Environmental Water Management in the Fitzroy River Valley

Information availability, knowledge gaps and research needs

Bradley J. Pusey
The University of Western Australia

&

Jarrod Kath
Western Australian Department of Water
Executive Summary

The Fitzroy River is the largest river in the Kimberley region of Western Australia and contains significant biological, conservation and geoheritage values. Socio/cultural values, especially Indigenous values, are significant also but are not considered here. Current land use is dominated by rangeland grazing and very limited irrigated agriculture. The water resources of the basin are significant and potentially available for expanded agricultural development but the impact on the environment of increased water use, especially of groundwater is largely unknown. The current report addresses the availability of information that could be used to guide the formation and implementation of management strategies aimed at maintaining existing values. Currently available information useful in this regard is highly limited. Moreover, available information was found to be rarely in a form (i.e. quantitative relationships between flow and environmental factors) that would enable a full assessment of the impacts of different water resource use scenarios to be undertaken. Similarly, there is limited information that could provide the basis for ongoing assessment (i.e. monitoring) of the efficacy of any imposed water management strategies.

Significant knowledge gaps were identified relating to five major themes:

1. The nature of aquatic habitats in the basin and their relationship to the flow regime and groundwater and including identity, extent and distribution, connectivity and conservation value;
2. Responses of riparian, floodplain and groundwater dependent vegetation to changes in water regime;
3. Responses of individual biotic elements and assemblages to changes in water regime and habitat structure and ecological interactions between elements and within assemblages;
4. The nature of the foodweb sustaining assemblages in different water bodies and its relationship to the flow regime, habitat structure and dependency on ground water inputs during the dry season; and
5. The absence of information concerning interactions between flow dependent phenomena and other non-flow related factors that may either exacerbate flow related impacts or obscure changes in environmental values in response to water regime change and thus lessen the capacity to evaluate the efficacy of environmental water management plans.

A significant research effort is needed to address these knowledge deficiencies and recommendations as to the nature of required investigations are made. A total of 22 distinct and separate research projects is proposed. Nine of the 22 projects are short-term in nature and are designed to make use of existing data to determine whether such data can provide useful guidance or specific flow ecology relationships. Long-term projects, in contrast, are field based and designed to gather new information which can be synthesised to provide quantitative flow ecology relationships. Each addresses one or more of the themes detailed above.


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values, provide important ecological background, provide quantitative flow ecology relationships and establish baselines against which future management strategies may be addressed is also given.
1 Introduction

Environmental water management is the delicate and complex art of balancing competing demands from a diversity of stakeholders for a limited supply of water. Balancing the competing demands on a limited water supply is critical for ensuring the long term future of that supply and a sustainable, minimally impacted future for those elements of the environment and society dependent on that water. Achieving that balance is entirely dependent on the quality and applicability of available information. Given the complexity of issues involved, information on the different ways in which value is ascribed (i.e. varying values may be ascribed relative to customary, spiritual, recreational, ecological and economic perspectives), the complexity and diversity of stakeholders and the diversity of outcomes (not all of which are acceptable to all stakeholders) that may arise from the process (Figure 1.1).

Figure 1.1. Sequential change in scope of participants, theoretical underpinning and scale of focus (evolving dimensions) within the process of environmental water allocation and management (source – Poff and Matthews 2013).

Environmental water management has evolved greatly since it first began to be practiced in the mid 1970s (Poff and Matthews 2013) (Figure 1.1). Initially, environmental water management was focussed on a small number of species (usually salmonids) and centred upon the maintenance of appropriate amounts of habitat. Although the sophistication of this approach increased over the next decade and a half, the process remained focussed at this level. By the 1990s however, researchers (mainly ecologists and hydrologists) began to take a wider view of the field, incorporating elements of ecological theory (i.e. intermediate disturbance hypothesis, river continuum concept, floodpulse concept), a more nuanced and empirical view of the nature of the flow regime and its components, and an expanded spatial scale of appreciation of the riverine landscape in recognition of the interconnectedness of the riverine landscape and adjacent ecosystems. This development is evident in, and led by, two seminal publications. The first, by
Arthington et al. (1992), enunciated the holistic and interconnected nature of the riverine landscape, identified different elements of the flow regime and the geomorphic and ecological functions that were dependent on them, stressed that the beneficiaries of environmental water management extended beyond fish to include a much wider range of faunal and floral groups and included important processes such as water quality management, water conveyancing, stream-channel maintenance, intra alia.

It must be stressed that the Holistic Approach enunciated by Arthington et al (1992) was not a methodology for arriving at the derivation of environmental water allocations, but a philosophical view about how allocations must be derived in full recognition of the totality of the relationship between the flow regime and riverine ecology and geomorphology. One strongly emphasised element of the Holistic Approach, possibly because its proponents were mostly either Australian or South African, was that variability at a variety of temporal scales is a key feature of the flow regime, has important implications for aquatic ecology and must be included in environmental water management.

The second seminal publication was that of Poff et al. (1997) who proposed the Natural Flow Paradigm in which the flow regime occupies primacy of influence of the contemporary and historical ecology of riverine ecosystems and species. It also identified six key independent elements of the flow regime; magnitude, timing, frequency, duration, rates of rise and fall, and predictability. Following from this, sets of hydrologic metrics were identified that could be used to characterise each of these elements of the flow regime to collectively and quantitatively describe a particular flow regime and by extension, how different a modified flow regime was from its natural expected state (Richter et al. 1996; Olden and Poff 2003).

Progressive increases in the number of “players” in the process and an expansion of the number of legitimate stakeholders involved to include indigenous peoples as well as downstream industrial or business interests (such as commercial fisheries or white water rafting, houseboating or a range of other tourist oriented activities) added further to the complexity of environmental water management. Increasingly a more quantitative understanding of the relationship between flow and ecology and between levels of development and hydrologic alteration (and consequently between development and ecological disturbance) was seen as needed to guide decision making. Furthermore, in recognition that such information wasn’t always available, the view emerged that insights or information about flow ecology relationships gathered from elsewhere could be applied to rivers. However, the extent to which they could be validly transferred was seen as dependent on the biogeographic and evolutionary differences in fauna of the two regions, geomorphologic and landscape equivalence (i.e. flow ecology relationships are likely very different in a braided river compared to a meandering one) and similarity of flow regimes.

The development of quantitative models of flow ecology relationships and flow regime classification (Kennard et al. 2010) to discern what rivers might viably provide transferable information) thus became an important part of the environmental water process. Flow ecology relationships provide, at best, indication of what discharge is needed to sustain particular processes and at least an indication of whether the relationship is linear (i.e. the state of a dependent variable decreases or increases linearly as discharge changes) or whether it is a stepped function (i.e. there exists a
threshold value). These developments are a key feature of the ELOHA (Ecological Limits of Hydrologic Alteration) approach Poff et al. 2010).

Irrespective of what approach to environmental water management provides the underpinning of any river specific management endeavour or what methodologies (of which there are many) are applied in the process, the availability and quality information related to environmental or ecological relationships with the flow regime is paramount (Arthington 2013).
2 Information related to flow/ecology relationships in the Fitzroy River

This report concerns the identification of available information to guide environmental water management in the Fitzroy River Valley (hereafter FRV), north-western Australia. It also concerns the identification of important knowledge gaps and what research, in both the short and long term, is needed to fill these gaps and provide the necessary quantitative information to ensure that the water resources of the FRV are used and managed in a sustainable manner (Figure 2.1). To an extent, this process follows that outlined as the best practice framework first developed by Arthington et al. (1998) and further refined in Arthington (2013). This framework recognises that in order for the best practice to arise, the separate endeavours of quantifying available water resources, deciding what elements of the flow regime can be harvested or stored (ie. groundwater vs flooding harvesting vs dry season abstraction) and decisions about how much, when and to where water is to be allocated must proceed in lock step with investigations of the flow ecology of the river and the potential impacts of that water use.

The water resources of the FRV have been identified as potentially significant and crucial to the expanded development of agriculture in the region (see below). What might be the consequences of increased agricultural water use on the ecology of the river? Our aim here is to identify the environmental values and associated data sources available for assessing the consequences of increased water use and where necessary identify what research is needed to guide the process. We also recognise that environmental water management is an iterative process of adaptive management and have accordingly identified existing research gaps that may confound any future assessment of the efficacy of an imposed water resource plan. It is important to recognise that environmental condition is not solely dependent on the flow regime but also influenced by processes that may be ongoing or novel in the surrounding catchment as well as non-flow related processes that may occur within the aquatic environment.

The structure of the remainder of this report concerns first an overview of the catchment (section 3), followed by a discussion of potential future agricultural developments (section 4). In this section, we identify where in the catchment such development is most likely to occur (in the most general sense) and identify what elements of the flow regime (groundwater vs surface water, flood harvesting etc) are most likely to be utilised. This is important as such differences are likely to result in very different hydrologic changes with potentially very different ecological outcomes. This is followed by a short discussion of what hydrosystems are present in the FRV and their relationship with the flow regime and what conservation values and conservation structures exist within the catchment (section 5). The largest section (6) concerns water/flow dependent assemblages (e.g. fish and waterbirds) and processes examined separately for each assemblage type. In section 7, we attempt to integrate flow dependencies and information availability and needs across the groups covered in section 6.
Figure 2.1. Potential timeline for the identification of available information and knowledge gaps (research needs) for the Fitzroy River in light of increased water resource use.
Throughout the body of the report, we have identified short-term and long-term research projects that are designed to fill existing knowledge gaps and provide the necessary information to allow an assessment of the potential impacts of different flow management scenarios. Short-term projects primarily involve synthesis of existing data into a form useful for environmental water management and are mostly, but not entirely, desk-top in nature. Longer term projects are field-based and address knowledge gaps that more on-ground data is needed to address. Moreover, such projects need to consider temporal (seasonal and interannual) variation and accordingly must extend over a longer time period. A synthesis of these short and long-term projects is provided in section 7. Some of the long-term projects could be usefully undertaken as postgraduate study projects (i.e. PhD). We identify existing data sets that may be of use in Appendix 1.

We make no attempt to assess the availability, or lack, of sociocultural information necessary to implement a considered environmental water strategy, aware that such a review will be undertaken elsewhere. However, we highlight the fact that much traditional ecological knowledge resides in the communities of the FRV and that to ignore such a valuable source of information in the absence of a robust scientific knowledge base seems unwise. Moreover, indigenous peoples of the FRV may have very different views to other stakeholders on values applied to particular biological or hydrological elements within the FRV (Jackson et al. 2014). For example, the value of fish derived from the river assumes great customary importance during periods of mourning for some groups within the FRV (Toussaint 2014). Furthermore, riverine production is a critical component of the household economy of many indigenous people within the FRV (Jackson et al. 2011) and the harvest activities of indigenous (and of non-indigenous) people is an important influence on the river’s ecology (Close et al. 2014).
Overview of the geomorphology, climate, hydrology and landuse of the Fitzroy River Valley

3.1 Geomorphology
The Fitzroy River Valley (FRV) covers about 90,000, km$^2$ in the north-west of Australia (Saynor et al. 2008). The upper catchment of the FRV is characterised by bedrock and bedrock confined and constrained rivers predominate. Bedrock confined rivers typically originate downstream of gorges. Within bedrock confined rivers, pools normally have a sand base, while riffles are made of gravel, boulders and/or bedrock. Pools in these systems can also persist through the dry season. Moving to the lower FRV anabranching rivers come to dominate (Saynor et al. 2008). Other river types (e.g. Meandering Rivers), while present in the FRV only cover a small area (Saynor et al. 2008).

3.2 Climate
The climate of the FRV is characterised by a distinct wet summer season (November-April) and dry winter season (May to October) (BoM 2015). The climatic classification of the FRV is predominantly grasslands with winter droughts, with small parts of the north-east classified as tropical savanna (BoM 2015).

Mean average annual temperate in the FRV ranges from around 26 °C in the south to 24-25 °C in the north, with the highest mean annual temperatures (around 27 °C) in the middle of the valley (Figure 3.1). Mean annual minimum and maximum temperatures are respectively between (16-21 °C) and (31-35 °C) (BoM 2015). Temperatures also vary substantially between dry and wet seasons. In the wet season mean temperatures range from 26 to 30 °C, while in the dry season mean temperatures range from 21 to 24 °C.

Rainfall in the FRV is inter-annually variable but intra-annually highly seasonal, with around 93 percent falling in the wet season (November-April) (CSIRO 2009). Wet season mean rainfall ranges from 364 to 922 mm, while in the dry season rainfall averages 59 to 177 mm (Figure 3.1, BoM 2015). Rainfall amount and predictability also decrease along a north-south gradient (CSIRO 2009).

Throughout the year APET (Areal potential evapotranspiration) is greater than rainfall and so the region is water-limited (CSIRO 2009).

3.3 Hydrology
The hydrology of the FRV reflects its seasonal climate. Rivers, streams and wetlands of the Fitzroy, range from those that rarely flow, or are inundated only occasionally (e.g. when large storm events occur) to those that flow most or all year round usually because of connections to groundwater. Groundwater aquifer types in the FRV include alluvial aquifers associated with rivers, Canning basin sedimentary rocks, Devonian reef limestone and fractured igneous and metamorphic rocks (Figure 3.2) (CSIRO 2009). The diversity of stream and groundwater systems in the FRV also means the surface-groundwater interactions are extremely complex (Harrington and Harrington 2015). Current knowledge of groundwater and surface-groundwater connections has been recently reviewed in detail by Harrington and Harrington (2015), as such below we only summarise information on surface water hydrology.
Figure 3.1. Mean rainfall in (a) dry and (b) wet seasons across the Fitzroy River Valley. Data is from BoM (2015) for the period 1961 to 1990.

Figure 3.2. Aquifers and groundwater and surface water draw points in the Fitzroy River Valley. The size of the circle representing draw points is proportional to the water allocation for each point. (data source=DoW2015b).
The FRV contains a diversity of hydrosystems largely typified by the wet-dry season dynamics of the region, with stream flow driven by rainfall in the wet and, in places, by groundwater inputs during the dry season. The baseflow index averages around 0.15–0.2 for the entire year (Fitzroy Crossing and Dimond Gorge) but increases to around 0.5 in the dry-season (CSIRO 2009). For Fitzroy Crossing, located in the middle of the valley (Figure 3.3), maximum flows occur in February (ca. mean daily discharge of 800 m$^3$ s$^{-1}$), while minimum flows (100 m$^3$ s$^{-1}$) occur from May to November (Figure 3.3).

Using gauging stations with long-term flow data in the FRV, Moliere et al. (2009) classified rivers and streams as perennial, seasonal and dry seasonal. Seasonal streams had low annual variability, but had no flow for most of the dry season. Perennial streams had low inter-annual variability and only very occasional zero flow days (Moliere et al. 2009). Dry season streams had high inter-annual variability and were dry for most of the year (Moliere et al. 2009). Any dry season flow that does occur is likely from regional groundwater aquifers (Jolly et al., 2000; Jolly, 2002; Moliere et al. 2009).

Mt Pierre Creek was classified as dry seasonal. The lower Fitzroy (downstream of Fitzroy Crossing) is predominantly perennial, while the upper Fitzroy (upstream of Fitzroy Crossing) is seasonal (Moliere et al. 2009).

Kennard et al. (2010) included four gauging locations from the FRV within the continent–wide classification of stream flow regimes. All four were placed within class 10 – predictable summer highly intermittent class, the dominant flow regime class across northern Australia. This study had very stringent criteria for inclusion of gauge data in the classification with respect to length of years of record, concurrency, presence and extent of missing data and extent of regulation. This latter criterion is important as it precluded inclusion of any gauges located downstream of Camballin Weir, thus the perennial signal identified by Moliere et al. (2009) for the lower Fitzroy River was not identified by Kennard et al. (2010). Moreover, it is clear that despite the presence of over 20 stream flow gauges in the catchment (Figure 3.4), there are few that have robust long-term data available.

![Figure 3.3. Mean daily discharge with 95% confidence intervals (blue shaded area) at Fitzroy Crossing from 1983 to 2014. Gauge number 802005. (data source: DoW 2015a)](image-url)
Coupled with high stream flow seasonality there is high inter-annual variability in flows. The stream flow gauges at Fitzroy Crossing, Wilare, Dimond Gorge, Fitzroy Crossing and Fitzroy Barrage, all show years with flows that vary by orders of magnitude between wet-seasons (Figure 3.4). These strong seasonal and inter-annual flow dynamics highlight that there are periods of both very high and very low water availability in the FRV. Incorporation of this level of variability is a key element of any future management strategy.

3.4 Land use – grazing and cropping

Major towns in the region are Derby, Fitzroy Crossing and Halls Creek. Derby and Fitzroy Crossing have estimated populations of 1500 and 5000 respectively (Kimberley Development Commission 2007). The total population of the Shire of Derby/West Kimberley, in which the Fitzroy River Valley resides, is in the vicinity of 12,000 (Kimberley Development Commission 2006). Resource extraction, service delivery, construction, primary production and tourism are the key industries in the valley (Kimberley Development Commission 2007). There are also some 130 Aboriginal communities throughout the valley (van Dam et al. 2008). Major land uses of the area are pastoral (grazing), with areas utilised for mining and some small areas of irrigated agriculture (Figure 3.5). The two main prospects for land use change through agricultural development in the Fitzroy River Valley are increased intensity of grazing, facilitated by centre pivot irrigation to increase fodder production (Grice et al. 2013) and irrigated agriculture for cropping.

The expansion and intensification of grazing (predominantly cattle grazing) will likely be a key driver of land use change in the Fitzroy River Valley. Aside from areas in the south and north, grazing dominates much of the Fitzroy River Valley (Figure 3.5). Grazing is an integral part of the socio-
economics of the Fitzroy River Valley and Kimberley. Cattle accounts for three-quarters of all agricultural outputs from the Kimberley (Deloitte Access Economics 2011).

\[\text{Figure 3.5. The distribution of major land uses in the Fitzroy River Valley. Note that the class ‘production from relatively natural environments’ refers to land use for grazing (source: DoW 2015b).}\]

Notwithstanding its socio-economic importance, grazing is a threat to biodiversity in Australia (National Land and Water Resources Audit 2002 – from Blanch 2008). Riparian, river and wetland habitats are particularly threatened by grazing, as cattle often congregate in and around sources of water and in the shade of riparian vegetation (Pusey and Kennard 2009). In areas where cattle congregate, soil compaction, trampling, degradation and loss of riparian vegetation and aquatic plants occur as does increased sedimentation and increased nutrient inputs from faeces, which decrease water quality (Brock 2003; Robertson and Rowling 2000; Allan 2004; Close et al. 2008; Pettit et al. 2012). Collectively these changes can have significant impacts on hydrology, water quality and aquatic ecosystems. The ecological impacts of expanding and intensifying cattle grazing therefore needs to carefully considered. It is important that any putative impacts of cattle grazing can be disentangled from those that result purely from changes to flow regime to quantify the latter and determine the potential for synergistic changes (Kath et al. in press).

Cropping, in contrast to grazing, is often more intensive but occurs over smaller spatial scales. Cropping requires the clearing and fragmentation of native vegetation and large inputs of pesticides, herbicides, fertilisers and water. The current loss of native vegetation cover in the Fitzroy River Valley is minimal and predominantly relates to land cleared for the Camballin Irrigation project (<0.004% in 2007) (Commonwealth of Australia 2007; van Dam et al. 2008). Clearing of native vegetation from a catchment may reduce water quality, increase sedimentation and alter hydrology.
(e.g. increases rate of run-off). In areas where large areas of native vegetation is cleared, freshwater biodiversity may be severely impacted (Allan 2004; Thomson et al. 2012).

Clearing of vegetation (particularly deep-rooted perennial vegetation), as well as water infiltration from irrigation, can cause groundwater levels to rise, which can cause salinization of both land and water ways (Gordon et al. 2003; Pannell and Ewing 2006). In the Ord River, to the immediate north of the Fitzroy River Valley, irrigated agriculture has been linked with the raising of groundwater levels and groundwater salinization and future productivity of agriculture is threatened as a consequence (Smith and Price 2009; Ali et al. 2010).

Additional to economic impacts on agricultural productivity, the salinization of groundwater tables has serious implications for freshwater biodiversity (Cañedo-Argüelles et al. 2013). Groundwater salinization has been linked to the widespread dieback of Eucalyptus camaldulensis forests of the Murray River floodplain, south-eastern Australia (Cunningham et al. 2011). Groundwater salinization can also compromise the drought buffering functions provide by groundwater fed habitats (e.g. freshwater pools, shallow groundwater that supports vegetation) (Kath et al. in press; McNeil et al. 2013). Consequently, in the FRV if salinity risks are not identified and managed appropriately there is risk that freshwater biodiversity and drought refuges, such as pools and shallow groundwater areas that support groundwater dependent vegetation, could be degraded.

3.5 Catchment disturbance and condition in the Fitzroy River Valley

The collective environmental disturbance of land use changes can be represented by the catchment disturbance index (Stein et al. 2002) which summarises the impacts of human activities, including infrastructure development, land use change and associated pollution that impacts on freshwater ecosystems (Close et al. 2012; Stein et al. 2002). In the Fitzroy River Valley, sub-catchments with high levels are shown in orange and red, while areas of low disturbance are shown in blue (Figure 3.6). The highest levels of disturbance are concentrated around the Fitzroy River, especially in the Margaret River subcatchment (Figure 3.6). In contrast the lowest levels of disturbance occur around the margins of the FRV (Figure 3.6)
Further assessment of catchment condition, specifically of river courses themselves was undertaken in the Framework for the Assessment of Riverine and Wetland Health (Dixon et al. 2010). Condition scores (0 – 1, poor to good) were generated for land use (0.71), fire extent (0.83 for catchment and 0.87 for riparian zone), hydrological disturbance (0.98), water quality (0.71), physical form (0.85), fringing zone (i.e. riparian zone) (0.72) and aquatic biota (macroinvertebrates, fish and aquatic plants) (0.78). An overall score of 0.78 was generated indicating that despite the presence of some impacts the overall condition of the catchment was moderately good. Despite the existence of significant relationships between some indicators and pressure/condition gradient, Dixon et al. (2010) stressed the difficulty in assessing condition in the absence of historical data (or modelled flow data) and the difficulty in identifying reference conditions in light of the widespread nature of cattle grazing.

