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Article

Fish Distribution in Far Western Queensland, Australia: The Importance of Habitat, Connectivity and Natural Flows

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Abstract: The endorheic Lake Eyre Basin drains 1.2 million square kilometres of arid central Australia, yet provides habitat for only 30 species of freshwater fish due to the scarcity of water and extreme climate. The majority are hardy riverine species that are adapted to the unpredictable flow regimes, and capable of massive population booms following heavy rainfall and the restoration of connectivity between isolated waterholes. The remainder are endemic specialists from isolated springs with very restricted ranges, and many are listed under relevant state and national endangered species legislation and also by the International Union for Conservation of Nature (IUCN). For these spring communities, which are sustained by water from the Great Artesian Basin, survival is contingent on suitable habitat persisting alongside extractive mining, agriculture and the imposition of alien species. For the riverine species, which frequently undertake long migrations into ephemeral systems, preservation of the natural flow regime is paramount, as this reinstates riverine connectivity. In this study, fish were sampled from the Bulloo River in the east to the Mulligan River in the west, along a temporal timeframe and using a standard set of sampling gears. Fish presence was influenced by factors such as natural catchment divides, sampling time, ephemerality and the occurrence of connection flows and flooding. Despite the comparatively low diversity of species, the aquatic systems of this isolated region remain in good ecological condition, and as such they offer excellent opportunities to investigate the ecology of arid water systems. However, the presence of both endangered species (in the springs) and invasive and translocated species more widely

indicates that active protection and management of this unique area is essential to maintain biodiversity and ecosystem integrity.

Keywords: Lake Eyre Basin; riverine fish species; Great Artesian Basin; spring-dependent species; endangered species; natural flow regime

1. Introduction

The distribution of living things on Earth is regulated by processes operating at a multitude of spatial and temporal scales ranging from prehistoric climate change [1] to local colonisation and extinction events [2,3]. During the modern era, these processes have been impacted by human-induced perturbations to natural systems such as the domestication of plants and animals, hunting pressure and the translocation of species around the globe. As a consequence, maintenance of native species richness is an important theme in conservation biology [4,5].

The existence of long-term data-sets enables the impacts of anthropogenic changes to be estimated. As an example, Cross and Moss [6] demonstrated the contribution made by habitat-altering flow reduction on the rate of species loss in arid-zone streams in Kansas. However, in the inland river basins of Australia (both the remote Lake Eyre and the more populated Murray-Darling), historical records are recent and patchy [7–11], and baseline sampling has mostly occurred after (rather than before) the regulation of waterways and the introduction of alien species.

Current Australian fish species distribution guides that rely on a combination of scientific surveys and anecdotal records are (and will be) subject to constant revision as more work in remote and/or inaccessible areas is completed [12–15]. Filling the existing knowledge gaps regarding the biodiversity and distribution of Australian freshwater fish should be a priority for management agencies nationwide [16]. This situation is acute in far western Queensland, the state where the headwaters of all the major arid-zone rivers (the Cooper, Diamantina and Georgina; Figure 1) are located. These desert rivers have been demonstrated to be among the most hydrologically variable on the planet [17]. Driven by erratic seasonal rainfall, they can alter from static, isolated waterholes to flowing rivers in the space of several hours [18] and dramatic changes in flow are the driving force behind the so-called "boom-bust" ecological dynamics that characterise such areas [19–21].

Fish surveys and ecological studies in the rivers and wetlands of the South Australian and Queensland areas of the Lake Eyre Basin [19,22–31] underpin current knowledge of fish distribution in these areas and demonstrate that fish diversity in the Lake Eyre Basin is influenced by a combination of antecedent flow history, the presence of suitable habitat and connectivity among habitat patches. Floods, or a series of high flows over several years, result in greater catch-per-unit-effort, population peaks and range extensions.

In addition to riverine species, a small subset of endangered fish is endemic to groundwater-fed spring complexes in the Queensland arid zone that are both ecologically and geographically unique [32]. Species with a fragmented distributional range are often susceptible to higher extinction risk [33], and fishes from the Sonoran Desert in North America with the most fragmented historic distributions have been demonstrated to be the most likely to suffer local extirpations [34]. The range-limited Queensland spring species, such as those from the spring complex at Edgbaston, have similarly suffered local

