LONG TERM ECOLOGICAL RESEARCH ON A PILBARA RIVER SYSTEM

ANALYSIS OF LONG TERM ROBE RIVER AQUATIC MONITORING DATASET

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LONG TERM ECOLOGICAL RESEARCH ON A PILBARA RIVER SYSTEM - Analysis of Long term Robe River Aquatic Monitoring Dataset

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Cover photograph: Robe River

ABSTRACT

Arid Australia has received little research attention despite escalating resource development. The Pilbara region of Western Australia is currently undergoing significant mining activities which have implications for water resources. The Pilbara region is characterised by episodic riverflow which is maintained predominantly by monsoonal rainfall over summer. During other periods, rivers are reduced to a series of pools which are important refugia for aquatic fauna. These pools, during the seasonal dry, may be sustained by groundwater and therefore possibly groundwater dependent ecosystems (GDEs). Permanent river pools in the Robe River (Pilbara) have been sampled annually since 1991 using consistent methodology. During this 17 year period, events with long return frequencies (*e.g.* Tropical Cyclones) have significantly changed the structural characteristics of the river. Consequently, this long term ecological research (LTER) is fundamental to understanding how these systems function and the influence of these large events. LTER is a 'network of networks', a global network of research sites located in a wide array of ecosystems worldwide that can help understand environmental change across the globe. LTER's focus is on long-term, site-based research.

Analysis of the long-term data on water chemistry, channel morphology, aquatic macroinvertebrates and fish revealed seasonal hydrology to be the main driver of pool biodiversity. Permanent pools are important refugia and the deeper pools generally showed higher levels of biodiversity due to water chemistry being more stable. Shallower pools showed greater fluctuations in water temperature and dissolved oxygen often to levels unsuitable for resident fauna. At a medium scale, again hydrology is an important ecological determinant depending on whether flows linked pools to the estuary. During these periods, estuarine fish ‘vagrants’ migrate upstream and are maintained in pools after separation where they have a strong influence in community structure. Large events (*e.g.* flood events derived from large Tropical Cyclones) are considered to set the overall structure of channel form and consequently pools. During periods of stability (*i.e.* prior to large events), community structure of pool fauna can be predicted by simple measures of pool morphology. After large flow events, this predictive capacity is lost and biodiversity of pools is largely unpredictable and considered stochastic (*e.g.* the product of chance events). The return of highly structured communities is relatively long-term.

- During periods of stability, seasonal hydrology interacts with pool morphology to be the main driver of regional biodiversity.
- Flows which link pools to estuaries result in the upstream movement of estuarine fish which influence pool community structure.
- Aquatic fauna of river pools is largely supported by algal carbon and represented by a simplified community structure characterised by limited trophic structure.
- Extreme events (*e.g.* large tropical cyclone derived flows) set the overall “structure” of channel and river pools. After large flow events, the previously predictable biodiversity of pools is lost and this appears to be largely stochastic (chance events).

- Disturbances which link pools to estuaries (i.e. dewatering) or which mimic large events (e.g. cyclones) will have a significant influence of pool biodiversity and ultimately the entire river system.

- Remote mapping of pools will require precision of <1km^2. The resolution of Landsat therefore may not be suitable and other techniques (*e.g*. Quick bird) may be required.

Implications for Management

River pools are important refugia for aquatic fauna and a focus for terrestrial species.

Large natural flow events are the major geomorphic structuring process of these pools.

The spatial distribution of permanent pools is geographically-restricted and structurally maintained by larger woody vegetation.

The freshwater fauna and ecological processes are resilient to disturbance, however recovery is slow.

Livestock access to pools results in nutrient enrichment and pool degradation and is a major source of pool degradation.

During the “dry”, river pools may be maintained by aquifer discharge and are possibly groundwater dependent ecosystems (GDEs) and consequently vulnerable to artificial drawdown.

Increasing the period of “no flow” will inhibit the migration of species among pools. This connectivity is important to allow species to re-invade the river system during the “wet”.

Pool dissolved oxygen levels are an important parameter particularly for fish. Decreased pool volumes which are a consequence of aggradation, may increase the incidence of anoxia and fish kills.

Mine de-watering will link pools downstream; this is not considered detrimental to freshwater biodiversity. However, permanent flows may increase the incidence of introduced flora (*e.g*. Indian fern).

Some sensitive macroinvertebrate species (*e.g.* taxa of the Pyralidae) are associated with macrophytes; consequently there is a need to maintain these plants around the fringes of pools.

Many new groups of stygofauna are associated with groundwater in the Pilbara. This group, clearly groundwater dependent, was not sampled during this study. However, groundwater abstraction could impact on the local distribution of species.

Contents

1. INTRODUCTION

1.1. BACKGROUND

The Robe River Valley is situated in the Pilbara biogeographic region of Western Australia. During the dry season, the river is restricted to a series of permanent pools that provide important refugia for both terrestrial and aquatic fauna. There is the potential for an increase in pressure on groundwater resources in the Pilbara to meet human, industrial and other water demands whilst to impact on the ecology of these important ecosystems. Following the Department of Water's Pilbara Regional Plan and Pilbara Coast Water Study, several aquifers were selected for further investigation and assessment. It was identified that long-term ecological data was lacking, and this knowledge gap is an important limitation in allowing informed assessments of ecological objectives to be incorporated into these policies and plans.

The Centre of Excellence in Natural Resource Management (CENRM) retains a significant long-term dataset on the aquatic ecosystem of the Robe River, located within the Pilbara region of Western Australia. This dataset derives from a riverine monitoring program undertaken by Streamtec Pty Ltd and commissioned by the Robe River Mining Company Pty Ltd (Robe) as part of an on-going commitment to asses and monitor any environmental impacts of mine development.

This Long Term Ecological Research (LTER) provides a rare database on an arid system within the Pilbara region facilitating improved understanding of the natural variability within the Robe River catchment in the context of climate shift and other parameters. The value of this program is in its long-term commitment where sampling design and methodology have remained constant across annual surveys providing both temporal and spatial variability. It was recognized that this data set held by CENRM represents a unique asset that would potentially assist in the process to establish ecological water requirements for aquatic ecosystems in the Pilbara. The WA Department of Water (DoW) therefore commissioned the Centre for Excellence in Natural Resource Management to prepare, analyse and interpret this information.

Through targeted analysis of the Robe River data set (and in combination with Department of Water, hydrological data sets for the same period) this project will address the following questions/topics;

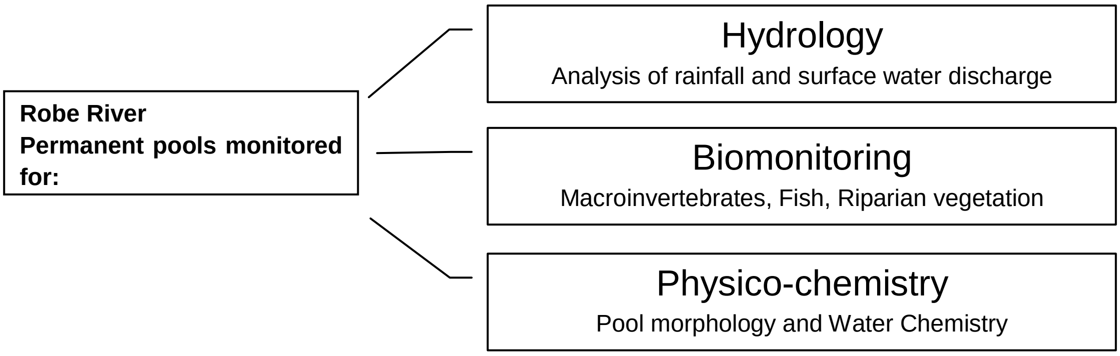
1. *Examine the relative importance of permanent pools in terms of population dynamics - if permanent pools are important as refugia is it possible to determine/estimate how important pools are in maintaining overall populations and what are the likely potential impacts of loss of permanent pools.*
2. *Examine 'long' term data sets to identify which components of the ecosystems are more sensitive / vulnerable than others e.g. macroinvertebrates and fish.*
3. *Use time series of monitoring of aquatic ecosystems to try to identify ecosystem response to declining water level / groundwater input. That is describe ecosystem response functions or characterize thresholds at which different species 'drop out' and also thresholds at which repopulation occurs. This should be combined with analysis of the hydrological data held by the Department of Water to identify periods of low and or no flow and flood / high flow periods.*
4. *The proposed characterization of permanency of pools by the Department of Water using analysis of satellite imagery and hydrological records is also considered an important potential input into these analyses.*

2. METHODOLOGY

Impacts on a river system can influence both its physical and chemical characteristics and potentially alter the habitat and environment of its flora and fauna. Assessments of the Robe River have therefore involved an integrated survey of physical characteristics of the river and surrounds; available habitats and their condition; water quality and biological characteristics (see summary below).

Since the commencement of this sampling program in 1991, sampling design and methodology have been standardised across surveys in order to make valid comparisons between monitoring periods. The strength of this sampling program lies is the long term nature of the surveys where the methodologies have not changed. A summary and general description of the standard sampling protocol is given below. Detailed information on sampling from Appendix 1.

Summary of Long-Term Monitoring Program (LTER)



2.1. SITES ON THE ROBE RIVER

Initial field investigations targeted ecologically significant pools which were representative of the major habitat types available. Once the permanency of pools had been established, surveys concentrated on eight focal pools to document and interpret changes in patterns of species richness, abundance and distribution of aquatic fauna. The database analysed in this report will therefore concentrate on eight focal pools that were identified in initial surveys in the Robe River; Medawandy Waters, Pannawonica Hill, Ngalooin, Yarramudda, Japanese Pool, Mussel Pool, Martangkuna and Gnieraoora. The location of the study sites is shown in Figure 1.

Sampling was initially conducted late in the dry season ('winter'), prior to summer rainfall; a time of considerable environmental 'stress' for aquatic fauna. Monitoring has also been conducted following the 'wet' season and high rainfall events, providing a database covering a wide range of conditions.

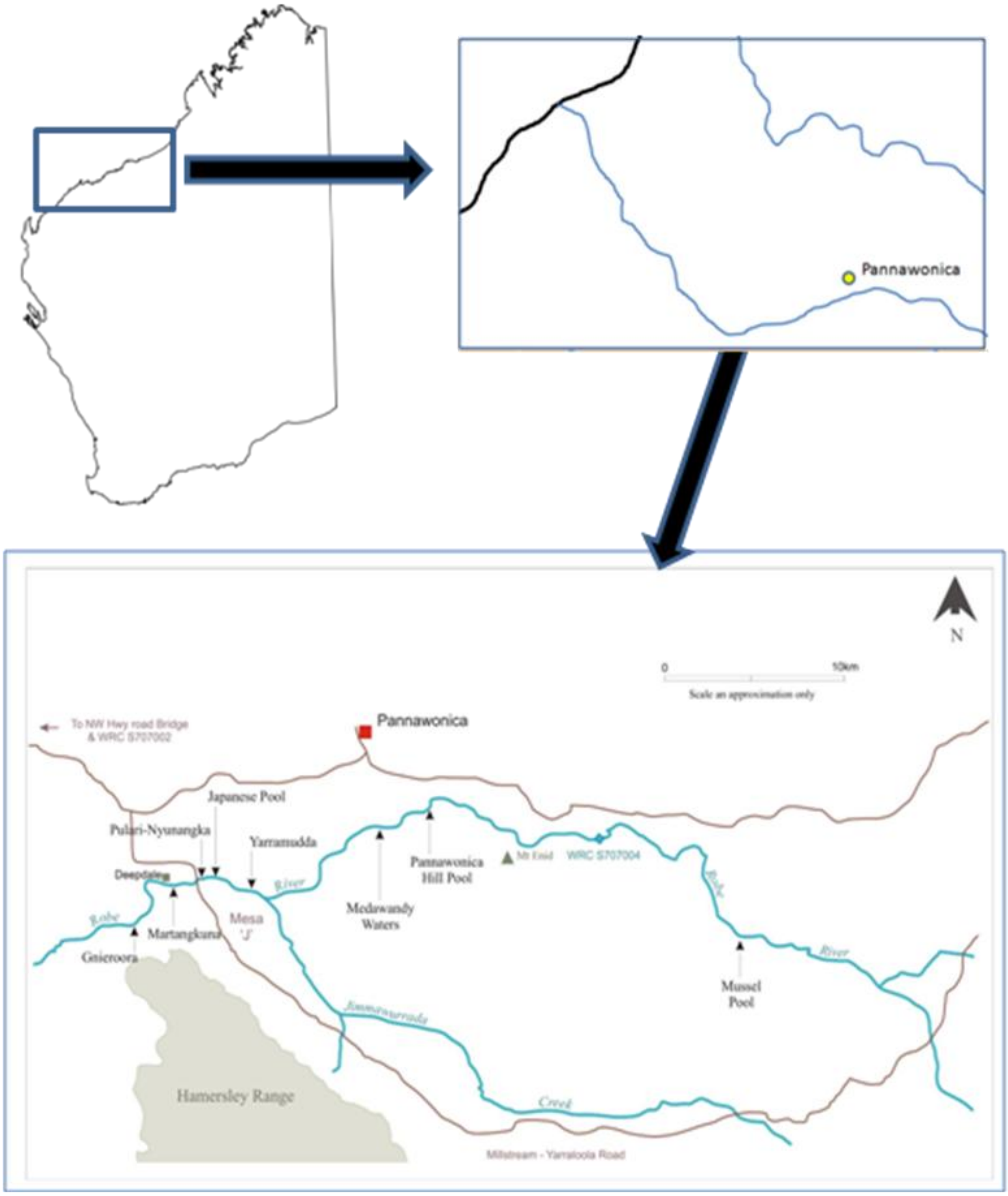


Figure 1 Location of survey sites on the Robe River (Pilbara region WA)

2.2. HYDROLOGY - RAINFALL AND RIVER DISCHARGE

Long-term rainfall data for Pannawonica (rainfall station 005069; 21°38'21"S, 116°20'51"E) was provided by Climate Services, Bureau of Meteorology (Perth). Yarraloola (S707002) is situated approximately 60 km downstream of our study sites (Mesa 'J'). Flow records for the Robe River were provided by the Water Information Branch, Department of Water (DoW). Patterns in rainfall and river discharge were analysed to review the hydrology of the Robe River and to determine the relationship between climate and changes in pool morphology and biology.

2.3. PHYSICO-CHEMISTRY, MORPHOLOGY AND WATER QUALITY

Measurements of pool morphology and selected water quality parameters were made in conjunction with the aquatic fauna sampling at each pool. Temperature, dissolved oxygen, salinity and pH were measured *in situ* using a YEO-KAL (YK-611) water quality analyser. Vertical profiles were recorded to determine the extent of any stratification. Water samples were taken for analysis of both total nitrogen and total phosphorus. Nutrient analyses were conducted by the Natural Resources Chemistry Laboratory, Chemistry Centre, Western Australia.

River pool morphology was determined with depth measurements (graduated pole) and pool width and length measurements (range finder). Levels of fine inorganic sediment and areas of deeper water in each pool were qualitatively assessed and coded by rank.

In addition to the biological monitoring program, a quarterly monitoring program was also set up with the Robe River Mining Company Pty Ltd (Robe). Measurements were focussed on five of the eight focal pools (Medawandy, Yarramudda, Martangkuna, Japanese and Gnieraoora) and measurements include nutrient status, salinity/conductivity, dissolved oxygen, temperature, pH, turbidity, heavy metals, and total petroleum hydrocarbons (TPH). Efforts were made to monitor the stage heights of pools, although high flood events removed both gauges and trees utilised to assess depth.

2.4. MACROINVERTEBRATE FAUNA

Macroinvertebrate communities were sampled using consistent methodology for the duration of the long term sampling. Methodologies for collecting fauna were designed to sample the major aquatic habitats and maximise the number of species recorded at each site. Qualitative sampling was conducted using a 'heel-kick' (*sensu* Davies, 1998) or sweep method (depending on habitat), compatible with the methodology of NRHP/MRHI protocols. All sweep samples, containing sediment, detritus and macroinvertebrate fauna, were preserved on site.

In the laboratory, macroinvertebrates were removed and identified to the lowest taxon possible either by use of keys or by matching specimens to an existing voucher collection. An estimate of relative abundance for each species was made using broad ($\log_{10}$) categories; 1 (1 individual), 2 (2-10 individuals), 3 (11-100 individuals), 4 (101-1000 individuals).

2.5. FISH FAUNA

Fish were sampled by a combination of methods including 250µm dip nets (in areas of sedge beds, bank undercuts and under logs), seine nets across the channel, or by direct observation. The same methods were consistently used for the duration of the sampling. A list of presence/absence for each species was constructed for each of the six pools. Details of field methods are provided in Appendix 1. Fish were identified to species level based on taxonomy of Allen (1989) and Allen *et al.* (2002). All fish caught were measured and returned live to the water.

