Government of **Western Australia**
Department of **Water**

Groundwater dependent ecosystems for Millstream: ecological values and issues

Ecological water requirements

Looking after all our water needs

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1 Introduction

1.1 Document purpose

This document describes the ecosystems that are largely maintained by discharge from the Millstream aquifer. The links between these ecosystems and the hydrogeology are described as conceptual models, and their future water management objectives are presented.

1.2 Background

The Millstream wetland system comprises approximately 20 km of the Fortescue River and tributaries. It includes four major permanent river pools (Deep Reach, Crossing, Livistona and Palm pools) interconnected by permanent flowing channels, spring-fed pools on tributaries (e.g. Chinderwarriner Pool) and large areas of riparian and wetland vegetation.

The area is partly within the Millstream-Chichester National Park and is listed on the Register of the National Estate and in the *Directory of important wetlands in Australia*. It is a significant area of isolated habitat for wetland flora and fauna and supports a number of regionally under-represented species. It is an outstanding example of a system of permanent river pools and springs in the semi-arid tropics and the best known in north Western Australia (2000).

The area's permanent pools and springs are fed by discharge from the Millstream aquifer. This large calcrete aquifer is also an important component of the West Pilbara water supply scheme that provides water to the coastal towns of Dampier and Karratha. Water is abstracted from the aquifer via eight production bores that the Water Corporation operates under licence from the Department of Water. A detailed description of the borefield's operation, management rules and monitoring programs, as well as the system's hydrogeology, is provided in Antao and Braimbridge (2009).

The ecological water requirements (EWRs) to maintain the system's groundwater-dependent vegetation and wetlands were determined by Welker Environmental Consultancy (1995). The borefield is currently operated under a set of rules developed, in part, to ensure protection of groundwater-dependent ecosystems. The following groundwater-dependent ecosystems are associated with the Millstream aquifer (Dames & Moore 1984; Welker Environmental Consultancy 1996):

- riverine pools and wetlands
- riparian vegetation
- aquifer ecosystems.

2 Identification and description of groundwater-dependent ecosystems

Ecosystems that either rely on groundwater directly (e.g. stygofauna or phreatophytic vegetation using water from shallow watertables) or indirectly (e.g. wetland vegetation or aquatic ecosystems sustained by groundwater discharge) have been identified as groundwater dependent.

Conceptual models describing the links between ecosystems, groundwater and hydrological support mechanisms have been developed based on previous studies (Muir Environmental 1995a; Dames & Moore 1984), the results of monitoring programs (Antao & Braimbridge 2009) and information collected for our current work.

Recent work that has fed into the identification of groundwater-dependent ecosystems has included:

- numerical groundwater modelling of the Millstream aquifer
- review of hydrological information to characterise hydrological regimes and potential water availability
- a digital elevation model derived from LiDAR data combined with hydrological data to characterise depth to water
- review of vegetation monitoring and hydrological data including remote-sensing vegetation monitoring
- field studies to confirm vegetation mapping and re-survey vegetation transects to supplement available information
- investigative studies to quantify riparian vegetation water use and identify sources of water used
- vegetation and wetland mapping to determine the distribution of groundwater-dependent ecosystems.

The distribution of potentially groundwater-dependent vegetation and wetlands is shown in figure 1.

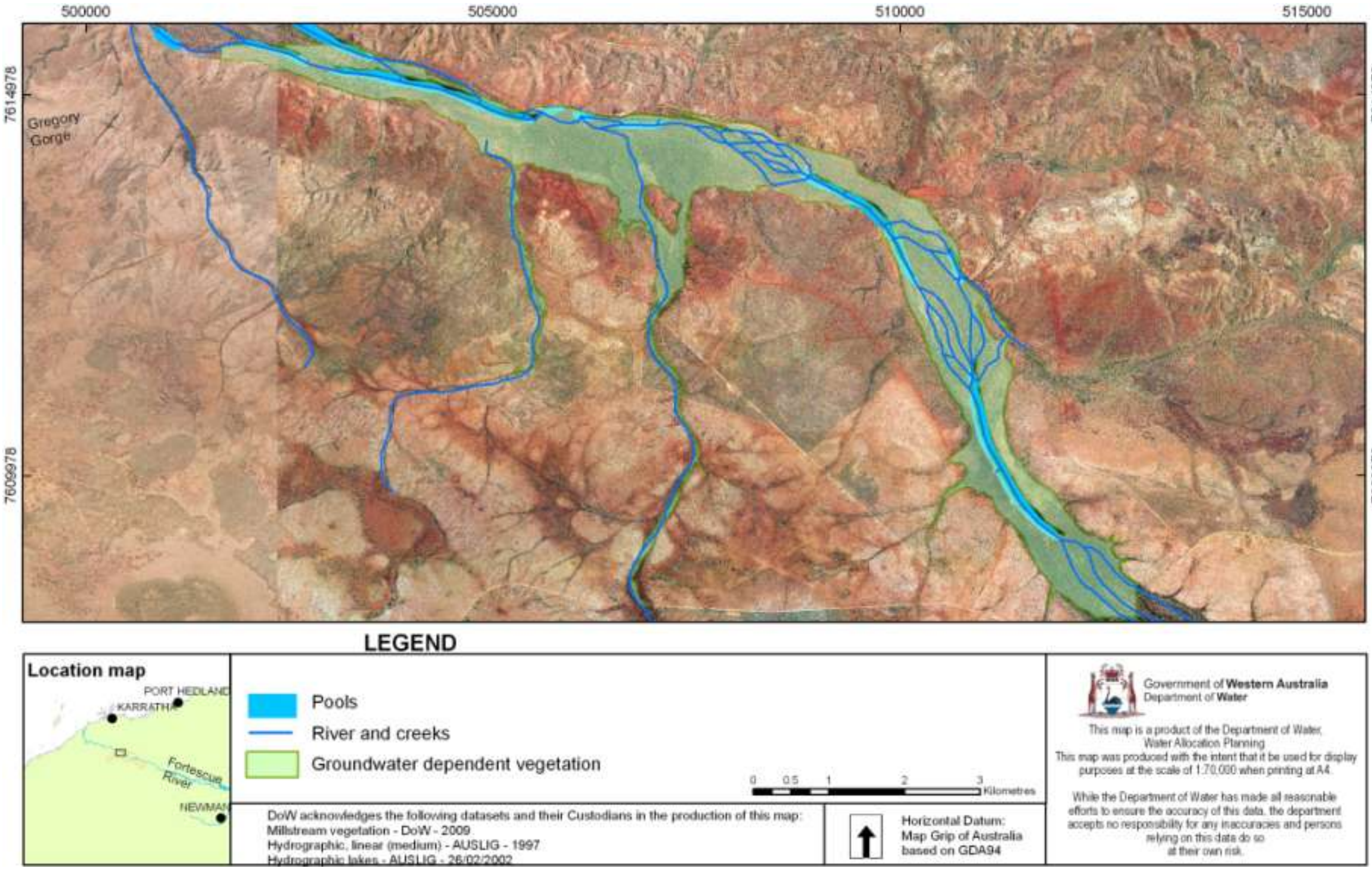


Figure 1 Distribution of potentially groundwater-dependent vegetation and wetlands

3 Wetland ecosystems

3.1 Hydrology and conceptual model of groundwater dependence

Discharge from the Millstream aquifer sustains a large wetland complex including permanent and semi-permanent riverine pools and flowing streams (Figure 2).

The largest quantity of aquifer discharge is into Deep Reach Pool. Discharge into the pool and subsequent overflow downstream along the Fortescue River is sufficient to sustain four major permanent pools – Deep Reach, Crossing, Palm and Livistona pools (see Figure 2 and 3) (Dames & Moore 1984).

The extent of groundwater-derived discharge varies with aquifer level (discharge into Deep Reach Pool increases with increasing aquifer level) and season (Figure 4). During the cooler months, and particularly when aquifer levels and discharge are high, aquifer discharge can sustain a series of less permanent and shallower pools as far downstream as Gregory Gorge.

The aquifer also sustains wetlands in the Millstream delta area and springs in the Palm, Peters and Woodley creeks – all of which are tributaries of the Fortescue River. Of these, the Millstream delta is the largest and most complex.

The aquifer discharges through a spring into Chinderwarriner Pool, which overflows into the delta wetlands via a series of channels and into the Fortescue River (Figure 2). The rate of spring discharge depends on aquifer level (Figure 5).

The local watertable in the delta is sustained by seepage from surface water flow in the delta channels and, at high aquifer levels at least, throughflow or seepage from the Millstream aquifer.

The groundwater contribution to surface water flows in the delta (in addition to spring-derived outflow from Chinderwarriner Pool) appears to vary with aquifer level. Depending on the Millstream aquifer's level and the subsequent levels of spring and subsurface seepage, delta channels may be either losing or gaining streams (Figures 6 and 7).

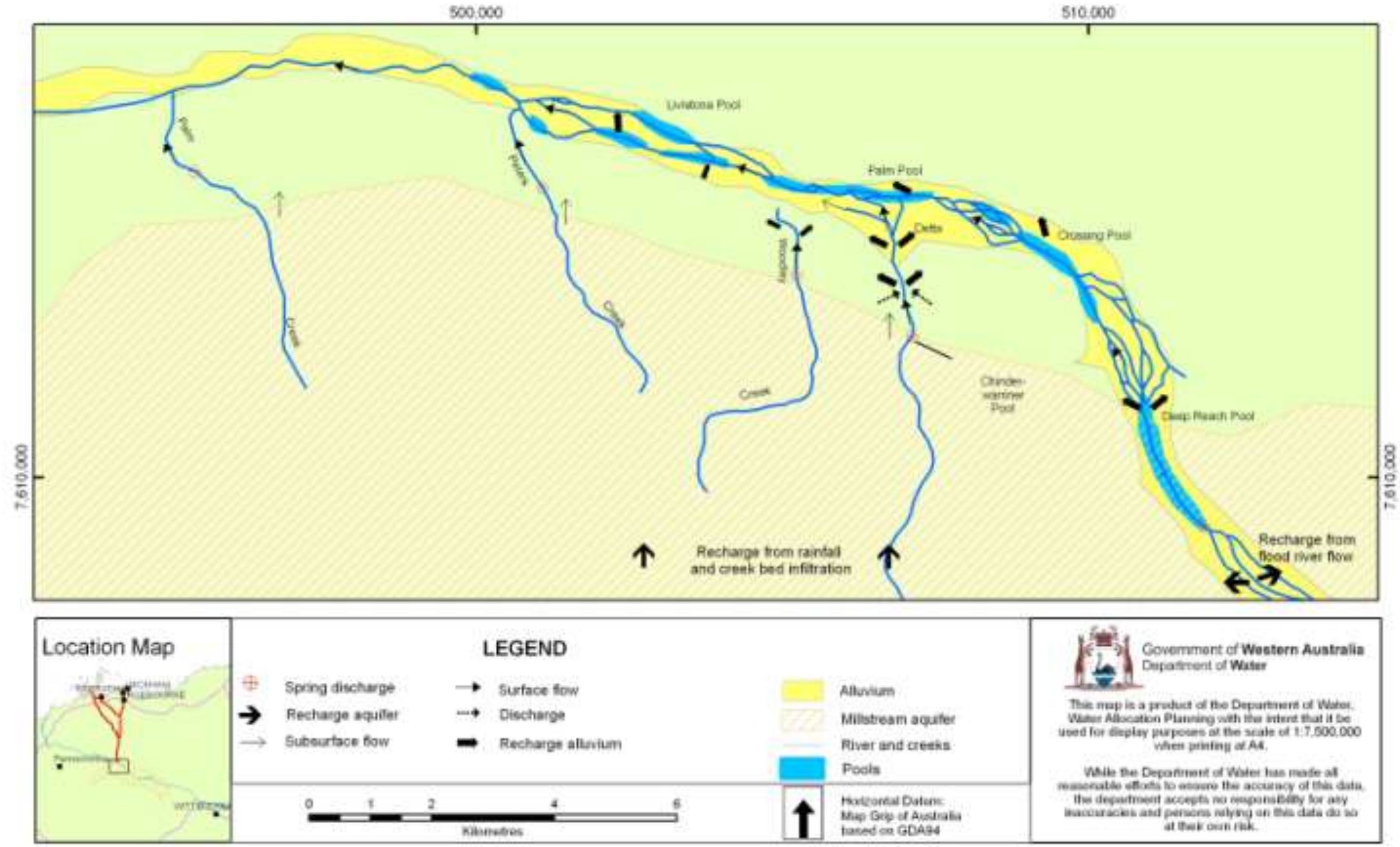


Figure 2 Millstream wetlands (river pools and channels) and extent of calcrete aquifer

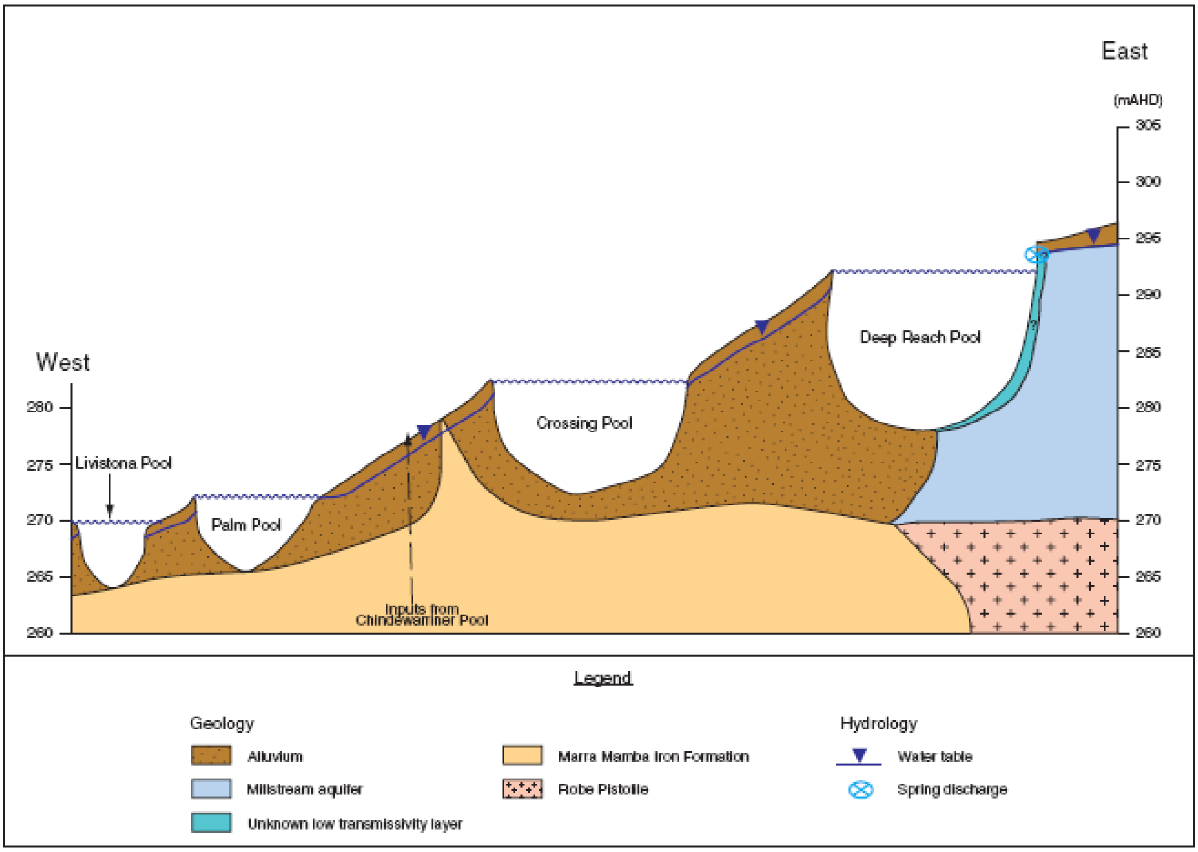


Figure 3 Longitudinal cross-section along the Fortescue River (revised from DEC 2007)

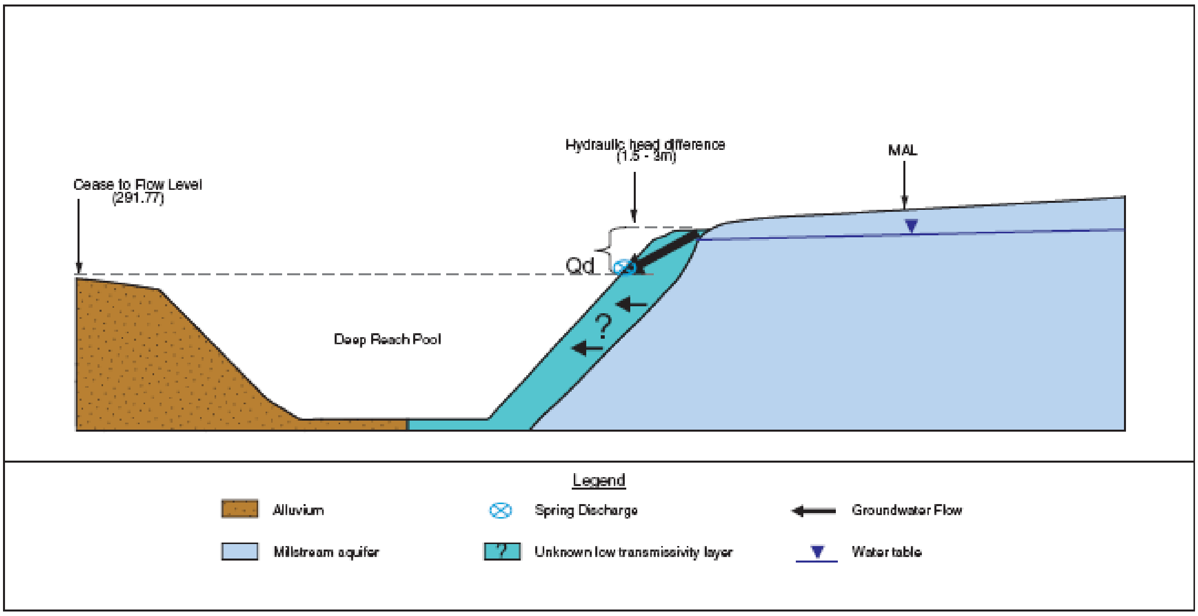


Figure 4 Conceptual diagram showing factors affecting discharge into Deep Reach Pool

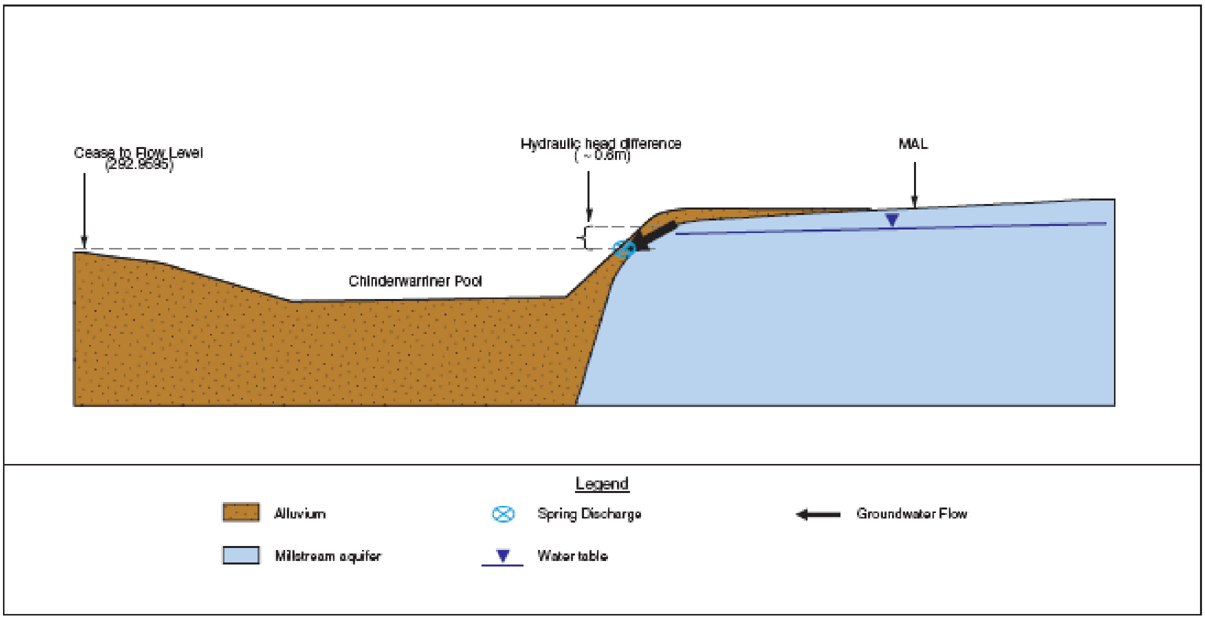


Figure 5 Conceptual diagram of Chinderwarriner Pool's hydrogeology, showing factors that affect the rate of discharge into the pool