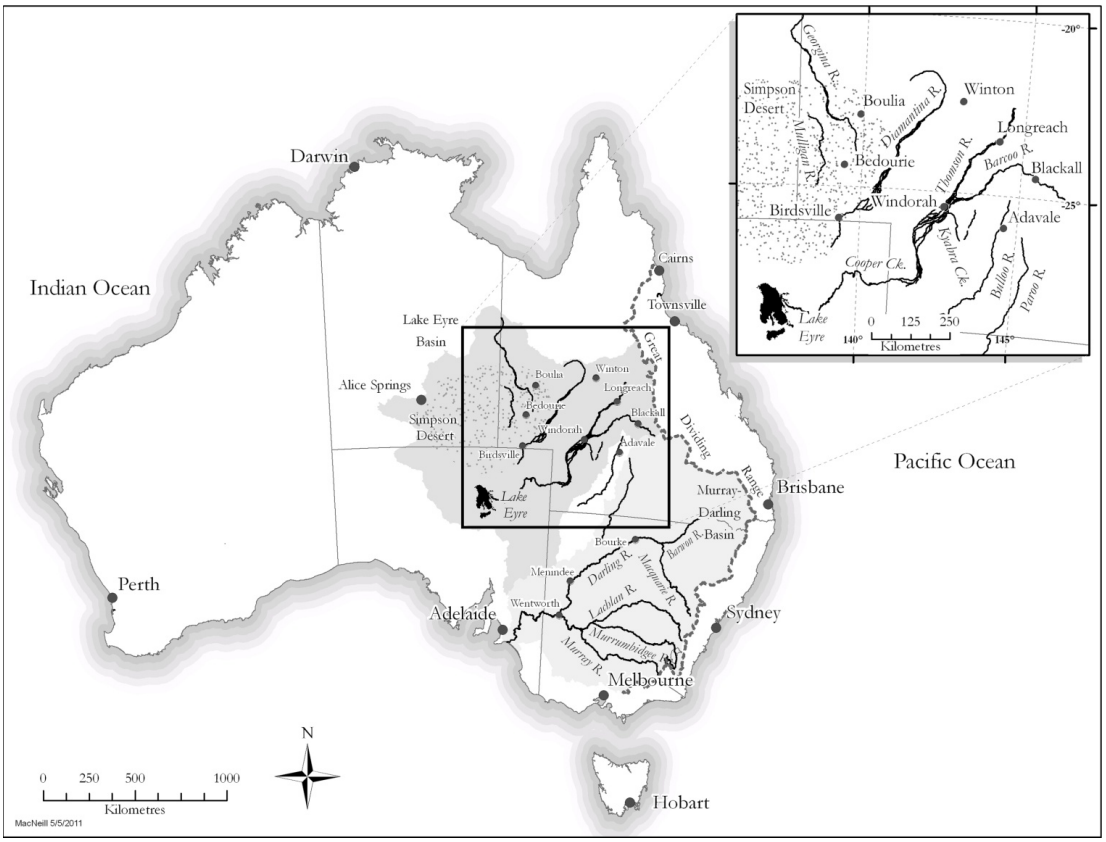
extinctions [3] and are under increased risk due to the colonisation of their small and isolated habitats by alien species such as the poeciliid *Gambusia holbrooki* [35].

For the purposes of this study we retain the temporal scale approach and aim to supplement preceding biodiversity research in the Lake Eyre Basin by investigating the distribution of fish communities at a catchment scale throughout the rivers of far western Queensland. We predicted that: (a) fish communities would exhibit spatial differences associated with catchment divides and barriers to dispersal; (b) fish communities would exhibit seasonal variability; (c) antecedent hydrology would influence fish species presence/absence (with species richness increasing following flooding and enhanced connectivity); and that (d) there would be a difference in fish species richness and composition of communities between permanent and ephemeral habitats.

2. Experimental Section

The study was conducted in waterholes of the Bulloo, Thomson, Barcoo, Cooper, Kyabra, Diamantina, Georgina and Mulligan catchments in far western Queensland (Figure 1). In the remainder of the paper the term "greater Cooper" is used to describe all sub-catchments that drain into the Cooper catchment (Kyabra, Barcoo, Thomson and Cooper: Figure 1). The Mulligan River, in the far west of the study area, has no permanent waterholes and is an entirely ephemeral river, The number of permanent waterholes increases along a west-east transect (*i.e.*, from the Georgina east to the Cooper), however all of the catchments are characterised by intermittent rivers that persist as isolated waterholes for the majority of the time and periodically connect during flow and floods.

Figure 1. Site map showing the location of the study area within central Australia and (inset) the Mulligan, Georgina, Diamantina, Cooper, Thomson, Barcoo, Kyabra and Bulloo catchments.