2.6. RIPARIAN VEGETATION AND WEEDS

Rapid assessments of local riparian vegetation condition were made on the basis of dominant plant species and relative degree of disturbance such as weed invasion, livestock access and fire etc. Assessments were broadly based on the rapid assessment methodology of Pen and Scott (1995) and WRC (1999). Opportunistic, qualitative surveys were also made of the noxious weed Indian Water Fern, *Ceratopteris thalictroides.*

2.7. STATISTICAL ANALYSES

Statistical analyses using ANOVA (analysis of variance) were used to compare spatial and temporal variations in water quality and fauna data.

PRIMER (Plymouth Routines in Multivariate Ecological Research) computer package was used to identify multivariate spatial and temporal patterns in macroinvertebrate community structure and relate these patterns to changes in measured environmental parameters (*e.g.* water chemistry). Analyses were conducted on species-level presence/ absence data. For valid comparison, all fauna were recorded at the same taxonomic level. The relationship between community structure and physico-chemical conditions of the pools was analysed using a sub-set of the physico-chemical parameters measured.

In summary, similarity matrices (between pools) were calculated based on macroinvertebrate assemblages. These similarity values were then represented graphically using hierarchical clustering (CLUSTER) and multidimensional scaling (MDS) to determine how similar pools were to each other. Principal components analysis (PCA) was used to summarise patterns in environmental data. Further details on analyses are given in Appendix 1.

Hydrological analysis of flow data was undertaken utilising the River Analysis Package (RAP) to determine links between ecological patterns and flow patterns in the period prior to survey dates (CRC, 2005). The Time Series Analysis module (TSA) on daily flow was used to calculate the flow characteristics between sampling events.

3. RESULTS AND DISCUSSION

3.1. STUDY SITES

The Robe River Valley is situated in the Pilbara biogeographic region of Western Australia. For the majority of its course, the Robe River is ephemeral in flow with a wide, shallow flood plain. During the dry season, water is often restricted to a series of permanent pools that provide important refugia for both terrestrial and aquatic fauna. Sub-surface flow maintains these permanent pools during dry periods (Bowman *et al*. 1991) and the fauna contract to these pools, to re-invade other regions of the riverine system during increased river flow.

The Robe River flows past the study sites as a third-order river (based on a 1:250 000 map) with local inputs from first-order creeks such as Jimmawurrada (Figure 1). Pressures on the catchment include tourism, camping, grazing and mining. These systems are typically less disturbed than their counterparts in more populous regions, yet despite recognition of the importance of water-bodies in the Pilbara; there has been only ad hoc ecological research. Research of the aquatic fauna of Australia's dryland river systems has been infrequent and sporadic in the past. Fish have received the greatest attention with descriptions of species distributions (Allen, 1889; Allen *et al* 2002 and Morgan and Gill, 2004). Aquatic surveys have been limited although more recently the Pilbara Biological Survey by the Department of Environment and Conservation (DEC) have conducted an aquatic survey over a four year period (2003-2007), as part of an assessment of biogeographic patterns (patterns in the distribution of biodiversity) in the Pilbara. Details of the hydrology of the Robe River/Jimmawurrada Creek system and of past flood studies can be found in Bowman *et al*. (1991), AGC (1989) and Halpern *et al*. (1993). This survey provides one of the first long term assessment of a Pilbara river system.

3.2. HYDROLOGY - RAINFALL AND RIVER DISCHARGE

3.2.1. Rainfall and Flow

The Pilbara biogeographical region is characterised by low annual rainfall (annual average 400mm) and, when coupled with high annual evapo-transpiration rates (e.g. typically about 12x annual rainfall), results in highly restricted aquatic ecosystems. Pannawonica receives the majority of its rainfall over summer in association with cyclone events. Peaks in rainfall typically occur during January to March with months of lowest rainfall occurring in September and October (Figure 2).

Rainfall is highly episodic as well as highly variable and rainfall across years can be highly unpredictable with significant variation in annual rainfall (Figure 3). The coefficient of variation (CV) for the Pilbara ranges from 0.4 to 0.7 in comparison with a CV for south-west Western Australia of 0.2 and for the Kimberley of 0.3 (DOE, 2004).

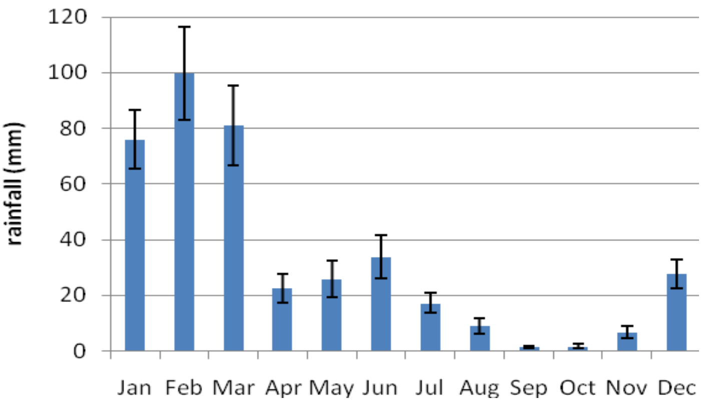


Figure 2 Average monthly rainfall (+ SE) data for Pannawonica (Stn 5069; 1972-2007).

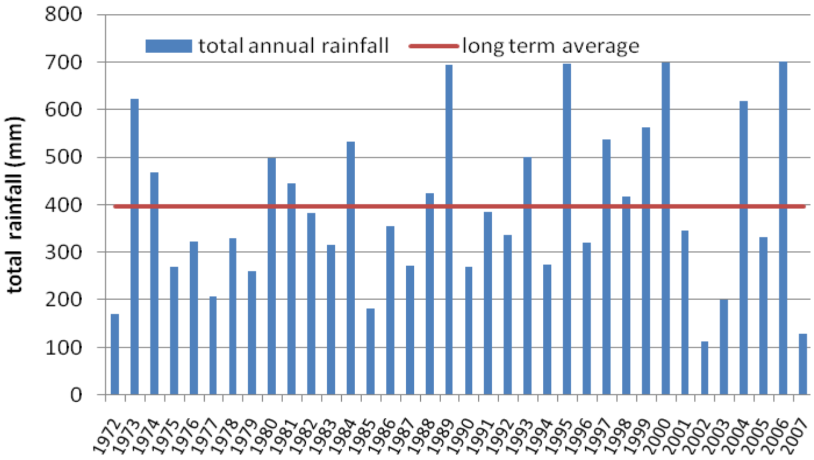


Figure 3 Average yearly rainfall (+ SE) data for Pannawonica (Stn 5069; 1972-2007).

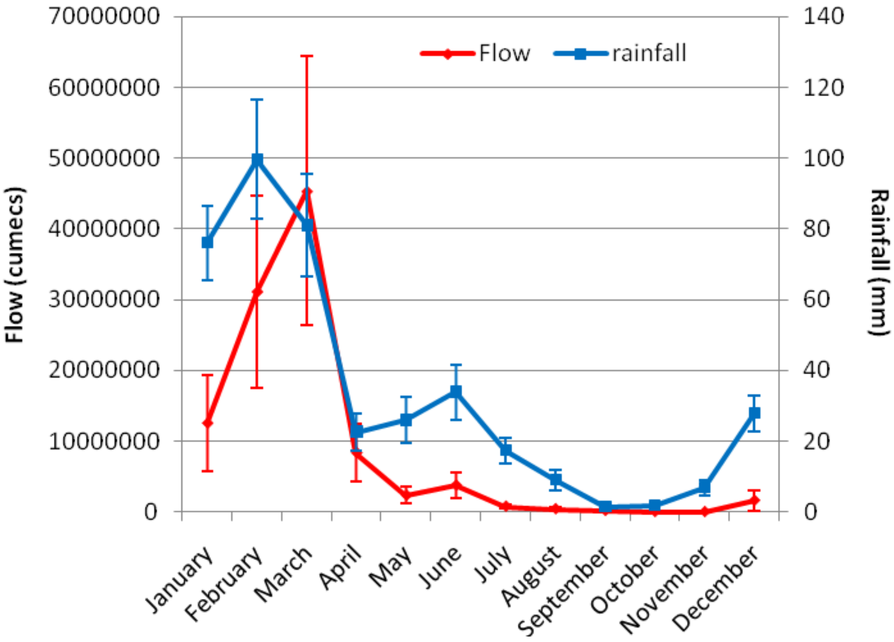


Figure 4 Average monthly flow and rainfall (+ SE) Yarraloola (Stn 707002) and Pannawonica (Stn 5069).

River discharge patterns are tightly coupled to the seasonality of rainfall events (Figure 4). Following trends in rainfall data, maximum flows are typically recorded between January and April and low or no flow from September to December. For the purpose of analysis, these two seasons will be referred to as the “wet” and “dry” respectively. This report also identifies two transitional seasons, the “ramp down” period where rainfall and hence flow declines following the wet and the “the ramp up” period in December when there is an increase in rainfall and flow following the dry season (Figure 4).

Heavy rainfall events in summer are generally associated with tropical cyclones or monsoons. The highest category cyclones that have impacted the Pilbara coastline are listed by the Bureau of Meteorology and include Orson April 1989, John Dec 1999 Monty March 2004, Clare Jan 2006, and Glenda March 2006. These cyclones all coincide with peaks in discharge in the Robe River (Figure 6). A number of flow events have also been recorded in years following above average rainfall in consecutive months (i.e. January 1997). The large Robe River floods of February 1993 and January 2000 were also associated with monsoon lows below cyclone intensity. Flooding is enhanced if the low follows rainfall that has already saturated the ground and elevated river levels. This data suggests that significant flow events in the Robe River pools are either pulse events that occur through peaks in monthly rainfall or when the duration of rainfall is sufficient to maintain high surface water levels in the river.

Stream flow data was used to predict the likely magnitude of events of a given return period (Figure 5a). Despite large flood events, periods of low flow or even zero flow are common. Flow duration curves based on long term gauging data (1972 - 2007) show that high flows are present for short periods and zero flows are exceeded less than 25% of the time (Figure 5b).

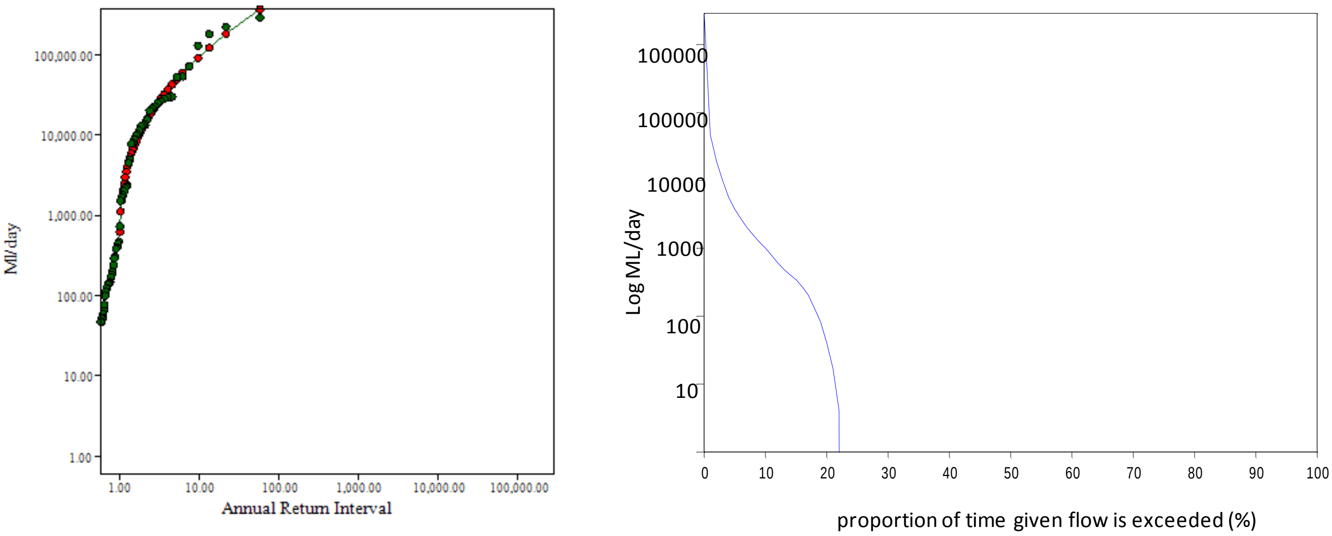


Figure 5 (a) Peak discharge annual return interval and (b) flow duration curve (Yarraloola Stn 707002).

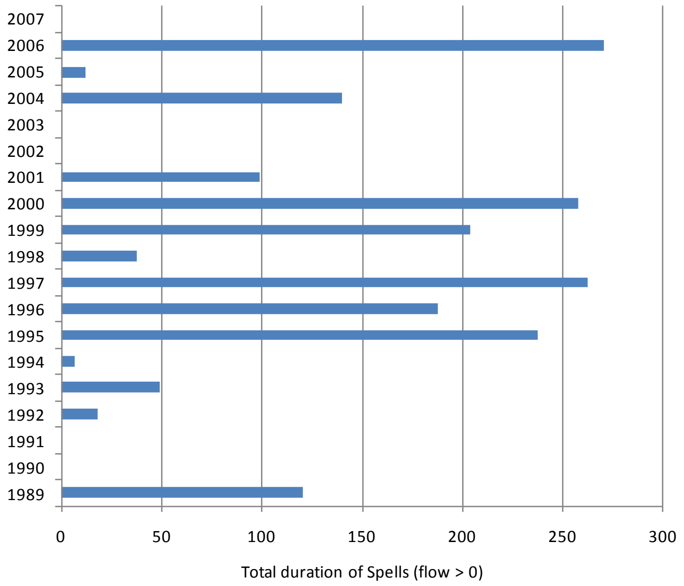


Figure 6 Spell Analysis showing days when flow was present in the Robe River (Yarraloola Station)

A daily spell analysis was performed for flow events in the Robe River (i.e. for any flow above 0) and shows that the Robe River is characterized by a highly variable and unpredictable flow regime across years (Figure 6). Beesley (2006) analysed flow records for the nearby Fortescue River according to Puckeridge *et al.* (1998) methodology and found that the river exhibited greater flow variability than other highly variable rivers in Australia, including Coopers Creek and the Diamantina.

3.2.2. Rainfall, Hydrology and Sampling Periods

Since the establishment of monitoring in 1991 a range of rainfall and flow conditions have been experienced in the Robe River. The timing of Robe River aquatic sampling events in relation to rainfall and major flow events are highlighted in Figure 7. Initial surveys in 1991 were conducted following a series of low flow years. In February 1993 extensive rainfall resulted in a flow event which at the time was the highest recorded peak discharge on record. In subsequent years, relatively high water levels were maintained in pools by a number of high rainfall events. Then, from January 2001, three consecutive years of lower than average rainfall (January 2001 to May 2003) resulted in significantly lower total annual stream flows being recorded at Yarraloola. A return to more typical (anecdotal evidence) summer river conditions was therefore seen between April 2001 and February 2004 with the Robe River ceasing to flow for an extended period at Yarraloola (Figure 7).

In March 2004, rainfall from Tropical Cyclone (TC) Monty resulted in significant total monthly flows in the Robe River. The Yarraloola gauging station recorded the highest monthly discharge since 1972 (596611 ML), and annual flows for 2004 were also the highest on record. Significant rainfall events from tropical cyclones (Glenda and Clare) during 'summer' 2006 resulted in significant total monthly flows being recorded. Three consecutive months of higher than average rainfall resulted in high levels of discharge being maintained during January to March 2006.