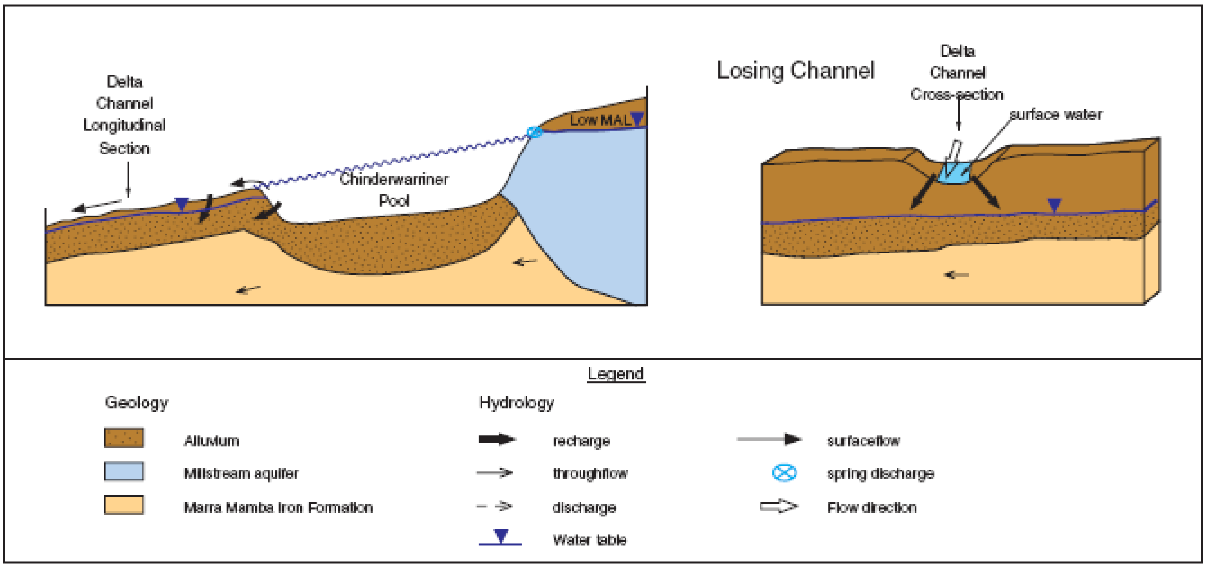


Figure 6 Conceptual diagram of Chinderwarriner Pool's hydrogeology and the channels across the Millstream delta

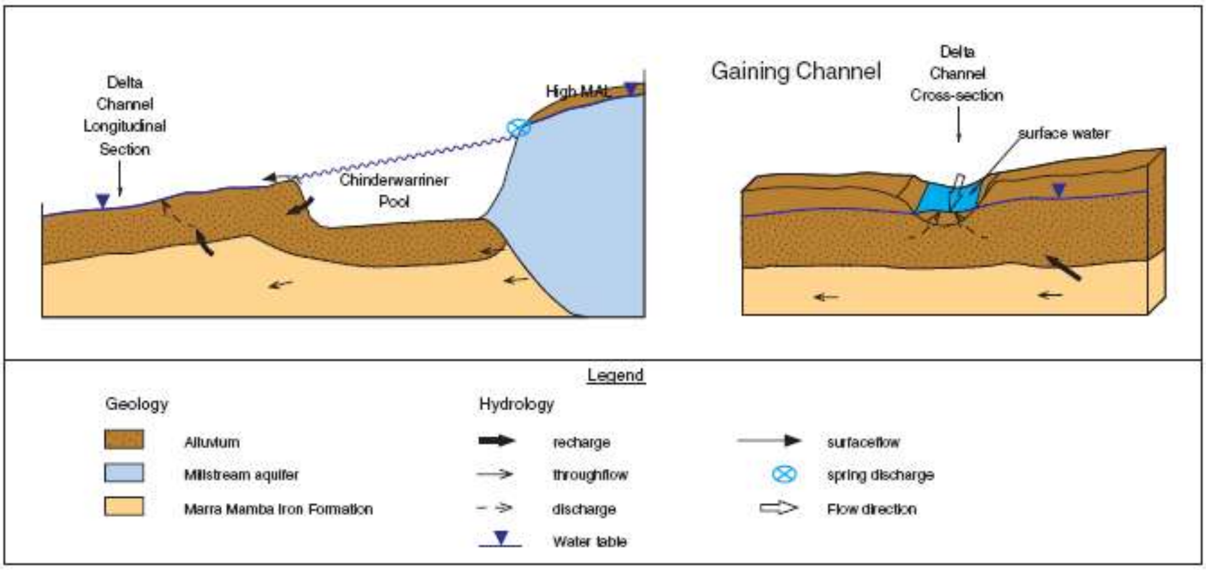


Figure 7 Conceptual diagram of Chinderwarriner Pool's hydrogeology and the channels across the Millstream delta during periods of high MAL

3.2 Ecology

The Millstream wetlands contain a diverse range of aquatic habitats that support a high diversity of biota. The habitats present include:

- deep permanent pools
- shallow permanent and temporary pools
- permanently fast-flowing sections of channel with gravel substrate
- slow-flowing channels with organic-rich silt and clay substrates (Charlton 1994).

Sampling of aquatic invertebrates and fish has been conducted at Millstream by Burbidge (1971), Charlton (1994), Masini (1988), Beesley (2006), Morgan et al. (2003) and Pinder and Leung (2009). The locations and parameters sampled are summarised in Table 1.

Table 1 Summary of site and sampling details of aquatic studies conducted at Millstream wetlands

Author	Date	Sites	Parameters
Burbidge	1971	Crossing Pool, Crystal (Chinderwarriner) Pool, Deep Reach Pool	Fish species diversity. Report also summarises existing knowledge of amphibians, macroinvertebrates and other vertebrate fauna. Existing information and additional survey (species lists and community descriptions) are provided for birds and vegetation.
Masini	1988	Palm Spring, Crossing Pool, Woodley Spring, Crystal	Water temperature, conductivity, dissolved oxygen, pH, turbidity, description of fringing vegetation, description of aquatic vegetation, phytoplankton concentration

Author	Date	Sites	Parameters
		(Chinderwarriner) Pool	and diversity, observations of birds and fish populations and zooplankton diversity.
Charlton	1994	Millstream delta channels	Fish species richness, macroinvertebrate species richness and abundance, aquatic vegetation distribution, substrate description, temperature, dissolved oxygen, pH, conductivity, water velocity, ionic composition, alkalinity and nutrient composition.
Morgan et al.	2003	Dawson Creek, Palm Pool (Gregory Gorge)	Fish species richness, salinity, temperature and pH.
Beasley	2006	Palm Pool	Pool length, width and maximum depth. Water temperature, conductivity, pH, dissolved oxygen and turbidity. Description of riparian and macrophyte vegetation and substrate. Fish community diversity, abundance, biomass and age classes.
Pinder and Leung	2009	Millstream delta, Palm Pool, Palm Spring (and Gregory Gorge)	Macroinvertebrate species richness and abundance, submerged macrophyte species richness and abundance, sediment description and water chemistry analysis.

3.2.1 Fish

Millstream's permanent pools support an assemblage of fish fauna that is abundant and diverse by Pilbara standards (May & McKenzie 2002). Nine species of freshwater fish (out of a total of 10 recorded for the Fortescue River) and one saltwater species (Table 1) have been recorded (Burbidge 1971; Morgan et al. 2003; Beesley 2006).

The relatively high number of species recorded for Millstream is likely due to the pools' permanency or stability (Beesley 2006; Burbidge 1971). The complexity or diversity of habitats within the pools also contributes to the high number of species present (Beesley 2006).

The Millstream pools' stability or permanence is likely to be important to the maintenance of fish populations in the Fortescue River as a whole. Like most Pilbara rivers, flows in the Fortescue River are highly variable and extended periods of no flow occur regularly. Permanent or stable pools provide a vital refuge for normally widespread species during times of extreme conditions.

Some of the species recorded at Millstream have a clear preference for – or are found only in – more permanent/stable pools (Morgan et al. 2003; Beesley 2006). For example, the salmon catfish (*Arius graeffei*), the northern eel (*Anguilla bicolour*) and bony bream (*Nematolosa erebi*) are species that preferentially inhabit or are restricted to larger, deeper pools (Table 2).

Other species such as the spangled perch (*Leiopotherapon unicolor*) and rainbow fish (*Melanotaenia australis)* are able to rapidly colonise temporary pools and shallower areas. These species are found throughout the system including minor tributaries and headwaters. Populations of these species in tributaries and headwaters are relatively dynamic across catchments and fluctuate with water availability.

All species, regardless of habitat preferences or life-history suitability to different zones within the river, rely on permanent refuge pools during periods of extended drought.

Table 2 Fish species recorded for the Millstream pools

Species	**Chinderwarriner (Crystal) Pool**	**Deep Reach Pool**	**Crossing Pool**	**Palm Pool**	**Millstream (site not specified)**
	1	**1**	**1**	**1,3**	**2**
Bony bream *(Nematalosa erebi)*		X	X	X	X
Eel *(Anguilla bicolour)*			X	X	X
Salmon catfish *(Arius graeffei)*			X	X	X
Catfish *(Neosilurus hyrtlii)*	X		X	X	X
Rainbow fish *(Melanotaenia australis)*	X	X	X	X	X
Spangled perch *(Leiopotherapon unicolor)*			X	X	X
Goby *(Glossogobius giuris)*	X	X	X	X	X
Barred grunter *(Amniataba percoides)*			X	X	X
Fortescue grunter *(Leiopotherapon aheneus)*	X	X	X	X	X
Mangrove jack *(Lutjanus argentimaculatus)*					X

1 Burbidge et al. (1971)

2 Morgan et al. (2003)

3 Beesley (2006)

Table 3 Description of freshwater fish habitat requirements or preferences (Beesley 2006; Pusey et al. 2004; Dames & Moore 1984).

Species	General description and habitat preferences
Bony bream *(Nematalosa erebi)*	A widespread and common species of northern Australia and inland rivers of south-eastern Australia. A detritivore commonly found in deep water in permanent and temporary pools. Susceptible to low dissolved oxygen.
Eel *(Anguilla bicolour)*	A long-lived species that is estimated to reach maturity at 10 to 25 years. Once mature it migrates to the tropical deep sea to spawn. Only breeds once. Strongly restricted to permanent pools due to life-history requirement for long-term stability.
Salmon catfish *(Arius graeffei)*	A relatively long-lived species with relatively late maturity. Requires deep pools for incubation of eggs and larvae. Mainly deeper parts of permanent pools.
Catfish *(Neosilurus hyrtlii)*	Very widespread species found across northern Australia in a wide range of habitats. In the Fortescue it is mainly found in permanent pools.
Rainbow fish *(Melanotaenia australis)*	Found throughout the Pilbara and Kimberley and into the Northern Territory in a wide range of habitats including shallow pools, streams and the margins of deep pools. Relatively tolerant of a range of environmental conditions.
Spangled perch *(Leiopotherapon unicolor)*	Very widespread and abundant across northern Australia in a wide range of habitats. Species is considered hardy and tolerant of a wide range of environmental conditions. It is often found in tributaries and upstream reaches.
Goby *(Glossogobius giuris)*	Widespread throughout northern Australia. Appears to have a preference for more permanent pools.
Barred grunter *(Amniataba percoides)*	Widespread across northern Australia but not recorded from the De Grey River. Found in a wide range of habitats but may be susceptible to low dissolved oxygen concentrations.
Fortescue grunter *(Leiopotherapon aheneus)*	A schooling species restricted to the Fortescue, Ashburton and Robe rivers. Found in shallow pools, streams and margins of deep pools.

3.2.2 Water quality

The water quality in wetlands and river pools (i.e. Deep Reach, Crossing, Palm, Livistona and Chinderwarriner pools and the delta wetlands) is relatively constant due to their permanency and the continuous input of water from the Millstream aquifer (Dames & Moore 1984). The Millstream wetlands are not subject to the same extremes in temperature, salinity and dissolved oxygen concentrations as the region's ephemeral wetlands.

The largest shifts in water quality in Millstream's wetlands and pools occur between flood-derived surface water inflows and groundwater-derived spring inflows (see Dames & Moore 1984 for an analysis of the dominant ions).

Interactions between flood flows and aquifer water quality, in particular salinity, are poorly understood. Aquifer salinities are lowest on the aquifer's flanks (about 500 mg/L) and highest along its centre (1250 to 1500 mg/L), where recharge occurs from the Fortescue River (Figure 2). Salinities of peak flows have been recorded during floods at around 200 to 300 mg/L, although salinities of the initial flush of flood flows have not been recorded and may be higher.

Salinities recorded for Chinderwarriner Pool range from approximately 650 to 1200 mg/L. In shallow riverine pools subject to concentrations of salts through evaporation, salinities up to approximately 8400 mg/L have been recorded (Dames & Moore 1975; Charlton 1994).

The influence of water abstraction on groundwater and spring-discharge salinities is also poorly understood. Anecdotal evidence suggests that salinity in Chinderwarriner Pool increases in response to groundwater abstraction, however it is difficult to identify a clear relationship (Figure 8).

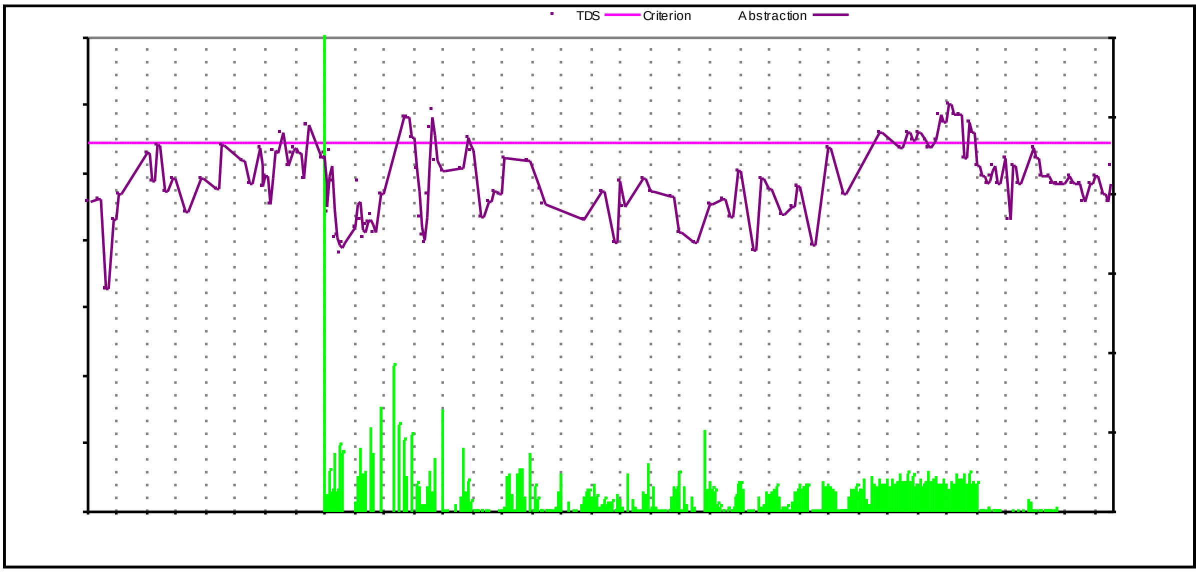


Figure 8 Salinity in Chinderwarriner Pool (TDS) and monthly total abstraction from production bores (KL)

Where the aquifer directly discharges via spring flow into pools and springs, the water quality remains relatively constant and reflects the aquifer's water quality. Charlton (1994) demonstrated the existence of a gradient of physico-chemical parameters along channels within the delta. Water in Chinderwarriner Pool and at the spring source is relatively warm and low in dissolved oxygen, but high in carbon dioxide and particular ion concentrations. Temperature decreases away from Chinderwarriner Pool and diurnal fluctuations become more pronounced. Due to the photosynthetic activity of macrophytes and algae, the levels of dissolved oxygen increase and levels of carbon dioxide decrease further along the channels. The oxygen/carbon dioxide gradient is reversed at night due to the respiratory demand of macrophytes and algae.

This trend of increasing divergence from groundwater characteristics and variability in physico-chemical parameters with distance from spring input is likely to be replicated downstream of Deep Reach Pool and other springs at Millstream.

3.2.3 Flora

Aquatic macrophytes are an ecologically significant component of the Millstream system. They provide habitat for macroinvertebrates and fish, with some species showing specific species to species associations. Macrophytes also significantly influence water quality and movement through the system.

The Millstream wetlands support a relatively diverse and abundant assemblage of aquatic macrophytes including submerged and emergent vascular plants (15 species) and non-vascular plants and algae (two species) (Table 4). The permanency of water in the wetlands and the diversity of habitats including fast- and slow-flowing channels are again likely to support this relatively high species diversity.

The abundance of macrophytes in turn affects other aspects of the system's ecology. The macrophytes provide habitat for macroinvertebrates and fish, influence water quality and chemistry and affect water flow within channels by increasing roughness.

Two species of aquatic macrophytes are considered weeds in the Millstream wetlands: *Ceratopteris thalictroides* and *Nymphaea macrosperma (*formerly *N. gigantea*). *C. thalictroides* is a cosmopolitan species found in the Pilbara and Kimberley (Western Australian Herbarium 1998). It is reported to have been introduced to Chinderwarriner Pool approximately 60 years ago and grows prolifically within the main delta channels (Charlton 1994).

The Department of Environment and Conservation (DEC) has been coordinating efforts to manage the spread and growth of the weed species through manual removal. Recent floods (March 2009), which saw record flows down Millstream Creek and through Chinderwarriner Pool, removed large amounts of *C. thalictroides* and *N. macrosperma* from the pool and delta channels. This large-scale removal of biomass may provide an opportunity to manage weed growth into the future.

Table 4 Submerged and emergent aquatic macrophytes recorded from the Millstream wetlands

Species	Common names	Habit	Beesley (2006)	Dames and Moore (1984)	Charlton (1994)
**Ceratopteris thalictroides*	Indian fern	Submerged		+	
Chara sp.	Stonewort	Submerged	+		
Cyperus involucratus		Emergent	+		
Eleocharis geniculata		Emergent			+
Lobelia quadrangularis		Emergent			+

Species	Common names	Habit	Beesley (2006)	Dames and Moore (1984)	Charlton (1994)
Myriophyllum verrucosum	Red water-milfoil	Submerged/ emergent		+	
Najas marina	Prickly waternymph	Submerged	+	+	+
Najas tenuifolia	Waternymph	Submerged		+	
Nitella sp.	Stonewort	Submerged	+		
**Nymphaea macrosperma*	Giant water lily	Floating		+ (as *N. gigantea* now revised as *N. macrosperma*)	
Peplidium sp.					+
Phragmites vallatoria	Tropical reed	Emergent		+ (as *Phragmites karka* now revised as *Phragmites vallatoria*)	+
Potamogeton tricarinatus	Floating pondweed	Floating/ emergent	+	+	
Ruppia megacarpa	Sea tassel	Submerged	+		
Schoenoplectus littoralis	Clubrush	Emergent	+		+
Typha domingensis	Bulrush	Emergent	+	+	+
Vallisneria sp.	Ribbonweed	Submerged	+	+ (as *Vallisneria spiralis* now excluded taxon)	

* Denotes introduced species

3.2.4 Invertebrates

Previous work on aquatic macroinvertebrates has focused on damsel flies and dragonflies. Approximately 30 species from these two groups have been recorded at Millstream (Burbidge 1971; Dames & Moore 1984). These included species known only from Millstream and species known elsewhere but with disjunct populations (Kimberley).

More recently Millstream was included in DEC's Pilbara Biological Survey. Sites sampled at Millstream included Palm Pool, Millstream Delta, Gregory Gorge and Palm Spring. The survey has identified Millstream as one of a small number of spring or spring-fed permanent wetlands in the Pilbara that support a specific suite of macroinvertebrate fauna (A. Pinder pers. comm. 2008).

Charlton (1994) found a link between macroinvertebrate community composition and habitat type and diversity. Riverine pools contained species not found in delta channels, most likely due to the presence of different habitats (different water quality, water velocity and substrate). Within the delta, certain species were associated with particular microhabitats. For example, certain species of freshwater prawn (*Caridina* sp.) were particularly abundant in areas of the submerged macrophyte *Najas marina*.

The permanency of water and flowing water at Millstream is again a key feature of the system that results in unique macroinvertebrate fauna (as is the case for fish fauna). Maintenance of a diverse range of habitats for macroinvertebrates is likely to be a key to preserving their diversity and abundance.

3.3 Conservation significance

The Millstream wetland system is listed in the *Directory of important wetlands in Australia* and on the Register of the National Estate (Environment Australia 2001). It is partly within the Millstream-Chichester National Park. The system has also been nominated for listing under the Ramsar Convention on Wetlands (DEC 2007).

These listings and nominations have been made in recognition of the Millstream wetland system's scale and uniqueness in the region and the high diversity of flora and fauna it supports. The system is also recognised as supporting a number of species that are restricted in their distribution and otherwise rare (DEC 2007; Environment Australia 2001; May & McKenzie 2002).

The permanency of flows and diversity of habitats are considered to be the key attributes supporting the diverse and unique fauna, including relictual species of Odonata. The continued contribution of groundwater to these habitats within the context of a dynamic and variable climate is essential to the ongoing viability of these systems.

4 Vegetation and flora

4.1 Hydrology and conceptual model of groundwater dependency

For the purposes of managing the ecological values associated with the Millstream aquifer and wetland system, groundwater-dependent vegetation has been identified as vegetation with direct access to groundwater and/or vegetation that is ‘fed’ by groundwater-derived discharge. That is, vegetation sustained directly or indirectly by groundwater.