A minimum of three waterholes were sampled in each catchment during seven sampling periods (September 2006, December 2006, January 2007, April 2007, August 2007, November 2007 and March/April 2008). Major overbank flooding occurred in the Mulligan and Georgina catchments in summer 2006/2007, in the greater Cooper catchment in summer 2007/2008 and in the Bulloo catchment during both summer periods. However major flooding did not occur in the Diamantina catchment for the duration of the study (for a more detailed description of this hydrological history see [30]). In the Mulligan catchment, waterholes evaporated quickly following filling in January 2007. Consequently, three sites were sampled in the Mulligan catchment in April 2007, two in August 2007 and one in November 2007. The Mulligan River had dried completely by March/April 2008. Subsequent fish sampling has occurred in the Mulligan catchment following more recent floods from 2009 to 2012 [31], but these results are not presented and are mentioned only if they are relevant to the main dataset.

2.1. Field Methods

Fish populations were sampled in all waterholes and sampling occasions using a combination of three methods; large fyke nets, small fyke nets and a manually-dragged larval trawl net. Large double-winged fyke nets with a 13mm stretched mesh and 8 metre wings were set parallel to the bank with their openings facing in opposite directions upstream and downstream from a central post. Cod-ends were secured above the water surface in order to allow air-breathing vertebrates to survive if they became trapped. Small fyke nets with a stretched mesh of 2mm and a wing width of 3 metres were set in an identical manner. All fyke nets were set in the afternoon (as close as possible to 2 pm) and retrieved the following morning (as close as possible to 9 am). At each site a larval trawl net (580 mm diameter opening, 2 m long, 500 μm mesh) was also dragged through the water for 5 minutes. Following the clearing of fyke nets and larval trawl nets all fish were held in shaded water-filled buckets prior to processing.

Fish species were identified using a combination of published literature relating to fishes of arid Australian rivers [12,13], however species identification of carp gudgeons, *Hypseleotris* spp., was not attempted. All sampled fish were measured from the tip of the snout to the base of the hypural bones in order to obtain a standard length (SL) measurement for each individual specimen. Following identification and measurement, native species were returned to the water alive and alien species were euthanased using a dilute oil of cloves solution followed by refrigeration. All sampling and euthanasia were carried out under General Fisheries Permit (No: PRM03315D) issued by the Queensland Department of Primary Industries and under a Griffith University Ethics Agreement. Permission to sample at all sites was sought and obtained from station owners and the Queensland Environmental Protection Agency.

2.2. Data Analysis

Data relating to each fish species at each site on each sampling occasion was combined for the three sampling methods used in order to calculate catch-per-unit-effort (CPUE). All fyke net samples were standardised to a 19 hour set time (as per [27]) and larval trawls were standardised to 5 minutes at each site on each sampling occasion. Subsequent analysis of fish communities was performed on samples taken in April 2007, August 2007, November 2007 and March/April 2008 for fish communities in the

Bulloo, Diamantina and Georgina systems. In the Mulligan system, all waterholes were dry prior to March/April 2008 and consequently analysis could be performed only on samples from April, August and November 2007. In most other catchments (Thomson, Cooper and Kyabra), data was available over a longer timeframe and included samples taken in September 2006, December 2006, January 2007, April 2007, August 2007, November 2007 and March/April 2008. Due to difficulties associated with storm conditions and road access, sites in the Barcoo catchment were not sampled in either December 2006 or January 2007.

Bray-Curtis similarity matrices [36] were constructed using CPUE totals transformed for presence/absence using PRIMER-E Version 5. One-way analysis of similarities (ANOSIM) was used to test for the influence of catchment, flow, season and waterhole type on fish communities using the same matrices. Results from ANOSIM calculate a test statistic "R" identifying the observed differences between treatments compared with the differences among replicates within treatments [37].

To test for the influence of season, sampling times were categorised as early summer (September to December), late summer (January to May) or winter (June to August). To test for the influence of flow, antecedent hydrology (the three months prior to sampling) was categorised as major flooding, minor to moderate flooding, within-bank connection flows or no flows.

To test for the influence of waterhole type, waterholes were categorised as permanent within-channel (waterholes situated in the main channel of rivers that did not dry during the study), ephemeral within channel (waterholes situated in the main channel of rivers that dried at least once during the study) or ephemeral lakes (floodplain waterholes that filled and dried at least once within the study period). In instances where ANOSIM revealed significant pairwise differences between fish communities explained by catchment, season, flow or waterhole type, SIMPER analysis in PRIMER-E Version 5 was used to calculate the average dissimilarity between paired samples and allocate the contribution each species made to this dissimilarity [37].