3.6 Current water use
In the Fitzroy approximately 16 GL yr⁻¹ of groundwater is currently allocated (DoW 2015b). This allocation is spread across some 405 extraction point (bores) across the FRV (Figure 5.2). The greatest levels of extraction occur in the lower Fitzroy, north of the Fitzroy River and in areas south of Fitzroy Crossing.

Key prospects for future groundwater extraction include the Canning Basin aquifers, Poole Sandstone and Grant group aquifers and the Devonian Limestone (Harrington and Harrington 2015). Prior to future development it is recognised that assessment of groundwater resources and levels is required so that the potential impacts of climate change and development on groundwater-dependent ecosystems can be appropriately assessed (CSIRO 2009). For further details on groundwater resources and their potential development see Harrington and Harrington (2015).
Figure 3.7. The flow regime disturbance index for broad (planning) spatial units in the Fitzroy River Valley (after Stein et al. 2002) (Derived from Kennard et al. 2010.)

Groundwater is seen as a key potential water resource for irrigated agriculture in the FRV and as such understanding groundwater extraction impacts on social and environmental values is a high priority (Harrington and Harrington 2015). Of particular concern in this regard is the potential impact of groundwater extraction on species and ecological communities that rely on groundwater to persist.

Groundwater extraction’s main impact is the lowering of the water table so that it is no longer, or less, accessible for some vegetation and stream biota dependent on groundwater waterbodies. Lowering of the water table can also cause rivers to become ‘disconnected’ for greater periods or at times that biota inhabiting streams are not adapted to. For example, many fish, turtles and invertebrates in the Fitzroy River rely on permanent stream pools that are refuge habitats during the dry season. These pools can often be fed by groundwater. The lowering of groundwater tables could cause the loss or degradation of important drought refuges for many species.

Levels of surface water extraction and flow alteration are currently low in the FRV. Throughout the entire FRV approximately 14 GL yr⁻¹ is allocated across 19 draw points (Figure 5.2). These surface water extraction draw points occur in both the upper and lower Fitzroy and are concentrated along the Fitzroy River (Figure 5.2).

Despite surface water extraction being minimal in the Fitzroy, there still may be some impacts on flow regimes. The impacts on water resource development on the flow regime of the Fitzroy River Valley has been assessed by Stein et al. (2002) using the flow regime disturbance index. The flow regime disturbance index provides a summary of the probable impacts of impoundments, flow diversion and levee banks within upstream areas. As expected, in the Fitzroy River Valley, flow regime disturbance impacts manifest downstream of extraction and impoundment points. As such
there are high levels of flow regime disturbance in the lower Fitzroy downstream of Camballin (Figure 3.7). Throughout the remainder of the Fitzroy River Valley flow regime disturbance is very low (Figure 3.7).

3.7 Water quality
Temporal changes in water quality, especially turbidity, dissolved oxygen and temperature, are important determinants of the health of aquatic systems, particularly in refugial pools. The influence of water quality on ecosystem dynamics, especially under a scenario including altered flow regime and increased agricultural development, is likely important and needs to be considered and accommodated within any management plan. We here do not specifically suggest that stand-alone research be directed at forming a river-specific understanding of the dynamics of water quality and its relationship to flow but suggest that most of the research projects outlined below would as a matter of course collect information in this regard and that this information should be integrated to provide the basis for developing this understanding.
4 Potential future water resource use for agriculture

4.1 Focus areas for increased water demand and potential water sources
A range of development options including expanded agriculture, mining and shale gas extraction are possible within the FRV. While mining and gas extraction may potentially use significant amounts of water, they are not considered here. Rather, this report is concerned with the potential impacts of increased water resource use associated with agriculture, as such use and impacts on the river’s flow regime are relatively better known at this point in time. Within the Fitzroy River Valley (FRV), the proposed development of water resources to support agriculture is currently focused along the Fitzroy River between Willare and Fitzroy Crossing. Areas of prospective development include land on Gogo Station, Bunuba, Mt. Pierre Station and Mt. Anderson Station. Nonetheless, we highlight here that water use associated with industries such as mining and shale gas extraction may be significant and would need to be considered if such developments were to eventuate.

Work is underway to assess the potential for groundwater resource use, with a focus on the Fitzroy Valley alluvium and deeper regional aquifers, to support expanded irrigation (Water for Food North Program 2015). Harrington and Harrington (2015) have identified prospective groundwater resources associated with the Canning Basin aquifers, Poole Sandstone and Grant group aquifers and the Devonian Limestone (see Figure 3.2). In addition, the potential to harvest and store floodwater from the river to support agriculture is also being investigated in the vicinity of Gogo Station.

4.2 Impacts of future water use on the hydrograph
The area and amount of water required for prospective agricultural development in the Fitzroy Valley is currently being investigated and estimates to this effect are, as yet, not finalised (see Harrington and Harrington 2015). Nonetheless, regardless of what future agricultural water use demands may be, a key issue is the extent to which this additional water use impacts on specific parts of the hydrograph at specific points in the riverine landscape. Groundwater use is unlikely to impact on wet season flows but may have substantial impact during the dry season when baseflows are much reduced and critical for connectivity, maintenance of refugial pool size and water quality and the maintenance of hyporheic flows. A groundwater allocation considered as only minor when referenced against the total discharge may be a proportionally much larger component when referenced against the dry season flow. As such, this small amount may have considerable ecological importance during the dry season.

Similarly, floodharvesting high in the catchment may have minimal impact on total discharge further down in the river but may have substantial impacts in the upstream reaches that convey this water, especially if those reaches are located in the lower rainfall portion of the catchment. Moreover, flood flows in the drier parts of the catchment may be critical in recharging local aquifers, in connecting off-channel waterholes and wetlands to the river and in determining intra-annual aspects of refugial pool structure (e.g. longevity). Furthermore, if temporal variation in flood flows is pronounced, as is the case when rainfall varies in amount and timing across a catchment, floods from individual tributary systems may be critical in determining the nature of recession flows in the main channel and important in determining the connectivity between the river and its floodplain and the point at which groundwater dominates the hydrograph and starts to control important aspects of refugial pool structure and value.
It is axiomatic that any plans to abstract water (from whatever source) are accompanied by detailed modelling of impacts on all aspects of the hydrograph at multiple locations in the catchment (e.g. Figure 2.1). In the absence of such information to guide this scoping review, we have assumed that the dominant impacts on the riverine environment will occur during the dry season due to groundwater abstraction but have included some consideration of the impacts of changes in the flood portion of the hydrograph where warranted.

5 Hydrosystems and Protected Areas in the Fitzroy River Valley

5.1 Hydrosystem definition

Although there are numerous ways to define different aquatic ecosystem types within the riverine landscape the Australian National Aquatic Ecosystem (ANAE) Classification Scheme (Auricht 2010) has been widely applied and forms the underlying classification scheme for the recent assessment of conservation values of aquatic systems of northern Australia (Kennard et al. 2011) and future assessments of the water resources of the region (Close et al. 2012). This classification scheme emphasise the connectivity between different ecosystem or hydrosystem types, a critical feature in aquatic ecology, and their dependence on the amount and temporal availability of the water that sustains them. The different types of hydrosystems are listed in Table 5.1.

Table 5.1. Hydrosystem types present with the Fitzroy River Valley (after Auricht 2010).

<table>
<thead>
<tr>
<th>Hydrosystem</th>
<th>Ecotypes present within the Fitzroy river Valley</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estuarine</td>
<td>Semi-enclosed embayments receiving sea water and freshwater inputs, mangrove forests, saltmarshes, saltflats, intertidal flats</td>
</tr>
<tr>
<td>Riverine</td>
<td>Rivers, streams and waterbodies that may have fringing aquatic vegetation (but not including the hyporheic zone)</td>
</tr>
<tr>
<td>Palustrine</td>
<td>Floodplains and vegetated wetlands such as marshes, bogs and swamps, including small, shallow, permanent or intermittent waterbodies</td>
</tr>
<tr>
<td>Subterranean</td>
<td>Groundwater environments including the hyporheic zone and undergrounds streams, lakes and water filled voids and including springs</td>
</tr>
<tr>
<td>Artificial</td>
<td>Reservoirs, farm dams, mine tailings dams, flood irrigated fields, canals and drainage channels</td>
</tr>
</tbody>
</table>

5.1.1 The Fitzroy River estuary and associated King Sound

The Fitzroy River estuary occupies 0.62% of the total area of the basin (Ward et al. 2011) and is suggested to be part of a globally unique system (with the tidal delta and King Sound) (Semenuik and Brocx 2011). The delta is a classic tide dominated delta with tidally oriented shoals and inter-shoal channel ways. Tidal mud flats are very extensive (Figure 5.1). Semenuik and Brocx (2011) describe the delta as having a very complex stratigraphic sequence that suggests that King Sound is partly filled by terrigenous sediments (at least its proximal portion) delivered by its contributing basins, of which the Fitzroy River is dominant. The present-day extensive saltflats have been developed by extensive sheet erosion of supratidal flats which were previously covered by grasses. Semenuik (1981, 1982) suggest that King sound is slowly infilling with sediment. Although tidal pumping and TEP (transparent exopolymeric particles – marine snow) are...
responsible for trapping fine sediment in King Sound in the dry season, Wolanski and Spagnol (2003) suggest that sediment is, in contrast, accreting on the flats.

The estuary (and King Sound) supports only a thin band of mangroves on its margins (165km$^2$) separating the supratidal flats from the intertidal salt and mudflats. Biotic communities in Doctors Creek have been studied as part of the impact assessment process for a proposed tidal power facility (http://www.tidalenergyaustralia.com/draftEIS/1_Environmental%20Impact%20Statement_SUMMARY.pdf). Mangrove communities were examined as part of the assessment process http://www.tidalenergyaustralia.com/draftEIS/Appendix%20D_%20Paling%20Mangrove%20Assemblages%20in%20Doctors%20Creek%20Derby%20and.pdf. The community consisted of 11 species, one of which Bruguiera parviflora was considered rare. The diversity of mangrove invertebrate communities has been partially described and the richness of both mangrove tree species and invertebrate species is reported to be consistent with that expected given its latitude (Hanley 1995). The flora and fauna has been described as typically tropical Indo-west Pacific and most species are widely distributed and turbidity tolerant (Hanley 1998).
Figure 5.1. Map of the Fitzroy River estuary and proximal portion of King Sound (from Semenuik and Brocx 2011).

Little else is known of the mangrove system of the estuary particularly with respect to its dependency (or otherwise) on discharge from the Fitzroy River (but see section 6.5.2). Comparatively little research has been conducted on the marine science of the Kimberley region in general and King sound in particular. One unknown is the extent to which riverine and estuarine production contributes to the food web of the Sound and to the marine zone in general. Research addressing this issue has commenced but is in its very early phases (i.e. Western Australian Marine Science Initiative) (Andrew Revill, CSIRO, pers. comm.). Brewer et al. (2007) inferred that freshwater inputs were important in near-shore coastal productivity dynamics of the Kimberley region but the extent of dependency is largely unknown. Knowledge gaps concerning the estuary are addressed in section 6.

5.1.2 Riverine hydrosystem

The Fitzroy River Catchment comprises approximately 23% of the area of the Kimberley region and includes internationally significant geological sites such as the Devonian reef system (e.g. Geike Gorge) and Mimbi Caves. The Fitzroy River system is characterised by a braided channel, anabranching and billabongs on the floodplain, and significant lowland floodplain storage. Deep permanent pools occur along its whole length separated by shallower reaches. The upper catchment of about 45,000 km² (upstream of Fitzroy Crossing) can be divided into the catchments of the Margaret and Fitzroy Rivers (Ruprecht and Rodgers 1998). The river has a significant storage capacity below Fitzroy Crossing and is characterised by braiding and anabranching (Storey et al. 2001).

Wallace et al. (2012) (in Close et al. 2012) employed remote sensing data over a three year period to examine the dynamics of pool formation, size and longevity in the middle section of the Fitzroy River. Irrespective of the size of the preceding wet season flood, pool number was approximately equal across years by the mid dry season. This similarity was suggested to reflect the fact that the existence of refugial pools is sustained by groundwater contributions but that groundwater inputs were not sufficiently large to balance evaporative water loss. Harrington et al. (2011) have investigated surface-groundwater connectivity in selected pools in the lower Fitzroy River, identifying likely contributing aquifers. However, these surface-groundwater connectivity values have not as yet been linked to pool dynamics. Combining the approaches of Wallace et al. (2012) and Harrington et al. (2011) may provide valuable information about the importance and sources of groundwater driving pool dynamics in the Fitzroy River.

The initial phase of fragmentation (from a single long pool at bank full stage) was accompanied by an increase in the number of pools as flow dropped, followed by a subsequent decline in pool number as some of the smaller pools dried out completely. Pool area, in contrast, declined steadily as the dry season progressed and in the driest year examined, decreased to only 7% of the maximum area (i.e. at bank full). Median pool size was between 0.3 and 0.5 km² but was just over 1 km² in the wettest year examined. Wallace et al. (2012) developed statistical relationships between daily discharge and pool size and number, which were suggested to be potentially useful in identifying critical threshold values. However, the relationships developed are based on three years of data and remain to be validated. None-the-less, this research appears to be the only available to guide
environmental water management concerning the relationships between flow regime and habitat quantity and quality.

There appears to be no integrated or cohesive description of the geomorphological nature of the Fitzroy River, the processes responsible for its current form or of the arrangement of habitat types throughout the river basin and the connectivity between them. This is a substantial knowledge gap and an impediment to informed management. Moreover, there appears to be no description of the relationship between physical riverine form and socio-cultural values that may be attached to various locations that would allow an assessment of how these spatio-cultural relationships might be impacted by increased water resource use.

**Potential research project 1. Develop an integrated description of the riverine environment of the Fitzroy River, assess and extend applicability of existing habitat/flow relationships and provide geospatial context for significant cultural values**

**Time Frame** – short term

Using available data sets (e.g. TRaCK Digital Atlas – Auricle, Stein et al. (2002)) and remote sensing data develop a comprehensive and quantitative description of the nature of the riverine environment. Assess the value and need for further development of existing relationships between flow regime, surface-groundwater connectivity and habitat (refugial pools and floodplain wetlands) in the river and if needed, extend these relationships by incorporation of more data and extend spatial relevance of existing relationships. A geomorphological/spatial context of potential development and water resource use is an important precursor for effective development of research projects and assessment of potential impacts of water resource use.

5.1.3 Palustrine hydrosystems

The floodplain from Fitzroy Crossing to Looma is often extensively inundated by monsoon rain. Unlike many rivers of northern Australia, in which floodplains are typically terminal (i.e. near the river mouth and adjacent to estuarine reaches), the floodplains of the FRV extend laterally from the river over much of the river’s length. Wallace et al. (2012) identified a total of 30 floodplain wetlands greater than 6 ha in area in the catchment (over the reach spanning 0-261 km river kilometres from the mouth). There a many more floodplain wetlands smaller than this however (see Figure 2.8 in Ward et al (2011) for example). Of these, 5 were not perennial. The minimum size of both perennial and non-perennial wetlands was about 7 ha (i.e. lower size limit for inclusion) but the maximum size of the non-perennial wetlands was 108 ha as opposed to 250 ha for Le Lievre, 380 ha for Mallala Swamp II and 469 ha for Camballin floodplain.

Wallace et al. (2012) modelled the inundation dynamics of the floodplain using a combination of topographic, conveyancing and hydrological data and validated the outcome using MODIS data for a small number of recent floods of known magnitude (2002, 2007). Larger floods inundate more area, connect more wetlands and connectivity remains in place for a longer period. Ten out of 30 wetlands did not connect to the river by overbank flows during the 2007 event which was a relatively small flood (1.5 year ARI). More wetlands (27/30) connected to the river during the larger
The average period of connectivity was 8 days in the smaller flood and 11.2 days in the larger. The larger floodplain wetlands mentioned above were inundated for 20, 21 and 22 days, respectively, in 2007 and 21, 24 and 27 days in 2002. Some wetlands connect in relatively small and frequent floods and others only connect in much larger, less frequent floods. Wetlands in the lower part of the floodplain tend to have greater connectivity because of the longer duration of inundation in this area. Additional information on inundation dynamics can be found at http://atlas.track.org.au/maps/inundation-frequency#fitzroy.

Figure 5.2. Aquifer types and location of major springs and groundwater monitoring sites in the FRV. (Source: DoW 2015b)

5.1.4 Subterranean hydrosystems
The groundwater aquifers underlying the FRV are described in section 3.3 and depicted in Figure 3.2 and further described in detail in Harrington and Harrington (2015). Cave systems are also present in the basin but poorly mapped. There are numerous springs throughout the catchment (Figure 5.2). The extent to which they provide important habitat for fauna and their vulnerability to water resource use is discussed in section 6.4, however it is very likely that there is significant variation in fauna present in springs vs shallow surficial aquifers vs deeper aquifers. Moreover within each, there is likely to be significant spatial variation related to position in the catchment and associated with aquifer age, chemical composition and extent of isolation.

5.1.5 Artificial
There are only two major artificial water storages in the catchment – 17 Mile Dam on Liveringa Station and the pool formed by the weir at Camballin. Issues associated with the latter are discussed in section 6.5.5

5.2 Protected areas
Kennard et al. (2010) identify the FRV as containing high conservation values when all criteria are integrated. Most areas of high value are clustered around the river channel itself and in the lower reaches of the catchment. Few of these high value areas are protected by State or Federal designations as important or contained within protected areas: almost none of the basin is contained with IUCN designated protected areas (see Figure 9.1 in Kennard et al. 2010), there are no listed RAMSAR sites within the basin, and the Camballin Floodplain (Le Lievre Swamp system) is the only wetland listed in the Federal Directory of Important Wetlands (http://www.environment.gov.au/system/files/resources/18f0bb21-b67c-4e99-a155-cb525398568/files/directory-ch12.pdf). (McJannet et al. (2009) identified only the Camballin floodplain and Geike Gorge (which is located in a very small (~31km²) National Park) as high value ecological assets in the Northern Australian Sustainable Yields project.
6 Water dependent assemblages and processes

6.1 Riparian and floodplain vegetation
Plant species occurring at the terrestrial-water interface of streams and wetlands, as well as across the floodplain are generally referred to as riparian and floodplain vegetation (hereafter collectively referred to as riparian vegetation). In the wet-dry tropics, vegetation of the riparian zone stands out as obvious green strips of vegetation that run throughout a sparsely vegetated savanna landscape (Dixon et al. 2011). Vegetation inhabiting riparian and floodplain zones is well adapted to the particular flooding regimes and groundwater dynamics that occur in these areas. If flooding and groundwater regimes are altered, either because of climatic changes or water resource development then changes in the condition, extent and composition of riparian and floodplain vegetation will likely follow. Managing these hydrological changes so that water can be used for agricultural development, while also maintaining the many important values associated with riparian vegetation (Pusey and Arthington 2003) is therefore a key challenge for environmental water management in the Fitzroy River Valley.

In the Fitzroy River Valley (FRV), environmental water management issues surrounding riparian and floodplain vegetation concern three broad topics:

1. identifying the distribution of high value/priority riparian and floodplain vegetation communities and species (specifically groundwater dependent vegetation);
2. quantification of the water requirements for key riparian and floodplain communities; and
3. maintaining links between riparian and floodplain vegetation and broader ecosystem functioning (e.g. maintaining habitat structure to support dependent bird and mammal species).

6.1.1 Identifying the distribution of high value riparian and floodplain vegetation (including mapping of groundwater dependent communities)
To manage riparian vegetation an essential first step is to know its distribution and the variety of species present. In the FRV, only coarse level vegetation community mapping is available (Figure 6.1) (Tille 2006). This broadly identifies areas of active, stable and alluvial floodplains (chiefly in the lower Fitzroy, Figure 6.1) that are likely to be inhabited by vegetation communities sensitive to hydrological changes. These include woodlands and cracking clay plains supporting Mitchell grass and ribbon-blue grass grasslands. On Alluvial plains, beefwood-bauhinia low woodland may also be sensitive to flooding regimes.

These broad vegetation classifications, while providing a useful starting point, are relatively coarse and do not indicate how sensitive each of the vegetation communities are to changes in hydrology – a necessary piece of information for environmental water management in the region.

Additional to this broad scale mapping, there have also been a limited number of one-off surveys and research on riparian vegetation within the Fitzroy River Valley. Vegetation observed in riparian and floodplain areas from these surveys was covered by Storey et al. (2001) and is summarised in Table 6.1. Storey et al. (2001) also surveyed the condition of riparian vegetation at nine different sites of the Fitzroy River and concluded that its overall condition is good. However, based on their review Storey et al. (2001) also concluded that there is little knowledge about the number and distribution of priority riparian taxa in the Fitzroy River Valley.
6.1.2 A special type of riparian vegetation - Groundwater dependent vegetation

Groundwater dependent vegetation includes species that require groundwater at any stage of their life-cycle in order to maintain their condition or persist in a particular location. Riparian and floodplain vegetation communities are often groundwater dependent, but not exclusively so, with woodlands and other vegetation types also using groundwater (O’Grady et al. 2010).