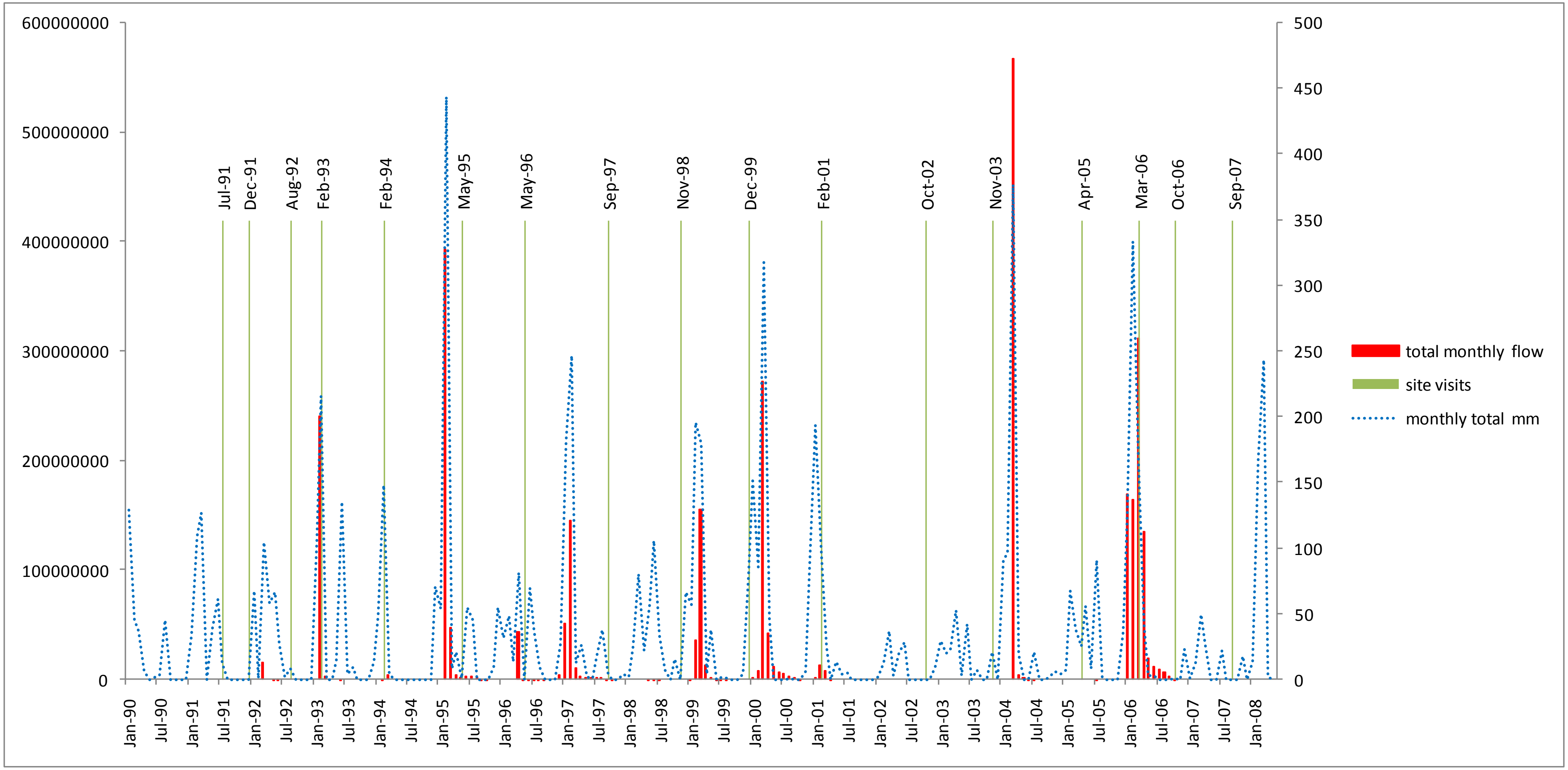


Figure 7 Total monthly river flow (ML discharge) at Yarraloola (Stn 707002), January 1995 – October 2007, and total monthly rainfall at Pannawonica (Stn 5069) (Jan. 1995-October 2007) demonstrating major flow events. (NB flow data only available to October 2007).

Following the October 2006 survey, monthly rainfall was below average and in 2007 'no flow' was recorded at Yarraloola. Although flow data was not available for 2008, the recorded higher than average rainfall suggests that flow events would have been recorded.

3.2.3. Hydrological Analysis of Robe River Catchment

Ecological processes in large rivers are considered to be controlled by their flow variability (Puckeridge *et al*, 1998). The antecedent flow regime for each sampling event was therefore summarised (using RAP) in order to determine the major flow characteristics that may influence pool ecology. Principal components analysis (PCA) was then conducted using these variables (listed in Appendix 2) to reveal the similarities and differences between sampling events (Figure 8).

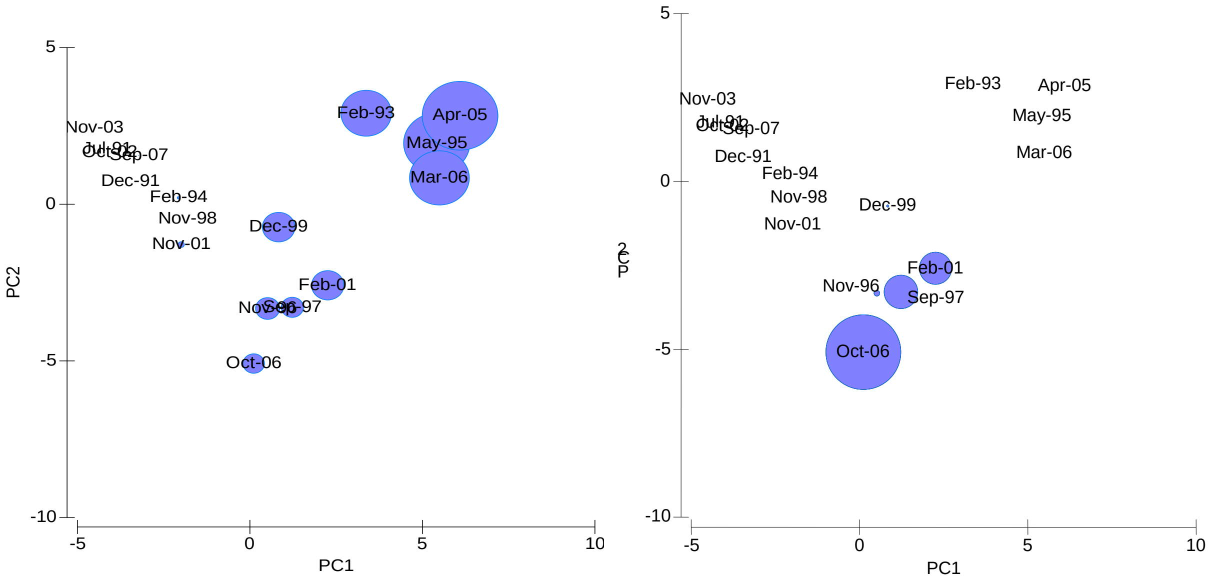


Figure 8 PCA ordination of hydrological data with values of parameters superimposed as bubble plots (a) max flow (b) median flow.

The first two axes (PC1 and PC2) of this PCA ordination accounted for 43.9%, and 19.9%, of the variability in the data matrix respectively, and thus together, these two components explained 63.8% of the variation between sampling periods (providing a reasonable summary of the sample relationships). Broadly, variation represented on the x axis (PC1) shows differences in sites due to the magnitude and rate of rises and falls in the hydrograph (mean magnitude, mean rate, greatest rate) and maximum and total flows for the period prior to sampling events. The number of zero flows, number of rises, duration of rises and minimum flow is represented on the PC2 axis.

In the PCA, sites were plotted together to form three distinct groups, and this differentiation was largely supported by a cluster analysis (Figure 9). The dendrogram separated years into four groups based on their similarity in flow characteristics. Group one includes March 2006, February 1993, May 1995, April 2005; Group 2 October 2006; Group 3 September 2007, November 2001, February 1994, November 1998, December 2001, November 2003, July 1991, and October 2002; Group 4 November 1996, September 1997, December 1999 and February 2001.

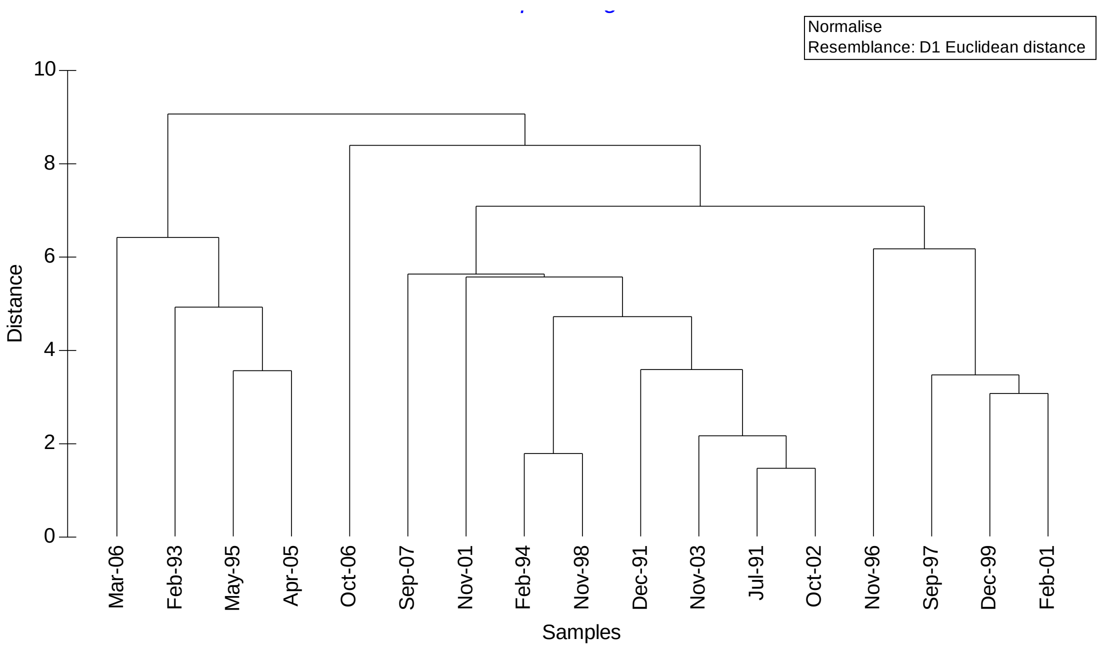


Figure 9 Dendrogram of hydrological data (produced from RAP) showing four main groups.

3.3. PHYSICO-CHEMISTRY, POOL MORPHOLOGY AND VEGETATION

Long-term analysis of quarterly water quality monitoring has shown that water chemistry of pools have shown predictable values/changes associated with the sampling season. Pool water quality in the Robe is typically fresh (<1,200 µS/cm ECond), slightly alkaline, with low levels of turbidity (<8 NTU). Rainfall and river flows have been identified as having the greatest influence on pool morphology and water chemistry (Streamtec 2001-2007).

A further description of individual pool characteristics and water quality parameters and their implications for aquatic fauna is given below.

3.3.1. General Pool Characteristics and Morphology

During dry season sampling the Robe River is reduced to a series of shallow pools. Given the high evaporation rates (e.g. 3-4m p/a), these pools have to be considered groundwater dependent ecosystems (GDEs). Water levels in the eight permanent pools have reflected rainfall, surface stream flow and groundwater recharge *i.e.* lowering slightly over the winter dry season and rising again following summer rainfall events.

The highly ephemeral nature of both rainfall and subsequent river flows emphasises the importance of the permanent pools as refuges for the maintenance of aquatic fauna in the Robe River and importantly adjacent pools outside the main Robe Valley would be connected to the main channel only during high flow events. A brief description of each of the pools is provided below in order of increasing size (Plate 1 – 8).

Plate 1 Pannawonica Hill Pool Clockwise from left Sep 2007, Oct 2002, Feb 1994, the shallowest survey pool situated below Pannawonica Hill. Pool maintained by groundwater, dry in some years. This pool has a low complexity of habitat and reduced shading in low flow years in comparison to high flow years.

Plate 2 Ngalooin Pool Oct 2002 and downstream from pool September 2007 (left to right). Pool situated furthest upstream.

Plate 3 Pulari– Nyunangka October 2002, Nov 2003 (left to right) shallow pool with areas of deep water surrounding roots of riparian vegetation, has been dry in some years.

Plate 4 Japanese Pool Feb 2001 Apr 2005 looking upstream (left to right). Riparian vegetation removed and pool morphology changed significantly following Tropical Cyclone Monty.

Plate 5 Medawandy Pool May 1995 and September 2007 (left to right). Deep pool with dense riparian vegetation.

Plate 6 Martangkuna November 1998 and Apr 2005 (left to right). Deep pool with dense riparian vegetation, flood damage of riparian vegetation following Tropical Cyclone Monty.

Plate 7 Gnieraoora September 1997 and September 2008 (left to right) most downstream site adjacent to Yeera Bluff. Vegetation on right bank removed following cyclone Monty 2004.

Plate 8 Yarramudda Nov 1996, Nov 2001. Large pool lies adjacent to the confluence of the Robe River and Jimmawurrada Creek.

Survey pools were chosen based on their permanency. Pool volumes were estimated for each sampling event and average dry season volume highlights the variation in the size of the eight focal pools: smaller and shallower pools (Pannawonica Hill, Ngalooin and Pulari – Nyunangka); medium pools (Japanese, Medawandy, Martangkuna and Gnieraoora); and the large pool (Yarramudda) (Figure 10).

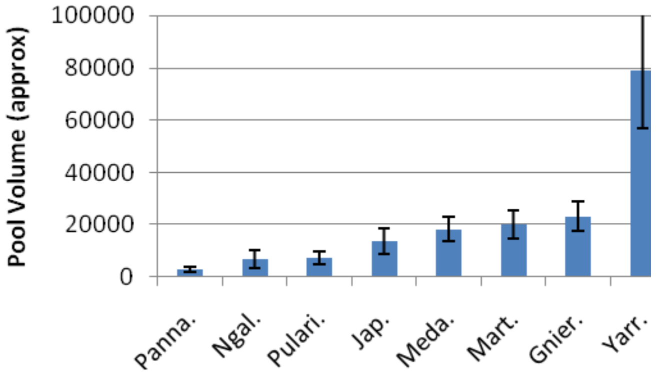


Figure 10 Average dry season volume (+ SE) of the eight focal pools.

Changes in pool morphology and sedimentation have been monitored and have been affected significantly by Tropical Cyclones and peak flow events. Substantial deposits of gravel, from high flow events during 2004 (TC *Monty*) and 2006, resulted in infilling of some pool habitats. These changes were initially evident in 2007, with Japanese Pool, Pannawonica Hill and Pulari – Nyunangka showing significant reductions in pool depth and size. In 2008 changes to pool morphology from peak flows were still evident with the most significant change at Japanese Pool, where riparian vegetation has been removed and the deeper sections observed prior to and during these floods having disappeared (max depth 0.3m).

3.3.1. Riparian Vegetation and Weeds

The Robe River / Jimmawurrada Creek riverine habitat is dominated by moderately-dense to dense mixed woodlands of Cajeput *Melaleuca argentea*, River Gum *Eucalyptus camaldulensis* and *Eucalyptus victrix*. The open understorey of tall shrubs is dominated by *Petalostylis labicheoides*, with scattered *Sesbania formosa* and *Gossypium robinsonii* over sedges and mixed herbs. Filamentous green algae are common in the waterways, together with emergent macrophytes, such as *Potamogeton* and *Vallisneria* species, and fringing rushes, such as *Eleocharis* sp. Further from the water's edge, the narrow zone of riparian vegetation gives way to low plains of Soft *Spinifex Triodia epactia* (= *T. pungens*) steppe with scattered gums *Eucalyptus leucophloia* (Snappy Gum) and *E. ferritcola* over-mixed Acacia species, *Hakea chordophylla* and *Grevillea pyramidalis* (Beard, 1975).

Major disturbances to pool vegetation have resulted from variation in the pattern and volume of rainfall. The force of floodwaters can uproot young plants and other plants may die from being submerged for extended periods. Qualitative assessments of riparian vegetation have shown significant physical uprooting evident in both riparian and floodplain vegetation. These changes were a direct result of the high flows and widespread flooding associated with high flow events, particularly Tropical Cyclone *Monty* in early March 2004. In the Robe River, the distribution and abundance of the weed, Indian Water Fern (*Ceratopteris thalictroides*), is considered related to both patterns of river flow and unrestricted livestock access to drainage channels (Streamtec, 2008).

In initial reports (ecologia & Streamtec, 1992), pools within the Robe River were considered dependant on the high rates of algal primary production to drive ecological processes. High algal growth is often observed in the monitored pools and it is likely that this is a major contributor to secondary water quality issues as the vegetation decays i.e. highest levels of nutrients have been recorded in pools with increased algal growth and increased turbidity levels (Plate 9).

Plate 9 Filamentous algal growth typical of pools surveyed and Indian water fern (left to right).

3.3.2. Turbidity

Natural turbidity and sedimentation are dependent on the hydrology and geomorphology of a site. Previous surveys of Robe pools have shown consistently low levels of turbidity in the dry 'season'. In the Robe River, quarterly monitoring shows that natural turbidity has the potential to be greatly elevated following pulse rainfall events (Figure 11). One-off samples of elevated turbidity (e.g. >70 NTU) have been recorded immediately following flood events (*e.g*. February 2001 and March 2006).

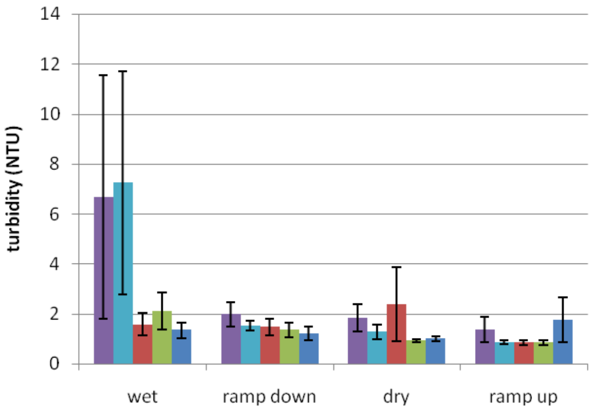


Figure 11 Results of Robe River Iron quarterly monitoring turbidity (NTU values mean + standard error).

3.3.3. Salinity

The low salinity of water in the north-west of Western Australia has been attributed to long-term geochemical processes (Williams & Buckney, 1976). A salinity gradient from upstream to downstream has been evident across years, with salinities increasing along the length of the river. This could be due to increased reliance of groundwater in pools in the upstream sites. Despite this gradient, salinity levels within all pools are categorized as fresh[1]. Long term quarterly monitoring indicates that although a slight increase in salinity is evident in the dry and ramp up seasons, there is no significant seasonal difference in conductivity/ salinity within sampled pools (Figure 12). The lack of seasonality in salinity levels is probably due to the continual input of low salinity water from the aquifer. This would help to buffer and reduce the concentration effects in the surface water of the pools caused by evaporation.