3. Results and Discussion

3.1. Fish Species Presence/Absence Results

Seventeen fish species were sampled in eight catchments in far western Queensland from September 2006 to November 2008 (Table 1). Bony bream, silver tandan, desert rainbowfish and spangled perch were the most widely distributed species and occurred in all catchments (Table 1). Hyrtl's tandan, glassfish, yellowbelly and Barcoo grunter were recorded from seven of the eight sampled catchments, and Welch's grunter were recorded from six (Table 1). The remaining species had more limited distributions, with Cooper Creek catfish collected from the Thomson, Barcoo and Cooper catchments, Australian smelt sampled from all of the greater Cooper catchments, banded grunter sampled from the Georgina and Mulligan catchments, golden goby sampled from the Georgina and Diamantina catchments and carp gudgeons sampled from the Bulloo and greater Cooper catchments (Table 1). A single sleepy cod (not native to the Lake Eyre Basin) was sampled in the Thomson catchment (Table 1). Alien fish species were confined to the greater Cooper catchment during this study, with goldfish recorded from the Thomson and Barcoo catchments and gambusia recorded from the Cooper (Table 1). The lowest number of species was recorded from the Mulligan catchment (7) and the highest from the Thomson catchment (14; Table 1).

Table 1. Fish species presence in sampled catchments of the Queensland Lake Eyre Basin between 2006 and 2008. Percentages represent the frequency of species presence in relation to the total number of sites sampled in each catchment, (eg: 100% = present at every site, smaller percentages = present at fewer sites). Blank areas indicate the species was absent from the catchment.

Species	Catchment (Total Number of Sites Sampled 2006–2008)							
	Mulligan (6)	**Georgina (12)**	**Diamantina (14)**	**Thomson (27)**	**Barcoo (19)**	**Cooper (21)**	**Kyabra (24)**	**Bulloo (12)**
Nematolosa erebi (Bony bream)	83.3	83.3	78.6	100	89.5	100	100	100
Neosiluroides cooperensis (Cooper Creek catfish)				44.4	26.3	33.3		
Neosiluris hyrtlii (Hyrtl's tandan)		75	42.9	62.9	47.4	80.9	58.3	66.6
Porochilus argenteus (Silver tandan)	83.3	50	71.4	74	57.9	85.7	91.6	91.6
Retropinna semoni (Australian smelt)			70.8	33.3	26.3	33.3		
Melanotaenia splendida tatei (Desert rainbowfish)	50	91.6	35.7	51.9	42.1	23.8	75	58.3
Ambassis sp. (Northwest Ambassis or Glassfish)	83.3	100		22.2	36.8	9.5	37.5	83.3
Macquaria sp. (Yellowbelly)		41.6	100	100	100	95.2	95.8	75
Amniataba percoides (Banded grunter)	16.6	83.3						
Bidyanus welchi (Welch's grunter)		8.3	7.1	22.2	10.5	28.6	25	
Leiopotherapon unicolour (Spangled perch)	100	50	42.9	77.8	42.1	42.9	87.5	100
Scortum barcoo (Barcoo grunter)	33.3	16.6	21.4	29.6	26.3	47.6	8.3	
Glossogobius aureus (Golden goby)		75	7.1					
Hypseleotris sp. (Carp gudgeon)				59.3	47.4	19	83.3	58.3
Oxyeleotris lineolatus (Sleepy cod)				3.7				
Carassius auratus (Goldfish)				7.4	10.5			
Gambusia holbrooki (Gambusia)						14.3		
Total Number Of Species	7	11	9	14	13	13	11	8

Analysis of Similarities (ANOSIM) indicates that the fish communities in many catchments in the Queensland Lake Eyre Basin are significantly different from one another (Table 2). Exceptions are Kyabra Creek *versus* the Thomson River, Cooper Creek *versus* the Thomson and Barcoo Rivers and the Thomson River *versus* the Barcoo River (all non-significant; Table 2). It should be noted that these four sub-catchments form the greater Cooper catchment and are periodically connected during flooding. Differences in fish species presence/absence can also be explained by sampling season (or time), antecedent flow regime and waterhole type (Table 2).

Table 2. Summary of One-Way ANOSIM results comparing fish presence/absence throughout the Lake Eyre Basin from April 2007–March/April 2008. All transformations presence/absence.