There are many species that occur in riparian and floodplain areas of the FRV that are likely to be groundwater dependent (approximately 40 different species - see Table 6.2). For example, many riparian tree species, including some *Melaleuca* species, obtain much of their water from groundwater during the dry season (O’Grady et al. 2006). Groundwater dependent vegetation, while most likely to be trees and shrubs, may also be herbs and climbers. A list of possible groundwater dependent vegetation in the FRV is given in Table 6.2, along with their common name and habit.
**Table: Riverine Vegetation**

<table>
<thead>
<tr>
<th>Species List</th>
<th>Location</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalyptus camaldulensis, Nauclea orientalis, Tristania grandiflora, Melaleuca argentea, Melaleuca leucadendra, Terminalia platyphylla, Eucalyptus affin. papuana, Pandanus aquaticus and Acacia suberosa</td>
<td>Riverine systems in the King Leopold Ranges</td>
<td>Beard 1979</td>
</tr>
<tr>
<td>Melaleuca leucodendra and M. argentea, an un-named Melaleuca sp, Eucalyptus camaldulensis, Barringtonia acutangula, Ficus racemosa, F. ronulata, F. hispida, Nauclea orientalis, Pandanus sp. and sedgeland (Phragmites karka)</td>
<td>Vegetation of Geikie Gorge consists of riverine forest</td>
<td>(Beard 1979, 1990). Storey et al. 2001</td>
</tr>
<tr>
<td>Eucalyptus microtheca occur within a fringing woodland of E. camaldulensis and Terminalia platyphylla along channels</td>
<td>North Fitzroy Plains - Close to principal drainage lines,</td>
<td>(Beard 1979, 1990). Storey et al. 2001</td>
</tr>
<tr>
<td>E. microtheca savanna with fringing woodland of E. camaldulensis and Terminalia platyphylla along the main channels, and may be associated with Ficus coronulata, F. racemose, Lophostemon grandiflorus, Adansonia gregorii and Nauclea orientalis. Many smaller tree species such as Melaleuca spp, Lysiphyllum cunninghamii, Acacia spp, Brachychiton spp, Planchnia careya and Pandanus spp. form a dense fringe to the channel.</td>
<td>Upper Fitzroy Floodplain</td>
<td>(Beard 1979, 1990). Storey et al. 2001</td>
</tr>
<tr>
<td>Dominant fringing tree species is Eucalyptus camaldulensis with Terminalia platyphylla along the main channels. These key species are associated with Ficus coronulata, F. racemosa, Lophostemon suaveolens, Nauclea adunatus, Andersonia gregorii and E. polycarpus</td>
<td>Upper Fitzroy (above Alexander Island)</td>
<td>-</td>
</tr>
<tr>
<td>E. papuana with various species of perennial bunch grasses, Eucalyptus microtheca is the dominant tree in the levee back slope areas, with perennial bunch grasses and few shrubs and forbs as the understorey. Further downstream, the levee back slopes are populated by scattered Lysiphyllum cunninghamii and Eucalyptus microtheca.</td>
<td>Upper Fitzroy (above Alexander Island)- levee crests - often 1 km wide</td>
<td>-</td>
</tr>
<tr>
<td>The plain is dominated by Mitchell grasses (Astrebla spp) and Ribbon Grass (Chrysopogon fallax). The semi-permanent wetlands and waterways are dominated by riparian woodland and open forest of Eucalyptus camaldulensis, Terminalia platyphylla, Ficus spp, and Melaleuca argentea.</td>
<td>Camballin Floodplain and wetland system</td>
<td>-</td>
</tr>
<tr>
<td>E. camaldulensis, Terminalia platyphylla, Ficus spp. and Melaleuca argentea supports extensive beds of Typha domingensis, tall thickets of Sesbania cannabina, Barringtonia sp. and a fringing forest of Melaleuca argentea, E. camaldulensis and Terminalia platyphylla.</td>
<td>billabongs along the Uralla Creek and Six Mile Creek, the Seventeen Mile Dam</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Common name</th>
<th>Species</th>
<th>Habit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crab's eye bean</td>
<td><em>Abrus precatorius</em></td>
<td>Climber</td>
</tr>
<tr>
<td>NA</td>
<td><em>Alternanthera nana</em></td>
<td>Herb</td>
</tr>
<tr>
<td>NA</td>
<td><em>Atalaya hemiglaucu</em></td>
<td>Small tree/shrub</td>
</tr>
<tr>
<td>Wing-leaf whitewood</td>
<td><em>Atalaya varifolia</em></td>
<td>Tree</td>
</tr>
<tr>
<td>Jigal tree</td>
<td><em>Bauhinia cunninghamii</em></td>
<td>Tree</td>
</tr>
<tr>
<td>NA</td>
<td><em>Barringtonia acutangula</em></td>
<td>Tree</td>
</tr>
<tr>
<td>NA</td>
<td><em>Caesalpinia major</em></td>
<td>Tall shrub</td>
</tr>
<tr>
<td>Bush caper</td>
<td><em>Capparis lasiantha</em></td>
<td>Climber</td>
</tr>
<tr>
<td>NA</td>
<td><em>Celtis philippensis</em></td>
<td>Tree</td>
</tr>
<tr>
<td>NA</td>
<td><em>Clerodendrum floribundum var. ovatum</em></td>
<td>Tree</td>
</tr>
<tr>
<td>NA</td>
<td><em>Corymbia bella</em></td>
<td>Tree</td>
</tr>
<tr>
<td>NA</td>
<td><em>Cyperus conicus</em></td>
<td>Sedge</td>
</tr>
<tr>
<td>River red gum</td>
<td><em>Eucalyptus camaldulensis</em></td>
<td>Tree</td>
</tr>
<tr>
<td>Mistletoe tree</td>
<td><em>Exocarpos latifolius</em></td>
<td>Tree</td>
</tr>
<tr>
<td>Snowball bush</td>
<td><em>Flueggea virosa</em></td>
<td>Tall shrub</td>
</tr>
<tr>
<td>Coffee fruit</td>
<td><em>Grewia breviflora</em></td>
<td>Tree</td>
</tr>
<tr>
<td>Helicopter tree</td>
<td><em>Gyrocarpus americanus</em></td>
<td>Tree</td>
</tr>
<tr>
<td>NA</td>
<td><em>Helicteres rhynchocarpa</em></td>
<td>Shrub</td>
</tr>
<tr>
<td>Musk-scented plant</td>
<td><em>Hypoestes floribunda var. varia</em></td>
<td>Shrub</td>
</tr>
<tr>
<td>NA</td>
<td><em>Jasmin didymium</em></td>
<td>Climber</td>
</tr>
<tr>
<td>NA</td>
<td><em>Lophostomen grandifloras</em></td>
<td>Tree</td>
</tr>
<tr>
<td>NA</td>
<td><em>Melaleuca alsophila</em></td>
<td>Tree</td>
</tr>
<tr>
<td>NA</td>
<td><em>Melaleuca argentea</em></td>
<td>Tree</td>
</tr>
<tr>
<td>NA</td>
<td><em>Melaleuca dealbata</em></td>
<td>Tree</td>
</tr>
<tr>
<td>NA</td>
<td><em>Melaleuca nervosa</em></td>
<td>Tree</td>
</tr>
<tr>
<td>NA</td>
<td><em>Melaleuca nervosa</em></td>
<td>Small tree</td>
</tr>
<tr>
<td>NA</td>
<td><em>Melaleuca viridiflora</em></td>
<td>Tree</td>
</tr>
<tr>
<td>NA</td>
<td><em>Mimusops elengi</em></td>
<td>Tree</td>
</tr>
<tr>
<td>Potato vine</td>
<td><em>Oeperculina aquisepala</em></td>
<td>Climber</td>
</tr>
<tr>
<td>NA</td>
<td><em>Opilia amentacea</em></td>
<td>Climber</td>
</tr>
<tr>
<td>NA</td>
<td><em>Pandanus spirialis</em></td>
<td>Shrub</td>
</tr>
<tr>
<td>NA</td>
<td><em>Pandanus aquaticus</em></td>
<td>NA</td>
</tr>
<tr>
<td>NA</td>
<td><em>Planchonia careya</em></td>
<td>Shrub</td>
</tr>
<tr>
<td>NA</td>
<td><em>Schoenoplectus subulatus</em></td>
<td>Sedge</td>
</tr>
<tr>
<td>NA</td>
<td><em>Sersalisia sericea</em></td>
<td>Tree</td>
</tr>
<tr>
<td>Gubinge</td>
<td><em>Terminalia ferinandiana</em></td>
<td>Tree</td>
</tr>
<tr>
<td>Blackberry</td>
<td><em>Terminalia petiolaris</em></td>
<td>Tree</td>
</tr>
<tr>
<td>Snake vine</td>
<td><em>Tinospora smilacina</em></td>
<td>Climber</td>
</tr>
<tr>
<td>Oyster-catcher bill</td>
<td><em>Tylophora cinerascens</em></td>
<td>Climber</td>
</tr>
<tr>
<td>NA</td>
<td><em>Typha domingensis</em></td>
<td>Sedge</td>
</tr>
</tbody>
</table>

*vine thicket species
In addition to the list of possible GDE vegetation species presented in Table 6.2, broad scale mapping of vegetation communities with potential connectivity with groundwater in the FRV (BoM 2015) is also available. Three classes of groundwater dependent vegetation are mapped:

1. Vegetation with a low potential of groundwater interaction covers large areas of the lower Fitzroy but is largely absent for the upper areas of the FRV (Figure 6.1). This vegetation includes – Grasslands, high grass savanna woodland; grey box and cabbage gum over mixed/white grass on basalt and dolerite, Grasslands, tall bunch grass savanna low tree; boab (Adansonia gregorii), bauhinia and beefwood (Grevillea striata over ribbon grass) amongst many others (BoM 2015) (Figure 6.2);

2. Vegetation with a moderate potential for groundwater interaction dominates in the upper Fitzroy Valley and in a small area at the very lower parts of the Fitzroy River (Figure 6.2). This includes Grasslands, curly spinifex, low tree savanna; snappy gum & bloodwood (Eucalyptus dichromophloia) over curly spinifex and Hummock grasslands, sparse tree steppe; snappy gum & bloodwood (E. dichromophloia) & Eucalyptus setosa over spinifex Triodia intermedia, amongst others (BoM 2015) (Figure 6.2); and.

3. Vegetation mapped as having a high potential of groundwater interaction is restricted to an area in the middle of the Fitzroy River Valley (near Fitzroy Crossing). These include Grasslands, tall bunch grass savanna woodland, coolabah over ribbon/blue grass (Botriochloa spp.) and Medium woodland; river gum & Terminalia (BoM 2015) (Figure 6.2).

**Potential research project 2 - Assess the accuracy of currently available groundwater dependent vegetation mapping and its utility for environmental water management in areas of prospective groundwater use in the Fitzroy River Valley.**

**Time frame- short-term**

Use existing vegetation mapping, remote sensing information (e.g. NDVI) and hydrogeological information to identify areas where groundwater dependent vegetation is likely to exist. For areas with high likelihood of groundwater dependence use field surveys (e.g. isotope methods) to confirm groundwater dependence. This would also allow the assessment of current mappings accuracy (possibly allow for refinements using species distribution modelling) and information for identifying groundwater dependent species and also the variability of groundwater dependence illustrated by certain species (e.g. are certain species always, sometimes or rarely groundwater dependent). This information could feed into assessments of the likelihood that certain riparian vegetation species and ecological processes will be impacted by groundwater extraction.

The GDE atlas mapping (BoM 2015), while providing a qualitative classification of connectivity of vegetation communities with groundwater, has several limitations that may restrict its use for environmental water management. Firstly, because of the broad scale nature of the mapping its accuracy has been difficult to assess. The larger the polygon, less likely it is to accurately represent
groundwater dependent vegetation – only parts, not all, of the polygon may be a GDE (BoM 2015). Secondly, the influence of supplementation from rivers has not been incorporated into mapping, as such vegetation receiving surface water from rivers may have incorrectly been mapped as vegetation receiving groundwater contributions (BoM 2015).

Figure 6.2. Areas of potential groundwater dependent vegetation in the Fitzroy River Valley (from BoM 2015).

6.1.3 Valuing riparian and floodplain vegetation
In addition to being of unknown accuracy, current vegetation mapping is not also explicitly linked to environmental or broad social-ecological values. Such values could include ecological and conservation significance (e.g. threatened ecological community, such as monsoon vine thicket or for providing habitat and corridors for other mammal and bird species), utility for land management (e.g. maintaining water quality) or its socio-cultural value (e.g. customary sites and indigenous goods and services).

These diverse range of values highlight the many important links between riparian and floodplain vegetation and broader ecosystem function. Numerous faunal species are directly dependent on riparian and floodplain vegetation because of the important resources they provide (e.g. shelter, nesting sites or food) or indirectly because vegetation maintains habitat they require (e.g. increases bank stability, provides nutrient inputs, shading and temperature buffering water sources). For example, the widespread riparian and floodplain tree species *Eucalyptus camaldulensis*, which occurs in the Fitzroy, has been associated with the healthy functioning of rivers and plays an
important functional role through litter fall, carbon form and flux (Roberts and Marston 2000). In floodplain habitats, *E. camaldulensis* also provides organic material and a food source for aquatic invertebrates, habitat for birds, maintains soil structure and helps facilitate nutrient cycling between floodplains and rivers (Boulton and Lloyd 1991; Briggs et al. 1997; Law and Anderson 1999; Mac Nally et al. 2001; Francis and Sheldon 2002; Wen et al. 2009). The presence of species like *E. camaldulensis* is likely pivotal for broader ecological functioning in northern Australia and for providing habitat and resources for a diversity of species. Whilst the preceding and following discussion has focussed on *E. camaldulensis*, for which information is available and its importance is well-quantified, little is known of its role in northern Australian riverine ecosystems (nor of its water requirements) and other species, such as the many species of paper barks (*Melaleuca* spp.) may assume a similar level of importance but for which quantitative information is lacking. Clearly, the relative importance of different riparian tree species is an unknown.

Given the key role that riparian and floodplain vegetation plays in ecosystem functioning there are numerous bird, mammals, reptiles and fish species that could be impacted by declines in riparian vegetation condition or extent (e.g. Braithwaite and Muller 1997). For example, many bird species of the wet-dry tropics are highly dependent on riparian habitats (Woinarski et al. 2000; Skroblin and Legge 2012; Kyne and Dostine 2011). In other parts of the world strong links between hydrology and habitat suitability for riparian birds has been documented, suggesting that hydrological change may have important implications for terrestrial fauna such as some bird species (Merrit and Bateman 2012). Although, not studied in the wet-dry tropics, it is likely that similar relationships between hydrology and riparian birds may need to be considered alongside water resource development. Some mammal species of the wet-dry tropics (e.g Conilurus penicillatus, *Mesembriomys gouldii*, *Mesembriomys macrirus*, Antechinus bellus, Phascogale tapoatafa and Rattus tunneyi) and reptile species (e.g. freshwater turtles) are also likely to have strong links to hydrology because of their requirements for riparian habitat and food sources (Braithwaite and Muller 1997; Georges et al. 1993). Finally, the riparian zone also provides important sources of energy for riverine food-webs (Thorpe and Delong 1994). Pusey and Arthington (2003) review the many varied and strong links between freshwater fish species and riparian vegetation. The consumption of riparian fruits and seeds is particularly important in tropical Australian freshwater fish species.

Riparian and floodplain vegetation also facilitates many important socio-cultural values. Vegetation provides a range of socially important ecosystem services by supporting ecological functions (e.g. maintains water quality), provides food resources, regulates the environment (e.g. temperature) and providing places of cultural importance – all of which support important socio-cultural values (Millennium Ecosystem Assessment, 2005). In the FRV, the specific services and socio-cultural values that riparian and floodplain vegetation provide are incompletely documented although temporal changes in vegetation provides important cues about resource related events (Leidloff et al. 2013). For the Gooniyandi of the Fitzroy valley, the dropping of particular seeds, appearance of nectar rich paper bark flowers, *Eucalyptus* bark peeling and appearance of figs provide important cues about the availability of freshwater food sources (e.g. Black Bream, long-necked turtle, mussels and sawfish) (Leidloff et al. 2013). The flowering of Bambira (*Atalaya hemiglauca*), a tree species occurring on the floodplain, is also important for the Gooniyandi and is linked with the laying of freshwater crocodile eggs, an important food source (Liedloff et al. 2013). Loss of important vegetation cues, through disruptions to groundwater dependent vegetation could therefore have important implications for communities who rely on them to provide important cues about resource
availability. In the main however, there is little information on the sensitivity of high priority socio-cultural values linked to riparian and floodplain vegetation and how these can best managed alongside water resource developments. These are important issues, but will be covered in more detail by separate review focusing on socio-cultural values in the FRV.

6.1.4 Ground water requirements for riparian and floodplain vegetation in the Fitzroy River Valley

Once high value riparian vegetation has been identified, understanding the factors that determine its condition and persistence is critical for management. Riparian and floodplain vegetation are well adapted to specific hydrological conditions. Changes in hydrological conditions often lead to moisture stress for riparian vegetation, which in turn causes declines in condition (e.g. canopy thinning), tree death and ultimately the loss of riparian vegetation populations. For example, when trees are under moisture stress, canopy thinning and branch loss reduces transpirational demand eventually results in cavitation, failure in transporting xylem tissue and death (Tyree and Ewers 1991; Rood et al., 2000; McDowell et al., 2008). Consequently, detailed knowledge of the water requirements of riparian vegetation is required to ensure its long-term sustainability the important linkages to geomorphology maintenance and broader ecological processes (e.g. providing habitat for other species).

In the FRV, the management and provision of riparian and floodplain vegetation requirements will be broadly concerned with ensuring that vegetation can access groundwater and surface waters. First groundwater (i.e. groundwater water tables and dynamics are maintained within a range that vegetation can access when required, such as in dry season droughts). Second, the management of surface water regimes (floods and inundation events), which are important for not only providing water, but also for spreading propagules and facilitating recruitment for riparian vegetation.

In the FRV, the seasonal nature of the wet-dry tropics means that access to surface water is often limited to the wet season. In the dry season as surface waters recede, evaporation increases and soil moisture declines, groundwater becomes more important for vegetation (O’Grady et al. 2006). Indeed, outside of the wet season (i.e. in the dry season) many vegetation species might rely entirely on groundwater. To access groundwater, vegetation needs roots long enough to reach the water table or the capillary fringe of the water table (i.e. the zone where groundwater seeps upward from the water table). If water extraction from aquifer(s) causes the groundwater water table to drop below a depth that the plants roots can reach, then the vegetation is likely to suffer from moisture

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**Potential research project 3.**—Quantifying and mapping the broader values of riparian (including GDEs) vegetation for other ecological values in the Fitzroy River Valley to prioritise environmental water management.

Time frame – short-term if existing data available, but potentially longer-term.

Use species distribution modelling and literature review to identify the relative importance of riparian vegetation for other species of high value (e.g. its relative importance as a determinant of key mammal, bird, invertebrate and/or fish species), ecosystem function and maintaining channel form.
stress. Given the sensitivity of vegetation to water table depths it follows that any drop in groundwater levels, for example as a consequence of groundwater extraction, could have significant implications for groundwater dependent vegetation. Understanding how riparian vegetation access groundwater is therefore important for managing its persistence in the wet-dry tropics of the Fitzroy River Valley.

Many groundwater dependent vegetation species are widely distributed throughout the wet-dry tropics of Northern Australia (e.g. some *Melaleuca* sp.) and some even occur in most parts of Australia (e.g. River Red gum). Despite some species being widely distributed there is often little or no information about how reliant many plant species are on groundwater. The species for which some information is available are discussed below and provide an important starting point for helping to identify knowledge gaps about groundwater dependent vegetation in the FRV.

*Eucalyptus camaldulensis* (River Red gum) is a widely distributed tree species that inhabits riparian and floodplain areas throughout much of Australia and is widespread throughout the FRV. However, there are no detailed studies on the hydrological requirements of River Red gum in the Fitzroy Valley or even in the wet-dry tropics of northern Australia. There are nonetheless, numerous studies documenting River Red gums relationship with surface and groundwater hydrology in other parts of Australia that could provide insights into its hydrological and especially groundwater requirements within the Fitzroy Valley.

In the Condamine catchment of southern Queensland, the condition and likelihood of occurrence of large River Red gum was found to decline in areas of deeper groundwater, suggesting that these species may need groundwater tables maintained within a certain depth in order to survive over the long term (Kath et al. 2014ab). In the Murray-Darling Basin, many shallow groundwater aquifers have become salinized as a consequence of land clearing and irrigation activities that have caused water tables to rise and in doing so bring salts to the surface. In the Murray River floodplain, interactions between groundwater salinity and depth are important drivers of River Red gum forest dieback, with high levels of groundwater salinity being strongly related to forest dieback (Cunningham et al. 2011). As such, river red gum can show significant changes in condition in response to changes in groundwater hydrology. However, it is important to keep in mind that River Red gum relationships with groundwater hydrology in the wet-dry tropics of the Fitzroy Valley, may be substantially different from those identified in climatically different areas of Australia.

In addition to the widely-distributed and well-studied River Red gum there are studies documenting groundwater use by other species occurring in the FRV (i.e. *M. argenta*, *B. actungula* and *C. bella*). On the Daly River, *M. argenta* and *B. acutangula* appear to be strongly reliant on groundwater and are often restricted to riverbanks and low terraces with shallow groundwater (< 5 metres) (Lamontagne et al. 2005; O'Grady et al. 2006). In contrast, *C. bella*, is thought to use only minimal amounts of groundwater (if any) and is largely reliant on soil water reserves (Lamontagne et al. 2005; O'Grady et al. 2006). *Pandanus aquaticus*, which inhabits riparian areas in the FRV, may also be dependent on shallow groundwater (Skroblin and Legge 2012).

### 6.1.5 The importance of floods and surface waters for riparian and floodplain vegetation

During the wet season heavy rains and flooding rivers provide important sources of water and redistribute nutrients important for recruitment processes for riparian and floodplain vegetation (Pettit et al. 2001). Depending on their position in the landscape, during the wet season many
Riparian species will also be inundated for long periods of time. The frequency and duration that riparian vegetation is inundated is an important determinant of recruitment success as well as their condition and longer term persistence (Pettit et al. 2001; Cateli et al. 2015).

In the FRV, water resource developments, through damming of rivers, off-stream storage capture and direct extraction of water from streams and floodplains may change the frequency and duration with which riparian and floodplain vegetation are inundated by surface waters. Understanding how riparian and floodplain vegetation that is of high value respond to changes in the frequency and inundation of surface waters is a key first step in determining and thus managing potential surface water resource development impacts on riparian and floodplain vegetation in the FRV.

The only documented example of surface water flow alteration impacts on vegetation in the FRV are those associated with Camballin (Storey et al. 2001). Storey et al. (2001) observed that in sections of the river near associated with lower flows and regulation near Camballin, riparian vegetation had a younger population structure, higher weediness and increased livestock disturbance. Storey et al. (2001) argued that a reduction in scouring flows facilitated the persistence of weeds in these riparian areas.