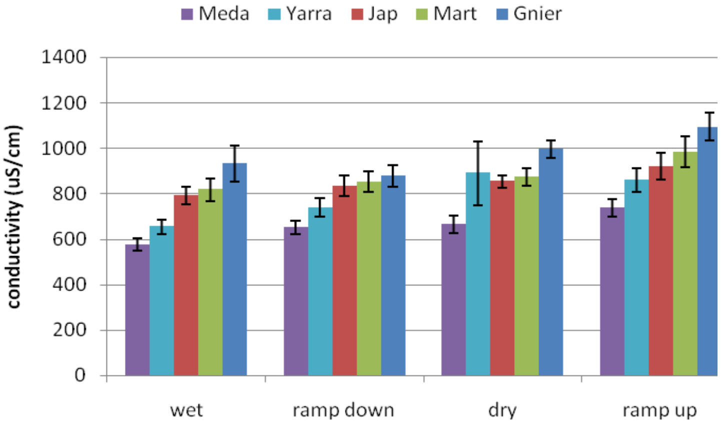


Figure 12 Robe quarterly monitoring conductivity (mean + standard error).

3.3.4. Dissolved Oxygen and Productivity

Within natural water bodies, spot measurements of dissolved oxygen are insufficient to show the magnitude of deil changes. In 1996, 1998 and 1999 data loggers were placed in the Robe pools to

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[1] Fresh defined as <2,700 µS/cm; brackish/moderately saline 2,700 – 9,000 µS/cm; saline 9,000 – 55,000 µS/cm. Dept. Agriculture, Government of Western Australia, 2002.

measure the magnitude of deil changes. Sufficient dissolved oxygen over 24h is a fundamental requirement of aquatic fauna Dissolved oxygen levels of 60 – 125% (*i.e.* typically >4 mg/L) are generally considered adequate for aquatic fauna. DO levels less than 2.0 mg/L are considered the critical threshold at which respiration becomes difficult for many fish (ANZECC/ARMCANZ 2000).

Dissolved oxygen in the survey pools has previously shown significant spatial and temporal variation. Spot measurements of DO, coupled with information from data-loggers have revealed concentrations ranging from overnight lows close to zero percent to supersaturated levels at midday (Figure 13). Smaller shallower pools showed the greatest variation in dissolved oxygen. In the shallowest focal pools (Pulari – Nyunangka and Pannawonica Hill) night time concentrations attained low levels (2-3mg/L) to the extent where they could be considered deleterious to aquatic fauna (Figure 13).

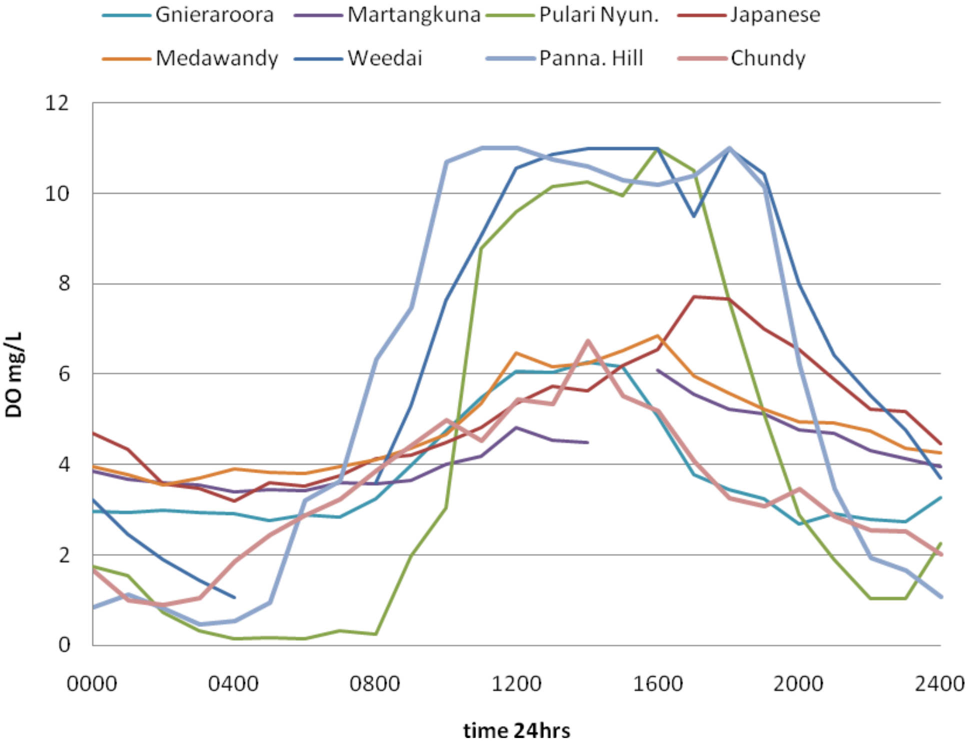

Figure 13 Deil changes in dissolved oxygen in pools during the 1996 sampling survey.

In rivers where rates of metabolism are high (*e.g.* where high microbial, algal or plant growth occurs), anoxic conditions (0% DO saturation) can prevail as a result of the high rates of respiration. Pools in the Robe River are characterised by substantial algal growth during the dry season and these lower levels reflect night-time respiration of the large plant biomass. Beesley (1996) showed that the smaller shallow pools underwent greater daily fluctuations in water temperature than large, deep pools i.e. would be more influenced by ambient temperature, higher in the afternoon but cooler in the morning. This reflects trends that the biggest dissolved oxygen changes occur in slow moving high productivity streams and low DO levels are a natural characteristic of water-bodies when both water temperatures and algal production are high.

3.3.5. Temperature and pH

Long term monitoring highlights the correlation between pool temperatures and ambient air temperatures (Figure 14). Values of ph range from slightly alkaline at around 7.45 to 8.26 which is typical of inland waters of the Pilbara (Masini, 1988).

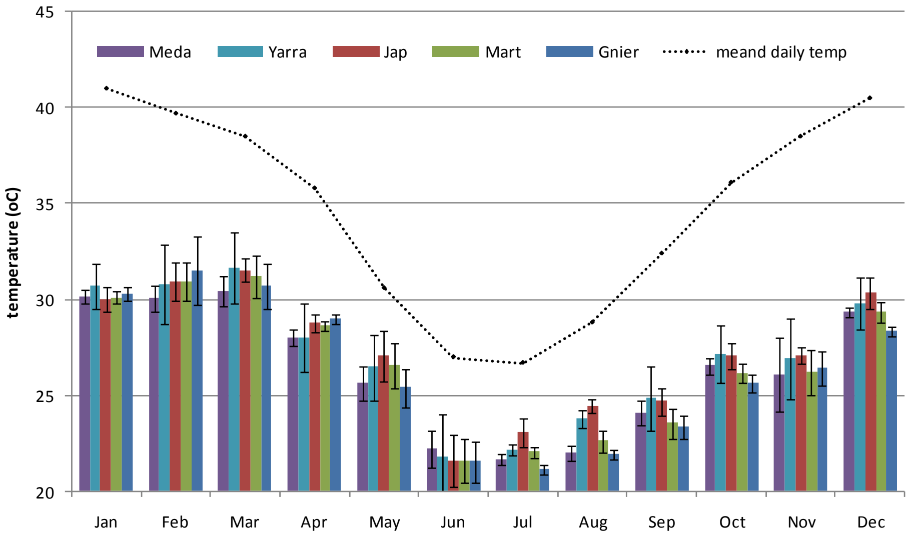

Figure 14 Robe monthly monitoring (average ± standard error) temperature.

3.3.6. Nutrients

During long term monitoring of the Robe River, nutrient levels have often exceeded guideline levels (ARMCANZ/ANZECC 2000). Nutrient enriched water bodies are typically characterised by high algal growth and higher nutrient levels have been recorded in the wet season associated with increased runoff (Figure 15). Elevated nitrogen and phosphorous levels recorded in pools are possibly the consequence of livestock access. It should be noted that guideline limits were developed primarily for water bodies other than those in the arid and semi-arid tropics of the Pilbara. The acceptable or 'normal' range of nutrients common to water bodies of this region remains poorly understood and long term monitoring of the Robe River suggests that the guidelines should be applied with caution.

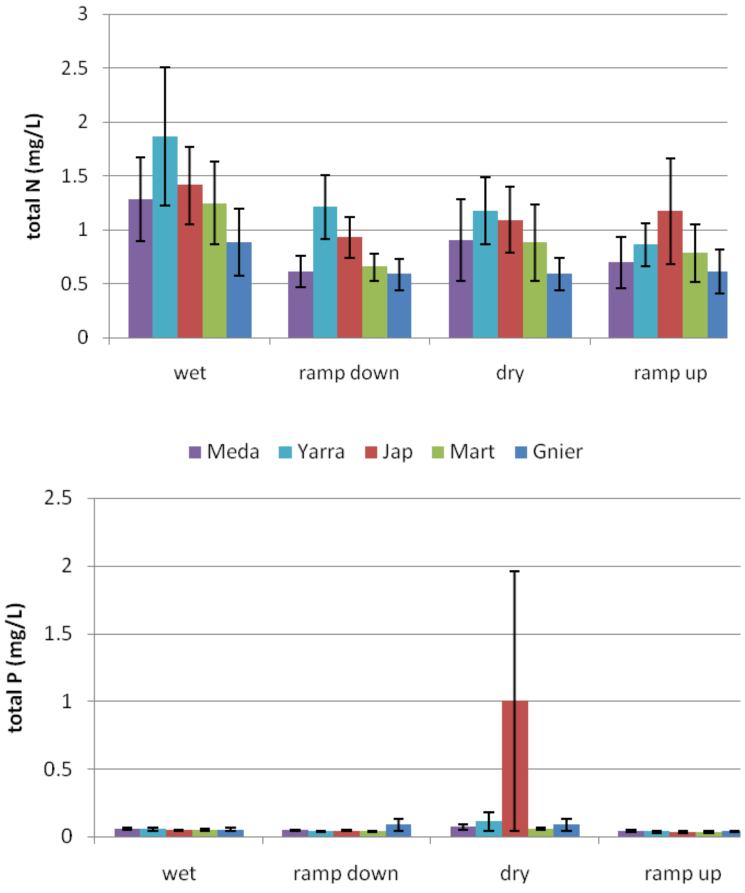

Figure 15 Robe quarterly monitoring (average ± standard error) (a) Total N (b) Total P.

3.4. MACROINVERTEBRATE FAUNA

A total of 112 macroinvertebrate taxa[2] from 64 families have been identified from the study sites since the commencement of the long term surveys. The macroinvertebrate fauna was characterized by regional endemics with no species considered rare or restricted in distribution (although, in part, this is based on limited taxonomic detail). A systematic list of all aquatic macroinvertebrates collected is given in Appendix 3.

3.4.1. Temporal variation in community assemblage

The changing patterns to the distribution of the aquatic fauna indicated the dynamic nature of the Pilbara aquatic ecosystem. Commonality in species across years was low with only half of the families recorded in 50% or more of the years. When combined at "species" level only 36% of the species were sampled in more than 50% of the years. Those families that were recorded in all sampling years included; worms (Oligochaeta), freshwater prawns (Atyidae), mayflies (Baetidae and Caenidae), seed Ostracoda, non-biting midges (Chironomidae), and beetles (Dytiscidae).

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[2] In this context equivalent to "species", although many individuals could not be identified to this taxonomic level and hence the total number of species may be higher

'Low-occurrence' taxa (*i.e.* taxa recorded at ≤ 10% of sites) accounted for approximately 20% of all species recorded. Kay *et al*. (1999) undertook the first comprehensive study of aquatic macroinvertebrate distribution patterns in northern Western Australian and also found that 20 - 30% of species occurred at most sites, while the remainder had widespread, but very patchy distributions. The majority of low occurrence taxa in the Robe pools are species of beetles (Coleoptera) and dragonflies (Anisoptera). Beetles also contribute significantly to the total taxa count each year and as they are low occurrence taxa they contribute significantly to variations recorded in community assemblages. In general, macroinvertebrate assemblages across years are dominated by families and species of beetles (Coleoptera), Diptera (including larval midges; chironomids and ceratopogonids), Trichoptera and lentic (still-water) crustacean species (Copepoda, Ostracoda Cladocera and freshwater prawns; *Caridinides* sp.) (Figure 16).

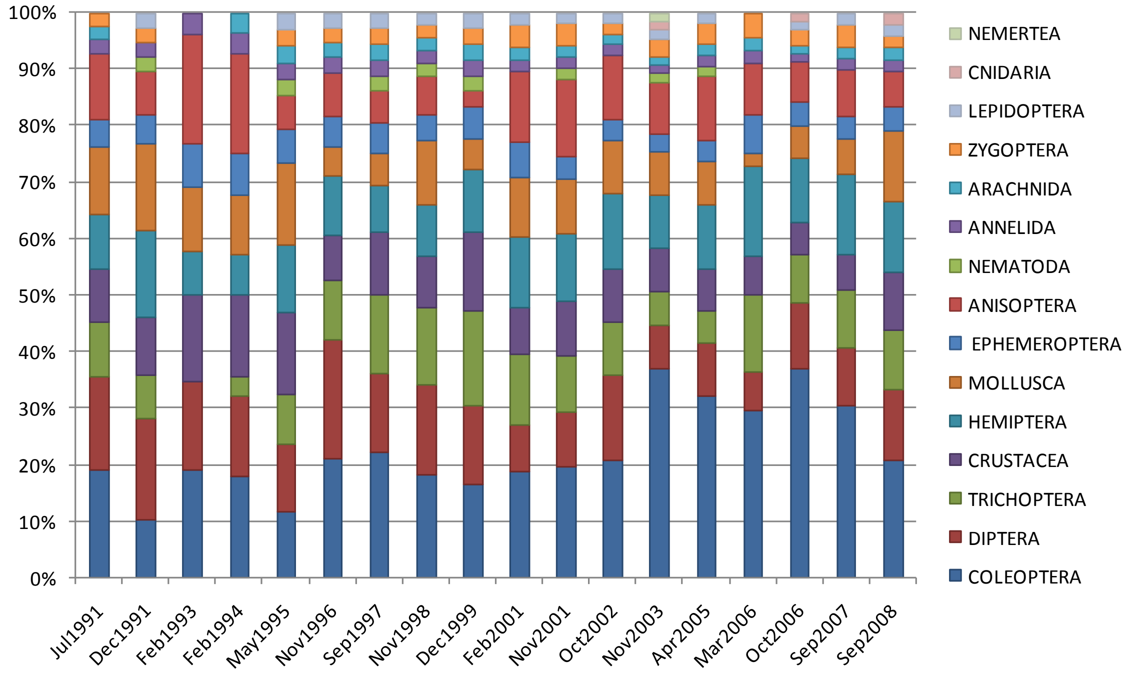

Figure 16 Percent composition of macroinvertebrate communities for all years (based on Species-level identification).

Temporal patterns in macroinvertebrate community structure were investigated using classification and ordination techniques. Interpretation of the ordination (MDS) is straightforward, with points closer together representing samples that are similar in species composition and sites far apart having different community structures. A comparison of all sites across years suggests that major differences in species assemblages are broadly related to parameters including sampling season and year (Appendix 4).

A multivariate ordination of community structure across years (grouping all pools within years) was produced to allow a comparison of variations in community assemblage at a regional scale (Figure 17). The results from the dendrogram were overlayed on the ordination to show three separate groupings for family level classification. Species level classification had similar groupings to family level but also highlighting the difference in species assemblage of the March 2006 sampling event (Appendix 4).