The mechanisms by which groundwater and groundwater discharge sustain groundwater-dependent vegetation are essentially the same as the mechanisms that sustain aquatic ecosystems. Discharge from the aquifer into Deep Reach and Chinderwarriner pools, and subsequent overflow into the Fortescue River and delta channels respectively, sustains riparian and wetland vegetation. That is, in the absence of intermittent surface water flows, the watertable in the riverine and wetland alluvial sediments is sustained by aquifer discharge. As previously discussed, discharge and groundwater-level measurements demonstrate significant subsurface or throughflow contribution to the alluvial sediments in the delta.

As a result of the continuous recharge, depths to groundwater in the vicinity of pools and along alluvial sediments is low (Figure 9). Maximum depths to groundwater in the alluvial sediments around Deep Reach Pool typically range from 0.7 to 3.1 m below ground surface. Within the Delta, maximum depths to groundwater range from 1.0 to 4.5 m below ground surface. Dominant tree and shrub species are likely to be accessing groundwater at these depths. Some species of riparian vegetation, such as *Melaleuca argentea*, are also likely to be accessing groundwater-derived surface water directly from pools and channels.

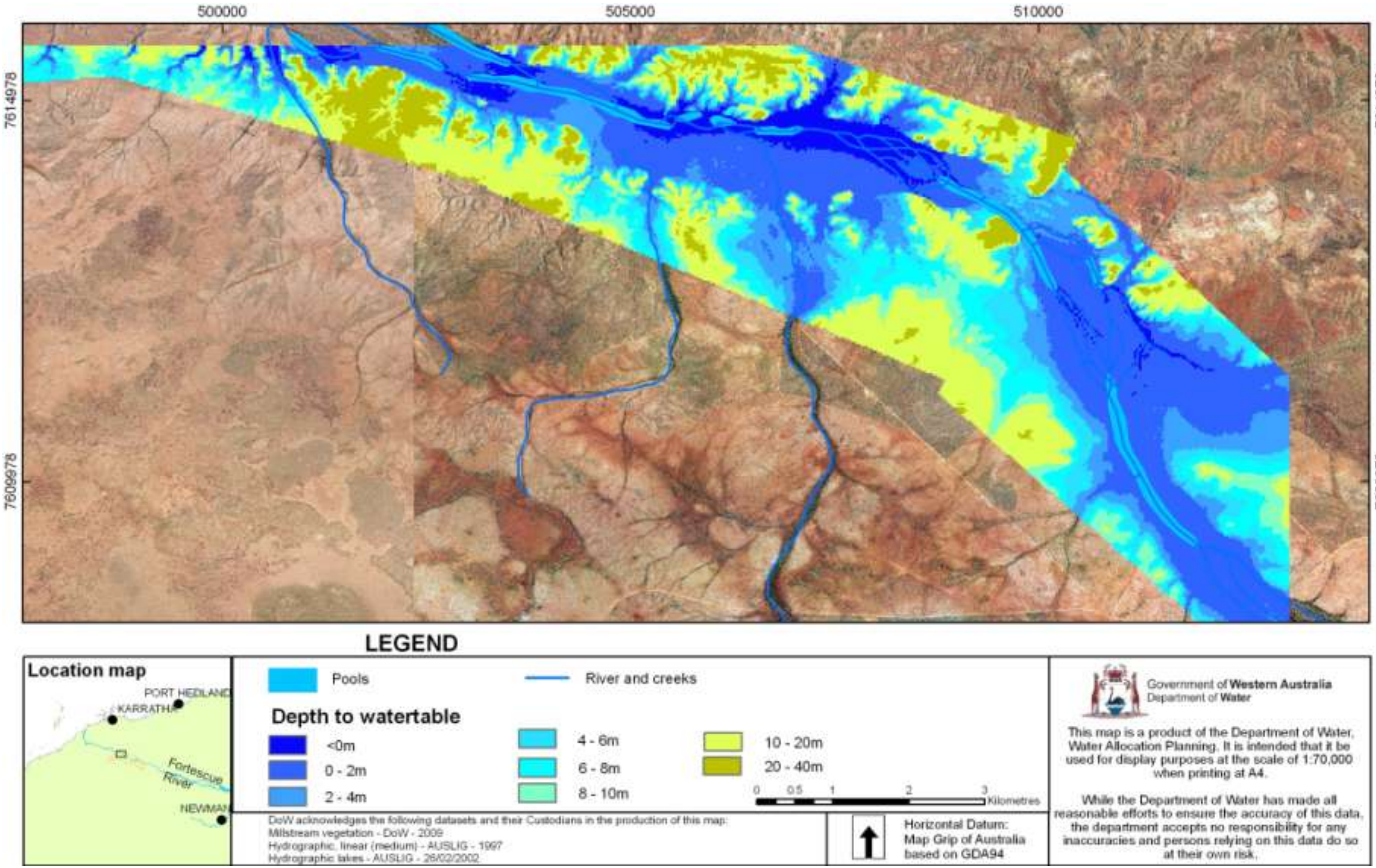


Figure 9 Estimated depth to groundwater across the Millstream riparian forest and wetland areas

4.2 Ecology

4.2.1 Vegetation communities

Land system mapping classifies the Millstream project area mostly as River land system but also includes or borders areas mapped as Mackay, Newman and Oakover (Figure 10) (Van Vreeswyk et al. 2004). Groundwater-dependent vegetation associated with the Millstream aquifer is most likely to occur within the River land system.

Van Vreeswyk et al. (2004) also describe ecologically based site types that provide a finer level of detail below the broader land systems. The groundwater-dependent vegetation of the Millstream Delta and riparian zone is most consistent with the gallery melaleuca eucalypt woodland (GMEW) but components may also represent an additional four site types (Table 5).

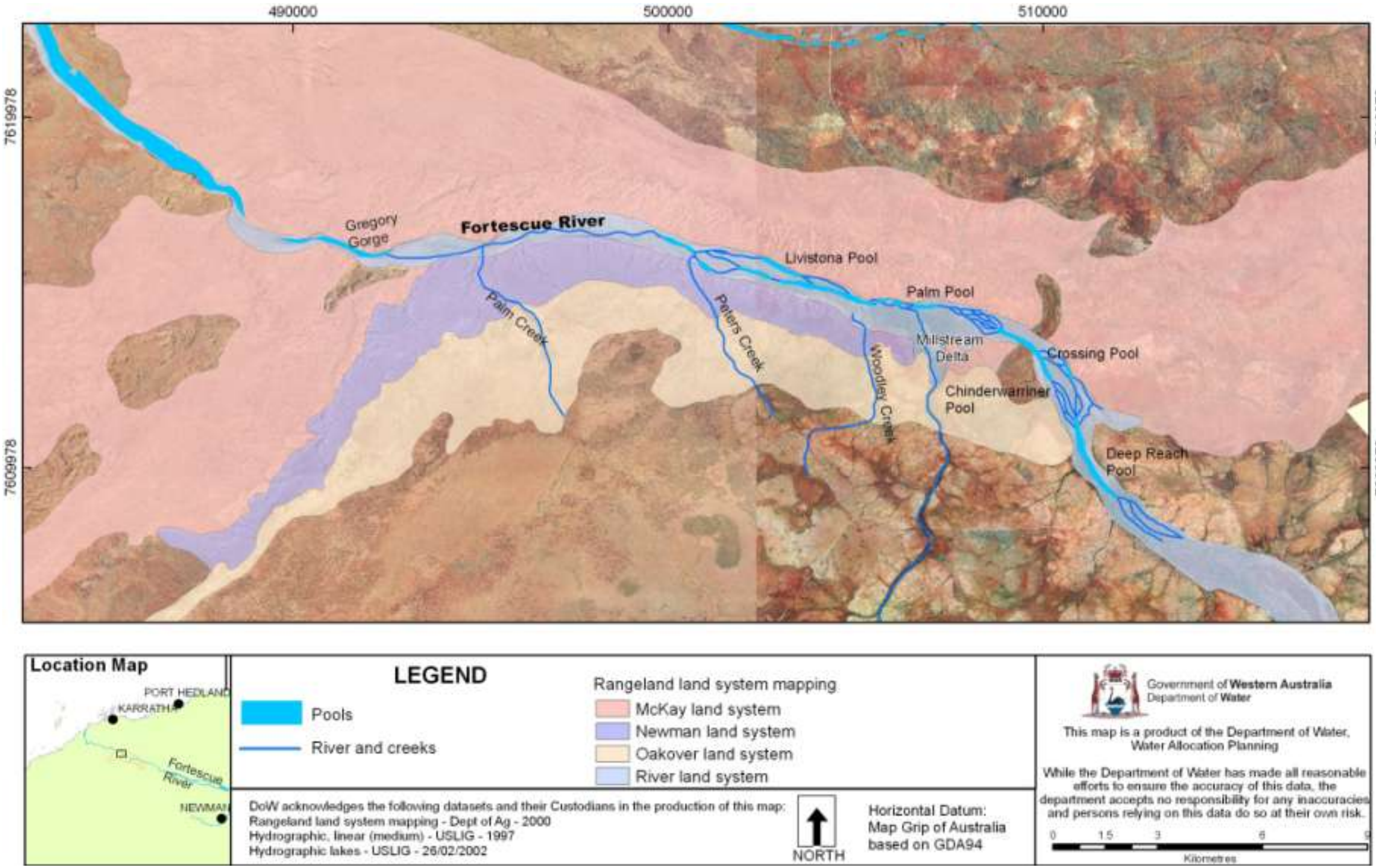


Figure 10 Land system mapping within the Millstream area (Van Vreeswyk et al. 2004)

Table 5 Description of site types likely to occur in the Millstream riparian forest and wetland areas

Type: AEBG – Alluvial plain buffel grass grassland with eucalypt overstorey
Description: *Cenchrus ciliaris* tussock grass grassland with eucalypt overstorey (most commonly *Eucalyptus camaldulensis* or *E. victrix* or as a eucalypt woodland with buffel grass dominated understorey. Occurs on floodplains, alluvial plains, levees and drainage tracts on loamy earths. The site type occurs as a minor component on the River and Yamerina land systems. Previously would have been dominated by native tussock grasses but now heavily invaded by buffel grasses.
Type: DAHW – Drainage acacia hummock grass shrubland/woodland
Description: Acacia shrubland or woodland commonly *Acacia aneura*, *A. citrinoviridis*, *A. trachycarpa* and *A. tumida* with a hummock grass layer most commonly *Triodia pungens*. Occurs on narrow drainage floors on deep sands, loamy earths and juvenile soils. Site type is widespread, occurring as a minor component of 36 land systems and is well represented on conservation reserves.
Type: DESG – Drainage spinifex grassland with eucalypt overstorey
Description: Hummock grassland commonly dominated by *Triodia pungens* with eucalypt overstorey commonly dominated by *Corymbia hamersleyana*, *Eucalyptus camaldulensis* or *E. victrix*. Often with a shrub layer of acacias such as *Acacia inaequilatera*, *A. pyrifolia* and *A. tumida*. Occurs on drainage tracts and floor. Receives sheet flow and overbank flooding from associated minor channels and creeks. Soils are deep sands, loamy earths and juvenile soils. Site type occurs as a minor component of 12 land systems and is represented in conservation reserves including the Millstream-Chichester National Park.
Type: DEGW – Drainage eucalypt and acacia grassy woodland/shrubland
Description: Widespread site type occurring on drainage tracts, drainage floors, floodplains, alluvial plains, levees and also on claypans and swamps. Soils are sandy and loamy earths, clays and juvenile soils. Acacia and/or eucalypt woodland of *Acacia aneura*, *A. citrinoviridis*, *A. coriacea*, *A. distans*, *A. holosericea* or *A. tumida* and *Corymbia hamersleyana*, *Eucalyptus victrix* or *E. camaldulensis* with a tussock grass layer. Grass layer commonly dominated by *Chrysopogon fallax*, *Cenchrus ciliaris* and *Eriachne benthamii*. Site type is well represented in conservation reserves including the Cane River Nature Reserve. It is common on two land systems (Coolibah and Fortescue) and a minor component on 46 land systems.
Type: GMEW – Gallery (riverbank and channel) melaleuca eucalypt woodland
Description: *Melaleuca argentea* or *Eucalyptus camaldulensis* woodland occasionally with a tall shrub layer of *Acacia* spp. or *M. glomerata* and ground cover of sedges or perennial grasses. Occurs along the banks and channels of major rivers on juvenile soils or channel soils of mixed lithology. The site type is an important refuge for native fauna and is well represented in national parks such as Millstream-Chichester and Karijini. It is a minor component on four land systems.

More specific mapping of vegetation communities was completed by Dames and Moore (1984). They identified 22 structural/floristic vegetation communities for the area, of which 17 occur in the river bed/stream channels.

Twelve potential groundwater-dependent vegetation communities have been mapped as part of this project (Figure 11 and Appendix A for more detailed community descriptions). These were based on a simplification of the 22 communities mapped by Dames and Moore (1984) and data from existing and re-surveyed vegetation transects. Nine vegetation transects were established in 1978 as monitoring transects and some of these have been resurveyed by Department of Environment and Conservation (and its predecessors) since then. Prior to this project eight of the nine transects were last surveyed in 1994. As part of this project the Department of Water resurveyed three of the transects.

Information from the Millstream groundwater model, monitoring bores and digital elevation model has also been used to confirm distribution of areas where access to groundwater by vegetation is likely (i.e. where depths to groundwater are < 4 to 6 m) (Figure 9).

At a course level the majority of the identified groundwater dependent vegetation communities are probably versions of the gallery melaleuca eucalypt woodland (GMEW). This site type is considered an important refuge for fauna and is reasonably well represented in reserves and on unallocated crown land (Van Vreeswyk et al. 2004).

One woodland community includes the priority 4 Millstream Palm (*Livistona alfredii)* as a dominant or co-dominant overstorey species. Two woodlands and one shrubland community with understorey dominated by sedges (e.g. *Typha domingensis, Baumea juncea*) were also described and are likely to be relatively rare or restricted in distribution in the Pilbara (Dames & Moore 1984).

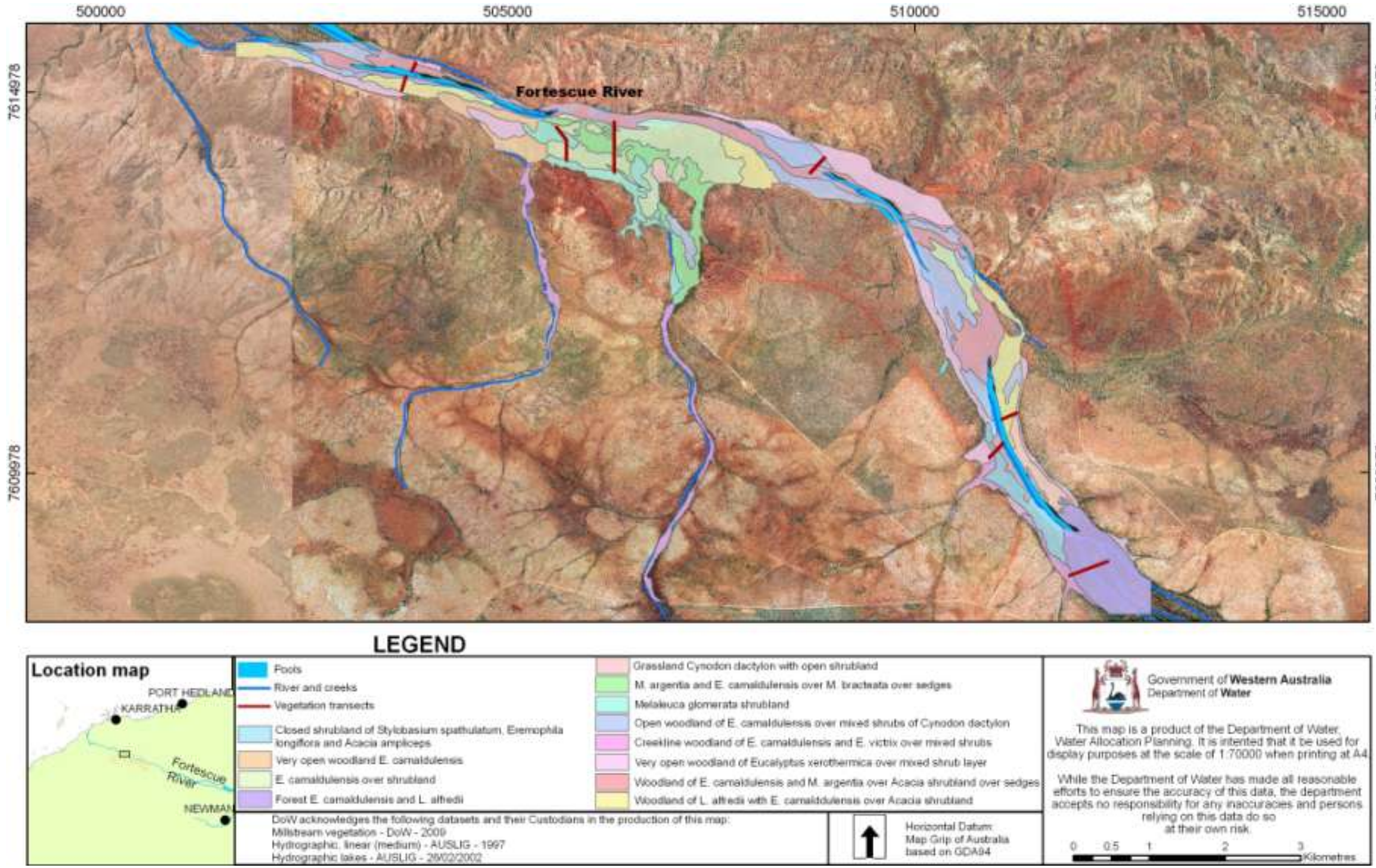


Figure 11 Groundwater dependent vegetation communities for the Millstream area

4.2.2 Groundwater-dependent species

A number of species in the Pilbara region are largely restricted to the relatively mesic environments typically associated with riparian zones and wetlands. Three of the most common in terms of distribution and dominance in riparian and floodplain communities are useful indicator species: *Melaleuca argentea*, *Eucalyptus camaldulensis* and *E. victrix*. These species are the most studied of the Pilbara riparian species.

Previous studies indicate that the shallow planiform root system of *M. argentea* is adapted to areas where surface water is present or groundwater is very shallow (maximum 2 to 3 mbgl). The species has difficulties adjusting to short periods of dry conditions or reductions in water availability (Graham 2001; Strategen 2006).

E. camaldulensis is also commonly associated with shallow depths to groundwater (2 to 5 mbgl), but has been recorded where groundwater is up to 21 mbgl (Landman 2001). The bimorphic root system (surface lateral roots and a tap root) of this species enables it to access both groundwater and water held in the unsaturated, vadose zone above the watertable.

The tolerance of the species is likely to depend to some degree on the local conditions. Although *E. camaldulensis* is reported to be capable of sinking new tap roots in response to groundwater decline, drawdown of > 10 m over a prolonged period may cause irreversible stress (Woodward-Clyde 1997). Deaths of *E. camaldulensis* have been recorded in the Millstream delta when the depth to groundwater increased beyond 5 m.

Although both *E. camaldulensis* and *M. argentea* are reported to be phreatophytic (Muir Environmental 1995b), they will access surface water/floodwater where available (O'Grady et al. 2002).

E. victrix tends to be found in drier areas than *E. camaldulensis* and *M. argentea* (Muir Environmental 1995b). Although tolerant of long periods of drought and less susceptible to drawdown, this species appears sensitive to prolonged inundation (Strategen 2006).

The Millstream Palm (*Livistona alfredii*) is a relictual palm species restricted to a few sites in the Pilbara, with the largest population located in the riparian and spring zones of Millstream. Details of the water requirements for *L. alfredii* are poorly understood. Although the main Millstream populations occur where depth to groundwater is typically between 1.5 to 3 m, some populations such as those associated with Palm and Chinaman's creeks are unlikely to have access to shallow groundwater (Dames & Moore 1984; Muir Environmental 1995a). The species is reported to have a relatively shallow rooting depth (to approximately 1.5 m) and must therefore be capable of satisfying water requirements from the shallow soil zone and/or limiting water use when moisture availability is restricted.

There are a number of additional riparian and wetland species that occur at Millstream where moisture availability is high as a result of shallow depth to groundwater and/or groundwater discharge.

DEC (formerly the Department of Conservation and Land Management) established nine vegetation transects in 1978 for the purpose of monitoring vegetation in the Millstream-Chichester National Park (Figure 11). These transects have been re-surveyed a handful of times since, the most recent in 2008 when the Department of Water resurveyed three of them. A total of 125 taxa from 39 families were recorded from the transects during the most recent sampling efforts. The results illustrate the distribution of species in relation to depth to groundwater/moisture availability.

The response of vegetation to altered water availability has also been investigated using satellite imagery and hydrological data. The project analysed remote-sensing-derived percentage foliage cover (PFC) data collected by DEC and hydrological data (groundwater levels, surface water flow and rainfall) collected by the Department of Water and Water Corporation (Appendix B). We found that:

- rates of change in vegetation density (as represented by PFC) are not uniform across Millstream and are driven by different processes
- mean aquifer level (MAL) and local groundwater levels are the most important determinants of vegetation density but pool levels, rainfall, fire and erosion also have an influence
- although infrequent, fire has a greater impact on PFC than other factors, essentially resetting vegetation density.

