zero

Project ID.	18	**Project Site Name**	Nocoleche Nature Reserve
NSW Fisheries ID.	88	**NSW Fisheries Site Name**	Nocoleche Nature Reserve
Functional Process Zone ID.	6	**Functional Process Zone Name**	Hungerford -North

Waterbody	Paroo River	**Altitude**	100 m
Latitude	-29.83510872	**Longitude**	144.1229793
		Reach Length	

Substratum	Grade
Bedrock	-
Boulder	-
Cobble	-
Gravel	-
Sand	-
Mud/Silt	A
Clay	-
Unknown	-

Flora	Grade
Native Trees	O
Exotic Trees	-
Shrubs	-
Terrestrial Grass	-
Rushes, Sedges	-
Littoral Grasses	-
Floating Macrophytes	-
Submerged Macrophytes	-
Algae	-

Cover	Grade
Rock	-
Timber	R
Undercuts	-
Plant Litter	-

Grades	
A	Abundant
F	Frequent
O	Occasional
R	Rare
-	Absent

Water Quality	
Temp (^{o}C)	-
pH	-
Conductivity (µs/cm)	-
Turbidity	High
Dissolved Oxygen (mg/L)	-

Waterbody Type	Waterhole
Flow	Low and Falling
Velocity	Zero

Other titles in this series:

ISSN 1440-3544 (NSW Fisheries Final Report Series)

No. 1 Andrew, N.L., Graham, K.J., Hodgson, K.E. and Gordon, G.N.G., 1998. Changes after 20 years in relative abundance and size composition of commercial fishes caught during fishery independent surveys on SEF trawl grounds. Final Report to Fisheries Research and Development Corporation. Project No. 96/139.

No. 2 Virgona, J.L., Deguara, K.L., Sullings, D.J., Halliday, I. and Kelly, K., 1998. Assessment of the stocks of sea mullet in New South Wales and Queensland waters. Final Report to Fisheries Research and Development Corporation. Project No. 94/024.

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