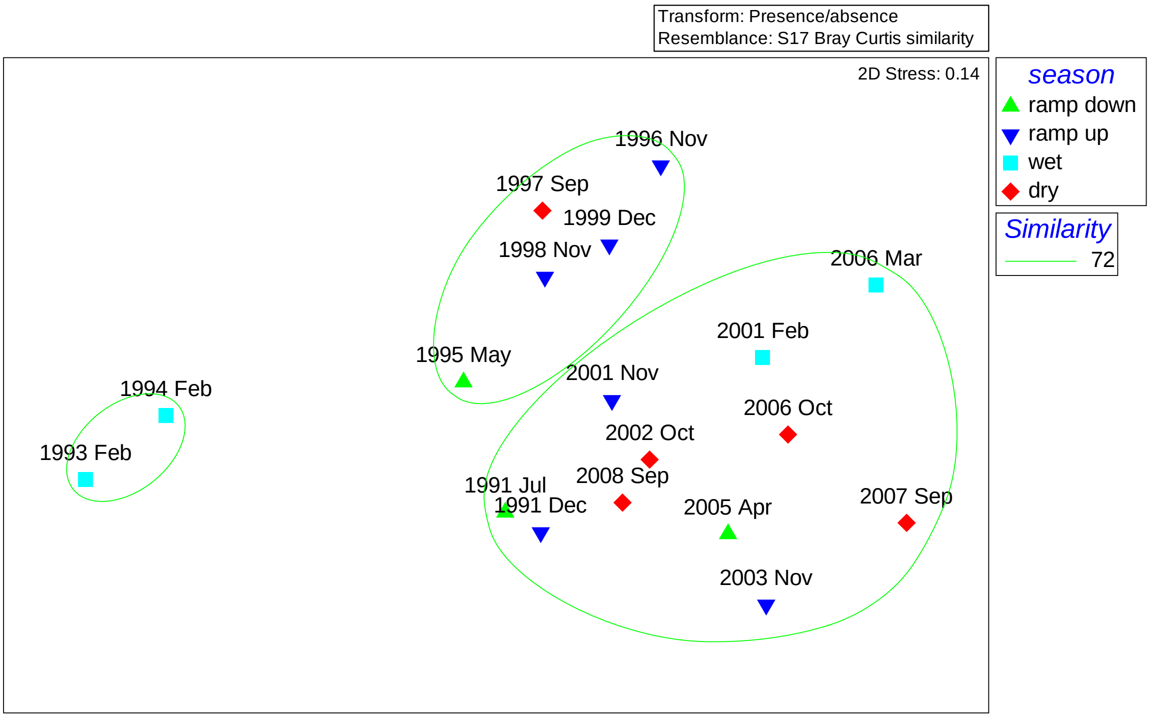

Figure 17 Ordination of all years based on family level classification R 0.705 0.1% Groups 1-3 (dendrogram groupings circled and sampling season overlaid).

Analysis at this broader scale highlighted significant differences in community assemblage following monsoonal rains and flows in 1993. Although these sampling events were conducted during the wet season, the separation of 1993 and 1994 was not only based on a seasonal shift in species composition but by the absence of a significant number of families (Figure 16). Three species of gastropods including the freshwater limpet *Ferrissia* sp., *Austropeplea vinosa* and the large bivalve *Velesunio* sp. were not present following the peak flow event in 1993. These species are vulnerable to flooding events as they attach to broad leaved aquatic vegetation typically removed by high water discharge rates. The bivalve, which had previously been abundant in the most upstream pool Ngalooin, is found in fine sediment and this habitat is readily scoured.

The 1993 and 1994 sampling years were also missing Trichopteran families that are known to be sensitive to environmental change (Leptoceridae and Ecnomidae). Other groups absent included families of Hemiptera (Belostomatidae, Gerridae, Veliidae) Coleoptera (Hydrophilidae, Elmidae, Hydrochidae, Limnichidae) and a reduction in damselflies (Coenagrionidae) (SIMPER ANALYSIS). The other two groups were separated based on presence of Lymnaeidae, Coleopteran and Trichopteran families.

A comparison of dry season sampling revealed a pronounced change in species composition following Tropical Cyclone Monty in 2004 (Figure 18) This shift in 2006 was followed by a further shift in 2007 highlighting an individual flow event that has had a significant overriding influence on macroinvertebrate assemblage. It appears that in 2008, macroinvertebrate assemblages are recovering with patterns consistent with pre-flood conditions. Despite this recovery, there has been a shift in species assemblages within the surveyed pools.

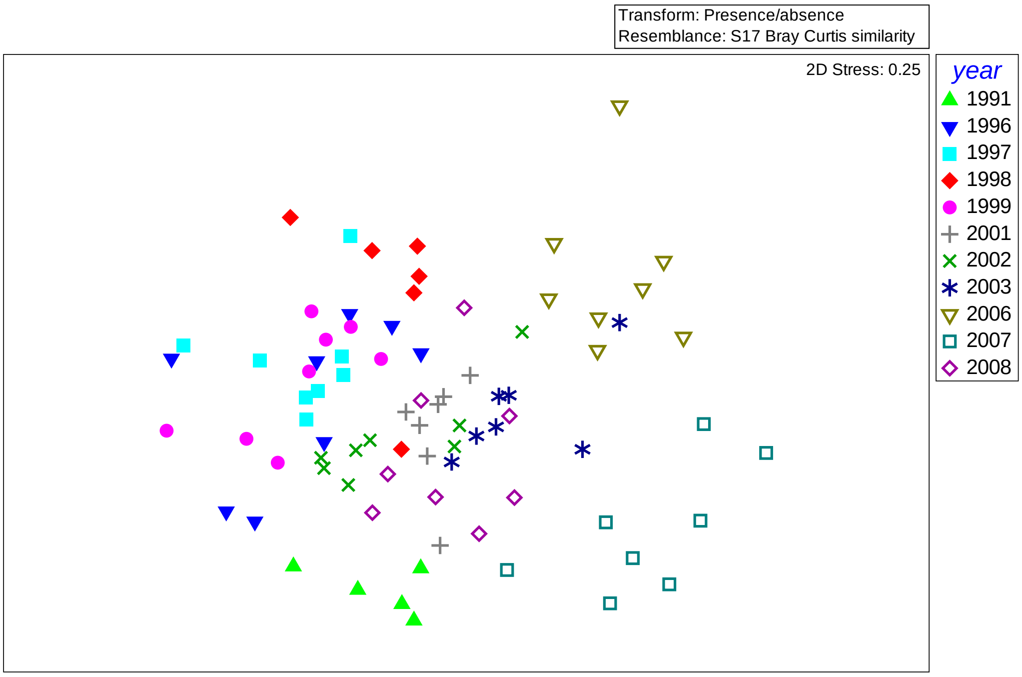

Figure 18 Ordination of dry season based on species level classification.

3.4.2. Relationship between macroinvertebrate assemblages/diversity and flow

Biodiversity across sampling surveys has ranged from a minimum of 26 in February 94, to a maximum of 70 in October 2006 (Figure 19). A comparison of species richness and community structure (Section 3.4.1) reveals rainfall and flow events to be one of the overriding determinants of community patterns. These high flows scour fauna from the pools and transport species downstream. The high flows dislodge fauna rather than remove structural habitat. Following high flow events, recovery to macroinvertebrate communities do not occur in a predictable manner with differences/shifts in species, recovery time and pool-related response. Recovery is considered stochastic and dependent on species actually "getting to" the sites and not inhibited by water chemistry, habitat etc.

The greatest reduction in species richness have occurred immediately following the monsoonal low and peak flow event in 1993 (at the time a 1:12 year flood event) and again following the highest recorded discharge from Tropical Cyclone Monty in 2004. These events resulted in $\geq$ 20% reduction in species diversity and a noticeable change in macroinvertebrate species assemblages (section 3.4.1). In contrast, an increase in species richness was recorded following high flow events in 1995 and 2006 despite their hydrological characteristics being similar to those in 1993 and 1994 (Section 3.2.3.).

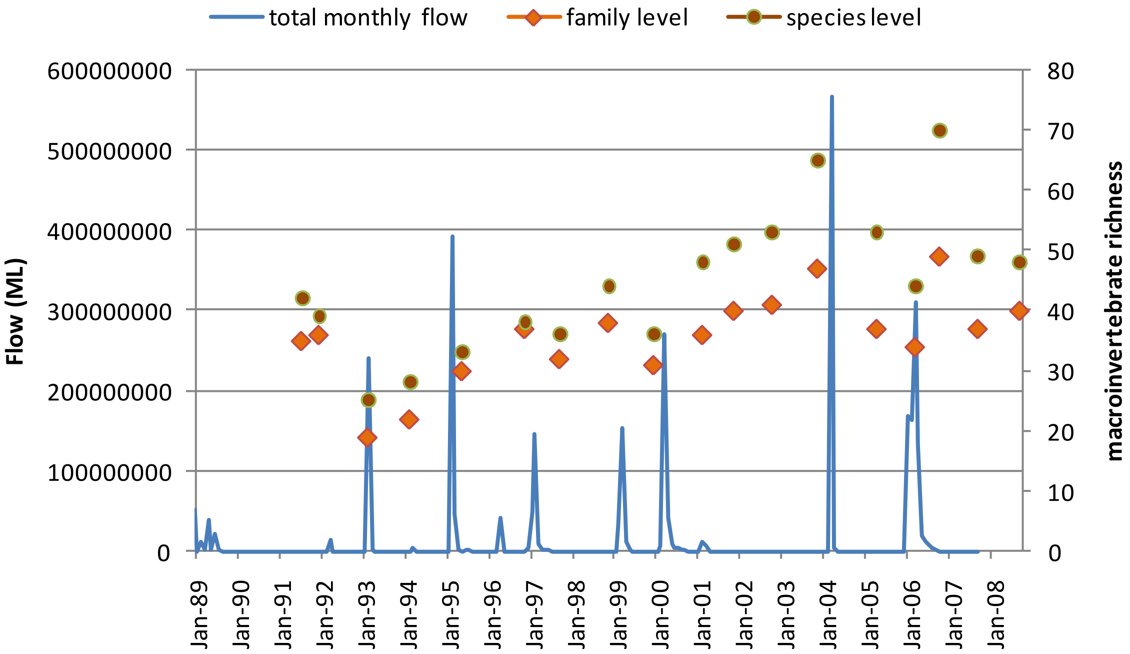

Figure 19 Species Richness of macroinvertebrates versus flow.

Recovery from disturbance is dependent on the ability of fauna to re-colonize suitable habitats and for species with entirely aquatic phases (*i.e.* holometabolous insects, fish, molluscs and crustaceans); this process can be inhibited by barriers to migration and the timing of large flow events. Spell analysis for 1995 and 2006 revealed that the total duration of flow was significantly longer for these years than in 1993 and 1994 (Figure 6). The prolonged flow in the Robe in 1995 and 2006 providing greater seasonal coverage (flow across the ramp up, ramp down and wet season coverage) possibly reduced the impact of high flows in these years by providing more time for species to recolonise after the initial high flow disturbance. This relationship has important implication for water extraction as recovery of macroinvertebrate communities following a disturbance may be prolonged if periods of zero flow are increased (*i.e.* if modifications are made to stream flow regimes that increase drying). This may inhibit the rates of recolonisation of pools from other sites.

In addition to cyclones and peak flow event, aquatic linkages can be lost as pools dry up during 'drought' periods (Lake, 2003). Pools retreat from the streamside riparian zone which, combined with the reduction in flows and flow types can result in the loss or reduction of important habitats (*i.e.* edge, water-plants, and riffles) especially for fauna that require flow. Although individual species have been sensitive to dryer years (section 3.4.1) a reduction in flow and water availability has not always resulted in a decrease in species diversity *e.g.* despite particularly low water levels, biodiversity in 2003 was much higher than in all previous survey years (Figure 19). This can be attributed the drying up of non permanent pools in the area and therefore a reduction in habitat availability. Important parameters were pool depth and habitat. This is supported by the greater number of low occurrence species that are present in dryer years which have a mobile adult stage (including Coleoptera) and an increase in groundwater species (Amphipods, Copepods, Ostracods).

3.4.1. Hydrology and Response/Sensitivity of Macroinvertebrate Fauna

The response and sensitivity of the major groups of macroinvertebrate fauna to broad changes in the hydrological regime are summarised below.

Aquatic nematodes occur in both lotic (flowing water) and lentic (still water) environments and are characteristically found in association with the substratum. Nematodes have been typically absent during wet season sampling (high flows) and have not been recorded since the scouring of the river channel by Cyclone Monty in 2004.

EPT scores are used as a measure of stream health and are calculated using the number of families of three sensitive orders of macroinvertebrates; Ephemeroptera (E: mayflies), Plecoptera (P: stoneflies) and Trichoptera (T: caddisflies). Trichopteran species were susceptible to changes in flow regime with a decline in the number of species following the 1993 and 2005 cyclone events. This species was also somewhat sensitive to 'drought' years with a reduction in the number of species coinciding with years of low spell duration. This sensitivity is possibly due to the fact that most species of Trichoptera are typically found in lentic (flowing) waters throughout Australia (Hynes, 1970). Temporal variation was not evident in the two families of Ephemeroptera present in the pools (Caenidae and Baetidae) as they have been recorded in all sampling years and Plecopteran species have not been recorded from the Pilbara region. The number of species of EPT and lack of knowledge of their life history traits and sensitivities limits the use of the EPT scores in monitoring programs.

Most of the odonate and caddis-fly 'indicator' species appeared to show a preference for higher DO content and increased flow. A relatively high abundance and diversity of odonate species is indicative of a "healthy" ecosystem where typical food webs and trophic structure are being maintained (Davis *et al*, 1987). Odonata were shown to be highly seasonal and species assemblages were also related to the hydrology, with more species of Anisopterans (dragonfly larvae) collected in years where the duration of spells was low (years where flow was only maintained for short periods). Species of Zygopterans (damselflies) were only absent following the 1993 flood event.

The Lepidopteran family, Pyralidae, prefer still, fresh waters with abundant macrophyte growth (Davis & Christidis, 1997). This family has been widespread in surveys and is one of only a few Lepidopteran families that have aquatic larvae. Lepidopterans were absent following the 1993 and 2005 cyclone events. As expected the groundwater species *Pilbarus millsi* (Halse *et al*, 2006) was more widespread in years of reduced rainfall and flow when pools are dependant and maintained by groundwater and absent during high flow events.

3.4.2. Spatial patterns in macroinvertebrate community structure

As highly episodic events (like cyclones) are important determinants of aquatic community structure there was no relationship evident between pool size and macroinvertebrate assemblage across years. Initially in the Robe system, there was a strong predictive model between simple measurements of pool size and macroinvertebrate community structure (Streamtec, 1992). This indicated a deterministic relationship. After significant cyclones, this model has shown less predictive success as recolonisation of species can be opportunistic and unpredictable.

Analysis of individual years has revealed a broad separation of pools based on measurements of pools size (particularly maximum depth) (Streamtec, 1991- 2008) although this relationship is not consistent. Initially, larger pools were thought to be of high environmental quality but following high flow events, the smaller pools can provide relatively higher environmental value, presumably as the flood has affected the larger pools with increased scouring etc to a greater extent than smaller pools. These small pools then become important for refugia and reinvasion once joined with flow. For example, Japanese Pool species diversity has not recovered since October 2006. Changes to pool morphology resulting from high flows appear to have influenced the distribution of habitat types and hence the macroinvertebrate fauna present.

3.5. FISH FAUNA

3.5.1. Species Occurrence

Primarily due to the aridity of the area, a sparse number of fresh water fish have been recorded in the Pilbara (12 species) (Allen et al, 2002). Ten of these fish species were recorded in the long term sampling of Robe River permanent pools (Table 1). Six of these species are classified by Allen *et al* (2002) as freshwater and the remaining four as freshwater/estuarine species. Pools were dominated by freshwater species, especially from the Tetrapontidae (Grunters) group. Of the estuarine species sampled, Mangrove Jack (*Lutjanus argentimaculatus*) typically utilise rivers as nurseries and Ox-eye Herring (*Megalops cyprinoides*) have been known to spend extensive periods in the pools beyond their juvenile stages. The Striped Butterfish and Threadfin Silver Biddy which sporadically occurred in pools in low numbers are known to inhabit marine or estuarine environments and only occasionally enter rivers (Morgan and Gill, 2004). The presence of estuarine species is considered the result of chance events and their presence, due to low numbers, appears to have little impact on the resident fish fauna (*e.g.* limited “top down” control).

It is important to note that, to date, no introduced species have been recorded in the eight permanent pools surveyed. This is consistent with fish surveys of the Robe River (Allen, 1889; Allen *et al,* 2002; Morgan and Gill, 2004).

Table 1 Species of Fish sampled in pools

FRESHWATER SPECIES		
CLUPEIDAE - HERRINGS	*Nematalosa erebi* GUNTHER	Bony Bream
PLOTOSIDAE - EEL-TAILED CATFISH	*Neosilurus hyrtlii* STEINDACHNER	Eel-tailed Catfish
MELANOTAENIIDAE - RAINBOWFISH	*Melanotaenia splendida australis* PETERS	Western-Rainbow Fish
TERAPONTIDAE - GRUNTERS	*Amniataba percoides* GUNTHER	Barred Grunter
	Leiopotherapon aheneus MEES	Fortescue Grunter
	Leiopotherapon unicolor GUNTHER	Spangled Perch

ESTUARINE SPECIES		
MEGALOPIDAE - TARPONS	*Megalops cyprinoides* BROUSSONET	Ox-eye Herring
SCATOPHAGIDAE-SCATS	*Selenotoca multifasciata* RICHARDSON	Striped Butterfish
GERREIDAE - SILVER BIDDIES	*Gerres filamentosus* CUVIER	Threadfin Silver-biddy
LUTJANIDAE-SNAPPERS	*Lutjanus argentimaculatus* FORSSKAL	Mangrove Jack

3.5.2. Temporal and spatial variation in species diversity

Australia's flat landscape and dry climate are not conducive to fish survival, yet within dryland systems in Australia, fish play an important role in ecosystem function. Unmack (2001) noted that the persistence of fish fauna in hostile desert environments is controlled by geology, geomorphology and the vagaries of sediment transport and that the persistence of fish must be considered at a regional scale.