4.3 Conservation significance

4.3.1 Threatened flora or communities

Eleven priority flora species have been recorded from the Millstream-Chichester National Park (DEC 2007). This includes the Millstream Palm (*Livistona alfredii*), which is widespread within the Millstream area but otherwise restricted in its distribution. *L. alfredii* was recorded on two of the three transects we re-surveyed during 2008. It had previously been recorded on seven of the eight transects established. As discussed previously, *L. alfredii* is relictual species that has survived in the Millstream area from the humid tropical paleoclimate.

Two additional priority flora species are likely to occur (DEC Threatened [Declared Rare] Flora database and Western Australian Herbarium 1998) in areas sustained in part by groundwater discharge. These are:

- *Fimbristylis sieberiana* which occurs in damp poolside locations and has previously been recorded on the edge of Palm Pool
- *Themeda* sp. Hamersley Station which occurs on clays and in clay pans and has previously been recorded in the Millstream Delta.

An additional two species have been recorded from the wider Millstream area but do not appear to occur in groundwater-dependent communities or habitats.

None of the vegetation communities recorded and described at Millstream are threatened ecological communities on state or federal ministerially-approved lists. However, DEC has listed three vegetation communities within Millstream-Chichester

National Park as priority ecological communities (i.e. communities that are recognised as possibly being at risk and requiring further investigation). None of these are linked to or depend on Millstream aquifer discharges.

Dames and Moore (1984) identified Melaleuca shrublands over *Baumea* sp. within the delta as the most restricted vegetation community they identified. This is considered equivalent to ‘community 6’ mapped and described in the current study (see Figure 11). This community appears restricted to the delta.

As mentioned previously, the Millstream wetlands are considered regionally rare and are listed as a wetland of national significance in the *Directory of important wetlands in Australia* (May & McKenzie 2002). This includes riparian and wetland vegetation which are considered a significant ecological community. In addition, the wetlands support a relatively high diversity of flora, provide a diverse range of habitats and occur in an areal extent that is not replicated elsewhere in the Pilbara region (Burbidge 1971; Dames & Moore 1975; Dames & Moore 1984; DEC 2007).

5 Aquifer ecosystems

Bicarbonate-rich aquifers such as Millstream exhibit an abundant and diverse assemblage of stygofauna (Reeves et al. 2007). Millstream is particularly rich, with the most species of stygofauna recorded for an aquifer in the Pilbara (Eberhard et al. 2005).

Early results from the Pilbara Biological Survey – focusing on the distribution of Ostracods – confirmed previous patterns of stygofaunal distribution within the Fortescue River Basin. That is, the existence of distinct groups of fauna for the lower and upper Fortescue River with an additional group focused on the drainage divide in the central Fortescue. This pattern of relatively disjunct localised populations is consistent for ostracods across the Pilbara and is thought to be due at least in part to the disjunct nature of aquifers, particularly calcrete aquifers (Reeves et al. 2007).

It is anticipated that more thorough comparisons of the significance of the stygofaunal assemblages at Millstream, in a Pilbara regional context, will be possible when the final results of the Pilbara Biological Survey become available.

The stygofaunal communities of the Millstream aquifer have been identified as a priority for classification as a threatened ecological community (May & McKenzie 2002).

6 Other fauna

In addition to fish and macroinvertebrates, a number of vertebrate fauna rely on groundwater-fed wetlands or groundwater-dependent vegetation for habitat. This includes reptiles and amphibians such as the specially protected Pilbara olive python (*Morelia olivaceae barroni*), the flat-shelled turtle (*Chelodina steindachneri*) and the skink (*Lerista frosti*) that need permanent pools for habitat (DEC 2007).

Millstream also provides habitat for a diverse bird assemblage. Of the 146 species recorded for the Millstream-Chichester National Park:

- 38 are waterbirds, many of which are uncommon in inland parts of the Pilbara
- 31 are listed as migratory species and/or are covered under various international conventions or agreements (DEC 2007).

Eight species of waterbirds are known to use the area for breeding. The riparian/wetland eucalypt and melaleuca forests provide important habitat for many of the bird species recorded.

Most native mammal species recorded for the Millstream-Chichester National Park area (36 species) have a preference for hummock grassland habitats, not potentially groundwater-dependent wetland areas (DEC 2007).

6.1 Conservation significance

Three threatened or specially protected fauna, as listed under the *Wildlife Conservation Act 1950* (WA), were recorded from the project area as being either aquatic for at least part of their life cycle or relying on aquatic habitats (Table 6).

Table 6 Threatened and specially protected fauna recorded for the Millstream area that rely on aquatic habitats

Species	**Conservation significance**	
Morelia olivaceae barroni (Pilbara olive python)	Specially protected	
Leipotherapon aheneu (Fortescue grunter)	Priority 4	Rare, Near Threatened and other species in need of monitoring
Nososticta pilbara (dragonfly)	Priority 2	Poorly-known species

An additional three threatened or specially protected fauna were recorded from the project area as being predominantly found in habitats associated with or near permanent water or watercourses (Table 7).

Table 7 Threatened or specially protected fauna that are associated with habitats near watercourses or permanent water

Species	**Conservation significance**	
Neochnia ruficauda subclarescens (Star finch)	Priority 4	Rare, Near Threatened and other species in need of monitoring
Phaps histronica (Flock bronzewing)	Priority 4	Rare, Near Threatened and other species in need of monitoring
Notoscinus butleri (skink)	Priority 4	Rare, Near Threatened and other species in need of monitoring

7 Summary of ecological values

This study identifies three groundwater-dependent ecosystems associated with the Millstream aquifer. The components of these ecosystems, their conservation significance and their links to the aquifer have been described. This section summarises their ecological values using the categories defined by Horwitz and Rogan (2003):

- biotic – key species and/or communities (including rare or threatened biota)
- functional – ecosystem services that maintain habitat for dependent populations or species
- land/waterscape – contributions to landscape connectivity, habitat provision, representativeness and ecosystem resilience to disturbance.

Cultural values will be discussed in a separate report.

7.1 Wetlands

The Millstream wetland system comprises approximately 20 km of the Fortescue River and tributaries. It includes four major permanent river pools (Deep Reach, Crossing, Livistona and Palm pools) interconnected by permanent flowing channels and spring-fed pools on tributaries (e.g. Chinderwarriner Pool).

The wetlands are hydraulically connected to the aquifer, which maintains pools and flows in between intermittent surface water events. The aquifer maintains a diverse array of habitats, which in turn support a diverse assemblage of biota.

7.1.1 Biotic values

The Millstream wetlands support:

- nine of the 10 freshwater fish species recorded for the Fortescue River
- 15 species of emergent and submerged aquatic macrophytes
- a diverse macroinvertebrate assemblage including relictual dragonfly and damsel fly species and a suite of aquatic species that are restricted in distribution
- 146 species of birds, including:
  - 38 waterbirds, many of which are uncommon to inland parts of the Pilbara
  - 31 listed as migratory species and/or covered under various international conventions or agreements
- vertebrate fauna including reptiles and amphibians such as the specially protected Pilbara olive python (*Morelia olivaceae barroni*), the flat-shelled turtle (*Chelodina steindachneri*) and the skink (*Lerista frosti*) that rely on permanent pools as habitat.

7.1.2 Functional values

The wetlands maintain key ecological processes important to habitat provision including:

- water quality
- nutrient cycling associated with productivity
- decomposition of organic carbon required for food webs.

7.1.3 Land/waterscape values

The wetlands hold a number of regional and broader-scale values. These include:

- connectivity – hydrological linking of pools plays an important role in the natural functioning of a major wetland system
- habitat provision – pools act as drought refuges for native flora and fauna
- representativeness – the wetlands are unique in the region in terms of their hydrology and scale
- resilience – the health/condition of the wetlands allow them to absorb seasonal changes (drought/flood).

7.2 Riparian vegetation

Discharge from the Millstream aquifer and areas of shallow groundwater support extensive and diverse riparian forests and woodlands.

7.2.1 Biotic values

The riparian vegetation contains:

- a diverse assemblage of vegetation communities including 12 considered to be groundwater dependent and some that are restricted in their distribution to the region
- at least 125 taxa of vascular flora from 39 families
- the relictual priority-four listed *Livistona alfredii* (Millstream Palm)
- an additional two priority flora species, *Fimbristylis sieberiana* and *Themeda* sp. Hamersley Station.

7.2.2 Functional values

The riparian vegetation maintains key ecological processes important to habitat provision including:

- maintenance of water quality through biofiltration
- soil/bank stabilisation
- mediating microclimate
- support of complex food webs.

7.2.3 Landscape values

The riparian vegetation of Millstream supports the following landscape values:

- connectivity – vegetation provides corridors allowing fauna to move between habitats (e.g. pools)
- habitat provision – vegetation provides both direct habitat and refuge habitat during drought
- representativeness – vegetation communities are good examples of the riparian ecosystems of the region
- resilience – the health/condition of vegetation allows it to absorb seasonal changes (drought/flood).

7.3 Aquifers

7.3.1 Biotic values

Aquifers in the Pilbara region have been associated with diverse subterranean fauna. Bicarbonate-rich aquifers such as Millstream exhibit an abundant and diverse assemblage of stygofauna (Reeves et al. 2007). Millstream is particularly rich, with the most species of stygofauna recorded for an aquifer in the Pilbara (Eberhard et al. 2005).

8 Environmental objectives for Millstream

The Millstream system is a unique and diverse wetland that is not replicated in terms of scale and type elsewhere in the Pilbara region. It supports a number of species that are restricted in their distribution within the region.

The permanent and stable pools that the aquifer maintains are important refuges for aquatic flora and fauna. These highly biologically productive areas are also likely to sustain ecosystems in the surrounding areas (Douglas et al. 2005).

Millstream is subject to a variable and dynamic climate and in recent times changes in land management. The ecosystems at Millstream have changed as a result of this variability and will continue to change. However, the presence of relictual flora and fauna species indicates that Millstream has provided a continuous refuge in an arid region for thousands of years.

Protection and maintenance of the Millstream system is a fundamental part of managing the region's water resources and the West Pilbara water supply scheme. This is enhanced through improving our understanding of ecological water requirements (EWRs) and refining management arrangements for the resource to best meet both ecological and consumptive needs. Setting clear objectives to guide the revision of EWRs and subsequent management arrangements is key to this process.

The current management arrangements are derived from ecological water requirements determined in the 1990s and were guided by the general water management objective:

- to ensure that the existing aesthetic, ecological and cultural values of the key areas of environmental and cultural significance are not adversely affected by the supply of water to the West Pilbara Supply Scheme (Welker 1996).

Since the original management objective was set, our understanding of the dynamic nature of the system has improved, as has our understanding of the role the aquifer plays in sustaining groundwater dependent ecosystems.

The overall objective to guide the revised assessment of the Millstream EWR has been developed with the variable climate and the system's role as a refuge in mind. The broad environmental water objective is to:

- maintain the extent and condition of groundwater-dependent ecosystems in the context of climate variability and natural ecosystem dynamics.

Specific objectives for ecosystem components have been identified based on conceptual models of ecosystem hydrology interaction. These will be used to frame the revised assessment of the EWR for Millstream and ultimately develop revised management criteria. With this in mind, parameters against which water requirements will be set and measured have also been identified.

The objectives and parameters have focused specifically on measures directly related to water management. While many other factors influence the health and distribution of groundwater-dependent ecosystems at Millstream, the management of these is mostly the responsibility of other agencies and not the focus of this project.

8.1.1 Vegetation

Groundwater-dependent vegetation is found along the riparian zone of the Fortescue River, within the delta area and around the other springs: Palm, Peters and Woodley. The vegetation's water requirements are met at least in part by access to groundwater directly (e.g. in the area adjacent to and immediately upstream of Deep Reach Pool) or indirectly via maintenance of the local watertable or soil moisture downstream of aquifer discharge (e.g. in the delta). The groundwater contribution to maintenance of the vegetation's water requirements is most critical during drought periods when soil water has not been replenished by rainfall or surface water flows.

To maintain the extent and diversity of vegetation communities dependent on groundwater discharge from the Millstream Aquifer the following objectives need to be met.

1 Sufficient water availability for groundwater-dependent vegetation during periods of no surface water inputs as provided by seepage from channels, throughflow/subsurface contributions and maintenance of watertable levels that are accessible to phreatophytic vegetation.

   a Parameters –
   - (i) minimum depth to watertable in local bores
   - (ii) rate of change in groundwater levels in local bores
   - (iii) moisture availability in unsaturated zone.

Wetland vegetation and aquatic macrophytes are maintained by surface water flows in channels within the delta and along the Fortescue River. Both are critical in maintaining the diversity of habitats that support fish and macroinvertebrate populations. In-stream and fringing vegetation is also critical in ameliorating fluctuations in water quality. In the absence of rainfall-derived surface water flows, groundwater discharge maintains flows and water levels in channels and pools.

2 Sufficient flow in surface water channels to maintain the extent and distribution of aquatic macrophytes.

   a Parameters –
   - (i) extent and/or rate of flow down delta and riverine channels
   - (ii) minimum mean aquifer level (MAL) to maintain sufficient outflow into the delta and subsurface contribution to delta channels.

3 Sufficient flow in surface water channels to maintain the extent and distribution of fringing vegetation.

   a Parameters –
   - (i) extent and/or rate of flow down delta channels
   - (ii) minimum MAL to maintain sufficient outflow into the delta and subsurface contribution to delta channels.

8.1.2 Wetlands

Preserving the diversity of habitats and permanency of pools are critical components of maintaining the Millstream wetlands. Habitats include flowing and permanent pools with a range of substrates and riparian and in-stream vegetation.

To maintain the extent and diversity of wetlands and wetland habitats within the context of a dynamic climate the following objectives need to be met.

4 Sufficient flows in surface water channels to maintain the extent and range of habitats for macroinvertebrates.

   a Parameters – (i) extent and/or rate of flow down delta and riverine channels

   (ii) minimum MAL to maintain sufficient outflow into the delta and subsurface contribution to delta channels.

5 Sufficient flows in surface water channels to maintain habitat for fish.

   a Parameters – (i) extent and/or rate of flow down delta and riverine channels

   (ii) minimum MAL to maintain sufficient outflow into the delta and subsurface contribution to delta channels.

6 Maintain deep permanent pools with a range of habitats as refuges for large-bodied long-lived fish species.

   a Parameters – (i) minimum pool levels to maintain sufficient habitat

   (ii) minimum aquifer level to maintain sufficient discharge into pools.

7 Provide/maintain connectivity between wetlands and the Fortescue River for fish and macroinvertebrate movement.

   a Parameters – (i) extent and/or rate of flow down delta and riverine channels

   (ii) minimum MAL to maintain sufficient outflow into the delta and subsurface contribution to delta channels.

8 Provide sufficient groundwater discharge to maintain water quality in pools and delta surface water channels.

   a Parameters – (i) rate of flow down delta and riverine channels

   (ii) minimum MAL to maintain sufficient outflow into the delta and subsurface contribution to delta channels

   (iii) suitable water quality within the aquifer.

9 Maintain connectivity to transfer carbon and nutrients between the Fortescue River and the delta wetlands.

a Parameters – (i) extent and/or rate of flow down delta and riverine channels

(ii) minimum MAL to maintain sufficient outflow into the delta and subsurface contribution to delta channels.

8.1.3 Next Steps

The Department is completing a separate report (Department of Water 2010) to determine the long-term sustainable yield and long-term reliable allocation for the Millstream aquifer. Both the yield and the allocation has been set in this report, consistent with the water management objective described here, namely to maintain the extent and condition of groundwater-dependent ecosystems in the context of climate variability and natural ecosystem dynamics.

Following this, the Department will refine its management criteria and monitoring arrangements in line with the specific objectives for the various ecosystem components. This will improve the operational management of the system but will not alter the long term sustainable yield or reliable allocation.

Appendices

Appendix A – Groundwater dependent vegetation community descriptions

Community	Description	Other species which may be present
1	Woodland of *Livistona alfredii* with *Eucalyptus camaldulensis* over *Acacia* spp. shrubland.	*Acacia ampliceps, Acacia trachycarpa, Gossypium robinsonii, Cynodon dactylon, Cyperus vaginatus, Melaleuca glomerata*
2	Woodland of *E. camaldulensis* and *Melaleuca argentea* over shrubland of *Acacia ampliceps* and *Stylobasium spathulatum* over *Cyperus vaginatus.*	*Acacia sclerosperma, Acacia trachycarpa, Hibiscus panduriformis, Petalostypis labichioides*
3	Open woodland of *E. camaldulensis* over open shrubland of *Acacia ampliceps* over *Cynodon dactylon*	
4	Very open woodland of *Eucalyptus xerothermica* over mixed open shrubland	*Acacia bivenosa, Acacia holorsericea, Acacia ligulata, Acacia sclerosperma, Cenchrus cilliaris, Ptilotus obovatus, Senna notabilis, Solanum lasiophyllum, Triodia wiseana, Waltheria indica*
5	Shrubland of *Melaleuca glomerata* with *A. ampliceps* over *C. dactylon* with occasional emergent *E. camaldulensis.*	*Acacia bivenosa, Melaleuca bracteata, Triodia wiseana*
6	Shrubland of *Melaleuca bracteata* with emergent *M. argentea* and *E. camaldulensis* over sedges *Typha domingensis* and *Baumea juncea*	*Acacia ampliceps, Cynodon dactylon, Pimelea ammocharis, Stylobasium spathulatum*
7	Woodland of *E. camaldulensis* over closed shrubland *A. ampliceps*, *M. bracteata*, *Stylobasium spathulatum* and *Gossypium robinsonii*	*Acacia bivenosa, Acacia farnesiana, Cenchrus ciliaris, Cynodon dactylon, Cyperus vaginatus*
8	Grassland *Cynodon dactylon* with open shrubland of *A. ampliceps* and occasional emergent *E. camaldulensis*	.

9	Closed shrubland of *S. spathulatum*, *Eremophila longiflora* and *A. ampliceps*	*Typha domingensis, Baumea juncea, Senna glutinosa, Cynodon dactylon, Melaleuca glomerata, Acacia ampliceps*
10	Forest *E. camaldulensis* and *L. alfredii* over closed shrubland of *Acacia ampliceps*, *Acacia trachycarpa* and *Cyperus vaginatus*	*Acacia sclerosperma, Acacia farnesiana, Juncus* sp.
11	Very open woodland *E. camaldulensis*	
12	Creekline woodland of *E. camaldulensis* and *Eucalyptus victrix* over mixed shrubland	*Acacia holorsericea*

Appendix B — Millstream satellite imagery data analysis

Background

The Millstream aquifer is a major source of potable water for the West Pilbara water supply scheme. With the significant resource and industrial development currently occurring in the Pilbara, increasing demands are likely to be placed on the aquifer to help meet projected water demands.

The aquifer also supports large and biologically diverse groundwater-dependent ecosystems (GDEs) where groundwater discharges into creeks and springs. These, along with the permanent pools they form, are culturally significant and have become a tourist attraction. As such, groundwater abstraction needs to be managed to ensure that aquifer levels do not decline and compromise discharge into the environment.

Water abstraction began in 1969, steadily increasing to 10 GL/year in 1980. Between 1981 and 1985 annual abstraction remained between 10.5 and 15 GL. These high abstraction rates contributed to a historical minimum mean aquifer level (MAL) of 293.08 mAHD, and coincided with reported tree deaths and vegetation decline in the Woodley and Millstream deltas.

In 1985 the Harding Dam came online and a combined/conjunctive water supply scheme was developed to reduce the amount of abstraction required from the Millstream aquifer. Since conversion to the conjunctive scheme, production has averaged 4.57 GL/year. MAL has subsequently increased and vegetation appears to have recovered. There remains, however, a provision to abstract the total license allocation of 15 GL/year when required, subject to environmental criteria and aquifer testing.

Three categories of environmental criteria – largely derived from Welker et al. (1995) – are applied at Millstream: absolute MAL, rate of MAL decline, and rates of outflow from selected pools. Absolute MAL sets the mean, minimum groundwater levels at key environmental areas on the aquifer. Rate of MAL decline sets the rate at which aquifer levels can decrease without adversely affecting groundwater-dependent tree species (*Eucalyptus camaldulensis* and *Melaleuca argentea*). Outflow criteria sets spring discharge from the aquifer to ensure that the environmental demand of the vegetation and the aesthetics of the pools are maintained.

Although not derived from direct observations of the health of GDEs and MAL, the criteria are based on the following assumptions:

1. environmental demand equals the difference between discharge at two points (taking into account rainfall and evaporation)
2. if the respective MAL is met, then the GDE will be healthy
3. *E. camaldulensis* and *M. argentea* at Millstream will be healthy if MAL decline does not exceed the specified rate.

A biological monitoring program for Millstream has included annual aerial photography and Landsat satellite imagery and less frequent on-ground vegetation and photo-point monitoring. Currently, the annual aerial photography is the only component of the program in place. The Department of Environment and Conservation (DEC) developed a method whereby relevant information extracted from the Landsat imagery is used to determine vegetation composition and percentage foliage cover (PFC) (Behn et al. 2007). Analysis of the resulting PFC data provides information on spatial and temporal changes in vegetation density. Two types of Landsat imagery with differing pixel size have been used: Thematic Mapper (TM) and Multispectral (MSS) (Table B1).