Factor	Global R	*p*	Significant Pairwise Tests
Catchment	0.314	0.001	Bulloo River *vs.* Kyabra Creek (0.029) Bulloo River *vs.* Cooper Creek (0.001) Bulloo River *vs.* Thomson River (0.004) Bulloo River *vs.* Barcoo River (0.005) Bulloo River *vs.* Mulligan River (0.001) Bulloo River *vs.* Georgina River (0.001) Bulloo River *vs.* Diamantina River (0.002) Kyabra Creek *vs.* Cooper Creek (0.001) Kyabra Creek *vs.* Barcoo River (0.011) Kyabra Creek *vs.* Mulligan River (0.001) Kyabra Creek *vs.* Georgina River (0.001) Kyabra Creek *vs.* Diamantina River (0.001) Cooper Creek *vs.* Barcoo River (0.032) Cooper Creek *vs.* Mulligan River (0.001) Cooper Creek *vs.* Georgina River (0.001) Cooper Creek *vs.* Diamantina River (0.001) Thomson River *vs.* Mulligan River (0.001) Thomson River *vs.* Georgina River (0.001) Thomson River *vs.* Diamantina River (0.002) Barcoo River *vs.* Georgina River (0.001) Barcoo River *vs.* Diamantina River (0.024) Mulligan River *vs.* Diamantina River (0.008) Georgina River *vs.* Diamantina River (0.001)
Season	0.064	0.035	Late summer *vs.* winter (0.038)
Antecedent flow	0.096	0.001	Within-channel flow *vs.* major flood (0.004) Within-channel flow *vs.* no flow (0.001) Major flood *vs.* minor/moderate flood (0.001)
Waterhole type	0.136	0.009	Permanent channel *vs.* ephemeral lake (0.003) Ephemeral channel *vs.* ephemeral lake (0.047)

Analysis of fish species presence/absence within the Queensland Lake Eyre Basin suggests that species with limited distributional ranges contribute strongly to the differences in species composition among catchments. In the Georgina catchment, the presence of banded grunter and golden goby always separated this catchment from all others (Table 1), and in the Bulloo and all greater Cooper

catchments the presence of carp gudgeon always separated these catchments from the Diamantina, Georgina and Mulligan (Table 1).

The number of species sampled at all sites was lowest in winter and highest in late summer. Analysis of the seasonal variation of fish species presence/absence within the Queensland Lake Eyre Basin using SIMPER indicates that a number of species, most notably Hyrtl's tandan, desert rainbowfish, spangled perch and glassfish, are likely to be absent or rare in samples taken during winter but present in late summer (Table 3).

Table 3. SIMPER analysis comparing fish species presence/absence in relation to season (or sampling time) in the Queensland Lake Eyre Basin from April 2007–March/April 2008. (Early summer = September–December, late summer = January–April, winter = May–August.)

Species	**Average abundance per sample**			**Percent contribution to observed differences (>5%).**
	Early summer	*Late summer*	*Winter*	*Late summer vs. winter*
Bony bream	100.74	76.81	13.08	5.14
Hyrtl's tandan	29.57	91.45	-	11.54
Silver tandan	10.70	39.30	7.46	9.48
Australian smelt	11.48	-	-	6.62
Desert rainbowfish	-	47.60	20.58	10.43
Glassfish	17.13	25.91	-	9.42
Yellowbelly	14.52	17.64	9.92	6.07
Spangled perch	9.57	30.51	5.65	9.96
Carp gudgeon	1.7	-	2.54	8.89

Antecedent hydrology had an influence on the number of species present in fish samples taken throughout the Queensland Lake Eyre Basin between April 2007 and March/April 2008. The highest numbers of species were recorded in the Georgina catchment in April 2007 following major flooding in January 2007, and in the Cooper catchment in March/April 2008 following flooding in January and February 2008 (Figure 2). Hyrtl's tandan and spangled perch were most commonly sampled following major flooding.

Species such as glassfish and bony bream contributed most to species presence/absence differences between ephemeral lakes and within-channel waterholes (both permanent and ephemeral; Table 4). Both bony bream and glassfish exhibited far higher average abundance per sample in ephemeral lake habitats than either permanent or ephemeral within-channel habitats (Table 4). In contrast, Hyrtl's tandan demonstrated higher average abundance per sample in permanent within-channel waterholes. Both silver tandan and spangled perch demonstrated higher average abundance per sample in all ephemeral waterholes (both within-channel and floodplain lakes), whereas desert rainbowfish demonstrated high average abundances only in ephemeral within-channel waterholes (Table 4).

Figure 2. Mean (±S.E.) number of species sampled in the Bulloo (grey bars), Kyabra (pink bars), Cooper (red bars), Thomson (orange bars), Barcoo (purple bars), Diamantina (blue bars), Georgina (green bars) and Mulligan catchments (yellow bars) in April 2007, August 2007, November 2007 and March/April 2008 **(bottom)**. Hydrographs of the Georgina River at Roxborough Downs (**top left**) and Cooper Creek at Retreat (**top right**) show major flooding in these catchments in January 2007 and January 2008 respectively, and arrows indicate the highest species richness in both catchments occurring after major flood events.