More broadly, for the FRV as a whole, there is relatively little research on how riparian vegetation may change in response to altered surface flows resulting from water resource development. Again however, River Red gum studies may provide useful insights. Previous studies that have examined River Red gum condition have linked hydrology, and specifically, flooding and the impacts of river regulation to declines in their condition (e.g. Bren 1988; Bacon et al. 1993; Briggs and Thorton 1999; Cunningham et al. 2011; Steinflod and Kingsford 2011; Catelotti et al. 2015). Roberts and Marston (2000) state that established River Red gum trees are highly dependent on the frequency and duration of flooding, the duration of the inter-flood period (or dry period) and the variability of these two factors. In Yanga National Park (south-eastern Australia), Wen et al. (2009) observed that River Red gum communities without direct access to stream water require overbank floods to maintain crown condition. In the Macquarie Marshes, New South Wales, Australia, low water availability was also associated with poor condition stands of River Red gum (Bacon 1996). More recently, Cateli et al. (2015) have shown that the probability of inundation in the previous 10 years is strongly related to persistence and recovery of River Red gum. For the FRV, these studies highlight that riparian vegetation are likely to be sensitive to water resource developments that alter the frequency and duration that they are inundated by surface waters.

Other riparian and floodplain vegetation species sensitive to changes in surface water inundation frequency and duration are likely to occur in the FRV (e.g. some of the tree and shrub species listed in Table 6.2). It is important to note that these species may have very different hydrological requirements from each other. For example, some species may benefit from a decrease in the frequency and duration of inundation, while others may be negatively impacted. In the FRV balancing the requirements of a diversity of riparian and floodplain vegetation, will be a challenge that requires a clear articulation of the values of key species and the importance of conserving and managing them alongside water resource development.
Transferability of previous DoW riparian vegetation studies

The Department of Water has undertaken previous on-ground investigations of the water requirements of riparian vegetation across Western Australia. This includes detailed ecophysiological studies in the Pilbara region and on the Dampier Peninsula in the west Kimberley. As the key abiotic conditions (e.g. climate and hydrology) of these areas are generally similar to those experienced on the Fitzroy and they share many of the same riparian species, the findings of these studies may be generally transferrable.

Overstorey species, generally trees, dominate riparian communities. There are a number of riparian species common to Pilbara rivers and the Fitzroy Valley including *Eucalyptus camaldulensis*, *Eucalyptus victrix*, *Melaleuca argentea*, *Melaleuca glomerata*, *Melaleuca bracteata* and *Atalaya hemiglauca*. In addition, there are a number of phreatophytic species common to both the Dampier Peninsula and Fitzroy Valley such as *Melaleuca dealbata*, *Melaleuca alsophila*, *Melaleuca nervosa*, *Melaleuca viridiflora*, *Corymbia bella* and *Lophostemon grandiflorus*.

A conceptual model of groundwater dependency of riparian vegetation was developed for a number of rivers and associated alluvial aquifers along the Pilbara coast (Antao and Braimbridge, 2010; Braimbridge, 2010; Loomes, 2010a; Loomes and Braimbridge, 2010), using vegetation mapping, groundwater data and water level contours.

It was found that the distribution of the riparian communities generally reflects the depth to groundwater and area inundated during flooding. The shallow depth to groundwater generally found in alluvial soils and especially along the rivers, provides areas where deep rooted vegetation can access groundwater. Although plants will use surface water and soil water where available, during sustained drought, riparian vegetation is reliant on groundwater to meet its water requirements.

In the Pilbara, surface water replenishes soil and bank storage and disperses seed during flood events. The recharge of groundwater from surface flows results in groundwater mounding under the river channels. As groundwater levels decline over a dry season or prolonged drought, a tree’s ability
to respond to reducing water availability depends on its physiology and adaptations to cope with stress (e.g. how quickly their roots will grow, and/ or morphological adaptation that reduce water stress). During sustained drought when soil moisture is depleted, many riparian species are reliant entirely on groundwater to meet their water requirements. During these periods, groundwater levels continue to decline. The duration, frequency and magnitude of droughts (or periods of low groundwater levels) are important determinants of riparian community health.

Average depths to groundwater along the Pilbara study rivers (De Grey, Yule, Robe and Lower Fortescue) were generally less than five metres. The actual water level range for species that are important or common to river and wetland systems of the Pilbara were described using the distribution of species across an elevation gradient (transect) and measured depth to groundwater or depth of inundation (Loomes, 2010b). Water level ranges were determined for 16 species – including 10 trees - across 23 sites on four rivers.

Figure 6.3 below illustrates the depth ranges experienced by the two most common/ important species – *E. camaldulensis* and *M. argentea* – both of which are also common on the Fitzroy River. Overall, both species showed preferences for depths of between two and five meters. At these shallow depths both species are likely to be highly groundwater-dependent. Consideration of the wider water level ranges of these and other species lead to a generalisation that at depths to groundwater of less than 10 m, riparian and floodplain vegetation is highly likely to be groundwater dependent. However, it is important to note that these values (i.e. 10 m) are based on surveys within the Pilbara, and as such should not be extrapolated to other areas without testing in the area of interest.

A trial of the effects of groundwater drawdown was undertaken in the Yule River. The Yule River is located 40 km west of Port Hedland. Like many other river systems in the Pilbara the lower reaches on the coastal plain overlie an alluvial aquifer. This aquifer has been used as a supply source for Port Hedland since 1967. The drawdown trial ran from December 2008 to April 2011. It was run as a collaborative exercise involving the Water Corporation, Department of Water, University of Western Australia, University of Sydney and later Astron Environmental (Braimbridge and Loomes, 2013). During the trial the rates of groundwater abstraction were increased and the physiological response of groundwater-dependent vegetation (*E. camaldulensis* and *M. argentea*) was monitored.

As expected, monitored vegetation parameters showed increasingly negative responses over the course of the trial as water availability declined (Table 6.3). From this trial, different risk levels of vegetation to groundwater changes (relative to antecedent groundwater conditions) were derived.
Figure 6.3. Blue boxes are the mean, minimum mean and maximum mean of depth to groundwater level that each species occurred at for each site and for the Pilbara overall. The black bars are the absolute min and maximum depths that the species were observed at.

Table 6.3. Different risk categories for different depth to groundwater categories (based on antecedent conditions) for the Pilbara.

<table>
<thead>
<tr>
<th>Depth to groundwater category</th>
<th>Low risk threshold – change in groundwater depth (m)</th>
<th>High risk threshold – change in groundwater depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5m</td>
<td>-1.38</td>
<td>-2.20</td>
</tr>
<tr>
<td>5-8m</td>
<td>-1.76</td>
<td>-2.70</td>
</tr>
<tr>
<td>8-10m</td>
<td>-2.22</td>
<td>-3.21</td>
</tr>
<tr>
<td>10-15m</td>
<td>-3.00</td>
<td>-4.00</td>
</tr>
</tbody>
</table>
The above values, while useful for the Pilbara, should not be directly or uncritically transferred to the FRV or other areas. Nonetheless, with further testing this approach could be transferable when determining potential responses of riparian vegetation to changes in groundwater availability / levels in the Fitzroy Valley.

A study using similar ecophysiological techniques as those in the Yule trial, was undertaken on the Dampier Peninsula to determine the level of groundwater dependence of riparian/ wetland tree species (Loomes, in prep). Results showed that the species listed above as occurring in both the Fitzroy Valley and Dampier Peninsula are highly groundwater-dependent.

The water levels ranges of common/ important riparian species of the Dampier Peninsula were described following the Pilbara process above. Similarly, the species considered were generally recorded at depths to groundwater of between two and five meters (Figure 6.4). However, some of these species were also noted in areas of greater depth to groundwater (but were not assessed). The ‘less than 10 m to groundwater’ assumption (above) may also apply to riparian/ wetland vegetation of the Dampier Peninsula and may be a useful guideline for directing research on GDE vegetation in the Fitzroy River Valley.

![Figure 6.4. Depth to groundwater level (boxes represent mean and SE, whiskers represent maximum and minim values) for selected plant species on the Dampier Peninsula.](image)

6.2 Aquatic plants and periphyton
Aquatic plants and periphyton both play important roles in the ecological functioning of freshwater systems in the wet-dry tropics - they are sources of food for many organisms (e.g. fish, birds and insects), help maintain water quality and provide habitat. Aquatic plants here refer to those that occur in water and have a submerged or floating growth habit (e.g. macrophytes). In contrast,
periphyton is a complex composite of algae, cyanobacteria, heterotrophic microbes and detritus on surface (stream bed substrata) in rivers, wetlands, streams, pools etc. Key management issues for aquatic plants and periphyton in the FRV are: 1) identifying the distribution and habitat (water regime requirements) of aquatic plants; and 2) how water resource development (groundwater extraction and overland flow harvesting) may impact on aquatic plants and periphyton.

6.2.1 Aquatic plants
In the wet-dry tropics the growth and production of aquatic plants is tightly linked to the seasonal hydrology. Aquatic plant growth starts with the flooding rains of the wet season (Finlayson 1991; Warfe et al. 2011). The extensive macrophyte (large aquatic plants) growth that occurs in the wet season provides important food and habitat for waterbirds, such as Magpie geese, which feed and nest in wild rice (*Oryza* spp.) and water chestnut (*Eleocharis dulcis* (Burm.f.) Trin. ex Hensch) (Warfe et al. 2011). As well as providing food and nesting sites for waterbirds, aquatic plants also provide critical habitat and/or food for aquatic invertebrates and small fish (Storey et al. 2001; Pusey and Kennard 2009; Jardine et al. 2012).

Despite the ecological importance of aquatic plants, there is no documented systematic survey of aquatic plants in the FRV. Nonetheless, certain areas may provide important habitat for aquatic plants. Streams and swamps in the King Leopold ranges are said to be rich in aquatic plants (Brash and Livesey 1994; Storey et al. 2001). Likewise, Brooking Gorge, provides small water courses with less intense flows, that provide habitat for aquatic plants with restricted ranges (e.g. it is the only known location of *Nymphaea immutabilis* subsp. *kimberleyensis*) (Storey et al. 2001).

While aquatic plants play important ecological roles, it must also be noted that excessive growth of macrophytes may lead to reductions in habitat diversity and water quality (e.g. reduction in oxygen levels) and therefore have detrimental impacts on freshwater animals (Pusey and Kennard 2009). Indeed in some seasonal water bodies the decomposition of aquatic plants that occurs as water levels decline can trigger anoxic conditions and fish kills. Excessive aquatic plant growth is typically caused by high nutrient inputs or changes to flow regimes (e.g. slower flows). As high nutrient inputs and flow changes are currently minimal in the FRV, excessive macrophyte growth is unlikely a major environmental concern. However, Storey et al. (2001) has noted that slower flows in the vicinity of Camballin have led to the encroachment of emergent macrophytes into previously uninhabited areas of the riverine network. For the rest of the Fitzroy River and its wetlands there is little information concerning aquatic plants.

6.2.2 Periphyton
Periphyton, while less conspicuous than the often larger aquatic plants, is no less important. On the contrary, recent research on water bodies in the wet-dry tropics have demonstrated that periphyton is critical source of energy for aquatic food webs (Jardine et al. 2013). In tropical systems for example, periphyton is far more important for fish, than other inputs from terrestrial and aquatic vascular plants (Jardine et al. 2012 and references therein). The importance of locally produced periphyton (i.e. within the water body the fish inhabits) is greater still in systems, such as the Fitzroy, where wet-season flood pulses are brief and only lead to short hydrological connections with the greater riverine network and floodplain (Jardine et al. 2012). In the Fitzroy River, tight coupling between local sources of production and both prawns and fish have been observed (Jardine et al. 2012). Jardine et al. (2012) argue that this is because when floods cease fish and prawns (and other
consumers) will likely be stuck within permanent pools and wetlands and thus almost wholly reliant on the production occurring locally within these habitats. The importance of periphyton in aquatic foodwebs cannot be overstated and it could be reasonably argued that responsible and efficacious environmental water management must be predicated on the maintenance of this component of aquatic biodiversity.

6.2.3 Water resource development impacts on primary production.
Given the importance of periphyton as a source of energy for freshwater animals, and the likely importance of aquatic plants as habitat, it is critical that the hydrological processes that facilitate their presence are maintained. Warfe et al. (2011) outline several different pathways that aquatic primary production (aquatic plants and periphyton) may be impacted by water extraction due to water resource development. In the dry season, water extraction increases the likelihood of hydrological disconnection, which in turn reduces water hole size, persistence and the amount of instream habitat, ultimately leading to decreases in aquatic primary production. In the wet season, water extraction may inhibit groundwater recharge and decrease the magnitude of peak flows and in doing so the extent and duration of floodplain inundation, both of which will decrease aquatic primary production. Finally, extraction of water at the end of the wet season/start of dry season will cause premature waterhole disconnection with the broader riverine network which drives declines in the number, persistence and size of water holes – all collectively leading to declines in aquatic primary production.

Potential research project 5: Understanding the hydrological conditions that determines aquatic production of macrophytes in dry-season stream pools and wetlands.

Time frame - long-term
Determine the hydrological basis for temporal and spatial variation in the production of aquatic macrophytes in the FRV, particularly the importance of groundwater inputs in dry-season refugial pools and wet season inundation of floodplain wetlands. Determine the importance of macrophytes in influencing nutrient availability for other primary producers and water quality (e.g. dissolved oxygen and pH) as well as providing important habitat for other organisms such as fish and macroinvertebrates. From this identify key aquatic habitats and the hydrological and geomorphological characteristics required to ensure that primary production of macrophytes is sustained within natural limits. Quantify the form of relationships between macrophyte production and hydrology (e.g. linear, stepped, threshold) in the Fitzroy River and propose management actions or abstraction limits required to ensure that primary production is not impacted by water resource developments.

Failure to manage aquatic primary production in stream pools and aquatic habitats could have several unwelcome consequences for freshwater biodiversity in the FRV. First, hydrological change disrupting the wet-dry cycling of riverine habitats can alter productivity, reducing habitat and food quality for some water birds (e.g. magpie geese) (Kingsford et al. 2000; Warfe et al. 2011). Second, since fish, and other consumers, are tightly linked to local sources of production, especially during
the dry season, any hydrological changes (e.g. groundwater extraction causing pools to contract) that limit periphyton production will also limit fish production (Karlsson et al. 2009; Jardine et al. 2013). Further discussion of the importance of primary production is available in section 6.8.

6.3 Macroinvertebrates

6.3.1 AUSRIVAS and similar condition assessments

No research specifically examining the flow related ecology of stream macroinvertebrates in the Kimberley region or specifically in the Fitzroy River is available to guide environmental water management in the FRV. However, several studies have examined macroinvertebrate communities from sites within the FRV as part of larger examinations of the nature of the fauna from a larger biogeographic perspective or from the perspective of using this faunal group as indicators of water quality and environmental condition. Kay et al. (1999) examined the patterns of distribution of macroinvertebrate families of north-western Australia (Gascoyne, Pilbara and Kimberley regions) and five sites included in that study were located in the Fitzroy River. Macroinvertebrates were sampled by three replicates of sweep netting (i.e. rapid assessment). About 75% of all families were collected in the first of the three samples. Kimberley samples were richer (~22 families per site) than those from the Pilbara (14 families) and the Gascoyne (~8 families). Typically, samples collected from macrophytes were most taxon rich (22), than riffles (20), channel habitat (18) and pools rocks (14). (These numbers are for Kimberley samples only.) Ordination revealed significant regional differences in fauna but whilst significant, there was a lot of overlap between regions. These authors suggest that although most previous collections of macroinvertebrates had been confined to the high rainfall areas of the Kimberley (i.e. museum collection in the Prince Regent River region), the number of families was not greatly different and was substantially complete at 77 families. Note that this assertion is based on a limited examination and applies to the family level only. Buckle et al. (2010) examined the macroinvertebrates of the upper Ord River in a similar fashion and detected 47 families from 14 sites. All families recorded were widespread across northern Australia.

Smith et al. (1999) also included samples from the Fitzroy river (in fact the same samples) to assess the capacity of the macroinvertebrates within the AusRivAS program (Australian Rivers Assessment Scheme) to assess ecological condition across all of Western Australia. The AusRivAS was a continent wide appraisal of the utility of macroinvertebrates as indicators. Sweep samples in channel and macrophytes habitats were used. The Kimberley, Pilbara and Gascoyne regions were significantly different in terms of family level composition from other regions in the state. These authors noted that the models developed based on family level variation in composition were not able to detect environmental degradation at anything other than the most severe level.

Specimens collected by Kay et al. (1999) and Smith et al. (1999) were identified to family level only for the purposes of those studies. It is unknown whether voucher specimens were retained that could provide guidance on specific identification. The study by Pinder et al. (2010) lists a web site (http://www.museum.wa.gov.au/research/records-supplements/attachments) that lists all taxa recorded but is unfortunately non-functional. However, it undoubtedly exists somewhere and it is likely that voucher specimens were retained.

Macroinvertebrates were used in the FARWH condition assessments within the Fitzroy River undertaken by Dixon et al. (2010) (see section 3.5). Dry season channel habitats were sampled at 21
sites throughout the catchment (9 small tributaries, 10 middle reaches and 2 in the upper reaches). Macroinvertebrates were identified to family level only or to subfamily in the case of Chironomidae and habitat variables were measured according to the AUSRIVAS protocol. A similar protocol was followed by Tingle et al. (2014) in a project undertaken with the Gooninyandi Ranger group (and in other collaborative projects between UWA researchers and Indigenous Ranger groups in the region).

The salient point here is that although there has been a significant amount of sampling of macroinvertebrate communities in the FRV (and elsewhere for comparison), it has occurred over a decade and a half and was undertaken by different researchers and for different purposes. The outcomes of this work, as they are, offer little insight into how macroinvertebrate communities in the FRV might respond to altered surface and groundwater discharge. None-the-less and encouragingly, these varied collections were all undertaken using the same sampling protocol and all measured a similar set of variables. Thus, there is significant scope for these data sets to be pooled and re-examined to determine whether they can indeed offer any insight into relationships between flow regime, habitat structure and macroinvertebrate communities. Most importantly, it is likely that these samples are archived in various locations and potentially available for further examination. Thus, these samples may be able to be re-examined and invertebrates identified to a higher taxonomic level more suitable for investigations of flow ecology relationships. At the very least, such a data set would provide a potentially useful means of monitoring the efficacy of water resource management options in the future.

**Potential research project 6:** *Can existing survey information of stream macroinvertebrates in the FRV be re-examined to provide insight into the flow ecology relationships of this biota?*

**Time frame:** short-term.

Various prior studies undertaken in the FRV using stream macroinvertebrates to assess watercourse condition have used similar collecting, sorting and identification protocols and have measured relevant aspects of habitat (depth, water velocity, substrate composition etc.) in a similar manner. As a result, these different studies could be potentially combined to form a larger data set that can be used to examine generate information on flow and habitat needs of this important group. Moreover, archived material from these studies could be re-examined and further identified to a higher taxonomic level (generic or specific level) to determine whether existing patterns are robust to the influence of taxonomic resolution and to determine whether the species involved are common to northern Australia (i.e. the extensive research work undertaken in the Pilbara or the Alligator rivers region of the Northern Territory) and hence, how transferable are flow ecology relationships developed elsewhere.

### 6.3.2 Macroinvertebrates in the Pilbara

More intensive examination of stream macroinvertebrate fauna has occurred in the Pilbara region (Pinder et al. 2009, 2010). The intent of Pinder et al. (2009) was to investigate relationships between pool aquatic invertebrates and habitat variables that may be affected by groundwater abstraction. A total of 10 permanent to near-permanent pools were sampled by rapid assessment protocols.
(replicated sweep netting) whereas an extensive number of water quality parameters were examined for a further 10 sites. A total of 253 species from 57 families (including subfamilies of Chironomidae) was recovered. This represented 25% of all aquatic invertebrate fauna (including ostracods, copepods etc.) known for the region, 41% of all known macroinvertebrates and 49% of all known clear pool macroinvertebrates. Richness varied from 15 to 79 taxa per sample (median = 30) and 53 to 105 (median = 70) taxa per pool. Classification revealed strong between-river and clear water-turbid water differences in faunal composition although all samples were dominated by Diptera and Coleoptera. Species richness tended to increase with increasing macrophyte cover and increasing litter availability and was higher on the edge of pools than in the deepest sections. Faunal composition differed with pool size and permanence, although only weakly, and with macrophyte cover, substrate composition and nutrient availability. Although significant, the relationships with these variables, individually and collectively, were weak.

Three conclusions were reached. First, river pools within areas of potential groundwater abstractions are not uniform with respect to the physical, chemical and biological characteristics. Second, river pools have ecological values that are not well represented elsewhere (i.e. distinctive faunal assemblages). Third, there are no relationships between aquatic invertebrate communities and pool characteristics such as size, permanence, depth and habitat characteristics that may be affected by groundwater extraction, although this final conclusion came with a proviso. That proviso was “To the extent that data allows, we can conclude that depth, permanency and pool size are not correlated with invertebrate communities to an extent that would allow thresholds to be recognised.” Nonetheless, these authors identify that below a depth of 76 cm, there does appear to be a relationship between depth and community composition and recommend that a depth of 1 m (for those pools that maintain depths greater than this) be set as an interim depth target. Caution must be expressed here as the interim depth target identified is a precautionary one, is not well-supported by data and is not transferable beyond the system for which it is suggested.

It is questionable whether the study design (particularly sample size and number of replicates) is adequate to derive such thresholds. Moreover, given that relationships between macrophyte biomass and cover were most strongly correlated with invertebrate composition, it may be more useful to examine this habitat element in more detail and derive depth thresholds for it in the first place. Furthermore, depth in this study referred to the depth at which the sample was taken, not the depth of the water body sampled and thus is unlikely to be an effective surrogate for factors related to pool size and permanence. In addition, it may be inappropriate to model invertebrate composition using variables which are unlikely to be relevant to small organisms with relatively rapid generational times (i.e. how relevant is permanence to an assemblage comprised of species with generation times less than the expected life span of a pool?).

Pinder et al. (2010) provide an excellent review of factors that influence arid zone stream invertebrate communities and examined community structure/environment relationships in a study encompassing 100 sites throughout the Pilbara. Over 1000 species were recovered from a diverse array of phyla (i.e. including insects, crustacean, rotifer, annelids etc). About 20% of the fauna is known only from the Pilbara whereas the remaining species are western endemics or occur more widely in northern and/or inland Australia. A number of distinct assemblage types was recognised and unique sets of environmental variables were correlated with variation within each type. Flow,
turbidity, salinity, sediments, macrophytes and hydrological persistence are among the environmental gradients most strongly correlated with occurrence patterns in the fauna.