Current groundwater monitoring comprises bi-monthly monitoring of the nine bores used to calculate mean aquifer level (MAL or referred to as MAL8). In addition significant environmental areas are monitored bi-monthly at four or more local monitoring bores.

Previous studies have suggested that rates of change in vegetation density are not uniform between different areas of the Millstream wetlands, with different processes dominating different parts of the system (Behn et al. 2007). While empirical evidence suggests a relationship between MAL and vegetation density, this relationship has not been quantified. Data derived from satellite imagery provides the opportunity to analyse changes in vegetation density/condition between 1979 and 2005 against a comprehensive MAL dataset spanning the same period.

Table B1 Date and type of satellite imagery used

Date	Landsat	Pixel size (m)
14/11/79	MSS	50
1980	n/a	n/a
25/10/81	MSS	50
1982	n/a	n/a
20/11/83	MSS	50
16/12/84	MSS	50
17/11/85	MSS	50
4/11/86	MSS	50
9/12/87	MSS	50
28/11/89	TM	25
15/11/90	TM	25
18/01/91	TM	25
6/02/92	TM	25
23/11/93	TM	25
28/01/94	TM	25
15/12/95	TM	25
15/11/96	TM	25
2/11/97	TM	25
5/11/98	TM	25
24/11/99	TM	25
18/11/00	TM	25
8/01/02	TM	25
24/11/02	TM	25
12/02/03	TM	25
5/12/03	TM	25
25/01/05	TM	25

Aims and approach

This assessment follows an earlier analysis by DEC of a less complete dataset. The main aim of that analysis was to determine the statistical relationship between changes in aquifer level (as MAL) and vegetation response (as change in PFC) for Millstream.

This work repeats DEC’s analysis using the updated dataset. It also assesses data at a more ‘local’ scale using groundwater levels from specific monitoring bores and local area PFC. This addresses the influence of different groundwater levels on key environmental areas (Figure B1). MAL and local area groundwater levels were further broken down into annual mean, maximum and minimum values.

Unless a change in groundwater level is severe, vegetation is unlikely to respond immediately to an altered water regime. To account for a possible lag between water level change and response in PFC, a one-year time lag was incorporated. That is, PFC values for one year were also compared with local groundwater levels from the previous year.

As factors other than groundwater influence changes in vegetation density, the relationship between PFC and total annual rainfall, annual river flow and average pools levels (where applicable) were also investigated. In addition, to account for possible lags in rainfall infiltration, a one-year time lag was considered for rainfall. Intervening events such as bushfires, erosion and weed eradication activities were also considered as they can have a significant effect on the spatial and temporal responses and are likely to bias results. A timeline was developed to identify the timing of these events.

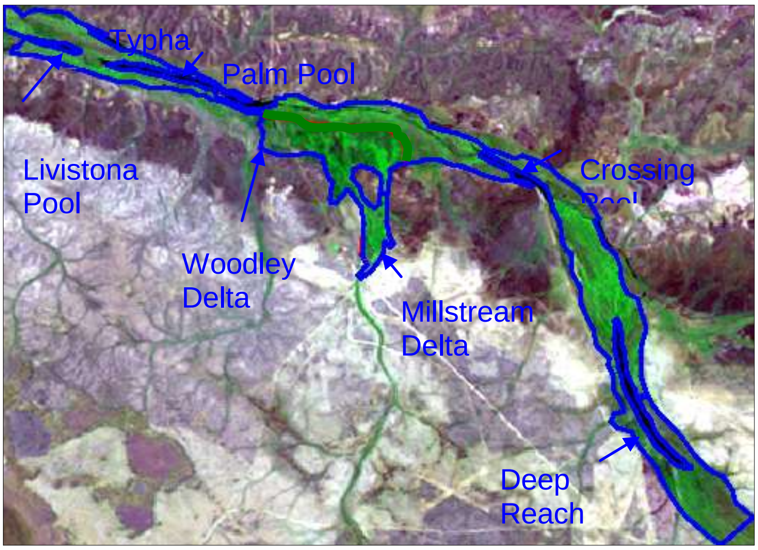


Figure B1 Location of key environmental areas and satellite imagery coverage within Millstream

Data analysis

Data were analysed on a whole-of-system basis for the Millstream delta and riverine areas considering numerous predictors. Further analyses were then carried out on a subarea basis across all ‘study areas’: Millstream delta, Deep Reach Pool, Livistona Pool, Woodley Creek, Typha Pool, Crossing Pool and Palm Pool. Local groundwater and pool levels were considered in subareas where data were available. However, MAL was considered for all sites (often as a surrogate for local groundwater) even though many of the ‘study areas’ do not sit on the aquifer.

Whole-system analysis

To understand the general trends across the whole system, the initial analysis compared PFC in the delta and riverine subsystems (Figure B2) with MAL, known hydrological events and ‘other’ factors including local groundwater levels, fire and rainfall. The specific questions addressed were:

- Are there similar trends in PFC in the riverine and delta areas?
- Does temporal variability in PFC correlate with known hydrological or ‘other’ events?
- Is there a statistical relationship between PFC and other factors?

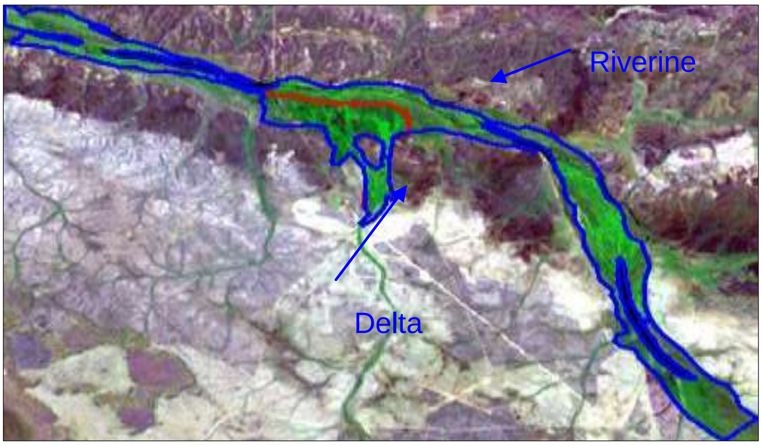


Figure B2 Location of riverine and delta subsystems used in the initial whole-system analysis

General trends

PFC in the delta and riverine subsystems track closely with only minor disparity. As would be expected, the delta has consistently higher values (except after the 1992 fires) due to constant irrigation and highly organic soils. The delta also appears more sensitive to changes in hydrological parameters, illustrated by a shorter time lag between periods of low water availability and decline in PFC and quicker recovery when water availability increases.

Temporal variability

Comparisons between PFC in the delta and riverine systems with mean MAL and intervening events between 1979 and 2005 are shown in Figure B3 and described below.

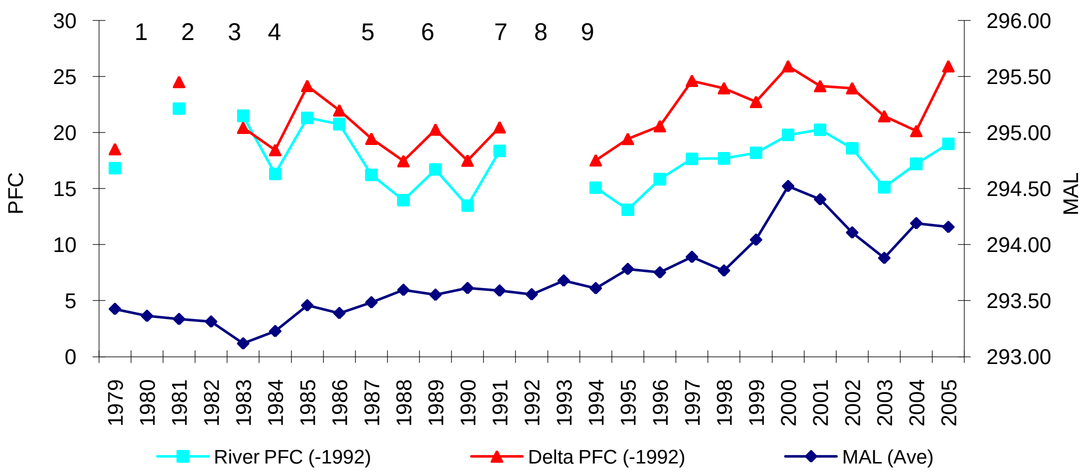


Figure B3 Delta and riverine PFC values and annual average MAL 1979–2005

1. 1979 to 1983 – high PFC during period of record low MAL, high abstraction rates, low flows (since 1976) and lower-than-average rainfall (since 1974).

This is the most contradictory trend in the data, and is seen across most of the PFC datasets. It may be linked to the absence of cyclones and associated scouring of vegetation since 1975 or possibly water stress causing an increase in weedy species.

2 1981 to 1984 – decrease in PFC coinciding with record low MAL, continuing drought conditions and high abstraction rates.

3 1985 – increase in PFC during period of increasing MAL.

Even though MAL is in a state of recovery, it is still significantly below the long-term minimum. It is likely that improvements in PFC are due to high rainfall, good riverine flows and supplementation into Chinderwarriner Pool – which are all recharging the local aquifers – rather than increasing MAL.

4 1986 to 1988 – decrease in PFC during period of increasing MAL.

While MAL is increasing, levels are still way below the long-term minimum. Declining PFC values are more likely to be a response to factors other than MAL. These include:

- supplementation ceased in 1986 so whilst MAL is increasing, the local delta watertable is in a state of decline
- scouring broke through to Crossing Pool in 1986, resulting in a decline in the local watertable, and there is evidence of vegetation stress through water availability and salinity
- first started clearing/burning palms near Deep Reach and in the delta
- record low rainfall in 1985 followed by record low flow rates in 1986.

5 1992 – significant decline in PFC in the delta as the result of a major fire.

6 1992 to 1997 – increase in PFC coinciding with increase in MAL.

This is also likely due to recovery from the 1992 fire, in conjunction with average rainfall and some good river flows. Extensive removal of palms occurred in the delta during this period (including the ‘great date palm massacre of 1994’) but this is not evident in time series data.

7 1999 and 2000 – increase in PFC coinciding with significant increase in MAL over high rainfall years.

8 2000 to 2003 – period of decreasing PFC coinciding with further clearing of date palms across delta and riverine areas between 1999 and 2002.

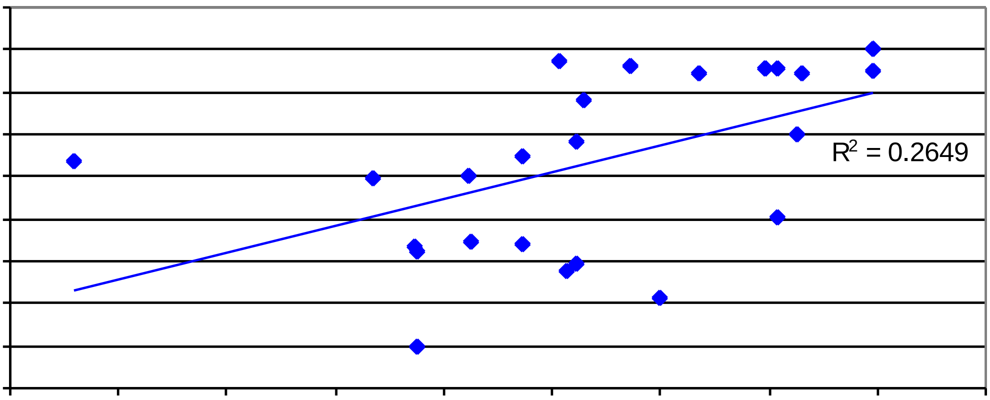
9 2003 to 2005 – increase in PFC in the riverine subarea coinciding with increasing MAL and recovery from January 2003 fire in Palm and Livistona pools.

Statistical relationship between PFC and other factors

Statistical analyses of available data were undertaken to identify the strength of relationships between PFC and other factors. As a first pass, linear regressions were run between delta and riverine PFCs and rainfall, Fortescue flow, Chinderwarriner flow, MAL and local groundwater for all years from 1979 to 2005.

Based on the r^2 values, MAL and local groundwater levels (measured at bore P3/77) showed strong predictive (statistically significant) relationships to delta PFC values. However, local groundwater levels appeared to be the greatest driver of vegetation density across the delta (Figure B4).

Analysis of the full riverine dataset (1979–2005) showed only a weak relationship between PFC and all factors. However, manipulation of the data to exclude values before 1993 (to exclude the influence of fires and represent a time of increasing MAL and PFC) showed strong, statistically significant relationships between PFC and MAL (Figure B4).



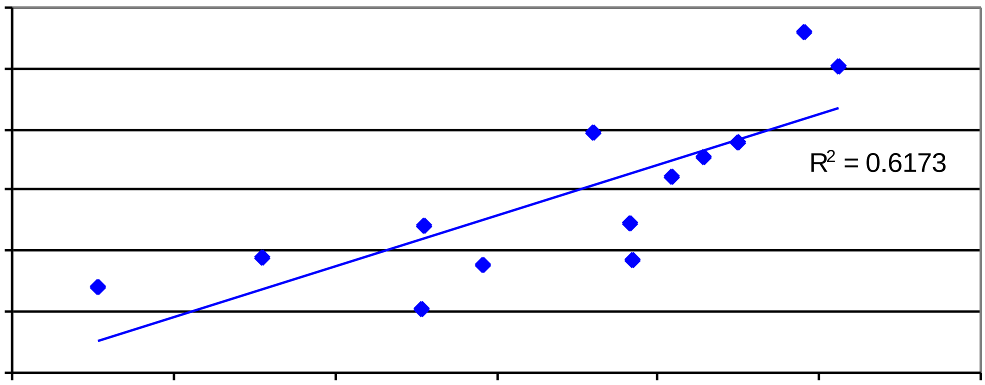


Figure B4 Linear regressions between delta PFC and maximum annual groundwater (P3/77) 1993–2005 (top chart) and riverine PFC and mean MAL 1993–2005 (bottom chart)

A 'Primer BIO-ENV' multi-linear regression was used to further investigate possible relationships. This procedure identifies the combination of environmental variables that best rank correlate with the dissimilarity matrix of samples (Clarke & Ainsworth 1993).

BIO-ENV was run for 1979–2005 PFC data from the delta and riverine area against MAL (annual minimum, maximum and mean), local groundwater levels (annual minimum, maximum and mean), total annual rainfall, total annual rainfall with a one-year lag, annual river flow (measured at Gregory Gorge), Chinderwarriner flow and fire. Although no statistical significance was afforded to any parameter, local area groundwater levels were the most important driver of changes in PFC (r = 0.02).

Analysis of Millstream delta subareas

Linear regressions and Pearson's correlations were run for delta subareas (west, east, central, Chinderwarriner and channels) to determine which of the parameters assessed through BIO-ENV (above) had the strongest relationship to PFC on a site-by-site basis (Figure B5). Analyses were undertaken across the entire 1979–2005 dataset and also from 1993–2005. The later time series appears to represent a time of increasing MAL and PFC across the delta subareas and removes the impact of the 1992 fires.

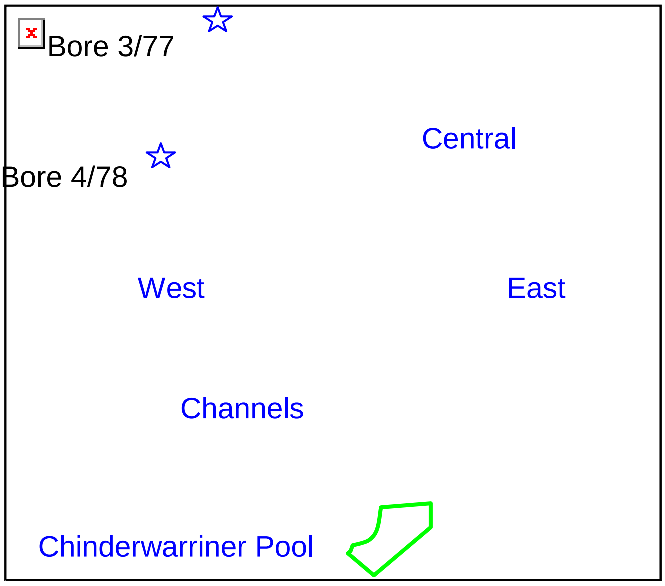


Figure B5 Millstream delta subareas

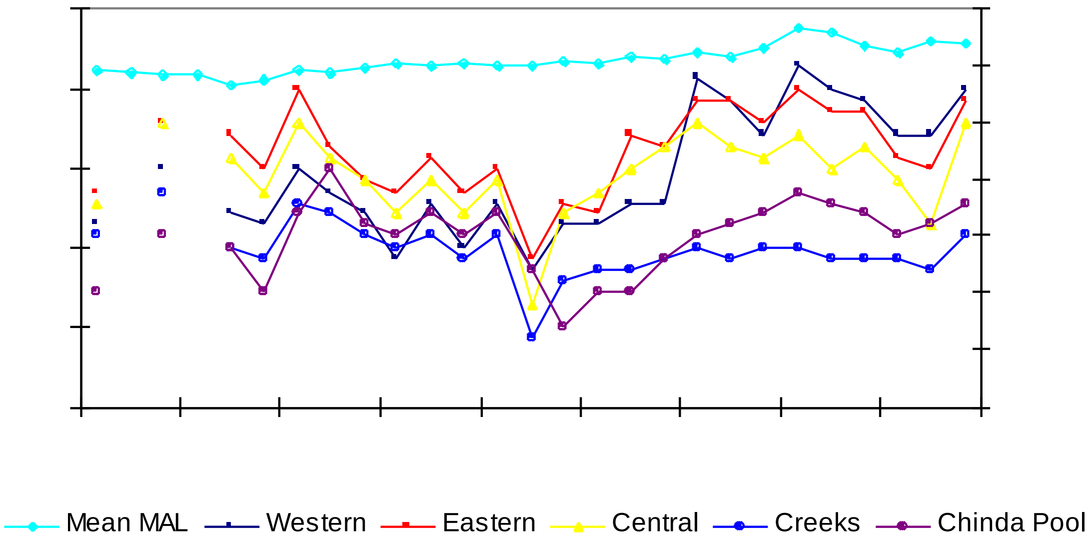


Figure B6 Millstream delta subareas PFC values and mean MAL

Analyses of PFC within the delta central and channels subareas showed no correlations to groundwater levels when the entire 1979–2005 dataset was considered; however, a modest yet significant negative (inverse) relationship existed with fire. The impact of fire on PFC in 1992 is evident in Figure B6. A similar relationship to fire was found in the eastern subarea; however, mean annual groundwater (measured at bore 3/77) and minimum MAL were also significant (Figure B8). Minimum MAL was also significant at Chinderwarriner Pool and the western subarea, where mean and maximum MAL along with mean annual groundwater (bore 4/78) (Figure B7) and flow in Chinderwarriner (Figure B9) were also significant.

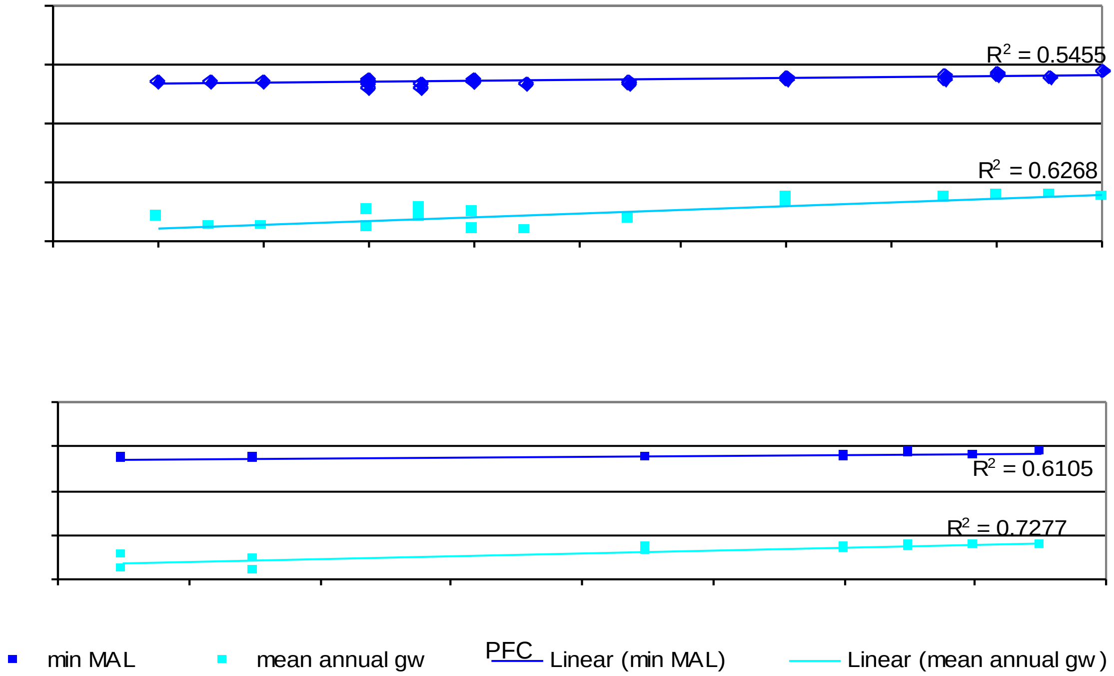


Figure B7 Western delta subarea PFC vs mean annual groundwater (bore 4/78): 1979–2005 (top chart); 1993–2005 (bottom chart)

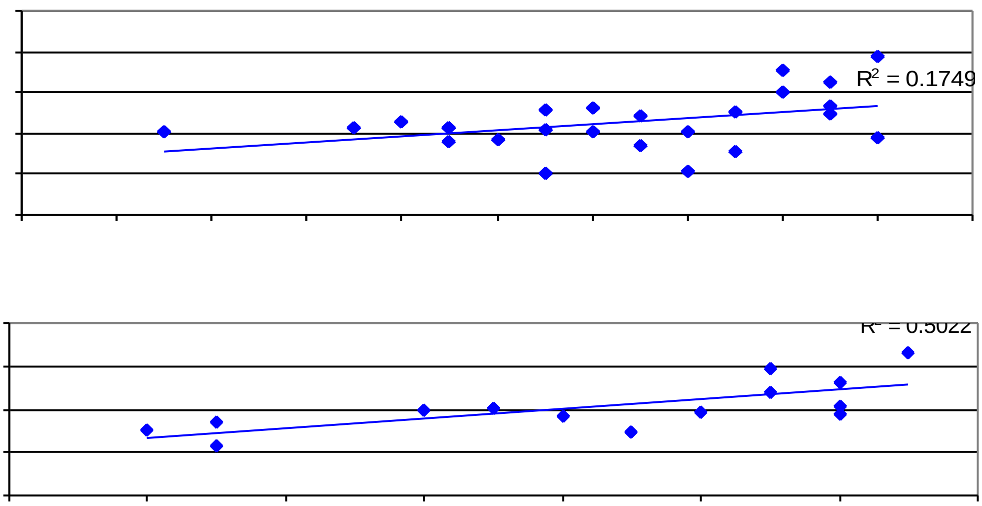


Figure B8 Eastern delta subarea PFC vs minimum MAL: 1979–2005 (top chart); 1993–2005 (bottom chart)

The 1993–2005 dataset generally showed stronger relationships between PFC and MAL levels at all subareas, with minimum MAL significant in all except delta central. Mean local groundwater (bore 4/78) was significant in the western and

Chinderwarriner Pool subareas. As would be expected, Chinderwarriner flow was significant at Chinderwarriner Pool.