All six freshwater species have been consistently present across sampling years, with the exception of Spangled Perch and Barred Grunters. These two species were absent in 1993, although this may reflect the high flows present during this wet season sampling. The high flows result in a reduction in sampling efficiency and/or a greater habitat availability with fish relocating to areas with reduced flow. The smaller bodied freshwater species are the most widespread showing the smallest variation temporally. The larger bodied freshwater species and the cryptic catfish exhibited the greatest variation in sites across the sampling periods (Appendix 5).

Table 2 Presence/Absence of Freshwater/Estuarine Fish Species across years

Month	Jul	Dec	Feb	Feb	May	Nov	Sep	Nov	Dec	Feb	Nov	Oct	Nov	Apr	Mar	Oct	Sep
year	1991	1991	1993	1994	1995	1996	1997	1998	1999	2001	2001	2002	2003	2005	2006	2006	2007
Estuarine Species																	
Ox-eye Herring	-	-	-	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓
Mangrove Jack	-	-	-	-	-	-	-	-	✓	✓	✓	✓	✓	✓	-	✓	✓
Striped Butterfish (Scat)	-	-	-	-	-	-	-	-	✓	✓	✓	✓	✓	✓	-	✓	✓
Silver biddy	-	-	-	-	-	-	-	-	-	✓	✓	-	-	-	-	-	✓

Freshwater/estuarine species, have exhibited the greatest variations temporally (Table 2, Appendix 5). Estuarine species were not present in pools when sampling commenced in 1991. Ox-eye Herring (*Megalops cyprinoides*) was the first species to appear in the pools (November 1996) followed by Mangrove Jack (*Lutjanus argentimaculatus*) and Butterfish (*Selenotoca multifasciata*) (in 1999). Since their introduction, these three estuarine species have persisted in the survey pools. The only exception is their absence from pools in March 2006 when a Tropical Cyclone interrupted sampling. The absence of estuarine species in March 2006 can be attributed to a reduction in the number of sites sampled and the increased water levels (similar to those seen during the 1993 sampling event) and hence greater availability of habitats. This theory is supported by the presence of these species in the next sampling event (October 2006).

Silver Biddy (*Gerres filamentosus*) individuals have only been recorded in the permanent pools in February and November 2001 and September 2007. Only a few individuals were observed on both sampling occasions and this species was only recorded in the downstream sites.

Patterns in species richness shows the major temporal shift in community structure across years is determined by the occurrence of estuarine species (March 2006 similar to initial sampling as during high flows from cyclone Monty and also only six sites sampled). Major differences follow the introduction of Ox eye Herring in 1996 and then the introduction of other estuarine species in 1999.

3.5.3. Temporal variation and flow

As expected in a system exhibiting distinct wet and dry seasons, species introduction, will be determined by the hydrological connectivity of the system. Connectivity is important in allowing estuarine/marine species to move both in and out of the river channel and this connectivity in the past has allowed species to recolonise pools following their absence from the Robe River. The long term data set provides an opportunity to analyse the flow characteristics during connectivity to determine which flow parameters are important (or required) for fish colonisation and migration within the survey pools (Figure 20).

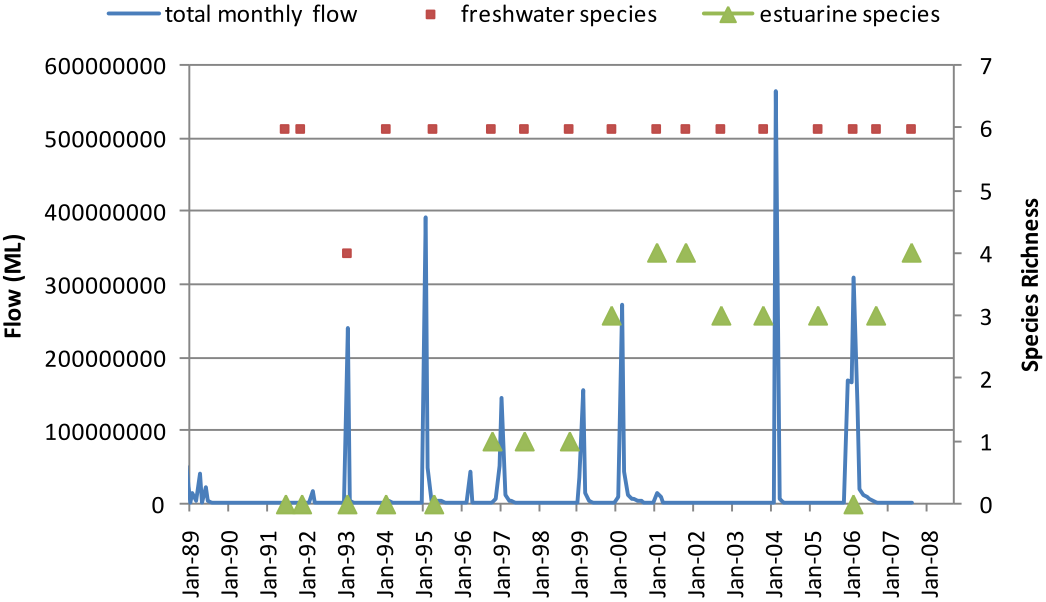

Figure 20 Comparison of species richness and total monthly flow at Yarraloola.

A comparison of species richness and monthly flow reveals the introduction of fish species in 1996 and 2000 following peak flow events (at Yarraloola) of 43595 ML and 9430 ML respectively. Despite flow events of greater magnitude in 1993 and 1995, no estuarine species were recorded in pools following these events (Figure 20). This suggests that the magnitude of peak flow events, whilst important for providing flow for pool connectivity, is not the only flow characteristic required for fish colonisation and migration within the survey pools.

The LTER of Robe pools allows a comparison of flow dynamics that affect biodiversity and population dynamics of fish. The relationship between ecological patterns and flow was determined by comparing temporal changes in fish species with patterns in the flow regime (Section 3.2.3.). All sampling events that recorded an increase in estuarine species richness were separated into the same group based on their flow characteristics (Dendrogram group 4 and 2), showing a strong link between the patterns in species richness and the hydrological parameters measured.

Further analysis of peak flow events with and without the introduction of estuarine species (1996 1999 and 2000; 1995 and 1993 respectively) revealed a number of significant differences in flow characteristics (Figure 21). When estuarine species were introduced the number of rises and falls were significantly higher, conversely the mean magnitude and mean rate of rise was significantly lower (Figure 21). Parameters related to the falls in the hydrograph were not significantly different and appear not to be as important as the rises.

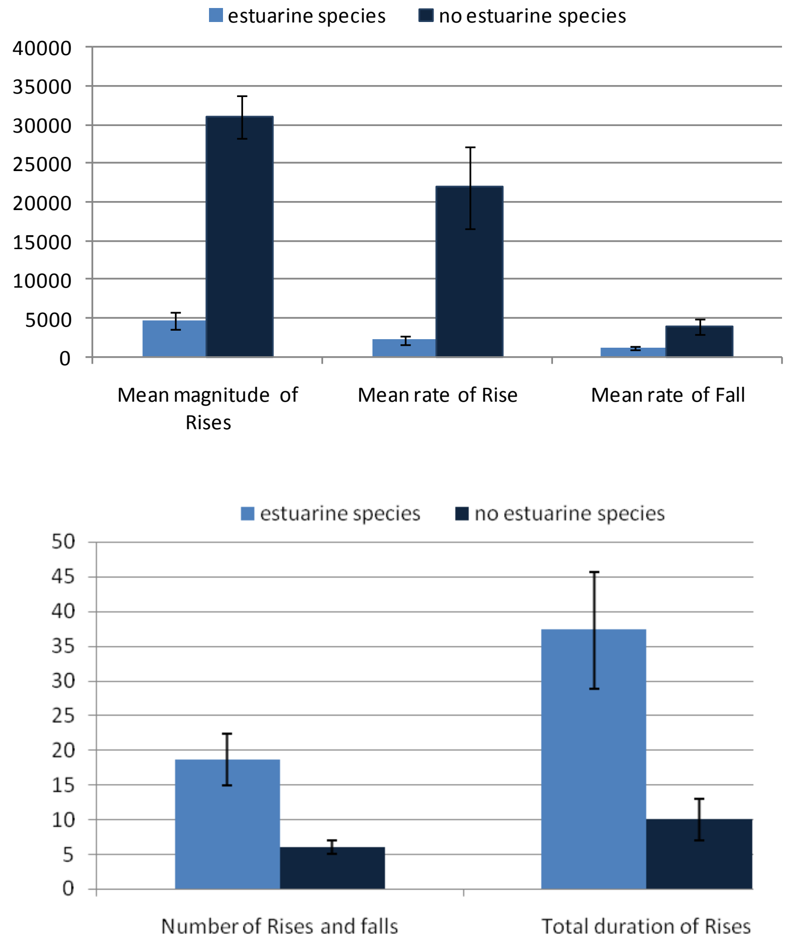

Figure 21 A comparison of mean hydrological characteristics between years where estuarine species were introduced and those years where no estuarine species were introduced.

A comparison of spells revealed that the length and distribution of spells may also be important in producing conditions that are suitable for estuarine species to recruit into the surveyed pools (Figure 6). In years of recruitment flow was present across the wet, ramp up, and ramp down periods. In years with no recruitment there were on average, fewer days of flow in the Robe and this flow was confined to the wet season

The introduction of estuarine/freshwater species is therefore not only reliant on the magnitude of peak flow but also requires consecutive months with high flows rather than short peak flow events.

In ‘flash’ flow events there is no opportunity for recruitment and when the rises are slower and the spell durations are longer the fish are able to migrate up river to spawn.

3.5.4. Spatial Variations in species diversity and community structure

Long-term monitoring of permanent pools in the Robe has shown that spatial variation in fish biodiversity can be linked to pool size (Figure 22 & 23). The relationship between pool size and species is thought to be related to habitat availability and also the associated water issues associated with smaller pools (*i.e.* smaller pools have greater variation in temperature and dissolved oxygen levels resulting in levels that can be deleterious to aquatic fauna). The higher diversity of marine species at Japanese Pool is considered to be related to the position of this pool in the catchment (further downstream).

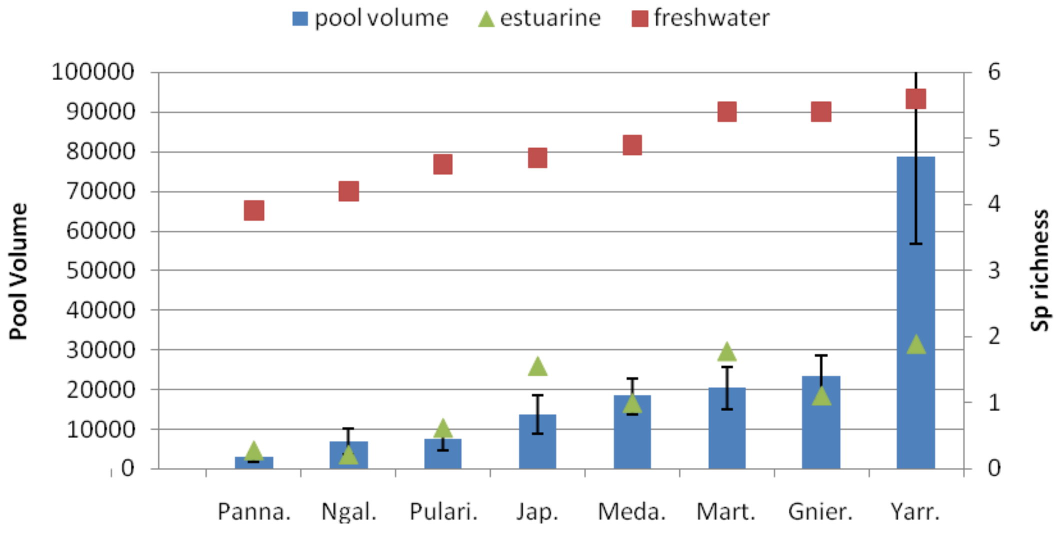

Figure 22 Average dry season pool volume plotted against average freshwater and estuarine sp richness for each site.

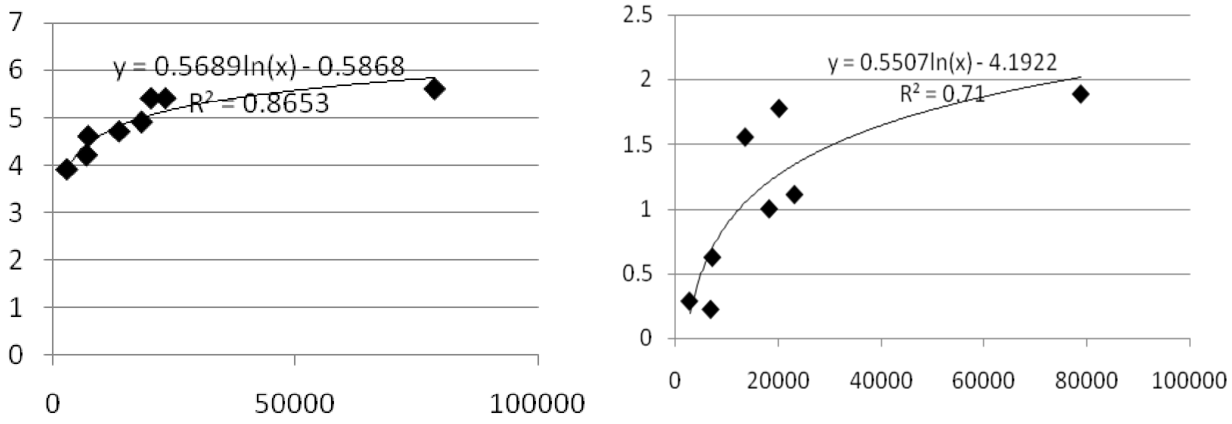

Figure 23 Correlation between pool size and freshwater and estuarine species respectively.

Ordination (MDS) of community structure revealed a larger variation in fish diversity is seen during high flow levels compared to low flow levels (Appendix 6). Fish during wet season have more available habitats and pools become more important when they cease to flow and are isolated from each other and the estuary.

Analysis of dry season sampling events shows that spatial variation in fish biodiversity can be linked to pool size (volume and depth) (Figure 24). Fish species assemblages were also related to the position of the pool along the river (i.e. upstream downstream). The furthest upstream sites have little recruitment of estuarine species sugesting connectivity is reduced, it is unclear if this is related to flow, distance or preference of species along the salinity gradient from upstream to downstream pools.

A comparison of individual species revealed that Bony Bream were more common in medium and large pools where there are extensive areas of deeper water. In contrast, Catfish and Barred Grunters were more common in medium and small pools. Marine species have also been sampled more often in larger pools (Medawandy, Martangkuna, Gneiraoora and Yarramudda) when compared to smaller pools (Japanese, Ngalooin, Pannawonica Hill, Pulari - Nyunangka).

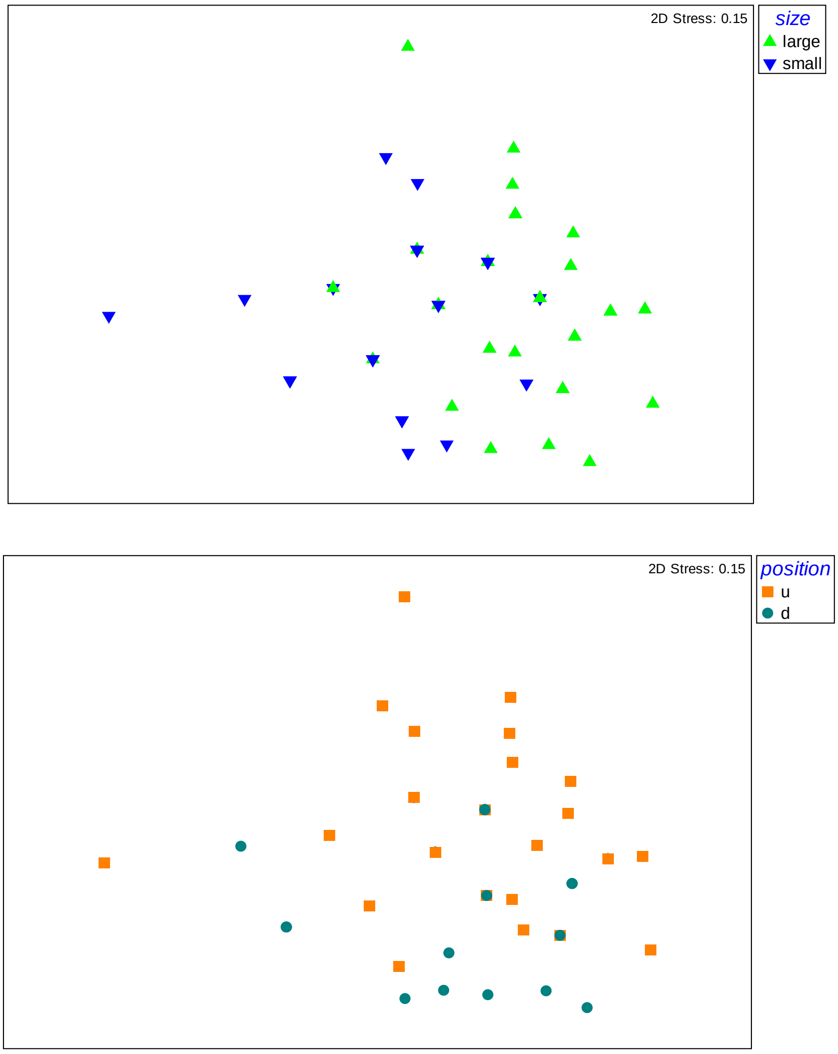

Figure 24 MDS on the presence/absence of species recorded for each pool across years (dry season only) with pool size and position along the river superimposed (Global R 0.114 0.1% between small and large).