Garcia et al. (2011) discuss the ecological importance of stream macroinvertebrates in northern Australian aquatic systems, highlighting the important roles they play within tropical riverine environments, especially within aquatic food webs. In addition to their roles in processing organic matter and primary production, most higher-order predators in northern Australian rivers, such as fish, consume invertebrates directly. Food webs are typically short (Warfe et al. 2013). Consequently, environmental changes that negatively influence stream invertebrates are likely to impact on food webs and other organisms such as fish. Indeed, stream invertebrates also play an important role in the terrestrial foodweb of the riparian zone with its rich bird and lizard assemblages. Garcia et al. (2011) also describe the human utility of stream macroinvertebrates highlighting their value as biological indicators. Macroinvertebrates are sensitive to a range of factors, especially water quality parameters such as dissolved oxygen concentrations, water temperature and pH, all of which are responsive to changes in water regime. As such this biotic group is useful as an indicator of the efficacy of management activities and decisions as well as providing information on the relationship between flow regime and ecological integrity. However, Garcia et al. (2011) were particularly concerned in this regard (i.e. indicators) with the invertebrate fauna of the well-studied Alligator Rivers Region and the extent to which information gathered elsewhere, can be validly transferred to the FRV is unknown.

Growns (1998) reviewed the use of macroinvertebrates in setting environmental water targets and identified a number of issues that limited their utility. First, and particularly relevant to the situation within the FRV, was that most previous attempts to base environmental water requirements on this faunal group were concerned with environmental flows and their capacity to provide appropriate water velocities for individual species and to maintain stream bed characteristics, such as substrate particle size, that are directly related to the abundance and persistence of individual species. Species specific information is important in this regard and lacking for macroinvertebrates of the

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**Potential research project 7 - Can seasonal and spatial variation in the structure of macroinvertebrate communities and relationships between habitat structure and water quality be used to infer flow ecology relationships in the FRV and provide guidance for the implementation of environmental water management?**

**Time frame:** long-term

Use existing information from elsewhere in northern Australia to construct a template of macroinvertebrate responses to flow regime for northern Australia and test it in the FRV. This could be done by implementing a field-based sampling program to examine the relationship between spatial and temporal variation macroinvertebrate community structure (richness, abundance, trophic structure) and habitat structure, flow regime (specifically groundwater inputs) and water quality. Derive relationships between aspects of the flow regime and ecology of macroinvertebrates suitable for use in testing scenarios of water resource use.
FRV. Second, and equally relevant, is that most such studies were undertaken in south-eastern Australia and have no practical transferability. Groundwater was not considered in the studies reviewed by Growns (1998) nor were relationships between macroinvertebrates and habitat quality in refugial pools. At best, emergent properties of macroinvertebrate communities, such as abundance, species richness, diversity and relative contribution of different functional feeding groups, may be the appropriate scale at which the environmental water needs of this faunal group are considered.

6.3.3 Macroinvertebrates of human significance

Some macroinvertebrates are also important as food for people, especially indigenous people. Chief among these is the giant freshwater prawn or cherabin *Macrobrachium spinipes*. This species is also an important prey item in the diet of many fish species, especially those important in commercial, recreational and customary fishing. Moreover, it is itself a “keystone” species, influencing organic matter deposition and primary production through its foraging activities and interaction with conspecifics. It is consequently a socially and ecologically important species.

The importance of cherabin is difficult to overstate. In addition to its ecological importance it has very high human value. In surveys of the contribution of riverine production to indigenous household economies of the FRV, cherabin were the 4th most collected species and the 3rd most consumed (Jackson et al. 2011). Indigenous residents of the FRV also collected large amounts of freshwater crab and freshwater mussel to use as bait. Cherabin are also intensively targeted and harvested by non-indigenous residents of the FRV, many of whom will travel widely to “get a feed” (D. Leslie, pers. comm.).

Cherabin has an amphidromous life cycle, and has recently been studied in the perennial Daly River in the Northern Territory (Novak et al. 2015). In that river, larvae are released into freshwater during the wet season and must drift downstream to the estuary in prolonged flood currents in order to finish their larval moult cycle. If appropriate salinities are not reached by the end of the second larval moult, the larvae perish. Newly metamorphosed juveniles then migrate back upstream at the end of the wet season. Two aspects of the flow regime are critical in this cycle. First, flood flows need to be sufficiently large and of sufficient duration to transport larvae downstream to the estuary and second, that no barriers impede their upstream passage at the end of the wet season. The weir at Camballin may pose as barrier but is probably surmountable as freshwater prawns are adept climbers. More importantly, if river flows cease early in the year and cause the pools within the river channel to become more disconnected, then there is a potential for upstream migrations to be truncated.

Although the recent work of Novak et al. (2015) offers some insight into the flow ecology of this species, the substantial differences in flow regime may make transfer of such insights tenuous at best.
Subterranean fauna

Subterranean fauna is comprised of stygofauna and troglofauna, the former being aquatic and the latter non-aquatic and occupying air-filled voids. Of these, stygofauna are most susceptible to impact from water resource use but troglofauna may also be reliant on groundwater in an indirect way (see below). Various distinctions are made between different types of stygofauna. Tomlinson and Boulton (2008) recognised three classes of stygofauna:

- **Stygoxenes** – species that occur in subterranean habitats incidentally and often by accident. Such species are particularly frequently found in stream gravel beds connected to the hyporheos. This group is not included here despite the fact that stygoxenic species are likely important in lotic systems of the region.
- **Stygophiles** – species that frequently found in subterranean habitats and may spend a significant portion, but not all, of their life cycle there.
- **Stygobites** – species that are restricted to subterranean habitats and frequently show marked morphological adaptation to such an existence.

(Note that species that take refuge in the hyporheos during periods of zeroflow would fall into the category of stygophile). Whilst the species comprising stygofauna are individually of interest in terms of ecological function, phylogenetic and biogeographical identity and biodiversity in general, they are frequently considered as components and indicators of Subsurface Groundwater Dependent Ecosystems (SGDEs).

Tomlinson and Boulton (2008) include aquifer and cave ecosystems within a broader class of habitats and ecosystems termed Subsurface Groundwater Dependent Ecosystems (SGDEs) among which are ecosystems dependent on the surface expression of groundwater (e.g. mound springs, baseflow rivers, refugial pools maintained throughout the dry season by groundwater and estuarine sea grass beds) and ecosystems dependent on the subsurface presence of groundwater e.g. vegetation having roots accessing groundwater. For the purposes of this review section, we are including moundsprings and springs within the category of aquifer and cave ecosystems. (Note the
term moundspring appears to be used very indiscriminately in the Western Australian literature, particularly by government, and is used to refer to springs in general whether they are raised or not.)

Stygofauna and the ecosystems of which they are a part occur in

- Unconsolidated aquifers
- Fractured rock aquifers
- Karst
- Calcrete
- Pisolite
- Ecotones (hyporheic and vadose zones)
- Aquitards (compact aquifers with reduced pore size and low hydraulic conductivity (<10m-6.sec-1) such as clay, loess, very fine sands and rock (Tomlinson and Boulton 2008).

The distribution of unconsolidated aquifers in the Fitzroy River Valley (FRV) is extensive and comprised of aquifers of different age (Figure 3.2). Unconsolidated aquifers of differing age are likely to contain differing stygofauna. Significant karstic areas in the FRV are limited to the Napier Range and Oscar Range areas on the northwestern boundary of the FRV and the Gieke Gorge area of the King Leopold Ranges (Humphrey 1995); the former area has been previously shown to contain significant stygofauna (see below). Wilson and Keable (1999) believed karstic systems and caves were common throughout the Kimberley but remained to be mapped well. Calcrete aquifers occur in the very southeast portion of the catchment (i.e. adjacent to Lake Gregory).

If sustainable groundwater use is an aim of water management, aquifers need to be considered as active ecosystems rather than just inert aquifers. In fact, Humphreys (2008) suggests that aquifers are the ultimate groundwater dependent ecosystem. Of the world’s ecosystems, aquifers are suggested to contain the highest proportion of rare taxa with restricted distributions (Hancock and Boulton 2005). In addition to the need to protect and conserve the biodiversity that resides in groundwater systems (which is very substantial; >4000 species of trogylbitic and stygobitic organism estimated to occur in western half of the Australian continent – see below), stygofauna play an important role in water purification and maintenance of water flow (i.e. provide significant ecosystem services). Without the grazing activity of stygofauna, bacterial and fungal populations proliferate and form a mucilaginous matrix within the pores of the aquifer and thus reduce hydraulic conductivity (see Tomlinson and Boulton 2008; Dillon et al. 2009). Stygofauna provides an important ecosystem service which ultimately may determine the quality of groundwater and the rate at which it can be abstracted.

Stygofauna and SGDEs are vulnerable to a range of anthropogenic impacts. Foremost among these is removal of groundwater and drawdown of the water table. Reducing the availability of groundwater may result in a gradual proportional decrease in health or areal extent of a given ecosystem or a threshold may be reached beyond which collapse occurs (Evans 1998). Knowledge for Australian systems is limited and it is unknown what form this relationship takes. Drawdown of the water table may occur because of abstraction for irrigation (less so from stock watering) or mine dewatering. Information on the impacts of such lowering of the water table are lacking, and particularly so the impacts of rapid seasonally fluctuations associated with irrigation.
Elsewhere, particularly in urban areas, aquifer recharge from stormwater (either natural or managed artificial recharge) and treated effluent (managed artificial recharge) may deliver toxicants and nutrients to subterranean ecosystems (Dillon et al. 2009). Nutrient pollution and hence high biological oxygen demand is a significant stressor despite a general hypoxic tolerance by most stygofauna (Tomlinson and Boulton 2008).

Although troglofauna are not directly reliant on groundwater, this element of the subterranean fauna are most abundant, if not largely confined, to the moist humid areas of caves (Moulds and Banninick 2012). Tropical cave systems are especially prone to dessication because dry season temperatures (and hence vapour pressures) are typically lower on the outside of caves and hence water will tend to leave the cave system – the tropical winter effect (Humphries 2008). Thus lowering ground water tables is likely to render unsuitable areas previously suitable for troglofauna.

Potential research project 9 – Diversity and distinctiveness of subterranean fauna within Fitzroy River Valley – preliminary survey

Time frame – 6 months (field based)

Implement field based program to sample stygofauna from bores, moundsprings (springs in general), river channel hyporheos and easily accessible cave water bodies. Determine the likely diversity, distinctiveness and pattern of endemism (i.e. short range) of stygofauna (i.e. cf. Pilbararegion). Determine likely spatial variation in relation to groundwater source (i.e. aquifer type) and prospective areas of groundwater use.

Although, the extent of investigation of stygofauna in the Kimberley region in general and the FRV in particular, has been very limited, what little sampling that has occurred has revealed the presence of a significantly biodiverse fauna. For example, Humphries (1999) investigated the stygofauna of aquifers to the north-east of the Ord River through a very limited survey of bores. A significant fauna was recovered, including a syncarid crustacean, from a small number of boreholes. A similarly diverse fauna was recovered from boreholes in the vicinity of the Sorby Hills mine site near Kununurra including 1 nematode, 1 oligochaete, 2 ostracod, 4 copepod, 1 syncarid and 1 isopod; all new to science (Benelongia 2012). Storey et al. (2011) investigated the fauna and limnology of the Mandora Marsh system on the very south-western edge of the Kimberley region. The Marsh is a relictual estuary with a diverse array of habitats including a mound spring. Among the fauna recovered from this spring was the endemic syncarid Kimberleybathynella mandorana. Wilson and Keable (1999) described a new genus and species of phreatocid isopod from a spring in the El Questro region. The taxon Crenisopus acinifer was suggested to represent a lineage that had developed very early in isopod evolution. Other new isopod species (and genera) have been recovered from cave systems in the Oscar and Napier Ranges. One such species, Tainisopus fontinalis was recorded from a pool in a cave as well as several springs whereas the other, Tainisopus napierensis was recovered from a cave pool (Wilson and Ponder 1992). This same pool also yielded
a new species of atyid shrimp *Caradina spelunca* (Choy 1996). Cavernicolous troglobytic fauna have also been reported from the Kimberley region. For example, Moulds and Bannink (2012) report a total of 5 troglobytic species (all as yet undescribed) from the Judburra/Gregory karst area to the east of Kununurra. This system also contained a stygobytic undescribed amphipod. Cavernicolous goblin spiders have also been recorded from the Kimberley region also (Harvey and Edward 2007).

Thus, although there has been only very limited investigation, it is highly likely that the Kimberley region and the FRV contains diverse stygo and troglofauna. The quantification of stygodiversity is highly dependent on the degree of sampling effort as many stygofauna are short range endemics (Eberhard et al. 2009). This is evident in the stygofauna research undertaken in the Pilbara region. For example, Eberhard et al. (2005) report a total of 78 species of stygofauna from the Pilbara region. Only a few years later this total had risen to ~350 species and an estimated total diversity for the region of 500-560 species was predicted (Humphrey 2008; Eberhard et al. 2009). Ostracods are an important component of this fauna and new species continue to be collected. Reeves et al. (2007) recorded 110 species (72% of which were new to science) within 21 genera from bores within the Pilbara region. They noted that the composition of the fauna recovered from bores varied along a number of gradients – richness was especially high in bicarbonate rich water; the fauna recovered from NaCl rich waters near the edge of the Great Sandy Desert was especially distinctive; and the fauna present in coastal and low lying alluvial groundwater was different from that recovered from upland aquifers (>300 asl).

The most recent estimate of subterranean diversity (both stygo and troglobytes) in the western half of the Australian continent is that of Guzik (2010) who predict a total of more than 4,000 species. Much of this new diversity is likely to be from the “hot spot” Pilbara region as mining provides the impetus for further sampling. However the Kimberley is likely to also provide a significant portion of this undiscovered diversity for two reasons. First, and as previously identified, sampling in the Kimberley region has been very limited and yet has revealed a rich and diverse fauna. Further investigation is thus highly likely to reveal many new species. Second, Humphrey (2008) noted that the current distribution of subterranean isopod families is almost entirely restricted to those areas of Australia that were never inundated by the sea since the Paleozoic (120 MYBP). The Kimberley region is almost entirely one such area and it likely contains many other relictual lineages (e.g. bathynellid syncarids) and high diversity of subterranean isopod families.

It is worth highlighting that what little sampling focussed on stygofauna that has occurred in the Kimberley region has been restricted to a small number of caves, one spring and a few isolated borefields. The fauna present within the hyporheos of the Fitzroy has not been investigated nor has the fauna within the alluvial aquifers that maintain baseflows within the river. Both are highly likely to contain a diverse and distinctive fauna.

It is also worth highlighting that most Australian studies on subtereanean fauna have been almost totally focussed on describing the identity and distributions of the fauna (i.e. primarily taxonomic). Little is known of how such fauna respond to seasonal or anthropogenic changes in groundwater level or anthropogenic changes in water quality (i.e. increased nutrient loads or elevated salinity). Nor are the effects of drawdown of water away from the hyporheos on this component of the fauna of Kimberley streams (or of surface taxa refuging in the streambed during the dry season) well

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known. Given their likely high biodiversity and ecological importance, a better understanding of the relationship of this faunal group to groundwater, especially hyporheic flow, is required.

**Potential research project 10 – How does subterranean and hyporheic fauna within Fitzroy River Valley respond to natural and anthropogenic variation in groundwater?**

**Time frame** – long-term

Implement targeted field based program to monitor seasonal changes and depth distribution of stygofauna from bores and river channel hyporheos. Determine the likely biotic responses to reduction of groundwater inputs to hyporheos or drawdown of aquifers associated with GW abstraction. Using stable isotopes, examine structure of foodwebs to identify basal production sources and potential for groundwater removal and nutrient enrichment to alter stygofaunal community. Potential for manipulative experiments (i.e. nutrient enrichment).

6.5 Riverine Fishes

Information concerning freshwater and estuarine fishes in the Fitzroy River Valley (FRV) relevant to environmental water management predominantly concerns the identity and distributional arrangement of fishes within the river and secondarily concerns connectivity between different components of the riverine landscape.

6.5.1 Distribution of freshwater fishes

Researchers from Murdoch University led by Dr David Morgan have been active within the catchment for over a decade. Morgan et al. (2004) first surveyed the fauna, recording a total of 37 species from 70 locations throughout the catchment. Of these, 14 were marine/estuarine dependent. This proportion is consistent with that recorded in a range of rivers across northern Australia (i.e. 30-40%) (Pusey et al. 2011). Supplementary sampling in the very lowest reaches of the river and adjacent creeks that also feed into King Sound recorded a range of other marine species including river sharks (*Glyphis garricki* – Critically Endangered), other shark species, popeye mullet, *Neoarius graeffei*, King threadfin and *Nibea* sp.

Significant spatial differences in distribution of individual species results in well-defined differences in species assemblage composition within the river. Distinct zones (lower, middle and upper) could be recognised within the river based on species present. Moreover tributaries contained a different assemblage than did riverine zones (but not sites located within gorges) as did floodplain billabongs (distinct from all except middle zone sites) (Morgan et al 2004). Warfe et al. (2013) (see below for a fuller account of sites number and arrangement) found that the determination of assemblage structure in the perennial reaches of the river were consistent with arrangement by niche rather than dispersal but that dispersal may play a weak although significant role in intermittent tributary streams.

In addition to these species recorded in field surveys by Morgan et al. (2004), these authors also list four additional species as present in the river; *Craterocephalus stramineus*, *Toxotes chatareus*, *Elops*...
*hawaiensis* and *Thryssa aestuaria*. No museum records placing the first two species within the river exist and Morgan et al. (2004) considered them both absent from the Fitzroy River. The latter two species are more properly considered estuarine and as they are common across northern Australia, it is likely they occur in the estuarine and lower reaches of the Fitzroy River.

Warfe et al. (2013) sampled a total of nineteen sites throughout the catchment, four of which were within perennial streams and the remainder in intermittently flowing streams. These authors do not list the species collected, being more concerned with discerning relationships between assemblages and local habitat. The data were collected as part of a TRaCK study on foodwebs in the river and the raw data is obtainable and available for further interrogation.

Dixon et al. (2011) included fish in a larger study examining the applicability of the Framework for the Assessment of River and Wetland Health (FARWH) to assess environmental condition in the Fitzroy River. The authors used a combination of backpack and boat electrofishing to sample fish assemblages (as did Warfe et al. 2013) at 24 unique locations according to the standard protocol used within all TRaCK surveys (e.g. Daly River Fish/flows project) and the earlier Northern Australian Freshwater Fish study. Data are therefore broadly comparable with a range of other studies across northern Australia. This study recorded a total of 23 species with maximum and minimum richness per site of 17 and 4 species, respectively. A well-supported model predicting richness was developed based upon within-site variation in landscape position (i.e. catchment area and distance from the river source), disturbance (% cleared, bank side disturbance, nutrient status) and water chemistry (TN, TP, conductivity and pH). These factors were strongly intercorrelated also.

Close et al. (2014, 2015) used these data to examine and predict the wider influence of customary and recreational fishing harvest on the structure of fish assemblages in isolated waterbodies. They found that such harvest was likely to be important in determining assemblage structure during the dry season, particularly in those locations close to major population centres and remote aboriginal communities.

### Potential research project 11 – Predictive model of freshwater fish distributions and identification of key conservation areas in the Fitzroy River Valley.

**Time frame** – short-term

Using existing data concerning fish distributions, landscape attributes, conservation importance and intra riverine connectivity, develop a predictive model and maps of fish distributions and conservation status to guide environmental water planning.

Data within Morgan et al. (2004) but not Warfe et al. (2013) nor Dixon et al. (2011) were used to model the conservation value of aquatic ecosystems across northern Australia (Kennard 2010). This investigation relied on the development of a predictive model allowing the distribution of species at fine spatial scales (i.e. planning units of approximately 400km²) to be predicted based on relationships between fish species presence/absence and landscape scale environmental variables discerned over the entire distribution of species involved. Thus while predicted distributions of
fishes and various criteria determining conservation value (e.g. endemism) within the Fitzroy River were developed they were not developed solely on models developed specifically for the Fitzroy River and based only on data collected from that river. None-the-less, this investigation of the conservation value of aquatic ecosystems of northern Australia found the Fitzroy River to be of high value. For example, the Fitzroy River, like many other Kimberley rivers, rates highly with respect to endemism although it contains only one endemic species (an undescribed ambassid glassfish). (See however the material below concerning sawfish).

Thus spatially explicit information concerning the distribution of freshwater fishes of the Fitzroy River is available from a total of 113 sites (70 – Morgan et al. (2004); 24 – Dixon et al. (2011); 19 – Warfe et al. (2013)). Of this total, presence/absence data are available from 43 sites (Morgan et al. (2004) report presence only information) with many sites examined also having accompanying information related to habitat structure. This is a high density of sampling locations. Linke et al. (2012) used similar data concerning fish distributions to develop a highly functional predictive model of fish distributions in the Daly River of the Northern Territory in an assessment of systemic conservation planning in this basin. The multiresponse feed forward neural network model, based on data from 55 sites, had high predictive value (81% correct classification, AUC = 0.75). A conservation plan based on this model merged with a series of rules concerning connectivity and penalties based on catchment condition was developed that identified three main conservation areas that conserved important conservation targets based on freshwater fishes. The identification of these key areas was considered critical for future development of conservation plans in light of projected increases in water use within the Daly River (Linke et al. 2012).

The development of such a predictive model would greatly aid the development of environmental water plans for the Fitzroy Basin, identifying which areas and subcatchments are of greatest conservation significance and what areas are essential in maintaining the overall conservation value of the basin and identifying the distributional limits and movement pathways of migratory species.