In summary, although not always the most significant, minimum MAL appears to be the most reliable predictor of PFC across the delta subareas, particularly during a time when MAL is increasing. Fire is obviously also an important factor.

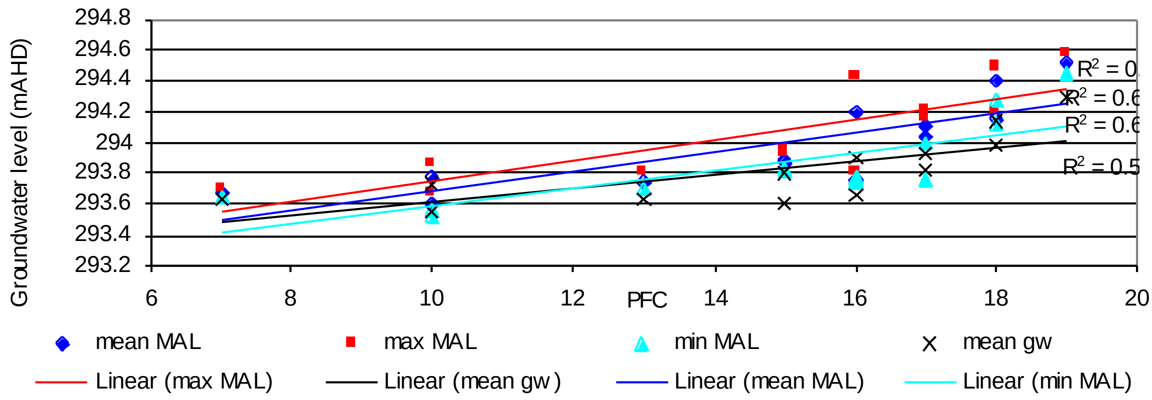


Figure B9 Chinderwarriner Pool PFC vs MAL and groundwater levels (bore 1E) 1993–2005

Analysis of Deep Reach subareas

Analyses of data were carried out for three subareas close to Deep Reach: toe, top and Coolawanyah (figures B10 and B11).

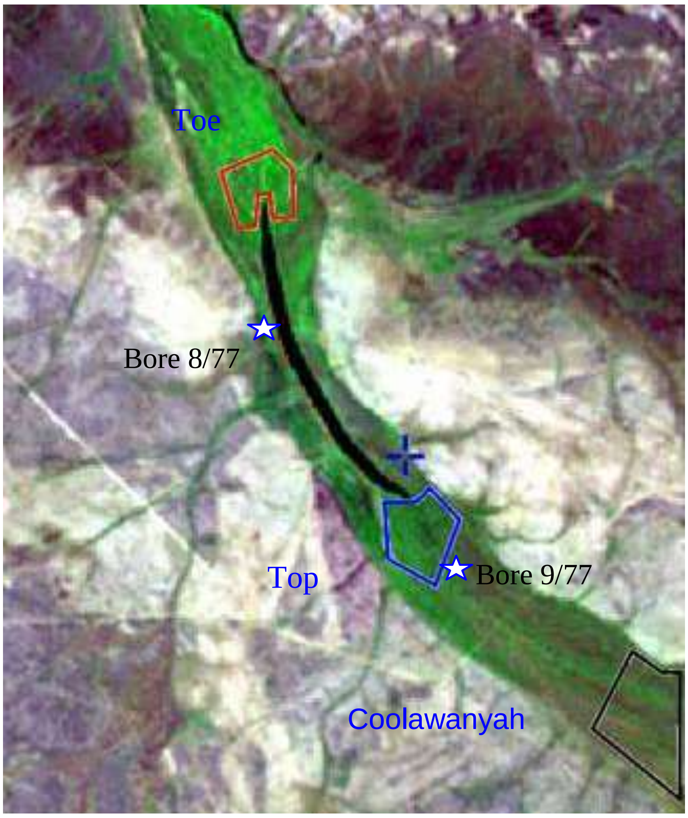


Figure B10 Deep Reach subareas

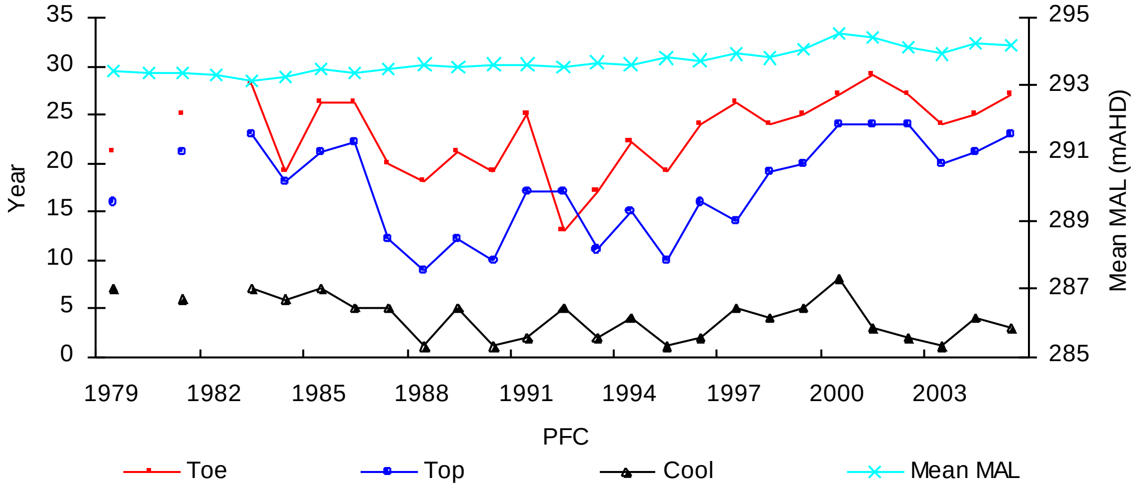


Figure B11 Deep Reach subareas PFC values and mean MAL

MAL was the strongest driver of PFC in the Deep Reach toe subarea across both time series (Figure B12) with mean and maximum MAL moderately significant over both datasets and minimum MAL moderately significant for 1979–2005. Mean annual groundwater at bore 8/77 was also significant across the longer time series. However, between 1979–2005 all relationships were negative; that is, the higher the water level the lower the PFC.

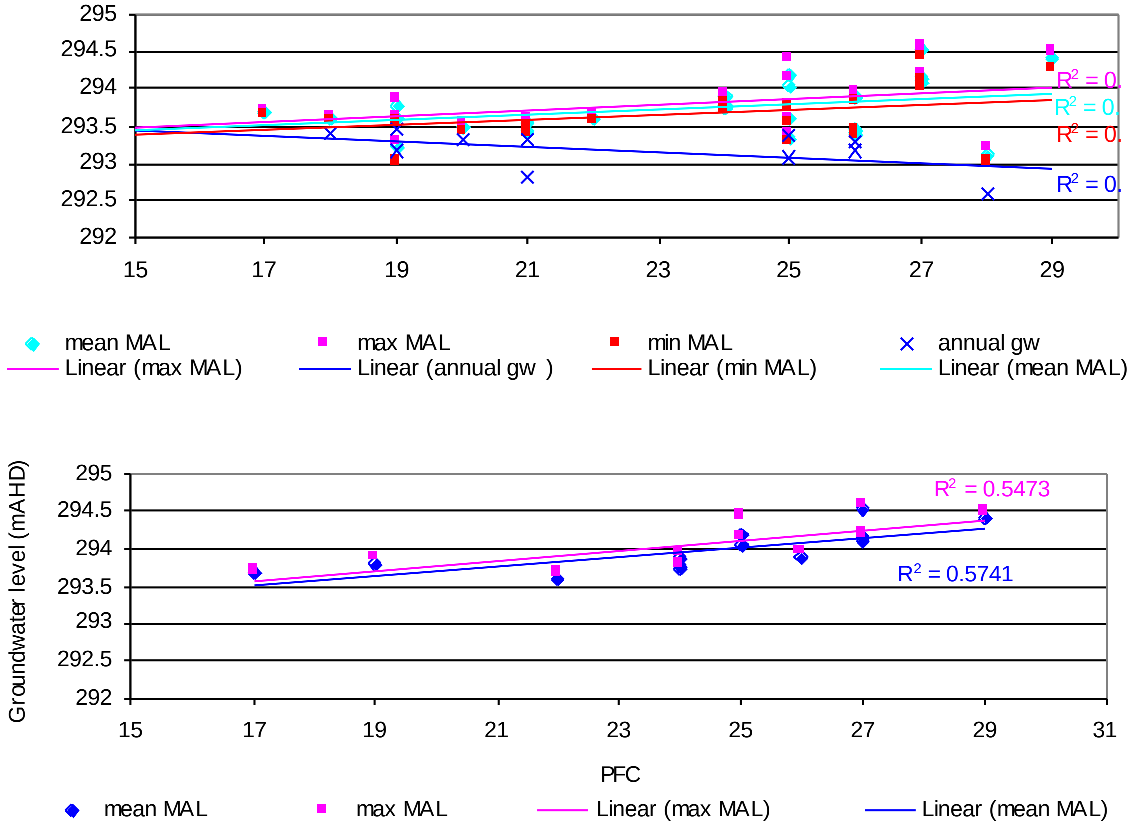


Figure B12 Deep Reach 'toe' PFC vs MAL and groundwater levels (bore 8/77): 1979–2005 (top chart); 1993–2005 (bottom chart)

Negative, moderate correlations were also found between PFC and MAL and local groundwater levels (bore 9/77) in the Coolawanyah subarea across the entire dataset. However, none of these relationships were statistically significant. The only significant relationship – Fortescue annual flow – was found in the 1993–2005 dataset.

In the top subarea, MAL (minimum, maximum and mean) and maximum groundwater with a one-year lag (9/77) were also correlated with PFC. Although these relationships were weak and non-significant across the 1979–2005 dataset, relationships strengthened to strong and statistically significant when the 1993–2005 data were considered (Figure A13). The strongest relationship from 1979–2005 was maximum groundwater with a one-year lag, and minimum MAL from 1993–2005.

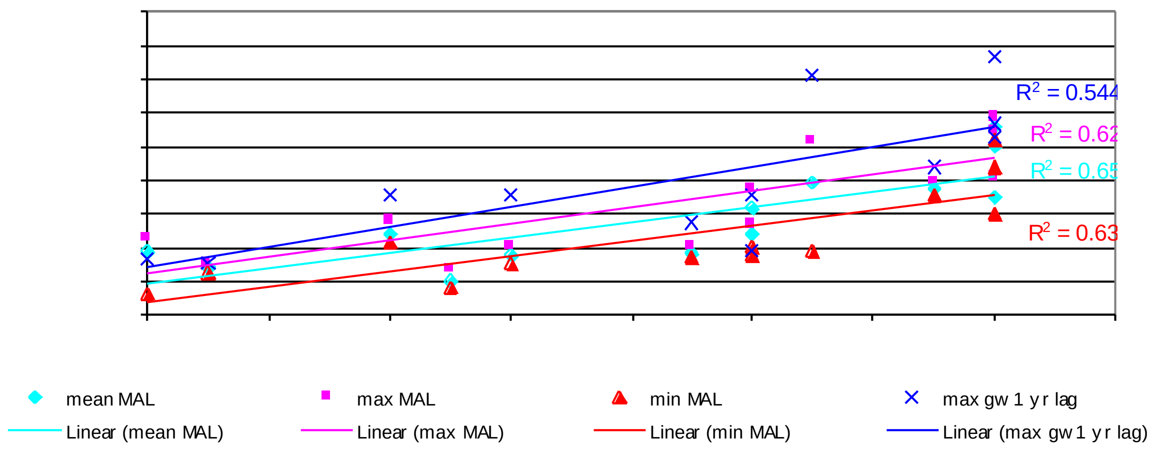


Figure B13 Deep Reach 'top' PFC vs MAL and maximum groundwater one-year lag (9/77) 1993–2005

In summary, there is no single driver of PFC in the Deep Reach area as a whole. However, the toe subarea PFC was most highly correlated with mean annual groundwater from 1979–2005 and maximum MAL between 1993 and 2005. In Coolawanyah, mean MAL was the greatest driver from 1979–2005 and Fortescue annual flow from 1993–2005, and maximum local groundwater level (with a one-year time lag) was the strongest driver within the top subarea, between 1979 and 2005 and minimum MAL from 1993–2005.

The negative correlations between PFC and MAL and groundwater levels in the toe and Coolawanyah subareas across the entire dataset appear counterintuitive. However, it is plausible that ongoing channel erosion and associated loss of trees in the toe subarea has a far greater impact on tree density, and therefore PFC, than other factors. As time series data were not available, this relationship could not be tested. Within the Coolawanyah subarea, PFC was consistently lower than other sites and showed very little temporal variation. It is possible that this consistency prevented the development of meaningful correlations.

Analysis of Livistona Pool subareas

Analyses of data were carried out for three subareas within Livistona Pool: upstream, bank and downstream (Figure B14). Unlike other areas, PFC was relatively stable from the late 1980s, with significant declines only occurring following fire events in 1993 and 2003 (Figure B15). In fact fire was the most strongly correlated variable across the 1993–2005 dataset with significant, modest to strong, negative relationships found in the three subareas.

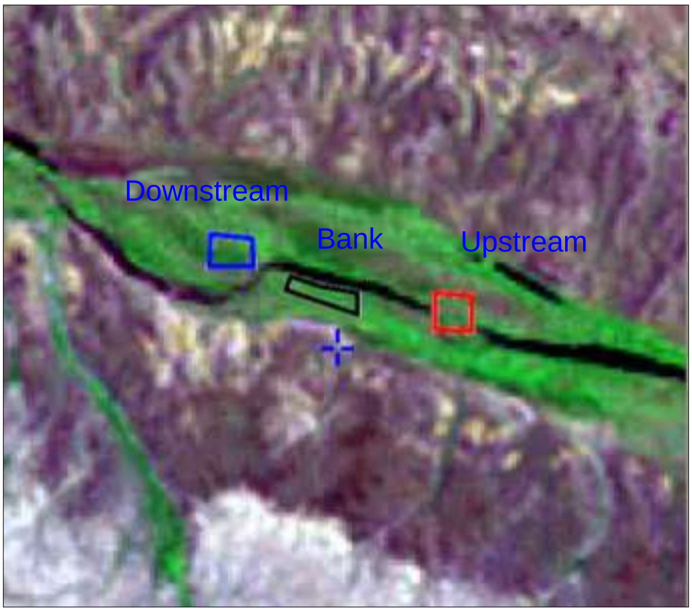


Figure B14 Livistona Pool subareas

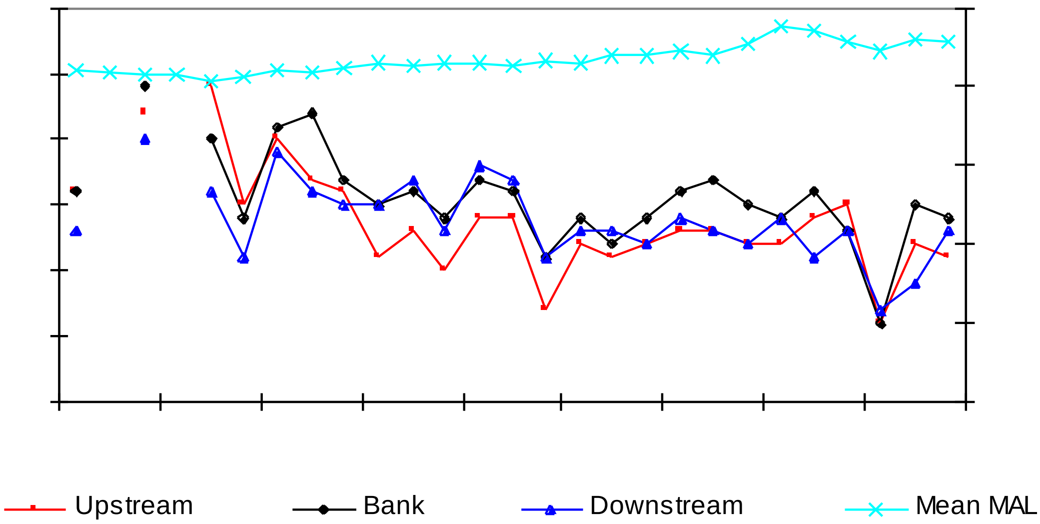


Figure B15 Livistona Pool subareas PFC values and mean MAL

Consideration of the entire 1979–2005 dataset showed significant, modest, negative correlations to maximum, minimum and mean MAL at all three subareas (Figure B16). Weak to moderate, non-significant, negative correlations were found between PFC and all other predictors. It is thought that river pools may generate perched local aquifers that sustain high soil-moisture levels (Kendrick 2007) during periods of low MAL, resulting in the relative consistency in PFC. However, when MAL increases as seen in the 1993–2005 dataset, there is the potential for associated alluvial recharge to also influence vegetation density. This is supported by positive yet weak relationships between MAL and PFC across this time period.

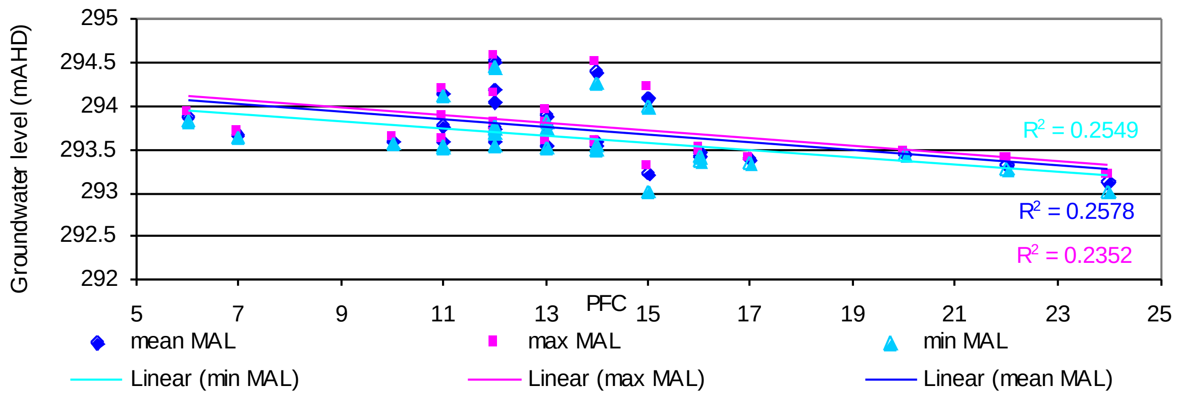


Figure B16 Livistona Pool 'upstream' PFC vs MAL 1979–2005

Analysis of Woodley Creek subareas

Analyses of data were carried out for three subareas within Woodley Creek: delta, north and south (Figure B17). PFC was relatively stable from the late 1980s in both the delta and north subareas; however, values in the south were fairly variable (Figure B18).