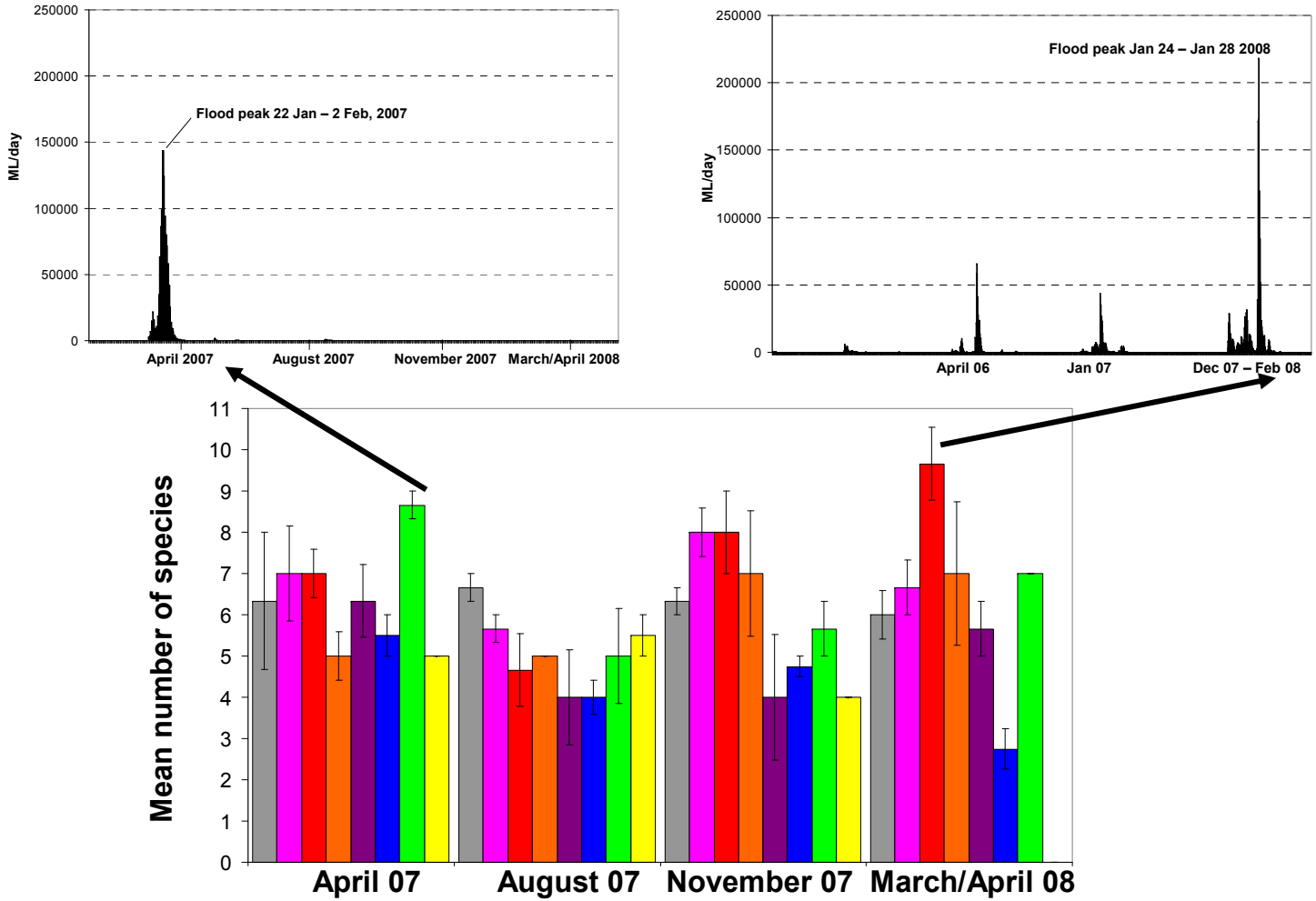


Table 4. SIMPER analysis comparing fish species presence/absence in relation to waterhole type in the Queensland Lake Eyre Basin from April 2007–March/April 2008. (Permanent within-channel waterholes = no drying within the study period, ephemeral within-channel waterholes = at least one drying event during the study period, ephemeral lakes = floodplain lakes that dried at least once during the study period).