6.5.2 Estuarine fishes
Contrastingly, there is extremely scant information concerning the fishes present in the estuary of the Fitzroy River. Museum (WAM) records are limited, listing only the previously mentioned T. aestuaria recorded 10km upstream of the river mouth, and the catfish Paraplotosus sp., recorded at the river mouth itself. Thus, in combination with the incidental observations of Morgan et al. (2004), less than a dozen species have been recorded from the estuary itself. This is in contrast to >250 species recorded from the South Alligator River of the Northern Territory (Pusey et al. in review). Clearly, the estuary has been undersampled. Holliday et al. (2011) undertook three plankton trawls within King Sound (about equidistant from river mouth to open sea) in the late wet/early dry season. Larval fish composition in these samples was dissimilar to those recovered from open ocean trawls and more closely resembled that of an estuarine system. The samples were dominated by Gobiidae (gobies - 27.3%), Sciaenidae (croakers or jewfishes - 18.9%), Sparidae (bream – 16.4%) and Sillaginidae (whiting – 15.5%). Whilst Gobiidae and Sciaenidae are similarly dominant families in estuaries of the Northern Territory, Sparidae and Sillaginidae are not (Pusey et al. in review). (Note however that these data refer to the abundance of larval forms not the number of species.) Pusey et al. (in review) described substantial biogeographic variation in estuarine fish composition across the Northern Territory and it is likely that this compositional turnover extends down the west coast also.
The presence of species within these families suggests that King Sound may function ecologically as a very large estuarine mouth of the Fitzroy River (see section on estuarine function). Recreational fishing and crabbing is an important component of the economy of the West Kimberley region (Raguragavan et al. 2010) and the continued persistence of healthy stocks of species such as sciaenid croakers and whiting (their principal prey) is likely critical for that to remain so. The importance of freshwater outflows to primary production and estuarine fish assemblages of the Fitzroy River estuary and King Sound remains a significant unknown. Elsewhere across northern and north-eastern Australia, a large body of research has identified the importance of wet season flows in determining the production dynamics of many species of estuarine fish (and crustaceans) of economic significance (see review by Robins et al. 2005).

### Potential research project 12 – Quantify lower riverine and estuarine fish biodiversity and determine the importance of freshwater inflows in maintaining diversity and structuring food webs

**Time frame** – long-term

Field survey of estuarine and freshwater fishes of the lower Fitzroy River and its estuary to quantify diversity and relationship between diversity and freshwater flows. Stable isotope survey during wet and dry season to determine importance of riverine production to estuarine metazoan production especially to fishes and crabs of ecological, recreational and economic significance.

### Potential research project 13 – Environmental water requirements of elasmobranches of conservation significance – a review and development of quantitative relationships

**Time frame** – short-term

Using existing data to review the relationship between the biology of species such as sawfish and aspects of the flow regime, including groundwater inputs to guide environmental water management. Develop qualitative and quantitative models relating habitat suitability and potential for movement with elements of the flow regime suitable for use in predictive models (e.g. BBN modelling of the impacts of various flow scenarios).

### 6.5.3 Elasmobranch fishes of high conservation significance

The Fitzroy River and King Sound contain seven elasmobranch species of conservation significance. The sawfishes *Pristis pristis* (previously known as *Pristis microdon*), *P. clavata*, *P. zijsron* and *Anoxypristis cuspidata* are all listed as Critically Endangered or Endangered in the case of *A. cuspidata*. The *Pristis* species are differentially dependent on estuarine and freshwater habitats with *P. zijsron* being most commonly recorded from marine coastal areas (only three records of it within King Sound are known), *P. clavata* being most common in near shore and estuarine habitats and *P. pristis* occurring as juveniles far upstream in the Fitzroy River as the Margaret River (Morgan et al. 2011). *Anoxypristis cuspidata* has a distribution similar to that of *P. clavata* but is uncommon. The freshwater whipray *Himantura dalyensis* (listed in the IUCN Red Book as Data Deficient) occurs in the Fitzroy River but is not commonly encountered. The most upstream record for this species is just
upstream of the junction of the Fitzroy River and Christmas Creek (Morgan et al. 2004). The final elasmobranches of conservation significance in the Fitzroy River are the Northern River Shark *Glyphis garricki* (Critically Endangered) and the Bullshark *Carcharhinus leucas* (Near threatened). *Glyphis garricki* has been recorded at the mouth of the Fitzroy River and adjacent systems (e.g. Doctors Creek) but does not penetrate far upstream. In contrast, *C. leucas* penetrates well upstream in the river and is an important predator, especially of juvenile sawfish (Morgan et al. 2004, 2005).

Research staff of Murdoch University have had a very active research interest in the biology of sawfishes in the Fitzroy River and continue to do so. Studies undertaken have examined aspects of life history including parasitology (Thorburn et al. 2004a, 2007, 2008; Morgan et al. 2010), systematics and conservation genetics (Phillips et al. 2009a, 2010; Morgan et al. 2011), habitat use and movement (Phillips et al. 2009b; Whitty et al. 2009) and cultural significance (Thorburn et al. 2004b). Ongoing Murdoch University research led by Dr David Morgan is concerned with studies monitoring movement (acoustic tracking), mapping of habitat suitability (especially related to permanence) of pools in different parts of the river, determining stage heights/flows for movement of sawfish (and other species) around barriers and determining the relationship between discharge and recruitment success of sawfish and bullshark. One project due to commence in July of 2015 concerns the energetics and temperature sensitivity (among other topics) of euryhaline elasmobranches in freshwater pools. It should be emphasised that these projects are positioned within a larger program of work which includes long term annual monitoring of fish and freshwater crocodile populations in Uralla Creek (2008 to present) and acoustic tracking of freshwater crocodiles and a range of freshwater fish species.

6.5.4 Relationships between fish populations and surface or groundwater

Various aspects of the annual hydrograph influence individual species in different ways and determine temporal variation in abundance and distribution (Rayner et al. 2009; Stewart-Koster et al. 2011). Moreover, flow ecology relationships may be context dependent; that is a particular flow events in one part of the catchment may have a different effect to a flow of the same magnitude in a different part of the catchment. Similarly, flows of the same magnitude may have different effects if they occur at different times of year or in relation to a range of antecedent flows (Kennard et al. 2008; Stewart-Koster et al. 2011).

Other than unpublished data collected by Murdoch University researchers for a limited number of species (e.g. barramundi and catfish), the life history responses of freshwater fishes to temporal variation in discharge is unknown. There is similarly no published material concerning temporal variation in abundance of individual fish species or assemblages in the Fitzroy River (see however reference to unpublished research in Uralla Creek above). Consequently there is little to guide environmental flow assessments other than reference to studies undertaken elsewhere in rivers of a similar hydrology (i.e the ELOHA approach). Unfortunately, there are very few northern Australian studies undertaken in rivers with a similar hydrology to that of the Fitzroy River (Kennard et al. 2010). Moreover, the fishes of the Kimberley region are biogeographically distinct (i.e. many species are distinct) from those present in other rivers that might provide comparative information on flow ecology relationships. Thus the extent to which such information is transferrable to the Fitzroy River is unknown.
At present, projected demands on water resources in the catchment are unlikely to impact greatly on the high flow end of the hydrograph. More likely is increased use of groundwater with the attendant risk that this will reduce baseflows and impact upon groundwater input into riverine pools in the dry season. Dry season pools are the principal dry season refugia for freshwater fishes, turtles and crocodiles in the river. Even under natural conditions, riverine pools contract in size and may become disconnected with the rate of contraction related to connectivity to groundwater (Wallace et al. 2012).

Studies undertaken in other dryland rivers (e.g. the large body of work undertaken in south-western Queensland by research staff of the Australian Rivers Institute (e.g. Sternberg et al. 2008, Arthington and Balcombe (2011)), the Pilbara (Morgan et al. 2009; Beesley and Prince 2010; Dobbs and Davies 2011) and elsewhere (Strauch et al. 2015) plus theoretical considerations (e.g. King et al. 2015) provide some guidance to the responses of fishes to reductions in baseflow and to pool contractions. Yet, the fact remains that these studies were undertaken in different systems often within very different landscape, hydrological and agricultural contexts.

Such studies do however indicate that a whole range of intrinsic and extrinsic factors can influence the fate of biota in refugial pools. Groundwater input is foremost important in determining pool persistence in the Fitzroy River (Wallace et al. 2012). However, persistence is also related to antecedent flow conditions (i.e. extent of previous wet season flood and gradient of receding arm of flood hydrograph) (Wallace et al. 2012). The fate of fishes restricted to such refuges may in the first place be related to the interaction between these hydrological factors and channel geomorphology and disturbance which in turn determines pool size (especially depth), rate of change in pool size, pool morphology, persistence, water quality and nutrient status which in turn influences autotrophic production dynamics and determines the potential for systems to tend to eutrophy. In addition, the nature of the community present at the beginning of the dry season, including such features as number and identity of species, number of individuals, body condition and trophic character (e.g. predators), is important in determining the nature of the community present at the end of the dry season. The condition of fishes at the commencement of the dry season is likely related to the extent of antecedent wet season flows and effect on floodplain and within channel production. In addition, in-situ reproduction may occur in some species over the period of the dry season.

Fish (and other elements of riverine production) are an important component of the household economies of indigenous peoples of the FRV. Importantly, Close et al. (2015) showed that customary and recreational fishing pressure is an important influence on community structure, and especially on the size structure, of fish assemblages in dry season waterholes of the FRV. Such impacts need to be considered as additional to impacts associated with water resource use, potentially synergistic (e.g. the removal of large bodied fish, many of which are important predators, may determine the structure of fish communities in dry season water holes) and need to be considered in water resource management strategies and in strategies aimed at assessing the success, or otherwise, of any imposed management actions (i.e. monitoring).
Clearly, fish survival is an end point of a multifactorial set of interactions. At present we have no real understanding of the dynamics of biotic (including fish) responses to natural seasonal variation in surface hydrology or groundwater inputs and consequently little capacity to predict ecological responses to anthropogenic driven changes to water regimes. There are certainly no quantitative relationships relating groundwater inputs with pool size and fish community health that could be used to guide environmental water management for the Fitzroy.

### Potential research project 14– Dynamics of fish assemblages and populations in refugial riverine pools

**Time frame – 3 years**

Establish temporal examination of fish populations in riverine pools across a range of degrees of groundwater input to examine sequence of changes and fate of fish population and importance of groundwater in pool maintenance. Parameters examined could include changes in assemblage structure, food web dynamics and growth, health and energetics of individual species in response to changing conditions (GW input, pool size, water quality). Manipulative experiments in which density of fish predators can be altered are feasible.

#### 6.5.5 Connectivity and movement

Rivers are highly interconnected ecosystems with longitudinal (tributaries, main channel, estuary and near shore coastal), horizontal (river to floodplain) and vertical (river channel to hyporheos and groundwater aquifers) linkages that pulse with the temporal variation in discharge. These linkages are easily disrupted by changes in flow through abstraction or impoundment and this can result in major changes in ecosystem function. The fact that more than one third of all fish species present in freshwater reaches of the river ultimately require access to the estuary and near shore zone to reproduce highlights the need for connectivity to be maintained. Many such species (such as barramundi) are important predators and influence the distribution and abundance of other species (see Pusey et al. 2004). They may act as keystone species, the absence of which results in a range of cascading impacts.

The weir at Camballin is a barrier and has demonstrable impacts on the movement of fishes (Morgan et al. 2005). This in turn has impacts upstream through the restriction of access and impacts downstream because of a concentration of large predatory fishes. The weir crest is located at a stage height of 11m and the weir drowns out completely at 12.3m. Drownout occurred nearly all years examined by Morgan et al. (2005). Fish passage over the weir was estimated to be possible when stage height was above 11m. Morgan et al. (2005) estimated that fish passage was allowed for less than 3 months per year in 14 of 17 years examined. In eight of those years, passage was enabled for less than 2 months of the year. Thus fish passage is enabled and available for only those species that migrate during the wet season. Species that migrate during the late wet or during the dry season would not be able to overcome the weir.
The migration phenology of fishes within the river is poorly described and provides little guidance as to the relative impact that Camballin Weir has on fish movement. Similarly the relative importance of the lack of predatory species above the weir and the overabundance of such species below the weir is poorly known. For example, the downstream extent of the concentration of bullshark and sawfish below the weir is unknown as only one site located 1 km downstream was examined by Morgan et al. (2005) as part of their assessment of the weir’s effects. Although quite marked impacts of heightened predation was observed at this location, it is unknown whether such impacts would be observed 5, 20 or even 50 km downstream. The impacts of increased water use (either increased groundwater abstraction, increased flood harvesting or a combination of both) on water levels at Camballin remain to be modelled (but see McJannet et al. 2009) and there is consequently, at this point in time, no capacity to predict what impacts this may have on fish passage time except to say that it will be reduced by an unknown amount of unknown ecological significance. The assessment of effects of Camballin Weir by Morgan et al. (2005) is not based on measured water velocities over the weir or fish species capacity to move upstream when the weir is overtopping but rather is based on an *a priori* belief that movement would be enabled by a stage height greater than 11m.

**Potential research project 15 – Dynamics of flow across Camballin Weir and provision of passable habitat linking refugial pools**

**Time frame** – short-term

Model the effects of different scenarios of groundwater abstraction and floodharvesting on the frequency and duration of flow events over Camballin weir to examine whether such scenarios result in reduced opportunities for upstream movement. Critically examine the stage height recommendations made by Morgan et al. (2005). Determine the influence of proposed flow regime scenarios on connectivity between refugial pools and the impact such changes may have on fish and macroinvertebrate passage.

Movement in rivers may be lateral as well as longitudinal. Lateral movements occur when fish move out onto floodplains to feed and reproduce. In some larger river systems of northern Australia floodplains may remain inundated for months and provide ideal circumstances for fish growth and reproduction (Jardine et al. 2012; 2013). Long inundation times allow fish to move back into the main river channel before floodplains begin to shrink sufficiently for avenues of connectivity to become severed. Such movement transports floodplain carbon back into the river where it may subsidise foodwebs therein.

The modelling of floodplain inundation and connectivity in the FRV under different sized floods by Wallace et al. (2012) revealed that flood peaks are typically very short (2-3 days in the upper river to 4-5 days downstream), inundation period similarly short, and many floodplain wetlands did not connect to the main river channel except during large floods... The results of this modelling exercise suggest that the use of floodplain wetlands by fish would be very limited and that any movement onto them would be one way only. Fish accessing perennial wetlands during the inundation phase would not be able to return to the main channel. If they accessed an ephemeral wetland they would die. If fish accessed a perennial wetland, they would need to wait another 12 months for an
equivalent flood or greater for the opportunity to emigrate back to the main channel. Most fish would likely die waiting and consequently most wetlands of the Fitzroy floodplain are likely sinks of riverine carbon and authochthonous floodplain production.

The floodplain also provides most of the recharge to the FRV alluvial aquifer and the extent to which the perennial wetlands on the floodplain rely on groundwater remains unknown. Consequently the extent to which some species are reliant on groundwater to maintain wetlands in a habitable condition is similarly unknown. However, for long lived species such as barramundi, these permanent wetlands may provide an important habitat for juvenile growth and they may quickly emigrate for downstream estuarine areas once connectivity is re-established.

Jardine et al. (2011, 2012) compared the extent of coupling between secondary consumers and primary producers (allochthonous and autochthonous) in dry season riverine pools across a range of rivers of varying flow regime type. Short-lived, non-vagile consumers (e.g. aquatic insects and small fish) were typically tightly coupled to the carbon production dynamics of the area from which they were collected. This relationship was recovered irrespective of whether the flow regime was characterised by long floodflows and floodplain inundation periods or short flood peaks and inundation periods. By extension, any impacts on such local production would impact upon these short-lived non vagile organisms. However, in rivers with long inundation periods and hence high connectivity, large mobile consumers such as fish were less reliant on local production and imported carbon produced elsewhere (i.e. mostly on the floodplain). Fishes of the Fitzroy River with its short inundation period and reduced connectivity were tightly coupled to local production sources like their invertebrate food source. These studies demonstrate the extent to which the food web of the Fitzroy River is reliant on production occurring within the river channel itself and highlight the importance of perennial flows in maintaining sufficient refugial habitat to maintain the riverine food web during the dry season.

Potential research project 16 – Dynamics of fish assemblages and populations in floodplain wetlands

Time frame – long-term

Establish temporal examination of fish populations in floodplain wetlands across a range of degrees of groundwater input and degrees of connectedness to examine sequence of changes and fate of fish populations and importance of antecedent flows and groundwater in wetland maintenance. Wallace’s connectivity model provides an excellent tool to design a study in which wetland variation across gradients of permanence, connectedness, frequency of flooding can be accommodated. Parameters examined could include changes in assemblage structure, food web dynamics and growth, health and energetics of individual species in response to changing conditions (GW input, pool size, water quality). As previous studies have indicated that customary fishing harvest is potentially important, manipulative experiments in which density of fish predators can be altered is feasible and desirable.
Arthington and Balcombe (2011) clearly identify the difficulties in defining environmental flows in rivers with highly variable flow regimes such as the Fitzroy River, among which was the fraught nature of transferring information from rivers elsewhere, especially those with differing hydrology. The only option identified by Arthington and Balcombe (2011) was to develop, through focussed field studies, a good understanding of the relationship between ecology and flow regime.

6.6 Amphibians and reptiles

6.6.1 Frogs

The Kimberley region contains a moderately rich frog fauna (~45 species; Pusey et al. 2011) and the discovery of new species in the last decade has been notable (Anstis et al. 2010; Doughty 2011; Catullo et al. 2014). These new species have been collected from the Mitchell Plateau region. Frog species richness across northern Australia declines sharply with decreasing rainfall and humidity (Figure 6.5) and the Fitzroy River is relatively species poor (~20 spp.). Species present within the catchment are typically widespread across the Kimberley but either limited to the high rainfall portion of the region or limited to near the river mouth. Species distributed throughout the catchment (9 spp.) are typically those with very wide distributions (e.g. *Litoria rothi* and *L. pallida*) or species typical of the arid zone (e.g. *Neobatrachus aquilonius* or *Notaden nichollsi*). Consequently both species richness and endemism scores are greatest near the river mouth (Slatyer et al. 2007).

![Figure 6.5. Frog species richness and endemism scores across northern Australia (adapted from Slatyer et al. 2007).](image)

There is little information available on the relationship between frog ecology and flow regime in the Fitzroy River (or for northern Australia). The role of frogs or their larvae in aquatic food webs is similarly unknown.
The cane toad (*Rhinella marina*) continues to spread throughout the Kimberley and is reported present in the upper reaches of the Fitzroy River. The impact of this alien species on higher order aquatic species has been summarised in Pusey *et al.* (2011b). Reptiles such as the monitor lizards (*Varanus mertensi, V. panoptes* and *V. mitchelli*) decrease in abundance and there are notable trophic cascade effects as a result (e.g. reductions in turtle egg predation and increases in riparian lizard abundance). Freshwater crocodiles have been reported to similarly undergo reductions in abundance after toads initially colonise river basins (Letnic *et al.* 2008; Britton *et al.* 2013). The Fitzroy River contains a large freshwater crocodile population and the population present in Uralla Creek has been studied for several years by Murdoch University researchers, thus providing some baseline pre-invasion information. Larval cane toads may achieve very high levels of abundance under some conditions and in dryland rivers are able to consume a large biomass of periphyton which would ordinarily be used by aquatic invertebrates located at the base of aquatic food webs (Pusey *unpubl. observations*).

**Potential research project 17** — *Establish baseline nature of fish populations and determine potential impact of cane toads on refugial pool communities.*

**Time frame** — long-term

Previously identified projects would substantially provide the baseline information needed to establish the potential impacts of cane toad invasion. Moreover, given that toads have recently become established in the upper reaches of the river, targeted sampling in these areas could provide an initial assessment of their impact, if any. Field survey in this regard could extend to an assessment of the abundance of freshwater crocodiles and monitors. Stable isotopes studies and manipulative experiments (i.e. exclusion of tadpoles or removal of higher order predators) could be designed to test the role of adult and larval toads on production dynamics and food webs in refugial pools.

The key knowledge gap with respect to cane toad invasion is the degree to which any impacts are related to changes in dry season flows and refugial pool characteristics and the extent to which their presence confounds any assessment of the impacts of changes in flow regime or groundwater inputs. For example, the maintenance of populations of fish and macroinvertebrates may be compromised in pools containing large numbers of toad larvae irrespective of whether groundwater inputs are maintained or not. Similarly, if toads reduce the abundance of freshwater crocodiles, then some fish species such as bony bream (*Nematalosa erebi*) or mullet (*Liza ordensis*), both of which are important consumers of primary production, may be released from predator control. Such changes may have “knock on” or cascading effects on other primary and secondary consumers unrelated to flow regime changes. In the absence of information on the potential impact of this species, it will be difficult to quantitatively assess the efficacy of environmental water management strategies in the future.

### 6.6.2 Turtles

The Fitzroy River contains only two freshwater turtle species; the northern red-faced turtle *Emydura victoriae* and the sandstone snake-necked turtle *Chelodina burrungandji* (Georges and Thomson Potential research project 17 – Establish baseline nature of fish populations and determine potential impact of cane toads on refugial pool communities. Time frame – long-term

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**Potential research project 17** — *Establish baseline nature of fish populations and determine potential impact of cane toads on refugial pool communities.*

**Time frame** – long-term

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**Time frame** – long-term

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The northern snake necked turtle *C. rugosa* has been reported to occur in the Fitzroy River, but Georges and Thomson (2010) do not list its distribution as extending into the Kimberley region. These two species of long-necked turtle hybridise readily when in sympatry, producing viable hybrids and the mitochondrial genome of all Northern Territory populations of *C. burrungandjii* has been replaced by that of its congener. Thus these two species cannot by distinguished on the basis of mitochondrial information. A species of long necked turtle endemic to the Fitzroy River, *C. wolloyarrina* has been previously described (MCord and Ouni 2007), however Georges and Thomson (2010) placed this species within *C. burrungandjii*. Some authors recognise the Fitzroy River populations as a distinct subspecies of *C. burrungandjii* (Atner 2008). Fox (2008) list *Emydura australis* as occurring in the Fitzroy River but Georges and Thomson (2010) suggest that all such of the records of this species from the Kimberley region are based on misidentification of *E. victoriae*.

Little is known of the flow related ecology of these turtle species in the Fitzroy River. In the case of *E. victoriae* it probably has a breeding phenology similar to other populations of this species and other species within the genus; mating peaks in autumn and spring, ovulation and oviposition in late spring and early summer and emergence occurs well before the onset of the wet season (see Pusey et al. 2011). Given that they readily hybridise, the breeding biology of *C. burrungandjii* is probably similar to that of *C. rugosa*; eggs are laid underwater or in moist soil and develop during the dry season. Georges et al. (1993) suggested that within river turtle diversity may be controlled by flow variability and its effect on the provision of suitable habitat and food resources. Unlike in the Daly River, turtles do not feature prominently in the indigenous harvest within the Fitzroy River (Jackson et al. 2011).