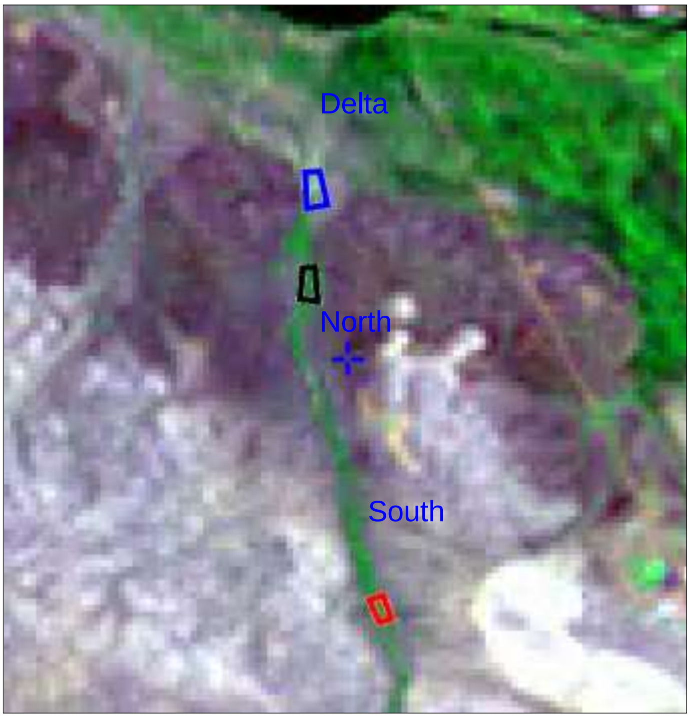


Figure B17 Woodley Creek subareas

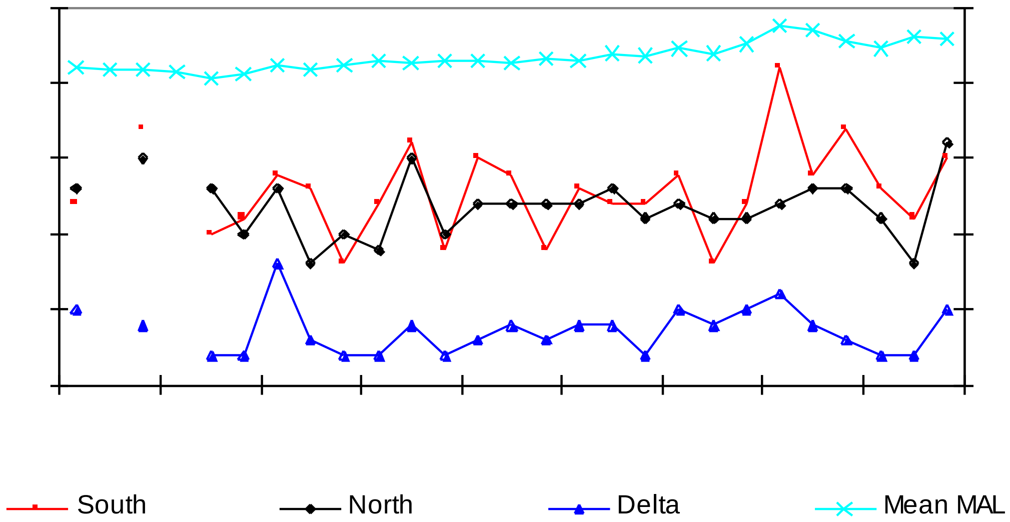
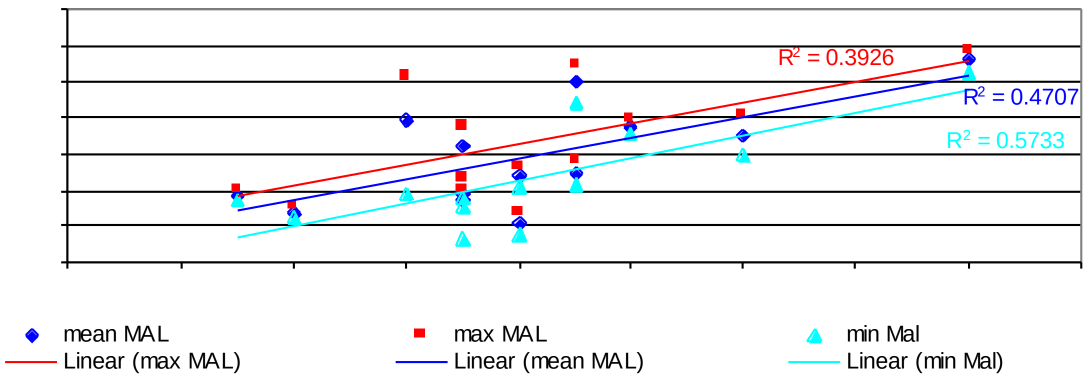


Figure B18 Woodley Creek subareas PFC values

PFC in the south subarea was most strongly correlated to MAL over both time series, although relationships were only statistically significant (with minimum, maximum and mean MAL) in the later dataset. This is not unexpected as the south subarea sits on the aquifer and vegetation condition/density should respond to changes in aquifer levels. The greater temporal variation in PFC values in this subarea in comparison with the other Woodley Creek sites therefore represents the influence of changing MAL.

The strongest correlation (weak, not statistically significant) in the north subarea between 1979 and 2005 was for total rainfall with a one-year time lag. This is not implausible as this subarea appears to sit off the aquifer downstream of the spring discharge point and some distance from the Fortescue. Consideration of the 1993–2005 dataset also shows some correlation with rainfall (weak, not statistically significant), and a negative, moderate, statically significant relationship with fire.



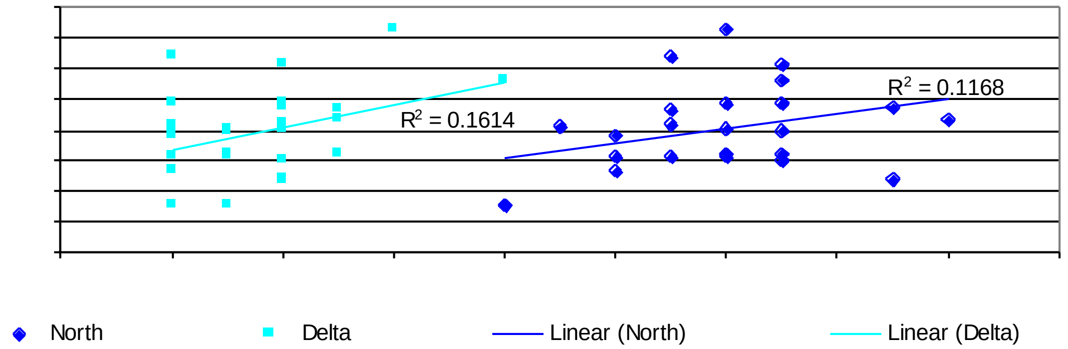


Figure B19 Woodley Creek. South PFC vs MAL (1979–2005) (top chart); north and delta PFC vs rainfall one-year lag (1993–2005)

It is thought that Woodley Creek recharges the alluvium and does not generally flow through the delta subarea to the river. In fact, groundwater in the delta subarea is fed largely by channels crossing from the Millstream delta (the relationship appears to be related to the distance that flow reaches down channel 6).

These factors may explain why PFC in this area was consistently the lowest recorded of any subareas across the entire dataset. It may also explain the correlations (moderate, not significant) with total rainfall with a one-year lag and total rainfall in the 1979–2005 and 1993–2005 time series (Figure B19) respectively.

Analysis of Typha Pool subareas

PFC from three subareas – upstream, bank and downstream – were assessed in the Typha Pool area (Figure B20). Values in all three subareas declined slightly from the mid-1980s until fire in 1993 caused a significant drop in vegetation cover (Figure B21). Cover then increased gradually until a second fire in 2003. The impact of the fires was reflected in the strength of the correlations (negative, moderate and statistically significant) in all three subareas across the 1993–2005 dataset.

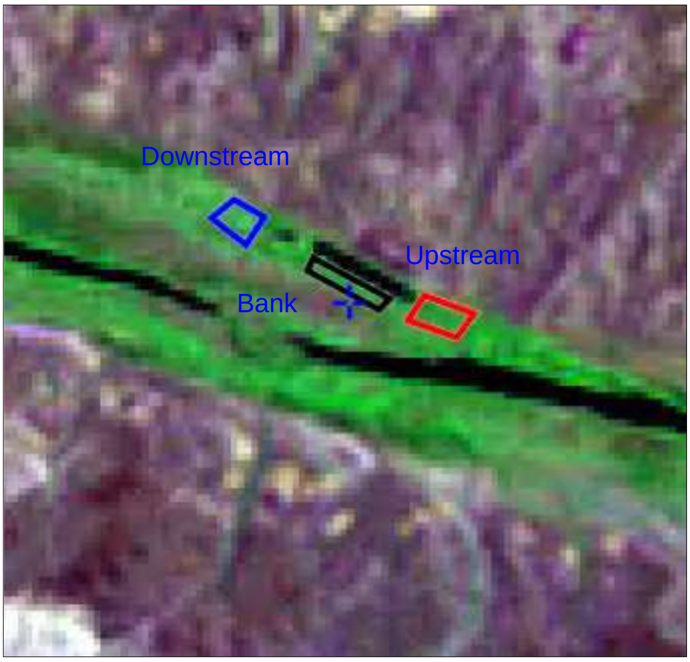


Figure B20 Typha Pool subareas

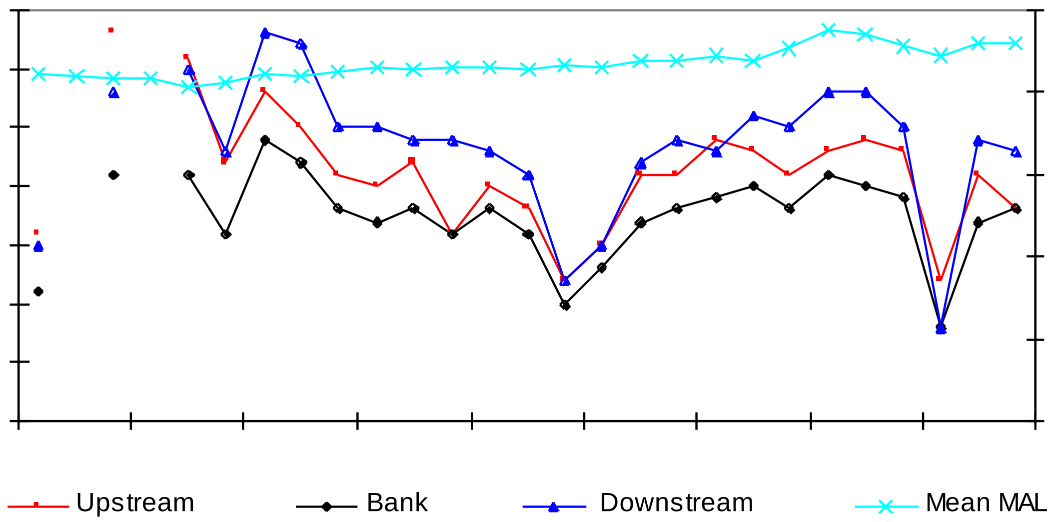


Figure B21 Typha Pool subareas PFC values and mean MAL

Similarly to Livistona Pool, there was a negative correlation between PFC and MAL (minimum, maximum and mean) in all three subareas across the 1979–2005 dataset. However, unlike the other pools, correlations were weak to very weak and not significant. As Typha Pool is also 'off' the aquifer, it is likely that riparian vegetation is accessing local groundwater during this time; however, this relationship was not tested. Although weak to very weak, the strongest positive correlation at these sites (1979–2005) was with total rainfall with a one-year time lag.

In contrast, the 1993–2005 dataset showed modest, positive, significant correlations between PFC and MAL at the downstream subarea (Figure B22) and modest relationships in the other two sites. Given the pool's location, it is possible that MAL had a similar influence to that postulated for Livistona Pool. That is, vegetation density responds to local groundwater during periods of low MAL, but during periods of high/increasing MAL the alluvium is recharged and has a greater impact on vegetation density.

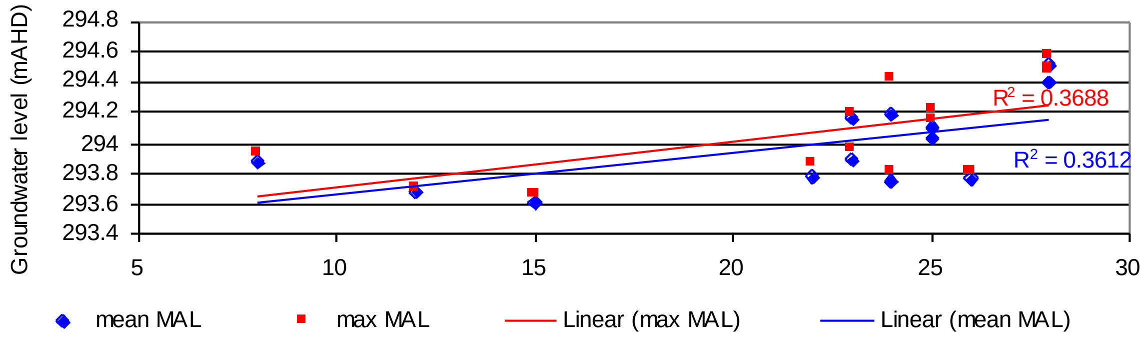


Figure B22 Typha Pool downstream subarea PFC vs MAL (1993–2005)

Analysis of Crossing Pool subareas

Two subareas were assessed within the Crossing Pool area: camp and gullies (Figure B23). PFC has generally declined since 1979 with the fires of 1992 evident as a significant drop in values that year (Figure B24). These declines also coincide with significant channel erosion at the southern end of the pool in the gullies subarea. Although some attempts were made to mechanically halt the process, no major maintenance has been carried out since 1995 (Chester 1998).

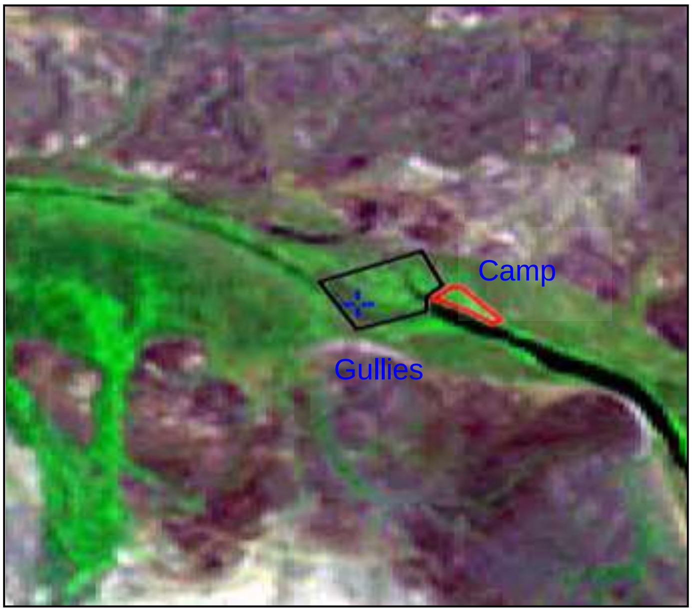


Figure B23 Crossing Pool subareas

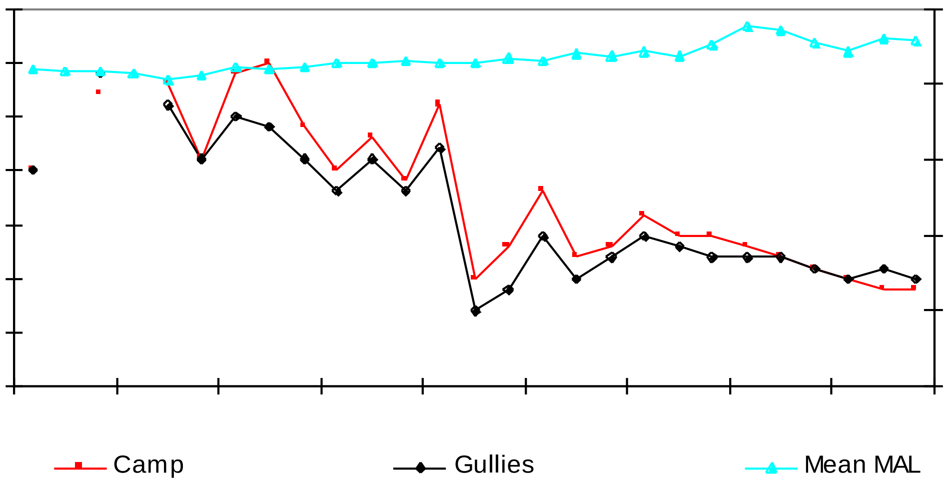


Figure B24 Crossing Pool subareas PFCs and mean MAL

As was the case with other pools, there were negative correlations between PFC and MAL (minimum, maximum and mean) in both subareas across the 1979–2005 dataset (Figure B25); however, the relationship was strong and significant.

In contrast, a positive, strong, significant correlation existed with PFC and minimum annual pool levels (Figure B26). Although it is expected that local groundwater levels have dropped in response to the declining pool levels, local bores have been inoperable (due to erosion and saltation) since the early to mid 1980s and the relationship to PFC could not be tested. The fact that Crossing Pool is also 'off' the aquifer also suggests PFC is responding to local groundwater conditions rather than MAL.

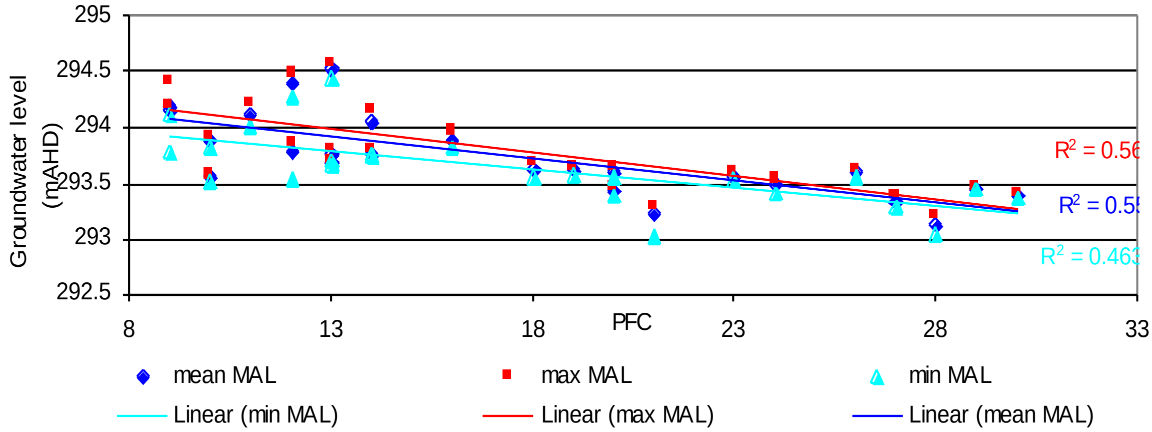


Figure B25 Crossing Pool camp subarea PFC vs MAL (1979–2005)

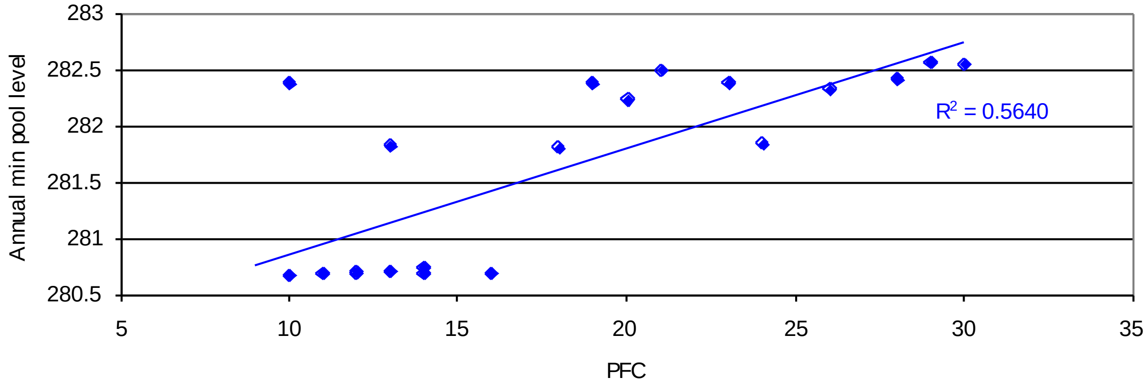


Figure B26 Crossing Pool camp subarea PFC vs pool level (1980–2003)

Analysis of Palm Pool subareas

Analyses of data were carried out for two subareas at Palm Pool: gullies and trees (Figure B27). PFC values generally declined until the late 1980s, rising again until fire in 1993; they then gradually increased until a second fire in 2003 (Figure B28).