Species	Average Abundance Per Sample			Percent Contribution to Observed Differences (>5%).	
	Permanent within-channel	*Ephemeral within-channel*	*Ephemeral lakes*	*Permanent within-channel vs. ephemeral lakes*	*Ephemeral within-channel vs. ephemeral lakes*
Bony bream	43.28	83.21	127.88	24.21	23.64
Hyrtl's tandan	34.11	-	-	10.24	7.85
Silver tandan	7.64	58.89	43.88	14.73	15.16
Desert rainbowfish	-	38.79	-	9.86	12.9
Glassfish	-	-	80.88	12.52	11.03
Yellowbelly	14.67	18.74	10.63	11.45	9.79
Spangled perch	11.05	37.47	25.94	7.71	9.68

3.2. Discussion

The catchments considered during the current study were found to support an expected diversity of native Australian fish species (15 riverine species and three spring species) and small populations of introduced species (two alien and one translocated species). On this basis alone, the river systems of the Queensland Lake Eyre Basin are in good ecological condition when compared with the Murray-Darling—a similar-sized Australian temperate to semi-arid zone system—where flow regulation and habitat degradation have depressed species richness and facilitated the spread of non-native species [11,38,39]. The spatial distribution of fish species was related to catchment boundaries, suggesting, as genetic studies of both invertebrates and fish have demonstrated, that species dispersal has been confined within individual catchments for an extended time period [40–42]. The role played by catchment boundaries in structuring fish assemblages within the area considered by this study is especially evident for species such as banded grunter, Cooper Creek catfish and Australian smelt, as these species were only collected within geographically separated catchments.

Variation in fish species presence/absence between catchments in the Queensland Lake Eyre Basin indicates that fish assemblages are broadly similar throughout the greater Cooper catchment and similar between the Georgina and Mulligan catchments. The endorheic Bulloo catchment also had a distinctive species composition. The most unusual result was that sites in the Diamantina catchment, rather than exhibiting similarities to the Georgina and Mulligan catchments (with which there is a periodic connection through Goyder's Lagoon in South Australia), instead were more similar to sites in the greater Cooper and Bulloo catchments. It seems likely that the hydrological history of the Diamantina and Georgina catchments may account for these differences: the Georgina flooded but the Diamantina did not. In the Georgina, banded grunter, glassfish and golden goby were common and comparatively abundant in all or most samples, whereas in the Diamantina banded grunter and glassfish were absent and golden goby noticeably rare. Indeed, these records are the first recorded for golden goby in the Diamantina catchment. Additionally, yellowbelly, though present at all sites on all sampling occasions in the Diamantina, were comparatively rare in the Georgina and absent from the Mulligan.

Results from the Georgina catchment indicate that the number of extant fish species is likely to rise at individual localities following major flooding, suggesting that connectivity drives within-catchment colonisation potential [43,44]. However, overall catchment fish species richness is not increased by flooding except in instances where an ephemeral sub-catchment (such as the Mulligan [31]) is connected to a more diverse source catchment such as the Georgina. In contrast, results from the Diamantina catchment provide evidence that prolonged dry periods are likely to result in a more depauperate fish fauna in Australian dryland systems, as this catchment did not experience major flooding during the study. This may have implications for the study of the effect of extended droughts and possible climate change on fish communities in arid areas [45,46], as it indicates that prolonged aridity is likely to reduce species diversity (and abundance) in arid-zone river systems.

The low number of species detected in winter supports the findings of previous studies [26,47] and also demonstrates that population peaks and increases in species diversity following flooding are most likely to occur during the warmer months [24,27]. Results demonstrating a preference for ephemeral habitats by certain fish species are also supported by data from this study, however it should be noted that the number of species declined dramatically in the ephemeral Mulligan catchment as it dried throughout 2007, a result not replicated in the Mulligan's parent river, the Georgina. The presence of permanent waterholes in the Georgina, and their absence in the Mulligan, accounts for this difference, and suggests that species and individuals likely to capitalise on the conditions afforded by ephemeral habitats originate from source populations in permanent refuges [31].