### 6.6.3 Crocodiles and monitor lizards

Two species of crocodile occur in the Fitzroy River, *Crocodylus porosus* and *C. johnstoni*. Both are widespread across northern Australia. The population size of *C. porosus* in the Fitzroy River is low compared to elsewhere across its range due to a lack of suitable nesting sites near the river mouth (Semenuik et al. 2011). In contrast, *C. johnstoni* is abundant throughout the freshwater reaches of the river and the population present is the most southern population in Western Australia. This species is an important predator of fishes and its presence in refugial pools during the dry season may be an important determinant of fish assemblage structure at the end of the dry season. This species is known to enter a non-active phase in the late dry season (Grigg and Kirschner 2015), perhaps related to the absence of its preferred prey. They are even able to endure in this state in the absence of surface water by seeking refuge in burrows or deeply undercut banks and may survive for several months in this manner (see summary in Grigg and Kirschner 2015).

Little is known of the ecological role that freshwater crocodiles play in seasonal tropical rivers except that they are important predators. Similarly, little is known of the environmental water requirements of this species. The environmental water requirements of freshwater crocodile have not been determined for any river system in Australia and they have certainly not been considered in anything other than a cursory manner. Clearly, they are well adapted to the seasonal flow regime present in the Fitzroy River yet significant unknowns exist. For example, what are the habitat requirements (e.g. pool size, depth etc.) of this species? If the longevity of refugial pools is reduced because of decreased groundwater inputs, what impact does this have on life history and ultimately on population size? Stunting has been described in freshwater crocodile populations and attributed to reduced food supply (Britton et al. 2013) and this presumably has demographic effects.
Importantly however, and in sense analogous to that described for cane toads and the ability to discern the efficacy of environmental water management strategies, what role do freshwater crocodiles play in determining fish assemblage structure as pool size deceases with the onset of the dry season? Does predation upon primary consumer fish species ultimately influence food web dynamics and other fish species? Understanding the water requirements and ecology of this species will likely prove essential to informed water management.

Potential research project 18– What are the environmental water requirements of freshwater crocodile Crocodylus johnstoni in the Fitzroy River (particularly in groundwater fed refugial pools) and what ecological role do they play in such habitats during the dry season?

Time frame – long-term

Determine the relationship between pool size, habitat structure, longevity and groundwater input and the ecology of freshwater crocodiles. Examine the role that crocodile predation on fishes influences fish assemblage structure over the dry season and influences the passage of autochthonous carbon through the aquatic foodweb. Potential for manipulative experiments to determine such questions as – does the absence of herbivorous fishes such as bony bream because of crocodile predation alter primary production dynamics (i.e. standing crop or biomass of periphyton)? Does this alter the dynamics and structure of food webs in refugial pools?

Monitor lizards (Varanus spp.) are also present in the catchment and both V. mertensi and V. mitchelli are important consumers of aquatic animals (Pusey et al. 2011). Their influence on aquatic systems has not been examined in detail but they may play a large, but under-appreciated, role as major secondary consumers (D.Warfe, pers. comm.) not unlike freshwater crocodiles.

6.7 Birds

In the FRV, environmental management issues concerning birds involve the identification of bird species and related habitats sensitive to water resource developments. Two broad categories of birds likely to be sensitive to water resource developments are (1) birds that inhabit riparian and floodplain vegetation and (2) water birds dependent on wetland habitat. These two groups are discussed in turn below.

6.7.1 Birds of the riparian zone

Riparian birds are here defined as any bird species that is either partially or wholly dependent on the habitat and resources provided by riparian (including floodplain) vegetation. There are no published studies that have focused specifically on riparian bird communities in the Fitzroy River Valley (but see Skroblin and Legge 2012 discussed below and Kyne (unpublished data) briefly discussed in Kyne and Dostine 2011). However, there are studies on riparian birds in similar areas, namely the wet-dry tropics of the Northern Territory, that allow some general inferences to be made about potentially sensitive bird species to water resource development (Woinarski et al. 2000).
Woinarski et al. (2000) studied the richness and abundance of bird species in the wet-dry tropics of the Northern Territory and was able to identify several bird species that occurred in significantly higher abundance in riparian habitats. Many of the species identified by Woinarski et al. (2000) as occurring in higher abundance in riparian areas also occur in the wet-dry tropics of the FRV (Table 6.4). Although it should be noted that while there is high overlap in species listings between the Fitzroy and Woinarski et al. (2000) (with 42 out of 45 species listed in Woinarski also observed in the Fitzroy), it is likely that some species are missing and as such the species listed should be treated as an indicative sample of potentially sensitive riparian bird species in the Fitzroy.

In the Fitzroy, one bird species, the Purple-crowned fairy-wren, has been shown to have particularly strong links with riparian vegetation (*P. aquaticus*) that is likely to be groundwater dependent (Skroblin and Legge 2012). Models for the Purple-crowned fairy-wren developed using data from the Kimberley, including the Fitzroy Valley, suggest that Pandanus crown cover was the most important predictor of its occurrence (Skroblin and Legge 2012). Skroblin and Legge (2012) argued that maintaining riparian condition and connectivity between riparian habitats would help ensure the persistence of Purple-crowned fairy-wren in northern Australia. Ensuring that water extraction impacts are minimised on riparian vegetation species, such as *Pandanus* spp., could therefore have implications for the Purple-crowned fairy wren and other riparian bird species in the Fitzroy Valley.

**Potential research Project 19: Identifying links between hydrology, riparian vegetation and riparian birds.**

**Time frame – long-term**

Determine the relationship between bird abundance and composition data across gradients of surface water inundation frequency, groundwater levels and riparian vegetation condition/structure. Using this data determine 1) whether riparian zones in the FRV are more or less important in sustaining regional diversity than reported elsewhere, 2) model the spatial and temporal variation in habitat requirements of riparian bird species (e.g. structure, tree species, connectivity etc.), 3) determine the extent to which riparian birds are reliant on secondary production derived from refugial pools or primary and secondary riparian production (gut/scat analysis and stable isotope analysis) and 4) identify key riparian elements dependent on groundwater that are important for riparian birds and that may serve as surrogates in the environmental water planning process.
Table 6.4. Bird species that occur in high abundance in riparian areas of the wet-dry tropics and that have been observed in the FRV.

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Scientific Name</th>
<th>Common Name</th>
<th>Scientific Name</th>
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</thead>
<tbody>
<tr>
<td>Australasian Darter</td>
<td>Anhinga novaehollandiae</td>
<td>White-browed Robin</td>
<td>Poecilodryas superciliosa</td>
</tr>
<tr>
<td>Australasian Figbird</td>
<td>Sphecotheres vieilloti vieilloti</td>
<td>White-faced Heron</td>
<td>Egretta novaehollandiae</td>
</tr>
<tr>
<td>Azure Kingfisher</td>
<td>Ceyx azureus</td>
<td>White-gaped Honeyeater</td>
<td>Stomiopera unicolor</td>
</tr>
<tr>
<td>Bar-breasted Honeyeater</td>
<td>Ramsayornis fasciatus</td>
<td>White-throated Honeyeater</td>
<td>Melithreptus albogularis</td>
</tr>
<tr>
<td>Barking Owl</td>
<td>Ninox (Hieracoglaux) connivens</td>
<td>Willie Wagtail</td>
<td>Rhipidura (Souloprocta) leucothrix</td>
</tr>
<tr>
<td>Bar-shouldered Dove</td>
<td>Geopelia humeralis</td>
<td>Yellow-tinted Honeyeater</td>
<td>Lichenostomus</td>
</tr>
<tr>
<td>Black Bitttern</td>
<td>Ixobrychus flaviollis</td>
<td>Northern Fantail</td>
<td>Rhipidura (Setosura) rufiventris</td>
</tr>
<tr>
<td>Blue-winged Kookaburra</td>
<td>Dacelo (Dacelo) leachii leachii</td>
<td>Peaceful Dove</td>
<td>Geopelia striata</td>
</tr>
<tr>
<td>Brown Goshawk</td>
<td>Accipiter (Leucospiza) fasciatus</td>
<td>Purple-crowned Fairy-wren</td>
<td>Malurus (Malurus) coronatus</td>
</tr>
<tr>
<td>Brush Cuckoo</td>
<td>Cacomantis (Cacomantis) variolosus</td>
<td>Rainbow Bee-eater</td>
<td>Merops (Merops) ornatus</td>
</tr>
<tr>
<td>Collared Sparrowhawk</td>
<td>Accipiter (Parasizias) cirrocephalus</td>
<td>Restless Flycatcher</td>
<td>Myiagra (Seisura) inquidea</td>
</tr>
<tr>
<td>Crimson Finch</td>
<td>Neochmia (Neochmia) phaeton</td>
<td>Rufous Whistler</td>
<td>Pachycephala (Alisterornis) rufiventris</td>
</tr>
<tr>
<td>Double-barred Finch</td>
<td>Taeniopygia bichenovii</td>
<td>Sacred Kingfisher</td>
<td>Todiramphus (Todiramphus) sanctus</td>
</tr>
<tr>
<td>Grey Fantail</td>
<td>Rhipidura (Rhipidura) albiscapa albiscapa</td>
<td>Spangled Drongo</td>
<td>Dicrurus bracteatus bracteatus</td>
</tr>
<tr>
<td>Intermediate Egret</td>
<td>Ardea (Mesophoyx) intermedia intermedia</td>
<td>Sulphur-crested Cockatoo</td>
<td>Cacatua (Cacatua) galerita</td>
</tr>
<tr>
<td>Leaden Flycatcher</td>
<td>Myiagra (Myiagra) rubecula</td>
<td>Varied Triller</td>
<td>Lalage (Karua) leucomea</td>
</tr>
<tr>
<td>Lemon-bellied Flycatcher</td>
<td>Microeca (Microeca) flavigaster flavigaster</td>
<td>Whistling Kite</td>
<td>Haliastur sphenurus</td>
</tr>
<tr>
<td>Little Corella</td>
<td>Cacatua (Licmetis) sanguinea sanguinea</td>
<td>Mistletoebird</td>
<td>Dicaeum (Dicaeum) hirundinaceum</td>
</tr>
<tr>
<td>Little Pied Cormorant</td>
<td>Microcarbo melanoleucus</td>
<td>Nankeen Night-Heron</td>
<td>Nycticorax caledonicus</td>
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</tr>
</tbody>
</table>

6.7.2 Waterbirds

Waterbirds are a highly valued group of bird species inhabiting river, wetland and floodplain ecosystems. There are numerous international obligations for protecting waterbirds to which Australia adheres. These include the RAMSAR Convention, the Convention on Conservation of Migratory Species of Wild Animals (the Bonn Convention), the China–Australia Migratory Bird Agreement (CAMBA), the Japan–Australia Migratory Bird Agreement (JAMBA) and the Republic of Korea–Australia Migratory Bird Agreement (ROKAMBA) (Kingsford et al. 2012). The ecologically sustainable
management of wetlands throughout the wet-dry tropics of northern Australia, including the FRV, is particularly important for ensuring international obligations concerning water birds are met.

The Kimberley is an extraordinarily important region for waterbirds especially shorebirds. It is used by over 3.7 million shorebirds, including 25 species which occur in the region in internationally significant numbers (i.e. > 1% of the flyway population). No other region in Australia, or indeed anywhere else in the East Asian Flyway, supports such large and diverse nonbreeding populations (Rogers et al. 2011). It is highly likely that the wetlands of the FRV provide important habitat for many of these migratory species.

Halse and Jaensch (1998) noted that the Fitzroy River is an important area for both migratory and non-migratory waterbirds. They identified four areas of major importance: (1) River mouth: around Willare, the riverine vegetation is in good condition (importantly supporting elements of vine thickets) and supports rich bird (and bat) communities. The mudflats at the river mouth occasionally supports high numbers of water birds; (2) small seasonal floodplain wetlands, particularly between Camballin and Fitzroy Crossing, which hold water for a short time and may support large numbers of waterbirds during the wet season; (3) large floodplain wetlands, especially at Camballin and Noonkenbah; and (4) permanent riverine pools and billabongs.

Figure 6.6. Locations of waterbird surveys listed in Storey et al. (2001). Circles show the location of each survey, the size of the circle is proportional to the number of waterbirds observed (log-transformed abundance) and the number next to each circle is the number of different waterbird species observed.
Surveys carried out in the 80's and 90's presented in Storey et al. (2001) and as part of the national waterbird assessment Kingsford et al. (2012) also suggest there are wetland habitats within and surrounding the FRV of high importance for waterbirds (Figure 6.6). Storey et al. (2001) argue that the Fitzroy River is probably one of the more important habitats for Magpie geese and Whistling-duck, with large numbers of Magpie geese breeding at Camballin (Storey et al. 2001). The geographic range of this species has contracted alarmingly in recent decades (see Bayliss et al. 2008; Kyne and Dostine 2011) and as such the occurrence of Magpie geese in the FRV could be regionally significant management issue. Storey et al. (2001) also observed large abundances and a high diversity of other waterbirds on the Camballin floodplain (Figure 6.6). A total of 67 species (and abundances up to 38,553) have been observed on the Camballin floodplain (Jaensch and Vervest, 1990; Storey et al. 2001). Based on the high abundance of waterbirds observed by Storey et al. (2001) the Camballin floodplain area meets key Ramsar criteria for being listed as a Wetland of International Importance (i.e. > 20,000 waterbirds). Given the high diversity of waterbird species observed it is also not surprising that many of the waterbirds in Camballin floodplain area are covered by numerous agreements (including the Japan-Australia and/or China-Australia Migratory Birds Agreements (Jamba/Camba)) and/or listed as priority or rare species (e.g. several snipe species and Freckled duck).

More recently, the waterbird richness of the Fitzroy valley has been modelled, as a part of assessments of high value conservation ecosystems for northern Australia (Kennard et al. 2010). Drawing on datasets collected since 1970, Kennard et al. (2010) modelled waterbird taxon occurrence using numerous habitat, terrain and climatic variables, as well as variables representing the distribution, size, productivity and characteristics of lacustrine and palustrine waterbodies. Using these variables the models explained around 20% of the variation in the occurrence of different waterbird species, a significant amount given the high mobility of waterbirds. In FRV the models predicted the highest levels of species richness in the Lower Fitzroy (Figure 6.7). This is consistent with the observations of high waterbird richness at Camballin floodplain in the lower Fitzroy by Storey et al. (2001) (Figure 6.6). However, while the models developed by Kennard et al. 2010 predicted waterbird richness reasonably well across northern Australia, they caution that because of the nature of the data used (presence-only) there is the potential for over-predicting presences and under-predicting absences. As a consequence they argued that a future research priority is to collect presence/absence data so that more robust models can be built.
6.7.3 Water resource development impacts on waterbirds

Water resource development has been implicated in changes to waterbird abundance and composition across many river and wetland habitats in Australia (Kingsford and Thomas 1995; 2004; Leslie 2001; Kingsford et al. 2004; Kingsford and Auld 2005; Kingsford and Porter 2009). Water resource development, and specifically river regulation and floodplain development, can decrease wetland area, which is strongly linked to waterbird abundance (Kingsford et al. 2012). In recent Australian wide surveys on waterbirds, Kingsford et al. (2012) also noted considerable differences in waterbird composition between unregulated and regulated rivers. Declines in water abundance were also observed in many regulated wetlands (Kingsford et al. 2012).

In the Fitzroy River Valley, while river regulation at a scale that has been linked with waterbird declines in other parts of Australia is unlikely, groundwater extraction and overland harvesting of flows are possible developments that may impact on wetland area and thus potentially on waterbirds. Groundwater extraction may lower water tables, potentially switching perennial groundwater-fed wetlands that may act as dry-season refuges to intermittent wetlands that contain no water in the dry-season – thus reducing dry-season wetland area. While, overland harvesting of floodwaters may locally reduce wetland area and thus the amount of potentially suitable habitat for some waterbird species. Consequently, water resource developments in the Fitzroy River Valley could trigger notable changes in some waterbird populations.

In the Fitzroy River Valley, Storey et al. (2001) argue that the greatest impacts on waterbirds are likely to occur in floodplain areas around Camballin and Fitzroy Crossing (Figure 6.6). Modelled predictions of waterbird richness from Kennard et al. (2010) also suggest that floodplain areas of the lower Fitzroy are where impacts on waterbirds may the greatest (Figure 6.6). Water resource development is likely to impact on waterbirds in these areas if there is a reduction in the frequency,
depth or duration of floodplain inundation (Storey et al. 2001). Nonetheless, Storey et al. (2001) caution that it is difficult to predict the impacts of hydrological changes on waterbirds, stating that in some cases impoundments may provide permanent water sources that could act as valuable dry season refuge habitat. Given these uncertainties there is need to identify the most likely impacts of water resource development on waterbird populations in the Fitzroy River Valley.

Potential research Project 20: Quantify links between hydrology, wetland area and waterbird abundance/composition to predict the changes of different types of water resource development

Time frame – long-term

Using existing data (or collecting additional bird abundance and composition data) examine the importance of wetlands within the FRV to waterbirds and determine the relationship between structural (size, waterplant abundance, water chemistry), geographical (proximity to coast, proximity to river, proximity to known important rookeries and stopover points for migratory birds) and hydrological (perenniality/intermittency, flood inundation frequency) wetland characteristics, and at different scales (e.g. individual wetlands to mosaics of wetlands across a landscape). From this assess the value of different wetlands (and wetland mosaics) for providing waterbird habitat. Model the potential impacts of different scenarios of (1) groundwater extraction that may reduce dry season permanent wetland area and (2) overland flood

6.8 Aquatic food webs

Riverine food webs are the integration and interaction of different species and ecological processes. Food webs include (1) the integration of ecological interactions among biota (predation, competition, mutualism and parasitism) (2) interactions between biota and physical and chemical characteristics of the environment (3) interactions between biota and in-situ primary production and its dependencies on habitat structure, light availability, nutrient status and water quality, and (4) the extent of connectivity between different parts of the riverine environment and the movement of organisms and the movement of energy and nutrients between and within the riverine environment. Food webs thus provide indicators of important species and processes that need to be maintained and are themselves endpoints that need to be sustained. There is little point in managing a flow regime to achieve desired endpoints such as continued presence of individual species or to ensure appropriate conditions for spawning if the energetic basis of the system is not also maintained.

There is a large body of research concerning the nature of aquatic food webs in Australian subtropical and tropical rivers (Bunn et al. 2003; Douglas et al. 2005; Rayner et al. 2010; Jardine et al. 2011, 2012, 2014; Warfe et al. 2013; Fellman et al. 2013; Blanchette et al. 2014). In brief, these studies reveal that tropical Australian aquatic food webs, like aquatic food webs elsewhere, tend to be short (<4 trophic levels) aquatic food webs indicating a rapid and efficient transfer of energy through the system. For example, the main prey of large predatory fish such as barramundi is dominated by algivorous/detrivorous fishes such as mullet and bony bream. These studies have indicated that periphyton is the major source of primary production that fuels aquatic food webs,
although terrestrially-derived detritus may at times (i.e. after floods that scour the river bed and thus remove periphyton) assume greater importance (Rayner et al. 2010; Blanchette et al. 2014) and in certain geomorphological circumstances (Fellman et al. 2013). They also point to a very important role of river floodplains in riverine foodwebs under some circumstances (see below).

Hydrological disturbance that increases suspended sediment loads and thus elevates turbidity and decreases light transmittance also alters the food web base, increasing the important of terrestrially derived organic matter (Blanchette et al. 2014; Roach and Winemiller 2015). Detritus may also be important in naturally turbid river systems, although even in such cases (Roach and Winemiller 2015), periphyton production in areas where light availability is sufficient to promote photosynthesis (i.e very shallow pool margins) can achieve high importance (Bunn et al. 2003). The description by Bunn et al. (2003) of a highly productive zone of production restricted to the euphotic margins of refugial pools and indentification of this production as the dominant source of energy in the foodwebs of these pools highlights the potential vulnerability of the food web base in some circumstances. Rapid yet minor changes in depth can quickly lead to disruption of production (i.e. the growth of the inner margin of production cannot keep pace with changes in depth) or a disruption of access by consumers to this source of food source.

Spatial variation in food web structure can be pronounced, reflecting local variation in depth, turbidity, water velocity, substrate, riparian extent and nutrient availability (all of which respond to altered flow regime). A significant survey of spatial variation in food web structure utilising stable isotopes has been undertaken within the FRV although the results are largely unpublished except for studies aimed at investigating larger scale emergent properties and influences such as the importance of connectivity (Jardine et al. 2012) and food chain length (Warfe et al. 2013). This research examined dry season food web structure (using stable isotopes) at 19 sites throughout the catchment; four floodplain waterbodies, four main river channel sites and the remainder distributed between permanent and intermittent tributary systems. In addition to material collected for stable isotope analysis, each site was quantitatively sampled for macroinvertebrates, fish and riparian and aquatic plant communities were quantitatively described. Six of these sites were resampled in the wet season also. These data represent an important source of information concerning the nature of aquatic food webs in the FRV and may be able to provide insight on the effects of environmental and temporal variation on food web structure.

**Potential research project 21 – What is the scale of spatial variation in food web structure within the FRV and can this inform environmental water management?**

**Time frame:** short-term

Significant research effort aimed at determining the nature of aquatic food webs has occurred within the FRV yet remains to be fully analysed and placed into a context useful for environmental water management. This project would review existing studies and draw together already collected information to compile a description of the spatial and temporal variation in food web structure within the basin and attempt to derive flow thresholds and guidelines. It would identify which components of the riverine landscape are most important in terms of production (contextualised by the outcomes of project 1) and identify linkages between production and the flow regime.
Jardine et al. (2012) compared the extent of coupling between local consumers and local production across a range of northern Australian rivers differing in the length of wet season floodplain inundation and among which was the Fitzroy River. In contrast to rivers with a long period of floodplain inundation and lateral and longitudinal connectivity, secondary consumers, such as large fish, in the Fitzroy River were very tightly coupled with local production. That is, that while primary and secondary production may be very high in floodplain waterbodies in the FRV, little of this production is exported widely throughout the riverine environment and is thus not available to subsidise food webs in distant reaches. The extent of spatial subsidy in northern Australian rivers was identified as a key determinant of factors, such as fish species richness and waterbird production (Jardine et al. 2014). A consequence of this finding is that should local in-channel production be disrupted in poorly connected rivers, then there is a high likelihood of significant change in biotic assemblages and secondary production dynamics. Food web subsidies are an important feature of the ecology of northern Australian rivers.