3.5.1. Pool stability

In the nearby Fortescue River, Beesley (1996) found that unstable pools contained fewer species, a greater fraction of juvenile size classes and underwent greater fluctuations in total intra-specific numerical abundance through time, than stable pools. Pool stability was measured by persistence of water through time, and variation in maximum pool depth through time.

As pools in the current study were chosen based on their permanence, pool stability was calculated using variations in maximum pool depth through time (Figure 25). Although stability was not directly related to the number of species present, fish communities in unstable pools underwent greater changes in community structure (*i.e.* lower stability in species richness). Pool stability reflects pools volume, with larger pools being more stable than smaller pools which suggest that larger pools not only contain more species but that these larger pools act as source pools as the number of species remain stable.

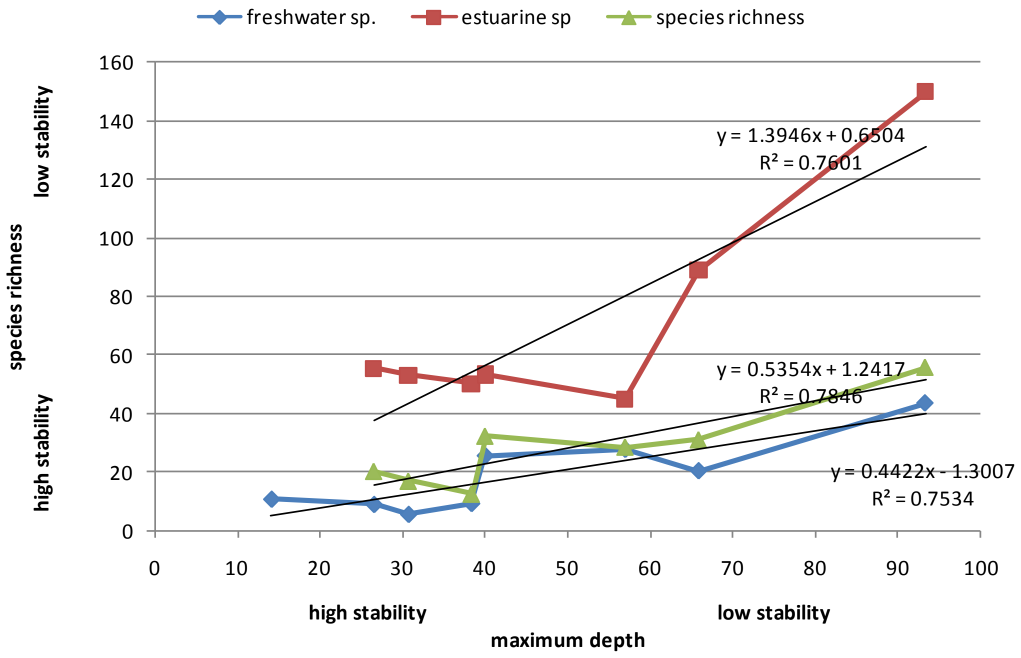

Figure 25 Correlation between variability in pool depth and variability in species richness

3.6. LANDSAT IMAGERY

Landsat imagery (25m pixel size) was tested by Department of Water as a tool for identifying permanent pools on the Robe River. Pools that were sampled in the current long term ecological research but were not detected by the Landsat imagery included the smaller pools; Japanese Pool, Pulari Nyunangka, Ngalooin and Pannawonica Hill (Table 3). The majority of these pools were detected following Tropical Cyclone Monty which could be explained by the increase in flow during this period or a result of the removal of significant amounts of riparian vegetation during this high flow event. Martangkuna and Medawandy were also under represented using this technique and these pools are shaded from dense riparian zone. The use of Landsat Imagery to characterise the permanency of pools in the Robe River may be limited therefore due to the size and extent of riparian vegetation.

Table 3 Permanency of Robe River pools from Landsat imagery (25m pixel)

(orange text; length x width of pools approximated for current sampling, green shading highlighting pools that were sampled but were not detected using Landsat imagery)

Pool No.	Name	Permanency	Landsat Est area 23/11/99 (30/11/99)	Est area 16/2/02 (11/01)	Est area 19/2/03 (10/02)	Est area 9/10/03 (11/03)	Est area 21/6/04	Est area 16/2/05 (4/05)	Est Area 2/9/07 (9/07)	Comments
1	Gnieraoora	7/7	3785 (900x35)	6310 (1000x32)	10070 (500x20)	5045 (337x29)	20750	14485 (1000x29)	30774 (500x50)	Nearby pool (100m south east)
2	Martangkuna	2/7	0 (800x20)	0 (1000x26)	0 (800x20)	0 (200x22)	635	0 (220x18)	1900 (280x17)	
3	Pulari Nyunangka	3/7	0 (1000x50)	0 (1000x44)	0 (800x20)	0 (30x6)	23259*	20754* (60x12)	20730* (40x5)	Nearby pool (600m east).
4	Japanese Pool	3/7	0 (1000x30)	0 (1000x62)	0 (500x10)	0 (100x20)	23259*	20754* (25x6)	20730* (40x5)	Nearby pool (600m east).
5	Yarramudda	7/7	1265 (600x20)	22610 (1000x70)	3780 (500x?)	3150 (500x55)	26345	10700 (500x45)	5670 (200x30)	Also known as Weedai Pool
6	Medawandy	4/7	1265 (1000x35)	2530 (1000x12)	0 (500x16)	635 (400x25)	0*	0 (200x25)	1265* (350x30)	Nearby pool (250m south west)
7	Panna Hill	4/7	2520 (400x10)	1265 (1000x12)	0 (300x10)	0 (dry)	3155*	635 (100x28)	0 (100x15)	
8	Ngalooin (Mussel Pool)	3/7	0 (600x30)	0 (1000x15)	0 (200x15)	0 (90x16)	25729*	635 (250x23)	3160* (250x20)	Nearby pool (350m south west)

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5. APPENDICES

APPENDIX 1: SAMPLING METHODS

1. WATER QUALITY

1.1 Water samples collected using clean 250 ml polyethylene bottle. One per site.
1.2 Bottles washed thoroughly three times with site water (with lid attached).
1.3 Undisturbed water collected near surface for laboratory analyses of total nitrogen and total phosphorus (analysed by Natural Resources Chemistry Laboratory, Chemistry Centre (WA)).
1.4 Both the bottle and lid labelled.
1.5 Sample kept cool in esky on ice or stored at 4°C where possible.
1.6 Measured dissolved oxygen, temperature, salinity, electrical conductivity and pH *in situ*.

2. MACROINVERTEBRATES – Qualitative – D-net sampling

2.1 Sampled all habitats with 250μm D-net (heel-kick with opening of net facing into flow).
2.2 Standardized protocol (see below).
2.3 Fixed composite sample in 5% formalin (37% w/w formaldehyde) in plastic bag with label.

Qualitative sampling was conducted using a 'heel-kick' or sweep method (depending on habitat); compatible with the methodology of NRHP/MRHI[3] protocols. 'Heel-kick' and sweep sampling was conducted with a dip net with 250 μm mesh, a 350 X 250 mm opening, 50-75 cm depth and a 1-1.5 m handle. The net was washed thoroughly after sampling each site to remove any adhering animals left from previous sampling. For channel and riffle habitats, the substratum was vigorously disturbed whilst holding the net downstream with its mouth facing the disturbed area and into the stream-flow. Cobbles were picked-up, turned over and rubbed by hand to dislodge attached organisms into the net. This process continued upstream over a total distance of approximately 50 m, covering both the fastest and slowest flowing sections of the specific habitat. Macrophytes were sampled by vigorously sweeping the net within the aquatic vegetation over a length of about 10m.

All sweep samples, containing sediment, detritus and macroinvertebrate fauna, were preserved in 80% ethanol in plastic bags. In the laboratory, samples were washed in a flume-hood to remove formalin. Organic sediments, including macroinvertebrates, were then separated from the inorganic material by water elutriation. The organic sediments were then washed through 3 mm, 500 μm and 250 μm mesh sieves to partition the sample into 'large' and 'small' fractions. The small fractions were sorted under a binocular microscope and collected macroinvertebrates transferred to 100% ethanol. For each sample, the entire 3 mm and 500 μm fractions were sorted, while 250 μm fractions were sub-sampled by one fifth. All animals were identified to the lowest practicable taxonomic level.

3. FISH

3.1 Standardised the time/effort where possible.
3.2 Fish identified to species.

Fish were sampled by a combination of methods including 250 μm dip nets (in areas of reed beds, bank undercuts and under logs), seine nets across the channel, or by direct observation. For most sites, direct observation proved the most efficient method for surveying species presence. In turbid waters a small 5 m wide purse type seine net (9 mm stretched mesh size) was used. The seine was either used for trawling or was placed across the stream and fish driven downstream into the net. It was not usually possible to standardise trawls between sites because of the high percentage of snags and dense aquatic vegetation at most sites,

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[3] NRHP/MRHI = National River Health Program and Monitoring River Health Initiative.

therefore sampling was standardised to two person-hours at each site. All fish caught were returned live to the water.

4. CHANNEL MORPHOLOGY

4.1 Measured average active channel width and where appropriate, pool length (range-finder).
4.2 Estimated flow/discharge.
4.3 Measured velocity (Marsh-McBirney Model 201M meter) across channel at 0.6 maximum depth (*sensu* Newbury & Gaboury 1993).
4.4 Measured average depth (graduated pole or metal tape measure).

To estimate discharge, a narrow segment of stream of uniform shape was selected and velocity measured, at intervals across the segment. Bankfull widths were interpreted from debris zones and high-water marks on banks and riparian trees. River bed materials were qualitatively assessed (e.g. sand, gravels, cobbles, organics *etc*). Sedimentation, as pool aggradation, was assessed as the relative amount of fine inorganic material covering the typical bed substrate. Mean sediment depth was calculated from 10 measurements made at random at each site. A graduated pole, pushed through the sediment to the bed substrate (*i.e.* 'first refusal'), was used to approximate depths.

5. RIPARIAN VEGETATION CONDITION

5.1 Note dominant species.
5.2 *Index of condition: weed invasion, cattle grazing, fire, other disturbances etc*.

6. PRIMER

To identify spatial (between sites) and temporal (between-sampling occasions) differences in water quality and macroinvertebrate community structure, data was classified and ordinated using PRIMER (Plymouth Routines in Multivariate Ecological Research) software (Clarke and Gorley, 2001). PRIMER performs multivariate analyses on data sets commonly recorded in biological monitoring of environmental impacts and is widely used for interpretation of community patterns.

Analyses of macroinvertebrates were conducted on presence/absence and abundance data. Similarity matrices were calculated using the Bray Curtis association measure which is appropriate for ecological data in freshwater systems. Sites were classified using hierarchical clustering (CLUSTER) which produces a dendrogram in which samples are grouped according to the similarity of their water quality or macroinvertebrate community composition. Hierarchical clustering is designed to provide ecological information on the occurrence of an assemblage of species from a number of sites - members of each division or group in the dendrogram have a more similar community structure and therefore more similar ecology. Analysis of Variance (ANOVA)-type tests were then performed to determine if there was a significant separation between groups. This was done by ANOSIM, which compares the mean within-group similarity to the mean between-group similarity. Data were then ordinated using non-metric multi-dimensional scaling MDS. The ordination represents the samples as points in low-dimensional space where sites closest together have more in common than those further apart. Groups identified in the CLUSTER analysis are then overlayed onto the ordination. Species contribution to similarity of groups was calculated using the SIMPER routine. By looking at the overall percentage of contribution each species makes to the average dissimilarity between groups, species can be listed in decreasing order of their importance in discriminating the two groups.

In order to link environmental variables with patterns seen in community structure, phys-chemical data was analysed separately and then its multivariate pattern was compared to that of species data. Ordination of environmental data utilised Principal Components Analysis (PCA). The BIOENV routine was then used to examine whether a particular environmental variable or groups of variables distinguished sites in the same manner as that of community structure.

APPENDIX 2. FLOW CHARACTERISTICS USED FOR HYDROLOGICAL ANALYSIS

Minimum
Maximum
Mean
Median
CV
Standard Deviation
Zeros
Total
S_Log
Lanes
Number of Rises
Mean magnitude of Rises
Mean duration of Rises
Total duration of Rises
Mean rate of Rise
Greatest rate of Rise

Number of Falls
Mean magnitude of Falls
Mean duration of Falls
Total duration of Falls
Mean rate of Fall
Greatest rate of Fall
Predictability based on monthly mean daily flow
Constancy based on monthly mean daily flow
Contingency based on monthly mean daily flow
total flow ML (between sampling)
days since flow
days since rain
days since peak flow
flow on day ML

APPENDIX 3. MACROINVERTEBRATE TAXA

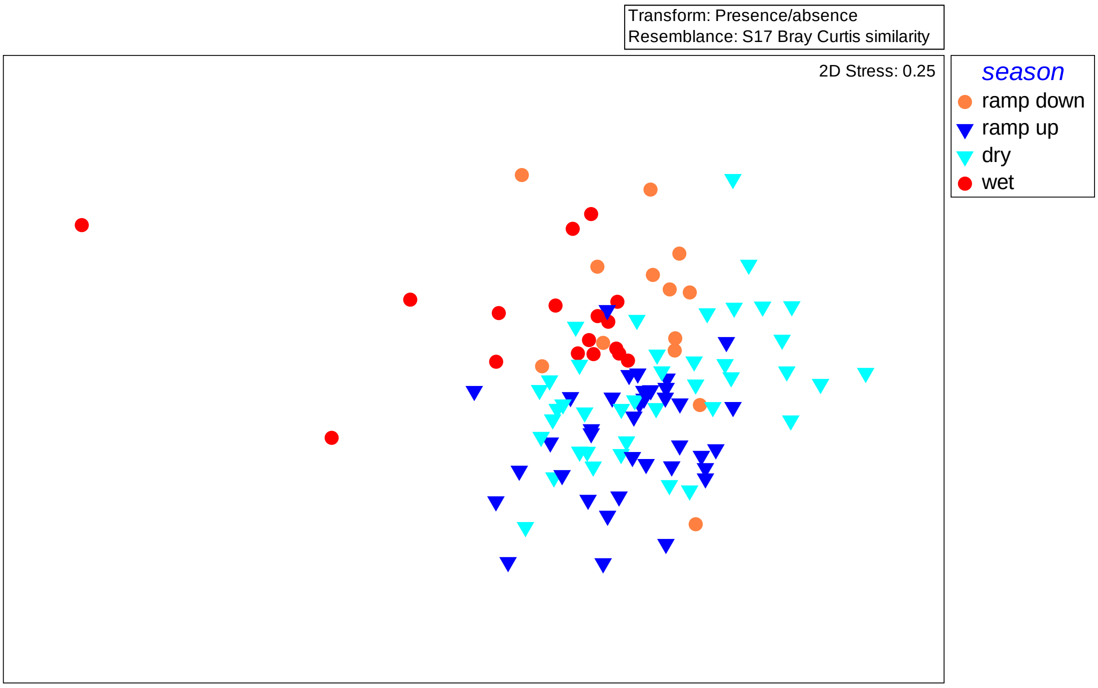
CNIDARIA		
HYDROZOA		
	HYDRIDAE	*Hydra* sp.
NEMERTEA		
		Nemertea sp.
NEMATODA		
		Nematoda sp.
ANNELIDA		
OLIGOCHAETA		Oligochaeta spp.
MOLLUSCA		
GASTROPODA		
	THIARIDAE	*Melanoides/ Thiara australis* sp.
	ANCYLIDAE	*Ferrissia petterdi*
	LYMNAEIDAE	*Austropeplea lessoni/vinosa*
		Lymnaea stagnalis
	PLANORBIDAE	*Amerianna* sp.
		Gyraulus essingtonensis
BIVALVIA		
	HYRIIDAE	*Velesunio sp.*
ARACHNIDA		
		Hydracarina spp.
CRUSTACEA		
CLADOCERA		Daphnia spp.
CHONCHOSTRACA		Conchostraca spp.
OSTRACODA		Ostracoda spp.
COPEPODA		Copepoda spp.
AMPHIPODA		
	PARAMELITIDAE	*?Pilbarus millsi*
DECAPODA		
	ATYIDAE	*Caridinides wilkinsi*
INSECTA		
EPHEMEROPTERA		
	BAETIDAE	*Cloeon* sp.
		Genus 1 UWA sp1
	CAENIDAE	*Tasmanocoenis arcuata*
		Wundacaenis dostini
ODONATA		
ANISOPTERA		
	AESHNIDAE	*Hemianax papuensis*
	GOMPHIDAE	*Austrogomphus gordoni*
		Austrogomphus lateralis
		Austrogomphus collaris
		Antipodogomphus hodgkini