3.2.1. Unique Species

Lake Eyre hardyhead, *Craterocephalus eyresii*, though not recorded during the surveys of this study, was present throughout the Mulligan catchment from 2009 to 2012, suggesting that preservation of the natural flow regime and the facilitation of colonisation opportunities through major flooding underpin the seasonal distribution of this species. On-going sampling of the Diamantina and Georgina catchments following major floods is required in order to accurately map the distribution of Lake Eyre hardyhead in Queensland, as these are the first records of the species from Queensland rivers. Prior to this work Lake Eyre hardyhead was assumed to be a South Australian species [12,13], and its presence in Queensland suggests that, like many other species, it demonstrates wide-ranging migration behaviour when conditions are favourable [31]. None of the endangered species known from spring complexes in Queensland, such as red-finned blue-eye, *Scaturiginichthys vermeilipinnis*, Edgbaston goby, *Chlamydogobius squamigenus*, and Elizabeth Springs goby, *Chalmydogobius micropterus*, have been recorded in Lake Eyre Basin rivers. However, regular sampling at Edgbaston and opportunistic sampling at Elizabeth Springs confirms that all three species are still present within their limited ranges [48]. The red-finned blue-eye remains the most endangered species within the Queensland Lake Eyre Basin due to colonisation of the remaining spring populations by the alien species gambusia [35].

3.2.2. Translocated and Alien Species

The presence of one sleepy cod in the Thomson catchment is a concerning result, as this hardy species is not native to the Lake Eyre Basin and has a natural distribution encompassing the north-east coast and Gulf of Carpentaria divisions [14]. Within the last 5–10 years sleepy cod has become a

popular aquaculture species [49] and numerous range extensions have been recorded throughout Queensland [50]. It is most likely that the presence of sleepy cod in the Thomson catchment is the result of unauthorised translocation rather than natural range extension. Subsequent sampling of waterholes in the Thomson/Barcoo/Cooper has confirmed that this species is now widespread throughout the greater Cooper catchment [51,52]. Sleepy cod is a voracious predator and once established could have a serious top-down impact on the food-webs of these arid waterholes.

The absence of alien fish species from all catchments except the greater Cooper indicates that neither goldfish nor gambusia have established in the Diamantina and Georgina systems despite the existence of occasional migration pathways during periods of high flow (via Lake Eyre and Goyder's Lagoon). The absence of alien fish species from the Bulloo River is also notable, particularly as populations of goldfish, gambusia and carp, *Cyprinus carpio*, are present in the north-western Murray-Darling (to the east) and populations of goldfish and gambusia are present in the greater Cooper catchment (to the west). These results indicate that alien fish are more likely to have originated from human introductions in the Lake Eyre Basin rather than by radiation from eastern populations. Although goldfish appear to be range-limited in the Lake Eyre Basin and presently confined to the greater Cooper catchment, gambusia is more widespread, with populations also present in remote areas of South Australia [26]. Although the low numbers of alien species are encouraging, these species should nevertheless be considered potentially damaging to the aquatic ecosystems of all rivers in far western Queensland, and education programs detailing their identification and alien status should be instigated by all relevant management authorities.

4. Conclusions

Unaffected by habitat modification and flow regulation, the rivers of far western Queensland provide an example of how intermittent arid floodplain rivers function and support biodiversity. Underpinning the persistence of the fish communities in these ecosystems is the presence of suitable habitat in the form of permanent waterholes. Fish species and communities are adapted to surviving dry periods in these habitats such that they can capitalise on flooding when it occurs. The absence of artificial barriers to migration in these remote rivers means that colonisation of available aquatic habitat is possible within a catchment when connection flows occur, and this opportunistic dispersal phenomenon includes migration into remote desert systems (such as the wholly ephemeral Mulligan River). Preservation of the ecological integrity of these systems is contingent on maintaining the natural flow regime, preventing the spread of extant alien and translocated species to catchments where they do not currently occur, preventing the liberation of more non-native species, targeted control of alien species where it is practical to do so, and active management of the endangered species that occur in specific habitats such as isolated spring complexes.

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General Fisheries Permits (Numbers: PRM03315D and 89212) issued by the Queensland Department of Primary Industries and under a Griffith University Ethics Agreement (AES/09/06/AEC). Permission to sample at all sites was sought and obtained from station owners and the Queensland Department of Environment and Resource Management. The authors thank three anonymous referees and the editor for their comments on the original manuscript.

Author Contributions

Adam Kerezsy conducted the field sampling and subsequent data analysis upon which this paper is based. The main sampling effort (from 2006 to 2008) formed part of his PhD research [29], and since that time Adam has continued to work in the rivers and spring complexes of arid Queensland, as well as advocate for their preservation [18,30–32].

Angela Arthington was the principal supervisor of Adam's PhD and has provided guidance and contributions to all subsequent publications, including this paper. Angela has a long history of involvement with the river systems described in the paper [27,19] and this experience has helped in all aspects of this work.

Stephen Balcombe provided advice regarding experimental design and data analysis for the paper. Stephen also has extensive experience working in the river systems that were studied and in other arid and semi-arid Australian systems [28,39,47].

Conflicts of Interest

The authors declare no conflict of interest.

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