Recent research has also identified the importance of dissolved organic carbon (DOC) in aquatic food webs and emphasises the different extents and rates at which DOC of different ages is taken up by bacteria and incorporated into the larger metazoan food web. Young DOC is derived from either the adjacent floodplain and delivered to the river after inundation via runoff or shallow groundwater aquifers or from direct leaching of organic compounds from riparian vegetation and represents inputs derived from contemporary primary production (Fellman et al. 2013). Older DOC is usually derived from groundwater and represents the storage and release of the products of historic primary production (Fellman et al. 2014). DOC of different ages is utilised at different rates and influences metazoan food webs in different ways. None-the-less, the delivery of DOC via groundwater is an important influence on riverine food webs particularly during the dry season in those rivers in which groundwater sustains aquatic habitat. Moreover, given the different sources of groundwater contributing to flow in the Fitzroy River (see section 3.3), there is substantial potential

Potential research project 22 – What roles do different elements of the hydrograph play in aquatic food web structure in refugial pools?

Time frame – long-term

This project would examine how different elements of the hydrograph influence the nature of foodweb dynamics in refugial pools. It would examine the influence of wet season flows in delivering material (carbon, sediment and nutrients) and in determining physical structure of the pools and hence where epiphytic and benthic primary production could take place. It would also examine the role of groundwater in maintaining pool structure and areas of primary production as well as the capacity for groundwater to deliver DOC and the extent to which this DOC is incorporated into the food web. It would further examine the types of DOC (i.e. age) delivered to the refugial pool environment from different sources (alluvial vs subterranean aquifers of differing ages) to determine whether this influenced DOC uptake and contribution. The project would be heavily focussed on deriving quantitative relationships between different aspects of the hydrograph that could inform environmental water management and would be closely linked to other projects concerning refugial pools.
for spatial variation in age of DOC inputs.

Groundwater inputs into refugial dry season riverine habitats are thus not only important in determining the size, shape (bathymetry) and longevity of refugial pools but also as a source of organic material available to bacterial and thence metazoan consumers. Moreover, groundwater is also important in determining the structure and vigor of riparian vegetation which, in addition to being an important element requiring consideration, can be a significant contributor to aquatic food webs through the donation of detritus, leaves, fruit and flowers and the terrestrial insects for which it provides habitat. Such imports are important component of the diet of freshwater turtles and of many species of freshwater fish particularly for culturally and recreationally species such as black bream (*Hephaestus jenkinsi*) (Davis et al. 2010). It is highly likely that groundwater inputs to refugial pools and availability to riparian vegetation plays a significant role in the maintenance of food web structure in refugial pools of the FRV. Determining the extent of this interaction and strategies to ensure it remained in place under a modified flow regime scenario would be keystone element of good management.
7 Knowledge gaps and research needs for environmental water management in the Fitzroy River Valley

Throughout this report we have identified what knowledge exists to guide environmental water management in the FRV, what knowledge is lacking and what research is needed to address those gaps or to bring existing information into a format useful in management. We have consistently couched research needs in a form that will either provide the spatial geomorphic and ecological context of management needs or provide quantitative information on flow/habitat and flow ecology interactions and that can be used to test different flow management scenarios and their potential impact on the environment.

Whilst the research needs identified in this report can and should be seen as a large cohesive and integrated research program on the flow ecology of the Fitzroy River and its aquifers, we have chosen to define those research needs as a series of inter-related (and sometimes co-dependent) research projects (Table 7.1). There are considerable cost advantages of such an approach.

The various knowledge gaps identified herein and the projects concern all aspects of the hydrograph but most strongly focus on the low end of the hydrograph and especially the importance of groundwater and its capacity to sustain aquatic habitats. This reflects our understanding of the most likely sources of water that could be developed to support expanded agriculture in Valley.

Key areas for which information is lacking are centred on the following:

1. The nature of aquatic habitats in the basin and their relationship to the flow and including identity, extent and distribution, connectivity and conservation value;
2. Responses of riparian, floodplain and groundwater dependent vegetation to changes in water regime;
3. Responses of individual biotic elements and assemblages to changes in water regime and habitat structure and ecological interactions between elements and within assemblages;
4. The nature of the foodweb sustaining assemblages in different water bodies and its relationship to the flow regime, habitat structure and dependency on ground water inputs during the dry season; and
5. The absence of information concerning interactions between flow dependent phenomena and other non-flow related factors that may either exacerbate flow related impacts or obscure changes in environmental values in response to water regime change and thus lessen the capacity to evaluate the efficacy of environmental water management plans.

Whilst some quantitative information is available concerning flow habitat relationships in the basin (i.e. inundation frequency and pool formation and duration), these relationships are based on very meagre temporal data and while the impacts on biotic communities may be surmised from knowledge garnered elsewhere, it applies in the general sense only. Quantitative relationships between biota or ecological processes and streamflow and groundwater are required for useful scenario testing and plan implementation.
**Table 7.1. Summary table of research projects required to address important knowledge gaps concerning environmental water management in the Fitzroy River Valley.** Key area refers to synthesis of commonalities in knowledge gaps (1-5). Where available, available data sets of relevance are identified (see Appendix 1). The value of each project to address social/cultural values, provide important ecological background, provide quantitative flow ecology relationships and establish baselines against which future management strategies may be addressed is also given.

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<thead>
<tr>
<th>Project no.</th>
<th>Key area</th>
<th>Title</th>
<th>Time frame</th>
<th>Aspect of the hydrograph addressed</th>
<th>Data availability (see Appendix 1 and refer to numbered rows)</th>
<th>Feasibility/risks/dependencies</th>
<th>Value/importance</th>
<th>Social/cultural</th>
<th>Ecological</th>
<th>Utility for informing management</th>
<th>Utility for establishing monitoring baselines</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td><em>Develop an integrated description of the riverine environment of the Fitzroy River, assess applicability of existing flow/habitat relationships and provide spatial context of significant cultural values</em></td>
<td>short</td>
<td>Flood flows, recession flows and baseflows</td>
<td>Use existing data and readily available GIS and remote sensing data</td>
<td>Low risk</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td><em>Assess the accuracy of currently available groundwater dependent vegetation mapping and its utility in environmental water management in areas of prospective groundwater use in the Fitzroy River Valley</em></td>
<td>short</td>
<td>baseflows</td>
<td>Mapping available (4), field work required to ground truth</td>
<td>Low risk, dependent on data availability</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>high</td>
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</tr>
<tr>
<td>3</td>
<td>2</td>
<td><em>Quantify and map broader values of riparian (including GDEs) vegetation and associated ecological values to prioritise environmental water management</em></td>
<td>short</td>
<td>Riparian vegetation mapping available (6)</td>
<td>Low risk, dependent on data availability</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>high</td>
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</tr>
<tr>
<td></td>
<td></td>
<td><strong>Determine the importance of surface/groundwater inputs to the recruitment and persistence of riparian vegetation in the Fitzroy River Valley</strong></td>
<td><strong>long</strong></td>
<td><strong>High and low flows</strong></td>
<td><strong>SW inundation frequency, extent and duration may be inferred from (18), GW data likely to be site-specific</strong></td>
<td><strong>Low risk, expertise and methods already available</strong></td>
<td><strong>high</strong></td>
<td><strong>high</strong></td>
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</tr>
<tr>
<td>5</td>
<td>2,3,4</td>
<td><strong>Understanding the hydrological conditions that determines aquatic production of macrophytes in dry-season stream pools and wetlands.</strong></td>
<td><strong>long</strong></td>
<td><strong>High flows, recession arm, low flows</strong></td>
<td><strong>Field data on primary production needed, field investigations of wetlands and in-channel pools need</strong></td>
<td><strong>Moderate risk</strong></td>
<td><strong>high</strong></td>
<td><strong>high</strong></td>
<td><strong>high</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td><strong>Can existing survey information of stream macroinvertebrates in the FRV be re-examined to provide insight into the flow ecology relationships of this biota?</strong></td>
<td><strong>long</strong></td>
<td><strong>Low flows</strong></td>
<td><strong>Existing data sets used to quantify river ‘health’ AUSRIVAS, FARWH, TRaCK related research</strong></td>
<td><strong>Low-Moderate, data collected for other purpose, resolution of identification (family only) may hinder development of flow/habit relationships</strong></td>
<td><strong>high</strong></td>
<td><strong>high</strong></td>
<td><strong>mod</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>3,4,5</td>
<td><strong>Can seasonal and spatial variation in the structure of macroinvertebrate communities</strong></td>
<td><strong>long</strong></td>
<td><strong>High flow, recession arm but</strong></td>
<td><strong>Field based program collecting new</strong></td>
<td><strong>Moderate</strong></td>
<td><strong>high</strong></td>
<td><strong>high</strong></td>
<td><strong>high</strong></td>
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</tr>
</tbody>
</table>
and relationships between habitat structure and water quality be used to infer flow ecology relationships in the FRV and provide guidance for the implementation of environmental water management?

| 8 | 3,4 | Flow ecology relationships of the Cherabin Macrobrachium spinipes and other aquatic invertebrates that are important in indigenous harvests. | long | High flow, recessional arm, low/base flows | Field based program collecting new data and focussed on small number of in-channel pools, as well as downstream sections (us/ds of Camballin Weir) | Moderate, Very high | high | high | mod |

| 9 | 3,4 | Diversity and distinctiveness of subterranean fauna within the Fitzroy river Valley – preliminary survey | short | GW | Field based sampling of fauna from existing bores and natural springs | low | high | high | high |

| 10 | 3,4,5 | How does subterranean and hyporheic fauna within Fitzroy River Valley respond to natural and anthropogenic variation in groundwater? | long | Baseflows and GW | Field based, focussed on small number of within channel hyporheic areas and bores | moderate | high | high | high |

<p>| 11 | 3,5 | Predictive model of freshwater fish distributions and identification of key conservation areas. | short | Use existing data from diverse sources plus habitat data generated | low | mod | low | moderate | high |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th><strong>Quantify lower riverine and estuarine fish biodiversity and determine the importance of freshwater inflows in maintaining diversity and structuring food webs</strong></th>
<th><strong>Environmental water requirements of elasmobranches of conservation significance – a review and development of quantitative relationships</strong></th>
<th><strong>Dynamics of fish assemblages and populations in refugial riverine pools</strong></th>
<th><strong>Establish baseline nature of fish populations and determine potential impact of cane toads on refugial pool communities.</strong></th>
<th><strong>What are the environmental water requirements of freshwater crocodile Crocodylus johnstoni in the Fitzroy River (particularly in groundwater fed refugial pools) and what ecological role do they play in the ecosystem?</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>3,4</td>
<td>long</td>
<td>High flows/base flows</td>
<td>Field based program</td>
<td>Moderate risk, difficult environments to work, scant existing data, fish difficult to identify</td>
<td><strong>through project</strong></td>
</tr>
<tr>
<td>13</td>
<td>3</td>
<td>short</td>
<td>Low flows</td>
<td>Desk top review</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>14</td>
<td>3,4,5</td>
<td>long</td>
<td>Baseflow/GW</td>
<td>Field based program</td>
<td>Moderate risk</td>
<td>high</td>
</tr>
<tr>
<td>15</td>
<td>1,3</td>
<td>short</td>
<td>Recession arm/low flows</td>
<td>Field based and desk top</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>16</td>
<td>3,4,5</td>
<td>long</td>
<td>High flows/GW</td>
<td>Field based</td>
<td>moderate</td>
<td>mod</td>
</tr>
<tr>
<td>17</td>
<td>3,4,5</td>
<td>long</td>
<td>Field based</td>
<td>moderate</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>18</td>
<td>3,4,5</td>
<td>long</td>
<td>Low flows/GW</td>
<td>Field based</td>
<td>moderate</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td></td>
<td>play in such habitats during the dry season?</td>
<td>long</td>
<td>High flows/low flows/GW</td>
<td>Field based, tightly linked to other riparian projects and their outcome</td>
<td>moderate</td>
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<tr>
<td>19</td>
<td>2,3,4</td>
<td>Identifying links between hydrology, riparian vegetation and riparian birds.</td>
<td>long</td>
<td>High flows/low flows/GW</td>
<td>Field based, tightly linked to other riparian projects and their outcome</td>
<td>moderate</td>
</tr>
<tr>
<td>20</td>
<td>2,3,4</td>
<td>Quantify links between hydrology, wetland area and waterbird abundance/composition to predict changes for different types of water resource development</td>
<td>long</td>
<td>High flows, GW</td>
<td>Field based, existing information of water birds (1,8), wetland inundation (16,17,18)</td>
<td>moderate</td>
</tr>
<tr>
<td>21</td>
<td>4</td>
<td>What is the scale of spatial variation in food web structure within the FRV and can this inform environmental water management?</td>
<td>short</td>
<td>High flows/recessional arm/ low flows/GW</td>
<td>Desk top making use of already existing information concerning food webs</td>
<td>low</td>
</tr>
<tr>
<td>22</td>
<td>4</td>
<td>What roles do different elements of the hydrograph play in aquatic food web structure in refugial pools?</td>
<td>long</td>
<td>High flows/recessional arm/ low flows/GW</td>
<td>Field based</td>
<td>moderate</td>
</tr>
</tbody>
</table>
8 Acknowledgements

We are grateful to the many people who assisted in the production of this report either through provision of research reports and published material, advice on the availability (or lack) of information, provision of text, helpful discussions or critical examination of the report. These include: Paul Close, Robert Cosshart, Rebecca Dobbs, Michael Douglas, Pauline Grierson, J. Russell Hanley, William Humphries, Robyn Loomes, David Morgan, Andy Revill, Fiona Tingle, Sandy Toussaint and Danielle Warfe.

9 References cited


Department of Water (DoW) (2015b) *Locations of surface and groundwater draw points in the Fitzroy River Catchment*. Department of Water, Western Australia.


Kingsford, R.T. and Porter, J. (2009), Monitoring waterbird populations with aerial surveys – what have we learnt? Wildlife Research 36:29-40


McJannet DL, Wallace JW, Henderson A, and McMahon J. *High and low flow regime changes at environmental assets across northern Australia under future climate and development scenarios*. A report to the Australian Government from the CSIRO Northern Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia


Morgan, D., Beatty, S., Allen, M., Gleiss, A., Keleher, J. and Whitty, J. (2011). Is a fishway at the Fitzroy River (Kimberley) Barrage necessary for the conservation of Freshwater Sawfish? Freshwater Fish Group and Fish Health Unit (Murdoch University) report to the Department of Water, Government of Western Australia.


## Appendix 1 – Potentially informative data sets and their location

<table>
<thead>
<tr>
<th>ID</th>
<th>Type</th>
<th>Description and Notes (e.g. temporal and spatial scale)/possible uses</th>
<th>Potential projects dataset to which applies</th>
<th>Reference</th>
<th>Dataset location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ecological data</td>
<td>• High conservation value aquatic ecosystem mapping (HCVAE)</td>
<td>• Fish (section 6.5) • Waterbirds (6.7.2) • Macroinvertebrates (section 6.3) • Turtles (section 6.6.2)</td>
<td>Kennard, M.J. (ed) (2010),</td>
<td><a href="http://atlas.track.org.au/">http://atlas.track.org.au/</a></td>
</tr>
<tr>
<td>1</td>
<td>High conservation value aquatic ecosystem mapping (HCVAE)</td>
<td>Modelled richness/diversity/phyllogenetic diversity of fish, macroinvertebrates, waterbirds and turtles. Also includes measures of hydrosystems (e.g. distinctiveness, representativeness etc)</td>
<td>• Riparian vegetation (section 6.1) • Vegetation data also likely to be useful as environmental predictor for models of other ecological responses (e.g. macroinvertberates)</td>
<td>Lymburner L., Tan P., Mueller N., Thackway R., Lewis A., Thankappan M., Randall L., Islam A., &amp; Senarath U. (2010) 250 metre Dynamic Land Cover Dataset of Australia (1st Edition), Geoscience Australia, Canberra</td>
<td><a href="http://www.auscover.org.au/xwiki/bin/view/Product+pages/Product+User+Page+GA+1">http://www.auscover.org.au/xwiki/bin/view/Product+pages/Product+User+Page+GA+1</a></td>
</tr>
<tr>
<td>2</td>
<td>Time series normalized difference vegetation index (NDVI) / Enhanced vegetation index (EVI)</td>
<td>NDVI, or the more recently derived enhanced vegetation index (EVI), is directly related to the fraction of photosynthetically active radiation and is an indicator of primary productivity</td>
<td>• Not directly relevant for potential research projects only relevant for DoW</td>
<td>Through request to DePAW</td>
<td>-</td>
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<tr>
<td>3</td>
<td>Threatened ecological communities,</td>
<td>Locations and descriptions of threatened flora and fauna.</td>
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<tr>
<td>threatened flora and fauna</td>
<td>environmental scans</td>
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<tr>
<td>4</td>
<td>Bureau of Metrology (BoM) groundwater dependent ecosystem mapping</td>
<td>Broad scale mapping of potential surface-groundwater interaction for river and vegetation. In some areas aquifers are also mapped. Only general locations are shown – mapped area does not imply that entire area is a GDE.</td>
<td>• Coarse scale of mapping likely makes it of little use for detailed analysis, but may be relevant for riparian vegetation (section 6.1) projects to identify possible sites for further investigation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Atlas of Living Australia data</td>
<td>Includes presence data for range of fauna and flora. Phylogenetic diversity (for acacia, amphibians and mammals) measures also available. (May have already been included in HCVAE mapping?)</td>
<td>• presence only data</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td><a href="http://spatial.ala.org.au/">http://spatial.ala.org.au/</a></td>
<td></td>
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</tr>
<tr>
<td>6</td>
<td>Field data – purple crown fairy wren presence/absence data and rip vegetation (aerially mapped from helicopter).</td>
<td>Presence absence data of Purple crown fairy wren and fine-scale habitat attributes (including riparian vegetation cover/condition) at Fitzroy (207 patches and 241km vegetation surveyed). Also has riparian vegetation mapped from helicopter surveys.</td>
<td>• Riparian birds (6.7.1) • Riparian vegetation (6.1)</td>
<td></td>
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</tr>
<tr>
<td>7</td>
<td>DoW Ecological Field data</td>
<td>WIN Biological data repository</td>
<td>No data currently in repository</td>
<td></td>
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<tr>
<td>8</td>
<td>The National Waterbird Database</td>
<td>Survey data from aerial bird surveys across Australia (May have already been include in HCVAE mapping)</td>
<td>• Waterbirds (section 6.7.2)</td>
<td>Kingsford RT, Porter JL and Halse SA 2011, National waterbird assessment, Waterlines report, National Water Commission, Canberra</td>
<td>A trial web version of the National Waterbird Database is available by contacting the Australian Wetlands and Rivers Centre at the University of New South Wales via email address: <a href="mailto:awrc@unsw.edu.au">awrc@unsw.edu.au</a>.</td>
</tr>
<tr>
<td>9</td>
<td>Macoinvertebrate data</td>
<td>Macroinvertebrate / AUSRIVAS data</td>
<td>• Macroinvertebrates (section 6.3)</td>
<td>Pinder et al. (2010)</td>
<td>(<a href="http://www.museum.wa.gov.au/research/records-supplements/attachments">http://www.museum.wa.gov.au/research/records-supplements/attachments</a>) - lists all taxa recorded but is unfortunately non-functional. However, it likely exists somewhere and it is likely that voucher specimens were retained.</td>
</tr>
<tr>
<td>10</td>
<td>Water bird data for various riverine, floodplain and wetland areas in the Fitzroy</td>
<td>Data is an appendix of Storey et al. 2001 (18 surveys)</td>
<td>• Waterbirds (section 6.7.2)</td>
<td>Storey AW, Davies PM and Froend RH 2001. Fitzroy river system: environmental values. Report prepared for the Waters and Rivers Commission. Perth, Western</td>
<td>Data is an appendix of Storey et al. 2001 (18 surveys)</td>
</tr>
</tbody>
</table>
| 11 | Macroinvertebrate, fish, riparian vegetation and aquatic weeds field survey data | 37 sites in the Fitzroy River Valley (note not all responses surveyed at each location). | Macroinvertebrates (6.3)  
Riparian vegetation (6.1)  
Aquatic vegetation (6.2)  
Fish (6.5)  
See Tables in Dixon et al. 2011 |
<table>
<thead>
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</thead>
<tbody>
<tr>
<td>12</td>
<td>Ground Cover Reference Sites Database of Western Australia (ABARES), Groundwater cover estimates at some sites</td>
<td>Potential environmental covariate for some projects</td>
<td></td>
</tr>
</tbody>
</table>
http://www.auscover.org.au/xwiki/bin/view/Product+pages/Australian+Ground+Cover+Reference+Sites+Database+ABARES |
WIN and see Harrington and Harrington 2015 for further details. |
| 13 | Surface-groundwater connectivity data | Surface-groundwater connectivity assessment using isotopes at ~32 river samples along the lower Fitzroy | Responses and relationships of in stream biota (e.g. fish) to surface-groundwater connectivity  
Data in document appendix |
| 14 | Stream flow data | Stream flow data for gauges throughout the FRV | Ecological responses dependent on stream flow  
DoW Water Information Network |
| 15 | Hydrosystem mapping (rivers, | Mapping of different hydrosystems | Useful for identifying potential study sites  
DoW 2015  
DoW Arc GIS layers |
| 16 | | | |

96
| 18 | Various biophysical data sets available on DoW network (including biota, climate, inland waters, geology etc.) | - | • General data layers useful for providing environmental covariate information for models and for identifying future surveys sites. | DoW Bunyup ArcGIS layers |
| 20 | Australian Land use mapping | Land use mapping (e.g. grazing, conservation, irrigated cropping etc.) for all of Australia | • All projects as environmental covariates. | ABARES Land Use Data Download - Department of Agriculture www.agriculture.gov.au/abares/ac lump/land-use/data-download |
| 21 | Bureau of Temperature and rainfall | - | • Useful for | http://www.bom.gov.au/ |
| Meteorology data | providing data for all that require information about rainfall and temperature. Also useful for planning for future research sites (e.g. across rainfall and temperature gradients) if interested in climatic influences. |  |