	LIBELLULIDAE	*Diplacodes haematodes*
		Trapezostigma stenoloba
		Diplacodes bipunctata
		Orthetrum caledonicum
		Orthetrum villosovittatum
		Macrodiplax cora
		Zyxomma elnegri
		Rhodothemis lieftincki
	MACROMIIDAE	*? Macromiidae sp.*
	LINDENIIDAE	*Ictinogomphus dobsoni*
	HEMICORDULLIDAE	*Hemicordulia ?australiae*
		Hemicordulia tau
		Hemicordulia koomina
ZYGOPTERA		
	ISOSTICTIDAE	Isostictidae spp.
	COENAGRIONIDAE	*Ischnura aurora*
		Ischnura heterosticta
		Pseudagrion microcephalum
		Pseudagrion aureofrons
		Xanthagrion erythroneurum
		Agriocnemis rubescens
		Coenagrionidae spp.
HEMIPTERA		
	GELASTOCORIDAE	*Nerthra* sp.
	PLEIDAE	*Paraplea* spp.
	GERRIDAE	Gerridae spp.
	HEBRIDAE	*Hebrus nourlangiei*
		Merragata hackeri
	NOTONECTIDAE	*?Paranisops sp.*
	CORIXIDAE	*Micronecta* sp.
	BELOSTOMATIDAE	*Diplonychus* sp.
	NEPIDAE	*Laccotrephes sp.*
		Ranatra sp.
	VELLIIDAE	*Microvelia* sp.
DIPTERA		
	ATHERICIDAE	Athericidae spp.
	CHIRONOMIDAE	Chironomidae spp.
		Chironominae spp.
		Orthocladiinae spp.
		Tanypodinae spp.
	CERATOPOGONIDAE	Ceratopogoninae spp.
		Forcypomiinae spp.
	CULICIDAE	Culicidae sp.
	SIMULIIDAE	Simuliidae sp.
	STRATIOMYIDAE	Stratiomyidae spp.
	TABANIDAE	Tabanidae spp

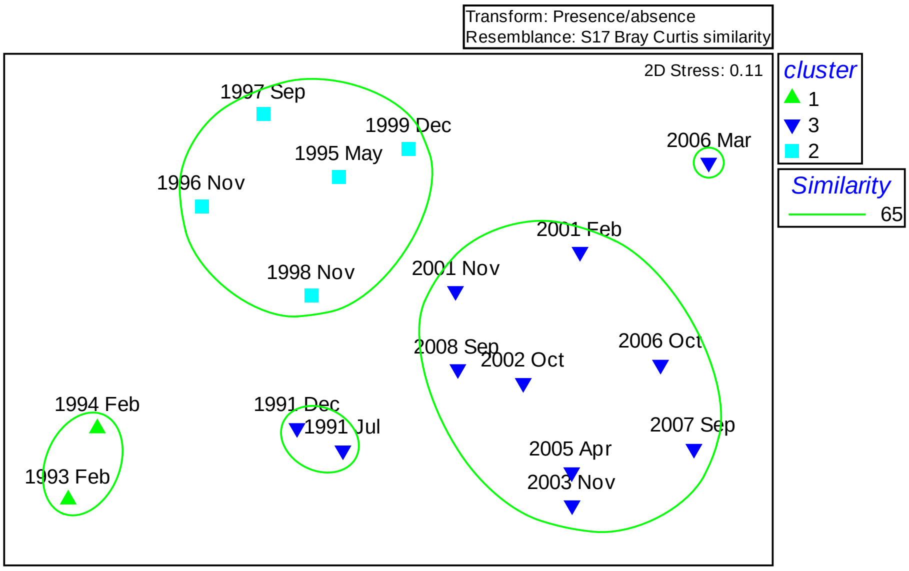
	TIPULIDAE	Tipulidae spp.
	DOLICHOPODIDAE	Dolichopodidae spp.
	SCIOMYZIDAE	Sciomyzidae sp.
LEPIDOPTERA		
	PYRALIDAE	Nymphulinae spp.
TRICHOPTERA		
	ECNOMIDAE	*Ecnomus* sp.
	HYDROPSYCHIDAE	*Cheumatopsyche modica*
	LEPTOCERIDAE	*Oecetis* sp.
		Triplectides ciuskus seductus
		Triaenodes sp.
		Notalina sp.
		Leptocerous atsou
		Leptoceridae sp.
	HYDROPTILIDAE	*Hellyethira/Acritoptila* sp.
	PHILOPOTAMIDAE	*Chimarra uranka*
	POLYCENTROPODIDAE	Paranyctiophylax sp. AV5
COLEOPTERA		
	DYTISCIDAE	*Allodessus bistrigatus*
		Batrachomatus wingi
		Bidessodes flavosignatus
		Bidessodes denticulatus
		Boongurrussp.
		Copelatus nigrolineatus
		Cybister tripunctatus
		Eretes australis
		Onychohydrus scutellaris
		Hydroglyphus daemeli
		Hydroglyphus trilineatus
		Hydroglyphus leai
		Hydrovatus ovalis
		Hydrovatus rufoniger
		Laccophillus sp.
		Hyphydrus elegans
		Hyphydrus lyratus
		Hyphydrus contiguus
		Laccophilus sharpi
		Liodessus ?dispar
		Limbodessus compactus
		Necterosoma regulare
		Platynectes decempuctatus
		Rhantus sp.
		Spencerhydrus pulchellus
		Sternopriscus sp.
		Tiporus tambreyi
		Onychohydrus sp. (L)

	Tiporus sp. L
	Hyphydrus sp (L)
	Hydrovatus sp. (L)
	Tribe Bidessini spp. (L)
	Dytiscidae (L)
	Dytiscidae sp indet
HYDROPHILIDAE	
	Berosus dallasi
	Berosus sp. (L)
	Berosus sonjae
	Coelostoma fabricci
	Enochrus deserticola
	Enochrus eyrensis
	Helochares percyi
	Helochares tatei
	Paracymus spencerii
	Paranacaena sp.
	Regimbartia attenuata
	Sternolophus marginocollis
	Hydrophilidae spp. (L)
HYDROCHIDAE	
	Hydrochus sp.
HYDRAENIDAE	
	Hydraena sp.
	Octhebiinae sp.
ELMIDAE	Austrolimnius sp. (L)
	Austrolimnius sp.
GYRINIDAE	Macrogyrus sp.
CARABIDAE	Carabidae spp.
STAPHYLINIDAE	Staphylinidae spp.
SCIRTIDAE	Scirtidae spp. (L)
LIMNICHIDAE	Limnichidae sp.
NOTERIDAE	Neohydrocoptus subfasciatus
	Hydrocanthus waterhousei
SPERCHEIDAE	*Spercheus* sp.

APPENDIX 4. MULTIVARIATE ORDINATION OF MACROINVERTEBRATE ASSEMBLAGES

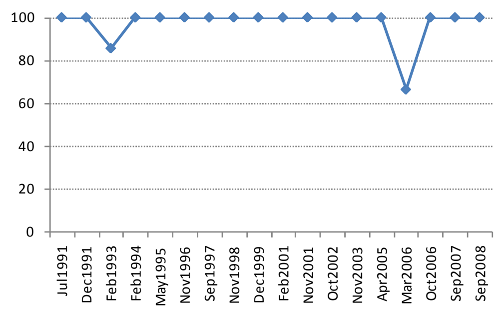


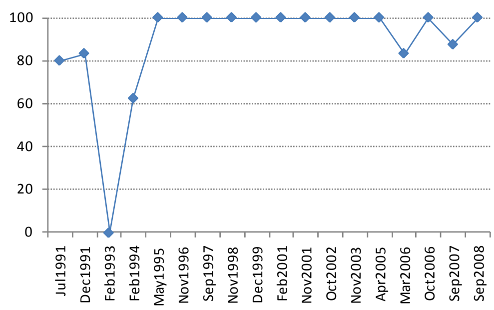
Ordination of macroinvertebrate presence/absence at all sites for all years based on family level classification (seasons overlaid).

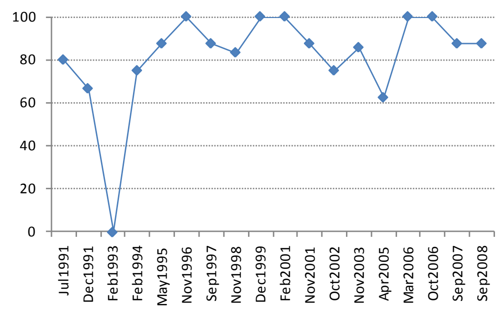


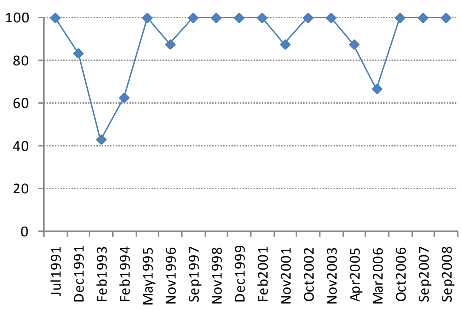
Ordination of macroinvertebrate presence/absence for all years based on family level classification (classification groupings overlaid).

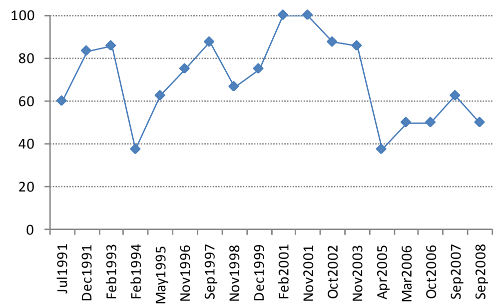
APPENDIX 5. SPATIAL VARIATION IN FISH SPECIES (% OF SITES) ACROSS SAMPLING EVENTS

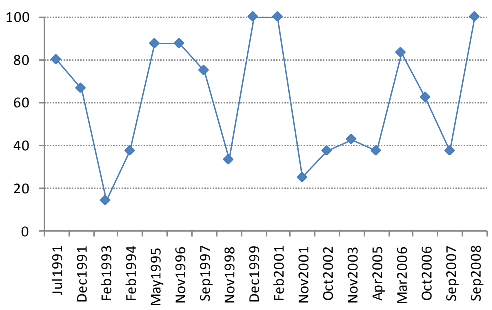

Rainbow-fish

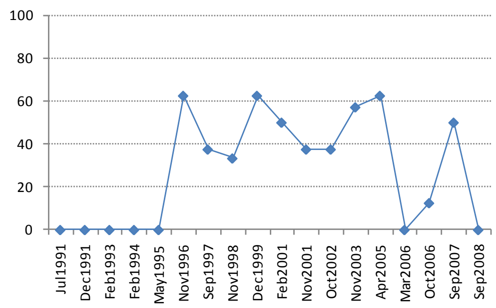

Spangled Perch

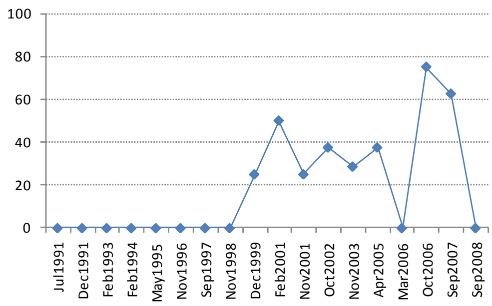

Barred Grunters

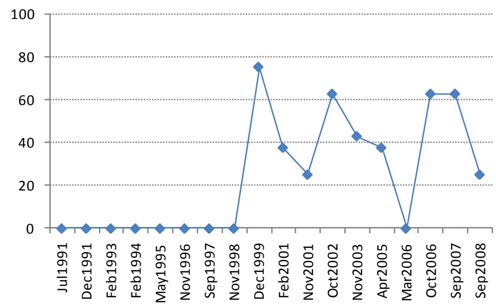

Fortescue Grunters

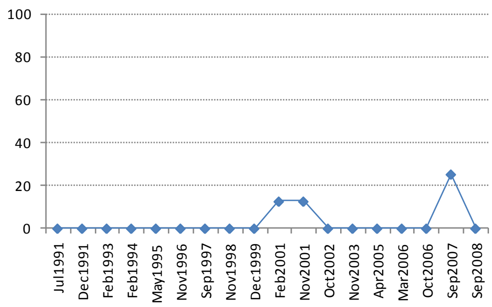

Bony Bream


Catfish

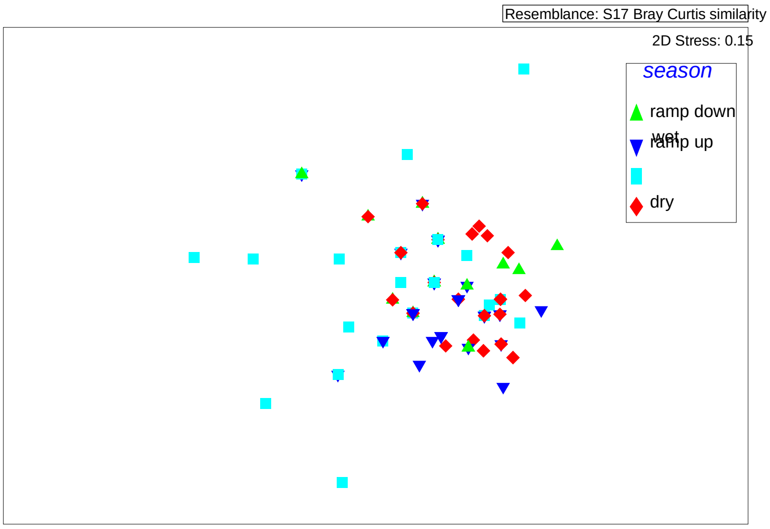

Ox-eye Herring


Mangrove Jack

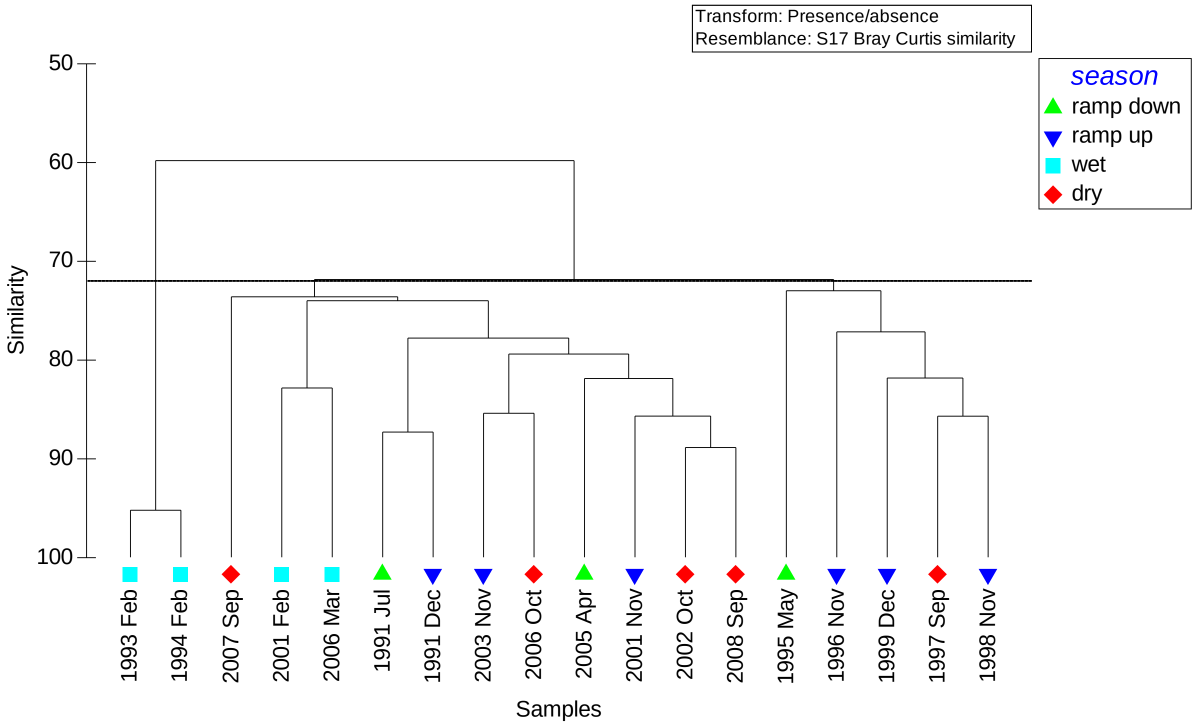

Striped Butterfish (Scat)


Silver biddy

APPENDIX 6. SPATIAL VARIATION IN FISH SPECIES (% OF SITES) ACROSS SAMPLING EVENTS



MDS Ordination on the p/a of species recorded for each pool across years showing greater variation fish assemblages during wet season sampling.



Dendrogram produced from a cluster analysis of fish species recorded for each year.