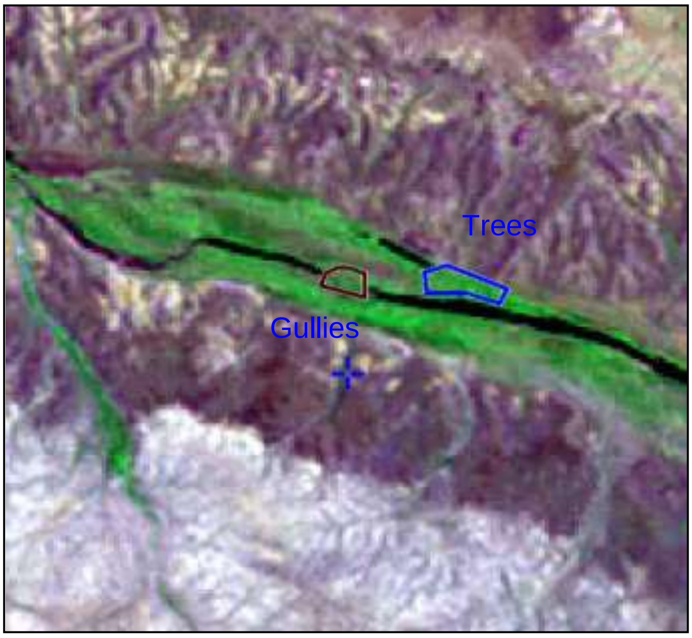


Figure B27 Palm Pool subareas

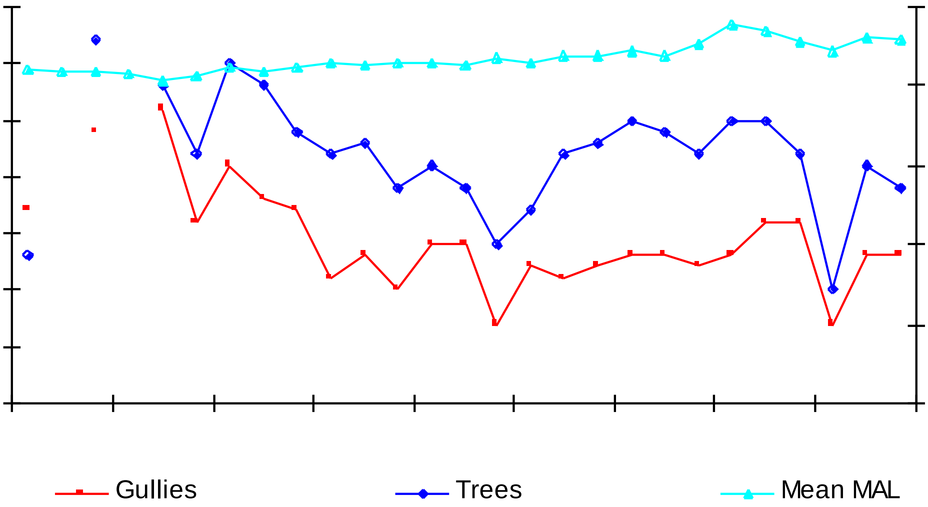
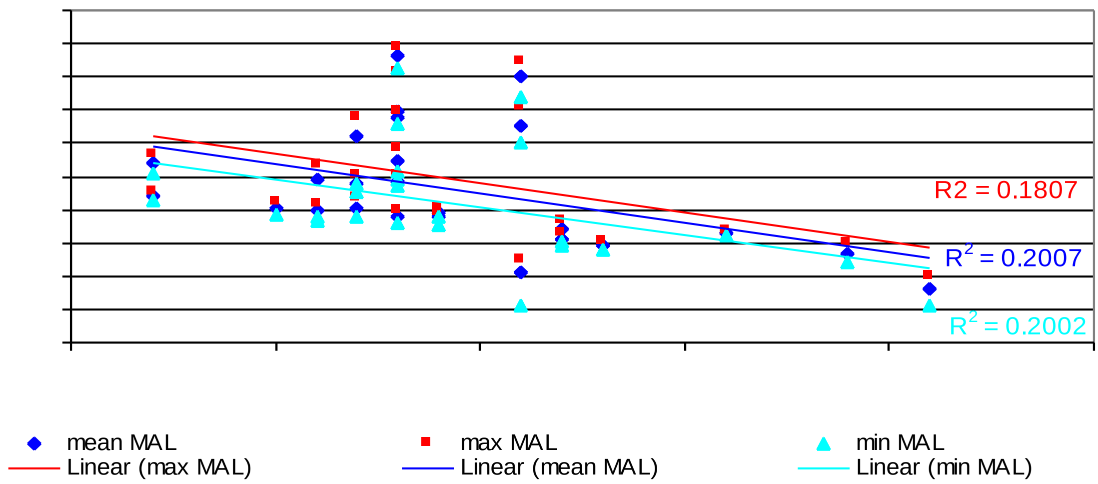


Figure B28 Palm Pool subareas PFC values and mean MAL

Yet again there were negative correlations between PFC and MAL (minimum, maximum and mean) in both subareas across the 1979–2005 dataset (Figure B29 top chart); however, the relationships were only significant in the gullies subarea. In contrast, modest, positive relationships were found between MAL and PFC in the latter dataset. Despite this, fire was most strongly correlated to PFC across this time series.

However, possibly the most relevant relationship was found with pool water levels, available from 1982–2003. These showed weak, positive relationships to PFC at both subareas across the whole dataset, improving to moderate and significant between 1993 and 2003 (Figure B29 bottom chart). The relationship was strongest in the gully subarea where PFC has been consistently lower than in the trees subarea. Given that gully erosion is also occurring at Palm Pool, it is possible that falling pool levels are also influencing local groundwater which in turn leads to declining PFC values.

The inverse (negative) relationship between PFC and MAL may also be due to Palm Pool being located off the aquifer. That is, similarly to Livistona and Typha pools, vegetation density responds to local water levels during periods of lower MAL, but during periods of high/increasing MAL the alluvium is recharged and has a greater impact on vegetation density.



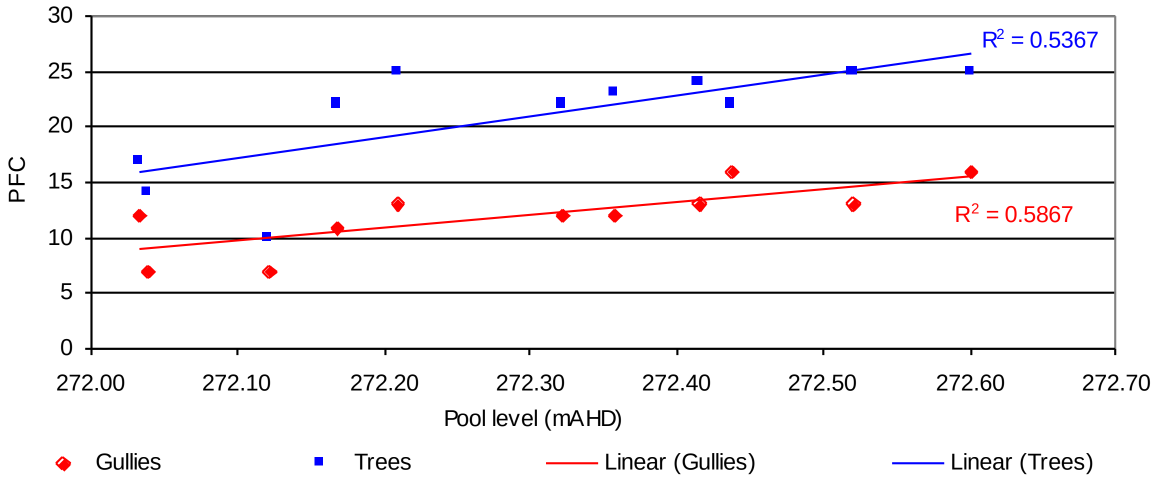


Figure B29 Palm Pool subareas. Gullies and MAL (1979–2005) (top chart); PFC vs pool level (1993–2003) (bottom chart)

Summary and recommendations

Summary

The results of this work support the findings of previous studies, which suggested that rates of change in vegetation density (as PFC) are not uniform across the Millstream wetlands and are driven by different processes.

Mean aquifer and local groundwater levels are the most important determinants of vegetation density; however, pool levels, rainfall, fire and erosion also have an influence. Although infrequent, when fire does occur, it has a greater impact on PFC than other factors. Factors driving PFC in each subarea are summarised below.

Millstream delta and Deep Reach:

- minimum MAL is the dominant driver during periods of high MAL (1993–2005)

- local groundwater is dominant during low MAL (1979–2002), as it responds more rapidly to supplementation, rainfall and river flow
- erosion and associated loss of trees in the toe subarea of Deep Reach has a far greater impact on tree density, and therefore PFC, than other factors
- there is some evidence of a one-year time lag with hydrological factors, mostly in the riverine area around Deep Reach (Time lags within the delta appear to be shorter than those within Deep Reach, so it may be acceptable to assume they are shorter than one year.)
- the impact of palm clearing in the delta is difficult to separate from increasing MAL; however, it does not appear to have affected the overall system's PFC values.

Livistona, Typha and Palm pools:

- during low MAL (1973–2002) there is an inverse relationship to PFC as river pools may generate perched local aquifers that sustain high soil-moisture levels
- MAL is the most reliable indicator during periods of high MAL (1993–2005), as it is likely that alluvial recharge increases vegetation density.

Woodley Creek:

- MAL is the most reliable indicator in the south subarea as it sits on the aquifer
- rainfall with a one-year time lag is important in the north subarea as it sits off the aquifer, downstream of the spring discharge site
- rainfall has the greatest influence on the Woodley delta as it is fed by channels crossing from the Millstream delta.

Crossing Pool:

- declines in pool water levels resulting from channel erosion have lead to declines in vegetation density. (It is likely that local groundwater has also declined and may have a stronger relationship to PFC but no bore data are available to test this assumption.)

Recommendations

Analysis of the PFC data has provided useful information on spatial and temporal changes in vegetation density across the Millstream area. However, there are a number of factors that should be considered in its application:

1 The current PFC data does not discriminate between overstorey and understorey vegetation density. This could explain why palm clearing in the Millstream delta was not evident in the dataset. That is, the palms' removal thinned the overstorey, but the understorey grew denser in response to increased light and water availability.

2 Fire effectively 'resets' vegetation density. Post-fire PFC data will reflect the re-establishment/regrowth of both overstorey and understorey and may mask the potential impacts of changed hydrology.

3 Different hydrological and environmental variables drive changes in PFC under different hydrological regimes (e.g. Millstream delta – MAL during high aquifer levels, local groundwater during low aquifer levels). This confounds the approach as long-term trends need to be considered when assessing annual data.

The issues outlined above combined with the time and expertise required to analyse PFC suggests this approach may not be the most efficient means of detecting changes in vegetation density at Millstream. However, the relationships between PFC and hydrological parameters discussed here (MAL, local groundwater, pool levels) suggest that ongoing monitoring of key parameters may be a quicker, cheaper approach. Further, the identification of hydrological trigger levels or thresholds relevant to key environmental areas could trigger management reponses before the impacts occur.

Delta and riverine – whole-system analysis

Area/ bore/ time series	Mean MAL	Max MAL	Min MAL	Total annual rainfall	Total annual rainfall 1 yr lag	Fort annual flow (GL)	Fire – yes 1 no 0	Annual min GW	Min GW 1 yr lag	Annual max GW	Max GW 1 yr lag	Chinderwarriner mean instantaneous Q (m^3/s)
Delta P3/77												
79-05	0.44440	0.43000	0.48000	0.00000	0.23000	0.14000	n/a	0.57070	0.52000	0.48000	0.57000	0.25000
93-05	0.69331	0.62401	0.77621	0.04800	0.37539	0.08927	n/a	0.76000	0.54000	0.44000	0.69000	0.44278
Riverine												
79-05	0.03555	0.04040	0.05404	-0.22073	0.17000	-0.01000	-0.0472	n/a	n/a	n/a	n/a	-0.03000
93-05	0.78570	0.76319	0.78023	0.02325	0.45454	0.18652	n/a	n/a	n/a	n/a	n/a	0.54947

Delta subareas

Subarea/ time series/ bore	Mean MAL	Max MAL	Min MAL	Total rainfall	Total rainfall 1 yr lag	Fort annual flow (GL)	Fire – yes 1 no 0	Mean annual GW	Chinderwarriner mean instantaneous Q (m^3/s)
Western P4/78									
79-05	0.7568	0.7495	0.7528	0.1149	0.2332	0.3080	-0.3542	0.7878	0.6110
93-05	0.7502	0.7101	0.7813	0.0182	0.1859	0.1717	n/a	0.8531	0.4918
Eastern P3/77									
	0.4050	0.3910	0.4164	0.1103	0.3111	0.2207	-0.5470	0.4854	0.2790
	0.5970	0.5323	0.6435	0.2484	0.3409	0.1520	n/a	0.5458	0.4103
Central P4/78									
79-05	0.1745	0.1522	0.2303	-0.0007	0.2607	0.0278	-0.6827	0.2290	0.0267
93-05	0.2477	0.1448	0.4443	0.0501	0.4933	-0.1541	n/a	0.2349	0.0552
Creeks/channels (1E)									
79-05	-0.2103	-0.2205	-0.1591	-0.1548	-0.0548	-0.1159	-0.6583	-0.1804	-0.3922
93-05	0.5012	0.4288	0.5890	0.0251	0.3927	0.0488	n/a	0.5390	0.3655
Chinderwarriner pool (1E)									
79-05	0.3932	0.3797	0.4247	-0.0763	0.1839	0.0296	-0.1694	0.3471	0.2199
93-05	0.8144	0.7950	0.7781	0.0091	0.3299	0.2135	n/a	0.7304	0.5909

Deep Reach subareas

Subarea/ time series/ bore	**Mean MAL**	**Max MAL**	**Min MAL**	**Total rainfall**	**Total rainfall 1 yr lag**	**Fort annual flow (GL)**	**Fire – yes 1 no 0**	**Mean annual GW**	**Min annual GW**	**Min GW 1 yr lag**	**Max annual GW**	**Max GW 1 yr lag**
Toe P8/77												
79-05	-0.4120	-0.4108	-0.4220	-0.2099	0.0541	-0.0966	-0.0996	-0.4758	n/a	n/a	n/a	n/a
93-05	0.5774	0.5989	0.4704	0.1665	0.3058	0.4181	n/a	0.5322	n/a	n/a	n/a	n/a
Top 9/78												
79-05	0.3367	0.3434	0.3269	-0.1931	0.1829	0.1838	-0.0472	n/a	0.0058	0.1283	0.2910	0.4388
93-05	0.7645	0.7308	0.7815	-0.2294	0.3409	0.0891	n/a	n/a	0.1853	0.3518	0.4670	0.6824
Coolawanyah												
79-05	-0.4125	-0.4117	-0.4098	-0.0919	0.1605	0.0986	0.1003	-0.3955	n/a	n/a	n/a	n/a
93-05	0.4641	0.4414	0.4640	0.4975	0.3878	0.6315	n/a	0.4516	n/a	n/a	n/a	n/a

Livistona Pool subareas

Subarea/ time series/ bore	Mean MAL	Max MAL	Min MAL	Total rainfall	Total rainfall 1 yr lag	Fort annual flow (GL)	Fire – yes 1 no 0
Upstream							
79-05	-0.5077	-0.4850	-0.5049	-0.3360	-0.0399	-0.2385	0.0855
93-05	0.3634	0.3925	0.3063	-0.1870	0.3183	0.0633	-0.6646
Bank							
79-05	-0.5432	-0.5556	-0.5034	-0.2009	-0.0093	-0.2729	0.0860
93-05	0.2409	0.2630	0.1915	0.3857	0.2632	0.2177	-0.8129
Downstream							
79-05	-0.5442	-0.5477	-0.4900	-0.2209	0.0841	-0.3525	0.2437
93-05	0.0258	-0.0367	0.1553	0.4137	0.4165	0.0510	-0.7326

Woodley Creek subareas

Subarea/ time series/ bore	Mean MAL	Max MAL	Min MAL	Total rainfall	Total rainfall 1 yr lag	Fort annual flow (GL)	Fire – yes 1 no 0	Annual mean GW
South								
79-05	0.2042	0.2248	0.2577	-0.1876	0.2255	-0.0217	-0.0412	0.1058
93-05	0.6861	0.6266	0.7572	-0.0134	0.5173	0.2370	-0.1939	0.4004
North								
79-05	-0.0016	0.0086	0.0164	-0.2617	0.3434	-0.1705	-0.2287	0.1877
93-05	0.1152	-0.0042	0.3380	-0.0973	0.2996	-0.3186	-0.6545	0.0545
Delta								
79-05	0.2283	0.2196	0.2176	0.0492	0.3684	0.2072	-0.1161	0.3224
93-05	0.3761	0.2917	0.4517	0.5516	0.4208	0.4101	-0.4086	0.2852

Typha Pool subareas

Subarea/ time series/ bore	Mean MAL	Max MAL	Min MAL	Total rainfall	Total rainfall 1 yr lag	Fort annual flow (GL)	Fire – yes 1 no 0
Upstream							
79-05	-0.1691	-0.1590	-0.1671	0.0193	0.1153	0.0375	-0.1851
93-05	0.5024	0.5207	0.4073	0.3854	0.2973	0.2921	-0.5510
Bank							
79-05	-0.0326	-0.0299	-0.0058	0.0435	0.2889	-0.0629	-0.2000
93-05	0.5488	0.5407	0.4999	0.4188	0.4298	0.2849	-0.6616
Downstream							
79-05	-0.1131	-0.1131	-0.0844	-0.0170	0.2823	-0.0527	-0.2280
93-05	0.6010	0.6073	0.5043	0.4638	0.4185	0.3701	-0.6680

Crossing Pool subareas

Subarea/ time series/ bore	Mean MAL	Max MAL	Min MAL	Total rainfall	Total rainfall 1 yr lag	Fort annual flow (GL)	Pool level	Fire – yes 1 no 0
Camp								
79-05	-0.8064	-0.7944	-0.7396	-0.1749	-0.0713	-0.2535	-0.7379	-0.2694
93-05	-0.4536	-0.4798	-0.3189	0.1949	0.2898	-0.0036	-0.4804	n/a
Gullies								
79-05	-0.7341	-0.7218	-0.66423	-0.2240	-0.0479	-0.2881	-0.7062	-0.3411
93-05	-0.0578	-0.0519	0.00768	0.0168	0.3395	-0.0293	-0.0200	n/a

Palm Pool subareas

Subarea/ time series/ bore	Mean MAL	Max MAL	Min MAL	Total rainfall	Total rainfall 1 yr lag	Fort annual flow (GL)	Fire – yes 1 no 0
Gullies							
79-05	-0.5232	-0.5217	-0.5100	-0.3439	-0.0388	-0.2535	0.0714
93-05	0.5507	0.5685	0.5005	0.0775	0.3423	0.0524	-0.5728
Trees							
79-05	-0.2012	-0.1923	-0.1865	0.0720	0.1900	0.0708	-0.1994
93-05	0.4350	0.4394	0.3714	0.4813	0.4076	0.3440	-0.7000

Shortened forms

DEC	Department of Environment and Conservation
DoW	Department of Water
EWR	environmental water requirement
GDE	groundwater-dependent ecosystem
GW	groundwater
MAL	mean aquifer level
MSS	Multispectral (Landsat imagery)
PFC	percentage foliage cover
TM	Thematic Mapper (Landsat imagery)

Glossary

Abstraction The permanent or temporary withdrawal of water from any source of supply, so that it is no longer part of the resources of the locality.

Aquifer A geological formation or group of formations capable of receiving, storing and transmitting significant quantities of water. Usually described by whether they consist of sedimentary deposits (sand and gravel) or fractured rock.

Bimorphic Having two distinct forms.

Biodiversity Biological diversity or the variety of organisms, including species themselves, genetic diversity and the assemblages they form (communities and ecosystems). Sometimes includes the variety of ecological processes within those communities and ecosystems.

Biomass The total amount of living material in a given habitat, population, or sample. Specific measures of biomass are generally expressed in dry weight (after removal of all water from the sample) per unit area of land or unit volume of water.

Biota The living organisms occupying a place together, e.g. marine biota, terrestrial biota.

Detritivore An organism that feeds on and breaks down dead plant or animal matter, returning essential nutrients to the ecosystem.

Ecological water requirement Water regime needed to maintain the ecological values (including assets, functions and processes) of water-dependent ecosystems at a low level of risk.

Ecosystem A community or assemblage of communities of organisms, interacting with one another, and the specific environment in which they live and with which they also interact, e.g. a lake. Includes all the biological, chemical and physical resources and the interrelationships and dependencies that occur between those resources.

Environment Living things, their physical, biological and social surroundings, and the interactions between them.

Flow Streamflow in terms of m3/s, m3/d or ML/a. May also be referred to as discharge

Food web a series of organisms related by predator-prey and consumer-resource interactions; the entirety of interrelated food chains in an ecological community.

Groundwater Water that occupies the pores and crevices of rock or soil beneath the land surface.

Groundwater-dependent ecosystems An ecosystem that is dependent on groundwater for its existence and health.

Habitat The area or natural environment in which an organism or population

	normally lives. A habitat is made up of physical factors such as soil, moisture, range of temperature, and availability of light as well as biotic factors such as the availability of food and the presence of predators.
Hydrogeology	The hydrological and geological science concerned with the occurrence, distribution, quality and movement of groundwater, especially relating to the distribution of aquifers, groundwater flow and groundwater quality.
Invertebrate	An animal without a backbone.
Life cycle	The series of changes in the growth and development of an organism from its beginning as an independent life form to its mature state in which offspring are produced.
Macrophyte	a plant, esp. an aquatic or marine plant, large enough to be visible to the naked eye.
Phreatophyte	A plant (often relatively deep rooted) that obtains water from a permanent ground supply or from the water table.
Planiform	having a flattened shape.
Stygofauna	fauna that live within groundwater systems, such as caves and aquifers, or more specifically small, aquatic groundwater invertebrates.
Surface water	Water flowing or held in streams, rivers and other wetlands on the surface of the landscape.
Wetland	Wetlands are areas that are permanently, seasonally or intermittently waterlogged or inundated with water that may be fresh, saline, flowing or static, including areas of marine water of which the depth at low tide does not exceed 6 metres.

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